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# Ultra-Low NOx Measurement and Emission Factors Evaluation of a Compressed Natural Gas (CNG) Heavy-Duty Engine

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ABSTRACT OF THE THESIS

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by

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Heavy duty on-road vehicles represent one of the largest sources of $NO_x$ emissions and fuel consumption in North America. Heavy duty vehicles are predominantly fueled with diesel, with the recent interest in natural gas (NG) systems. As emissions and greenhouse gas regulations continue to tighten new opportunities for advanced fleet specific heavy duty vehicles are becoming available with improved fuel economy. $NO_x$ emissions have dropped 90% for heavy duty vehicles with the recent 2010 certification limit. Additional $NO_x$ reductions of another 90% are desired for the

South Coast Air basin to meet its 2023 $NO_x$ inventory requirements and the California optional low NOx standard in 2015.

One of the difficulties in quantifying $NO_x$ emissions at the levels proposed in this research (90% of the 2010 certification level ~ 0.02 g/bhp-hr) is the measurement methods are approaching their detection limit to sufficiently quantify $NO_x$ emissions. Three upgraded $NO_x$ measurement methods were considered which include a raw $NO_x$ measurement integrated with real time exhaust flow, a real-time ambient correction approach, and a trace level ambient analyzer for accurate bag analysis. In summary the improved methods varied in their success where the raw sampling approach showed to be the most accurate and precise over the rage of conditions tested.

The ISL G NZ 8.9 liter NG engine met and exceeded the target $NO_x$ emissions of 0.02 g/bhp-hr. This engine significantly reduced 97%-100% of $NO_x$ emissions compared with previous ISL G 8.9 engines. The NOx emissions decreased as the duty cycle was decreased which was the opposite trend for the diesel vehicles. It is expected NG vehicles could play a role in the reduction of the south coast $NO_x$ inventory problem given their near zero emission factors demonstrated.

*Key words:* $NO_x$ emission, Particle mass, Particle number, Natural gas engine.

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# Acronyms and Abbreviations

SCR ………………………………………... Selective catalytic reduction

SCAQMD …………………………….. South Coast Air Quality Management District

SCAB ………………………………….. South Coast Air basin

CARB.................................................California Air Resources Board

$CH_4$ ……………………………………. Methane

OC …………………………………...... Oxidation catalyst

bcf/y …………………………………….billion cubic feet per year

TWC …………………………………….three way catalyst

EGR …………………………………….engine exhaust recirculation

CE-CERT...........................................College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)

CFR...................................................Code of Federal Regulations

CO.....................................................carbon monoxide

$CO_2$...................................................carbon dioxide

CNG..................................................compressed natural gas

CWI...................................................Cummins Westport Inc.

FID....................................................flame ionization detector

$NH_3$ ..................................................ammonia

g/bhp-hr.............................................grams per brake horsepower hour

MEL..................................................mobile emission laboratory

NOx...................................................nitrogen oxides

OEM..................................................original equipment manufacturer

PM.....................................................particulate matter

PM2.5................................................ultra-fine particulate matter less than 2.5 µm (certification gravimetric reference method)

PN .....................................................particle number

PSD...................................................particle size distribution

RPM....................................................revolutions per minute

scfm...................................................standard cubic feet per minute

THC....................................................total hydrocarbons

UCR ....................................................University of California at Riverside

FE.......................................................Fuel economy

NG......................................................natural gas

CNG ....................................................compressed natural gas

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# 1. Introduction

The presence of atmospheric pollutants plays a vital role in the overall quality of the environment and health of the living beings in their surroundings. Among the air pollutants, ozone ($O_3$) and nitrogen oxides ($NOx = NO + NO_2$) are of particular interest [1]. Long term exposures to $O_3$ have been shown to increase the risk of death from respiratory illness, have adverse effects on the human health and impact the well-being of children exposed to air pollution [2]. Though, NO does not significantly affect human health, it is one of the main compounds involved in the formation of ground level $O_3$, and it can react to form nitrate particles, acid aerosols, and $NO_2$, which also causes respiratory problems and contributes to the acid rain formation [3, 4]. The photochemical reaction through which NOx produce more ozone ($O_3$) is shown by the following reaction equations.

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + hv(+O_2) \rightarrow NO + O_3$$

The main sources of NOx in the air are combustion processes, especially vehicle emissions in high traffic areas. Heavy duty on-road vehicles represent one of the largest sources of NOx emissions in North America. Heavy duty vehicles are predominantly equipped with diesel engines, which have been subject to increasingly more stringent requirements. With the introduction of 2010 0.2 grams per brake horse power hour (g/bhp-hr) certification limit, NOx certification emission levels have dropped 90% for heavy duty engines compared to 2002 levels [5]. While this led to the widespread introduction of selective catalytic reduction (SCR) systems, additional reductions are still needed to meet air quality standards in various areas in California. Currently, thirteen basins in California did not meet federal standards 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 it off that list. 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. It has been estimated that NOx reductions of another 90% for heavy-duty vehicles will be needed for the South Coast Air basin (SCAB) to meet future air quality 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. The California Air Resources Board (CARB) has defined this Near Zero emissions certification level of 0.02 g/bhp-hr NOx as being equivalent to a 100% battery truck using electricity from a modern combined cycle natural gas power plant. There is also consideration of implementation the 0.02 g/bhp-hr NOx standard to all new heavy-duty engines as part of future regulations.

One fuel that has been considered to be a promising alternative to diesel fuel for achieving emissions reductions has been natural gas (NG). NG and NG engines have employed in some capacity in heavy-duty applications for several decades now. NG or compressed NG (CNG), which is primarily composed of methane ($CH_4$), has unique chemical properties with a high H/C ratio and high research octane number (about 130). The low levels of carbon-carbon bonds in NG and the absence of aromatics compared to diesel fuel reduces soot formation in NG engines [9]. Another potential advantage of NG is that it has become more available domestically and its production has increased considerably in recent years, along with the extent of available reserves. In the United States (U.S.), NG annual production has increased from 24,119 billion cubic feet per year (bcf/y) in 2003 to 30,005 bcf/y in 2013, resulting in a 24.4% increase in NG production over that period (U.S. EIA, 2015). United States is also the world's largest NG producer, followed by Russia and Iran.

Increasing the performance to NG engines to be comparable to that of diesel engines can be a challenge due to the low calorific value of the air–fuel mixture, slow combustion speed, and low intake volumetric efficiency [10]. First generation NG engines were based on spark ignition lean-burn technology. Initially, these engines featured open loop air-fuel control, but toward the mid-1990s, closed loop control was implemented [11]. Oxidation catalysts (OCs) were also incorporated in the mid-1990s with NG engines, as needed, to meet tougher emissions for THC and CO emissions [12]. These engines generally provided emissions reductions compared with similar diesel engines, although not under all test conditions, and in some cases they even can produce much higher emissions than a comparable diesel engine without exhaust gas aftertreatment [13]. Additionally, there were limitations to level of NOx reductions that could be achieved through the lean burn technology engines, as OCs are not designed for the reduction of NOx.

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. To meet the more aggressive emissions standards, stoichiometric NG engines with three way catalysts (TWCs) were introduced. The drawback for such engines is that they have to operate with a stoichiometric mixture, which leads to higher heat losses, higher pumping work at low to medium loads, higher thermal stress on the engine and higher knock tendency. One way to reduce these drawbacks is to dilute the stoichiometric mixture using exhaust gas recirculation (EGR). The EGR system can recirculate a portion of an engine's exhaust gas back to the engine cylinders, which results in lower combustion temperatures. As a result, stoichiometric natural gas engines with TWCs and EGR were developed, with the Cummins Westport Inc (CWI) [13]. ISL G NG engine being the most extensively produced such engine. By operating the engine stoichiometric with EGR and using a TWC, NOx emissions could be reduced by 99.9% and HC emissions by 90-97% compared to the lean high-efficiency strategy. Hajbabaei et al. [14] compared emissions of a bus equipped with lean burn combustion and OCs with a stoichiometric CNG bus equipped with a TWC and EGR and found that the stoichiometric engine bus showed significantly reduced NOx and THC emissions compared to the lean burn buses, but did show higher levels of carbon monoxide (CO) and ammonia ($NH_3$).

More recently, the stoichiometric ISL G engine has undergone additional improvements to reduce NOx emissions down to the 0.02 g/bhp-hr level. These engines, designed by CWI, are being certified as ISL G 8.9 L near zero (NZ) engines. The ISL G NZ also meets the 2017 EPA greenhouse gas emission requirements with a 9% GHG reduction from the current ISL G. They are designed to be used in transit buses, refuse haulers, medium duty trucks shuttle buses and school buses. One of the early demonstrations of this engine technology in a vehicle is with a refuse hauler operating in the greater Los Angeles area. This vehicle has been used in the field as part of its demonstration. It was also important, however, to verify that the low NOx emissions levels obtained during certification are maintained under a variety of operating conditions.

The goals of this study were to measure and evaluate the ISL G 8.9 NZ liter ultra-low NOx NG vehicle emissions with chassis dynamometer and mobile emissions laboratory (MEL). The vehicle evaluated is one of the initial demonstrations of the engine technology in a refuse hauler. The emissions collected in this study include PM, PN, NOx, CO, fuel economy (FE), $NH_3$, and $CO_2$. An important aspect of this study was the accurate characterization of NOx emissions at and below the 0.02 g/bhp-hr level. Given the low NOx concentrations expected, additional measures were implemented to help quantify the low NOx emissions, as the traditional measurement methods with ambient subtraction are approaching their quantification detection limits. In additional to two traditional methods, three upgraded NOx measurement methods were utilized in this study for comparison. The results for this engine are compared with previous ISL G engines that were certified to 0.2 g/bhp-hr for NOx emissions to evaluate the effectiveness of the new technology in reducing emissions.

# 2. Experimental procedures

## 2.1 Test fuel

California pipeline fuel was used for this study which represents typical NG available in Southern California. The fuel properties were measured during the emissions testing and are presented in Table 1. The gas composition is reported on a Mole percent basis. The H/C or hydrogen to carbon atom ratio in the hydrocarbon portion of the gas blend was 3.905. 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 |

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 1. 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) = 0.58. MN methane number determined via California Air Recourses Board (CARB) calculations [15, 16] was 95.90. The Wobbe number, which is the HHV/square root of the specific gravity of gas blends with respect to air, was 1363. The higher the Wobbe number 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. Methane number is a measure of the knock resistance of a gas, with the knock resistance of a gas increasing with increasing methane number [17].

## 2.2 Test engine and vehicle

The test article was a stoichiometric spark ignited ISL G near zero (NZ) 320 Cummins Westport Inc. (CWI) Natural Gas engine. The specifications of the engine are provided in Table 2. The engine was initially certified at 0.2 g/bhp-hr NOx and 0.01 g/bhp-hr PM based on the family number ECEXH0540LBH found on the engine label and the executive order (EO) published on the CARB website. 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 engine is equipped with EGR system and a TWC.

**Table 2** Summary of selected main engine specifications

| Mfg | Model | Year | Eng. Family | Rated Power (hp @ rpm) | Disp.(liters) | Adv NOx Std g/bhp-hr | PM Std. g/bhp-hr |
|---|---|---|---|---|---|---|---|
| CWI | ISL G NZ | 2014 | ECEXH0540LBH | 320 @ 1800 | 8.9 | 0.02 | 0.01 |

For this program, a test weight of 56,000 lb was used for all test cycles, as discussed below. This weight is representative for refuse haulers operating in the SCAB. A test weight of 56,000 lb. was also utilized during previous testing of refuse haulers with diesel and NG engines by UC Riverside and West Virginia University (WVU) [18].

## 2.3 Test cycles and measurement protocol

The test vehicle utilized an 8.9 liter NG engine, which is used for three typical vocations in the South Coast Air Basin, 1) refuse, 2) bus, and 3) goods movement. The engine was provided in a refuse hauler application, which is one of the more common uses for the 8.9 liter engine. In order to characterize emissions from this engine over a wider range of in-use applications, goods movement and bus cycles were also tested. The vehicle was tested following the three port cycles (Near Dock, Local, and Regional), the Urban Dynamometer Driving Schedule (UDDS) cycles, the Central Business District (CBD) bus cycles, and the refuse truck cycles (RTC). These cycles are representative of Sothern California driving. Some cycles are short (less than 15 minutes), so composite driving schedules using two or three back-to-back iterations of these cycles (2x or 3x) cycles were utilized in order capture enough PM mass to quantify emissions near 1 mg/bhp-hr. A description of the main characteristics of each of the test cycles is provided in Table 3.

The William H. Martin RTC (Refuse Truck Cycle) was originally developed by WVU to simulate waste hauler operation [19]. The cycle has an average speed of 10.6 miles/hour and covers a total distance of 6.17 miles. The cycle consists of a transport segment, a curbside pickup segment, and a compaction segment.

**Table 3** Summary of statistics for the various proposed driving cycles

| Cycle | 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 | 3661 |
| UDDSx2 | 5.55 | 18.8 | 1061 |
| CBDx3 | 3.22 | 20.2 | 560 |

## 2.4 Emission testing

The chassis dynamometer testing was 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 emissions measurements were obtained using CE-CERT's MEL with a full constant volume sampling (CVS) system [20, 21]. For all tests, standard emissions measurements of total hydrocarbons (THC), nonmethane hydrocarbons (NMHC), $CH_4$, CO, NOx, carbon dioxide ($CO_2$), and PM mass were performed according to CFR (Code of Federal

Regulations) Title 40 (40 CFR) 1065 requirements. Information from the engine control module (ECM) was collected under the J1939 protocol.

Total particle number (PN) counts, particle size distributions (PSDs), and PM mass were measured through a secondary dilution tunnel. Total PM mass was collected using 47 mm Teflon filters and measured with a 40 CFR Part 1065-compliant microbalance in a temperature and humidity controlled clean chamber. The laboratory was equipped to measure PSDs with TSI's Engine Exhaust Particle Sizer 3090 (EEPS), PN with a TSI 3776 condensation particle counter (CPC), soot PM mass with AVL's Micro Soot Sensor (MSS 483), $NH_3$ emissions with an integrated real-time tunable diode laser (TDL), and integrated bag measurements of nitrogen dioxide ($N_2O$) emissions with a Fourier Transform Infrared Spectrometer (FTIR) configured for low concentrations.

One of the difficulties in quantifying NOx emissions at 90% of the 2010 certification level (0.02 g/bhp-hr) is that the exhaust NOx emissions are near the background levels, making it difficult to quantify the NOx levels. Two traditional methods were used for this study, including real-time modal and bag measurements from the traditional CVS using the traditional ambient correction. . In additional to the two traditional methods, three NOx upgrade methods were considered for this project. These included 1) real-time raw sampling and exhaust flow measurements, 2) real-time ambient second by second corrections, and 3) advanced trace type analyzer bag measurements. The new measurement methods required instrumentation upgrades which are discussed as method 3, method 4 and method 5 below. The improved methods varied in their success, as discussed further below.

**Two traditional Methods:**

The traditional NOx measurement methods are described in the next two equations. The first equation is the real-time modal measurement corrected for the ambient bag concentration and real time dilution factor, Method 1 (M1). The second traditional equation (M2) is based on dilute bag and ambient bag concentrations and an integrated dilution factor over the cycle.

$$NO_{x\_m1} = \sum_{i=1}^{n}\left(Q_{cvs_i} * \Delta t_{\mathrm{i}}\right) * \rho_{NO_x} * \left(C_{m_i} - C_a * \left(1 - \frac{1}{DF_i}\right)\right)_{M1}$$

Where:

| | |
|---|---|
| NOx_m1 | the Method 1 NOx measurement method (g/cycle) |
| Q $cvs_i$ | is the instantaneous CVS flow |
| ρNOx | is the density of NOx from 40 CFR Part 1065 |
| $Cm_i$ | is the instantaneous NOx concentration measured with the dilute NOx 600 HCLD CAI analyzer |
| Ca | is the ambient bag NOx concentration measured by the 600 HCLD CAI analyzer |
| $DF_i$ | instantaneous dilution factor |

$$NO_{x\_m2} = \left(Q_{cvs\_ave} * \Delta t\right) * \rho_{NO_x} * \left(C_d - C_a * \left(1 - \frac{1}{DF_{ave}}\right)\right)$$

Where:

| | |
|---|---|
| NOx_m2 | the Method 2 NOx measurement method (g/cycle) |

| | |
|---|---|
| Qcvs_ave | is the average CVS flow |
| ρNOx | is the density of NOx from 40 CFR Part 1065 |
| Cd | is the dilute bag NOx concentration measured with the dilute NOx 600 HCLD CAI analyzer |
| Ca | is the ambient bag NOx concentration measured by the 600 HCLD CAI analyzer |
| DFave | average dilution factor |

**Raw NOx measurements**

The raw NOx measurements utilized a 300 HCLD CAI analyzer which sampled raw exhaust through a low volume heated sample line. A low volume design was utilized to improve the response time of the analyzer to provide a better correlation with the exhaust flow measurements. The heated filter for this sample line was acid treated to minimize $NH_3$ interferences with the NOx measurement. A real-time high speed exhaust flow meter (100 Hz model EFM-HS Sensors Inc) was used to align the NOx concentrations with real-time exhaust flow measurements. The EFM-HS was correlated with UCR's dual CVS system prior to testing to improve the accuracy between the raw and dilute CVS methods and to eliminate exhaust flow biases from propagating through the comparisons between methods. For Method 3 (M3) there is no ambient correction.

**Trace level NOx analyzer**

A trace level chemiluminescence NO-$NO_2$-NOx analyzer model 42C manufactured by Thermo Environmental Instruments Inc (TECO) was used for the real-time ambient measurements and the low level bag analysis. This analyzer has been operating within CE-CERT's atmospheric research laboratories for ambient NOx quantification for several years. This analyzers was calibrated and integrated specially for this ultra-low NOx project. The span for the TECO instrument was set to 600 ppb and it showed a signal to noise ratio about an order in magnitude lower than the traditional (600 HCLD) analyzer. The signal averaging was reduced from 30 seconds to 1 second for the TECO and it showed a T10-90 and a T90-10 just over 10 seconds (slightly higher than the specifications of 40 CFR Part 1065). The slightly slower time constant should not impact the gradual transients expected during real-time ambient measurements or bag concentrations. Although this trace analyzer does not meet the requirements of 1065, it does provide a good assessment of NOx emissions below 1 ppm with an ambient trace type NOx analyzer. For Method 4 (M4), the real time dilute NOx is corrected using real time ambient NOx measurements on a second by second basis. For Method 5 (M5), the trace NOx analyzer is used to measure the dilute bag and ambient bags (similar to Method 2).

**Table 4** NOx measurement methods traditional and upgraded

| Type | Analyzer | Meth. ID | Description |
|---|---|---|---|
| Traditional | 600 HCLD dil | M1 | Real-time modal measurement corrected for the ambient bag concentration and real time dilution factor |
| | 600 HCLD amb | | |
| Traditional | 600 HCLD dil | M2 | Dilute bag NOx measurement corrected for the ambient bag concentration and average dilution factor |
| | 600 HCLD amb | | |
| Upgrade | 300 HCLD raw | M3 | Real-time raw NOx (no ambient bag correction).Acid filter was used to reduce the effect of $NH_3$ |
| Upgrade | 600 HCLD dil | M4 | Real-time modal dilute NOx with ambient real time correction |
| | TECO amb | | |
| | TECO dil | M5 | Trace analyzer dilute bag with trace ambient bag correction |
| Upgrade | TECO amb | | |

# 3. Results and Discussion

The emission are presented on a g/bhp-hp basis, which is the same unit used during certification testing for comparing to the regulatory limits. The work of the engine is calculated utilizing the friction torque, actual 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.

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

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)

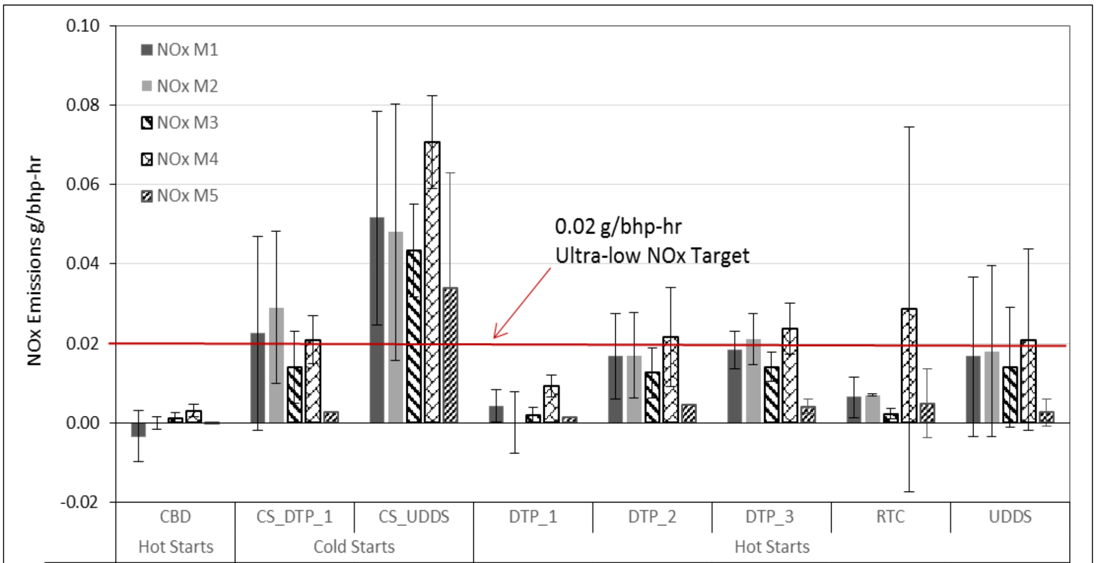
Torque_reference reference torque (ft-lb) as reported by the ECM (J1939)

The error bars in the graphs represent a single standard deviation of the average due to the relatively large magnitude of the error bars in relationship to the low emission levels measured for several species. Based on the three repeats that were performed on each cycle, the 95% confidence interval can be obtained by multiplying the single standard deviation by 3.182.

The UDDS cycle is the representative test cycle for comparisons to the engine certification FTP cycle, while the other cycles (port, refuse, and bus) provide a comparison in-use driving under low duty cycles, cruise conditions, and other vocational specifics of the real world.

## 3.1 $NO_X$ emissions

The NOx emissions are presented in Figure 1 or each of the methods evaluated and for all the test cycles performed. In general, the NOx emissions were at or below the ISL G NOx certification standard of 0.02 g/bhp-hr for most tests and below the in-use NTE standard of 0.03 g/bhp-hr. The NOx emissions were below the demonstration 0.02 g/bhp-hr emissions targets for the hot DPT1, RTC, and the CBD for all measurement methods, except for method 4 on the RTC cycle. The NOx emissions were extremely low for the CBD cycle, which was originally designed for transit bus. The average value for the CBD cycle is about 0.00086, or near zero. It should be noted that negative emission rates for some tests are due to high ambient bag concentrations compared to the dilute exhaust concentrations. Importantly, NOx emissions did not increase with the low duty DPT1 cycle. The low NOx emissions under low duty conditions is different from diesel engines, which typically cannot achieve high enough exhaust temperatures for the SCR system to work at low loads. This may be partially accounted for by higher exhaust temperatures for the NG engine during lower duty cycles compared to typical diesel engines. Within the experimental variability, NOx emissions were either at or below the 0.02 g/bhp-hr level for the cold start DPT1, the local and regional port cycles (DPT2 and DPT3), and the UDDS cycles. The cold start emissions were higher than the hot tests when comparing between like tests (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 are due to the catalysts being below its light-off temperature when the catalyst begins from a cold condition.




| | CBD | CS_DTP_1 | CS_UDDS | DTP_1 | DTP_2 | DTP_3 | RTC | UDDS |
|---|---|---|---|---|---|---|---|---|
| | Hot Starts | Cold Starts | | Hot Starts | | | | |
| NOx M1 | -0.003 | 0.022 | 0.052 | 0.004 | 0.017 | 0.018 | 0.006 | 0.017 |
| NOx M2 | 0.000 | 0.029 | 0.048 | 0.000 | 0.017 | 0.021 | 0.007 | 0.018 |
| NOx M3 | 0.001 | 0.014 | 0.044 | 0.002 | 0.013 | 0.014 | 0.002 | 0.014 |
| NOx M4 | 0.003 | 0.021 | 0.071 | 0.009 | 0.022 | 0.024 | 0.029 | 0.021 |
| NOx M5 | 0.000 | 0.003 | 0.034 | 0.001 | 0.005 | 0.004 | 0.005 | 0.003 |

**Figure 1** Measured NOx emissions of 5 methods for the various test cycles

The variability shown by the large error bars in Figure 1 was investigated further by evaluating the real-time NOx emissions. 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. Figure 2 shows the real-time NOx emissions and engine speed for three UDDS cycles, where '0813', '0915' and '1020' represent different test IDs. The real-time data shows that the majority of the higher NOx mass emissions resulted from a few large spikes. These NOx spikes 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 shows that the NOx concentration and exhaust flow spikes occurred simultaneously and were usually a result of a rapid acceleration.

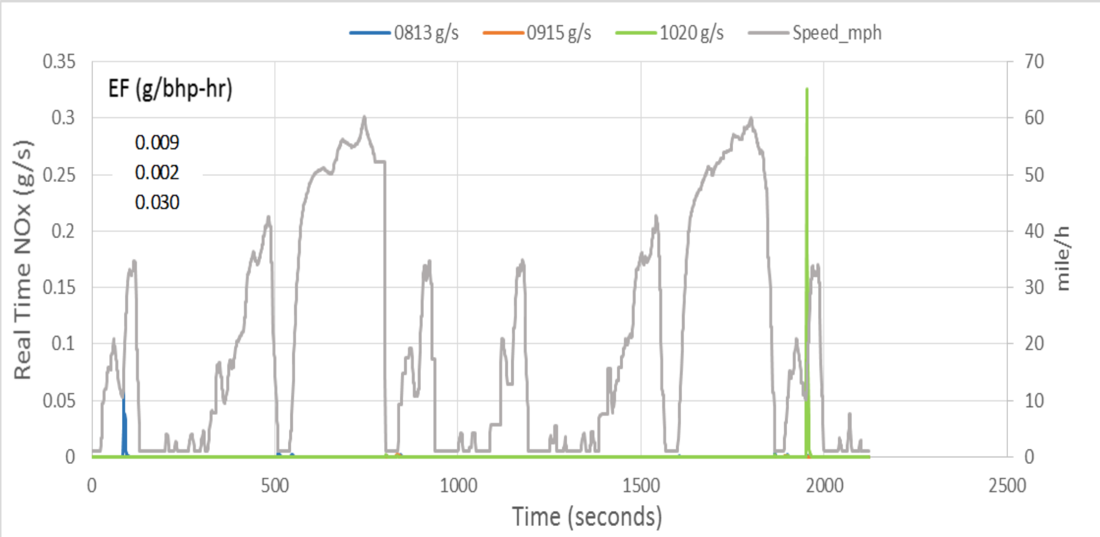



**Figure 2** Real-time NOx emissions of hot UDDS cycles

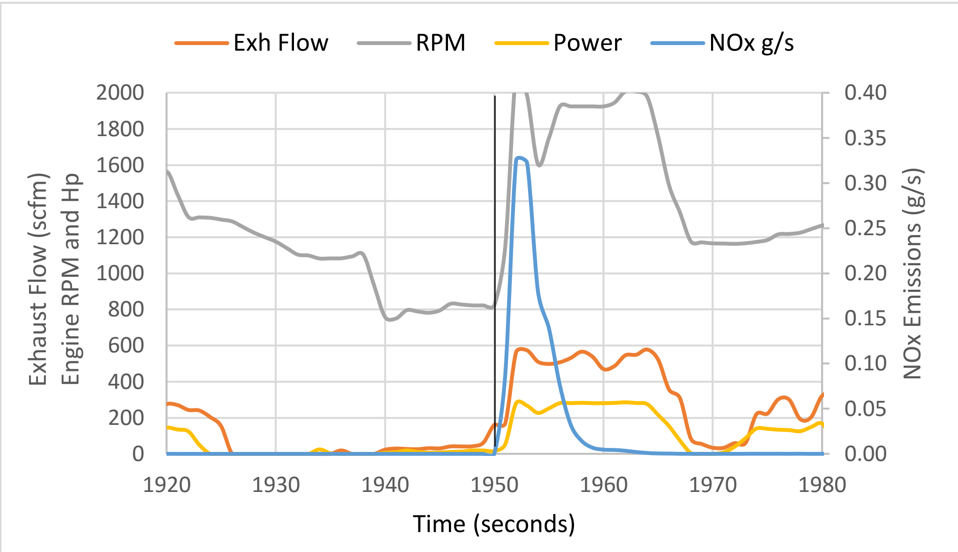



**Figure 3** Real-time NOx emissions compared with Exhaust Flow, Engine RPM and Hp

Comparisons were also made between the NOx emissions for the different measurement methods. The mean differences in average NOx emissions for the different measurement methods compared to method M1 are shown in Table 5. For M2 the average NOx emissions was very similar to M1, only 5% higher on average, but varied from higher to lower than M1 from cycle to cycle. M3 was slightly, but consistently, lower (-18% on average) than M1, except for the CBD tests. The M4 average NOx emission rate was notably higher than M1, and generally more variable. M4 is on average 40% higher than M1. The M4 utilized real-time ambient concentrations for background subtraction. Since M1 and M4 both utilize the same dilute modal NOx measurement, the differences in these two measurements can be attributed to differences in the ambient measurements. Specifically, the ambient measurements from M1 are consistently higher than those for M4, such that the net concentration of the dilute sample minus the above the ambient concentration is higher for M4. This is especially true for the cold start (CS) UDDS cycles and RTC cycles. The average for M5 was significantly lower for all tests compared to the M1 traditional method. For the M1 to M5 comparison, the M5 dilute measurements were consistently lower than those of the M1 method, for nearly all tests. The nature of this discrepancy is not understood, but could be related to drift or analyzer stability issues with the M5 analyzer, or to some other issues. In this regard, it should be noted that the M3 measurements, which represent a third independent measurement of NOx concentrations, were closer to the M1 method, suggesting that the M1 measurements are more reliable than the M5 measurements.

**Table 5** NOx emission average percent difference from Method 1

| Cycles | M2 | M3 | M4 | M5 |
|---|---|---|---|---|
| CS UDDS | -17% | -40% | 96% | -87% |
| CS DPT1 | 31% | -42% | -8% | -99% |
| UDDS | 7% | -13% | 21% | -70% |
| RTC | 4% | -21% | 111% | -7% |
| DPT1 | -21% | -11% | 25% | -14% |
| DPT2 | 3% | -20% | 25% | -61% |
| DPT3 | 12% | -22% | 27% | -72% |
| CBD | 19% | 23% | 32% | 16% |
| Ave | 5% | -18% | 41% | -49% |
| Stdev | 17% | 20% | 40% | 42% |

A comparison of the statistical significance between the traditional M1 and other methods, using the average of all the cycles, is provided in Table 6. The two tailed paired t-test results suggest the two traditional methods do not have statistically different means at the 95% confidence level, see Table 6 where the M2 p-value >> 0.05, which indicates that there were no statistically differences in the measurement variability for M1 and M2. The upgraded methods compared to M1 showed a great difference. The M3 (raw exhaust flow approach) mean difference was not statistically significant at 95% confidence (M3 p-value > 0.06), but was at the 90% confidence level. The M4 and M5 upgraded methods, on the other hand, both have statistically different means (p-value < 0.05 for both).

**Table 6** Comparison to traditional Method 1 measurement (modal dilute NOx)

| Method | t-test p-value | f-test |
|---|---|---|
| M2 | 0.521 | 0.998 |
| M3 | 0.060 | 0.152 |
| M4 | 0.021 | 0.141 |
| M5 | 0.001 | 0.104 |

As discussed previously, the ambient concentration is subtracted from the dilute concentration prior to calculating the mass based emissions for methods by M4. Under standard testing conditions, this subtraction is typically a larger number minus a small number. At the 0.02 g/bhp-hr emission level, however, the concentrations in the diluted exhaust are now at much more similar levels as the ambient concentrations. The ambient corrected NOx concentration (Ca_cor) utilized in the dilution measurements is the product of ambient NOx concentration and an inverse ratio of the dilution factor, see equation below. If Ca_cor is divided by the dilute NOx measurement, we get a factor that is representative of how large the ambient concentration is in comparison with the dilute NOx measured. This factor demonstrates the influence that ambient measurements have at and below 0.02 g/bhp-hr NOx emissions. Figure 4 shows the ambient fraction of dilute NOx concentration distribution for M1. The graph includes a total of 24 tests, which includes each of the 8 test cycles done in triplicate. The distribution results show that for 7 tests, or approximately 29 percent of the tests, that the ambient concentrations were equal to or higher than the dilute exhaust concentrations. Additionally, for 16 cycles, which is about 60% of the total cycles, the ambient fraction of dilute NOx concentration is equal or larger than 60%, such that the actual NOx concentration being quantified by difference is less than half of the ambient level. The numbers indicate the ambient background subtraction at the low concentrations measured by dilute methods will have an important impact for all the methods, except for M3 that utilizes a raw sampling approach where no ambient correction is needed.

$$C_{a\_cor} = C_a * \left(1 - \frac{1}{DF_{ave}}\right)$$

Where:

| | |
|---|---|
| Ca_cor | is the ambient NOx concentration factor corrected for the dilution term |
| Ca | is the ambient bag NOx concentration |
| DF ave | cycle average dilution factor (typically 20-30) |
| $\left(1 - \frac{1}{DF\_ave}\right)$ | dilution factor term (varied from 0.95 to 0.98 in this study) |

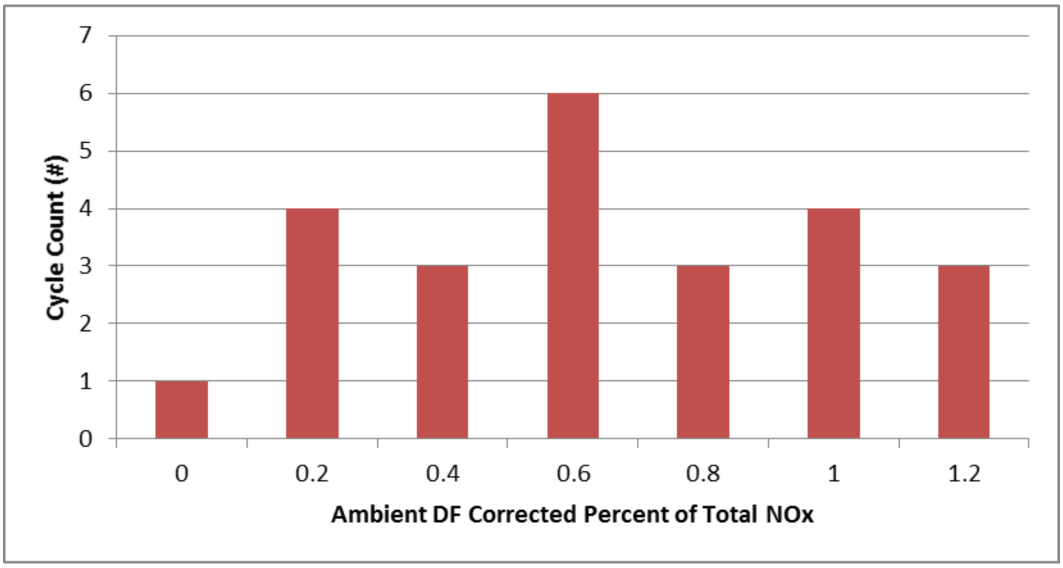



**Figure 4** Ambient fraction of dilute NOx concentration distribution

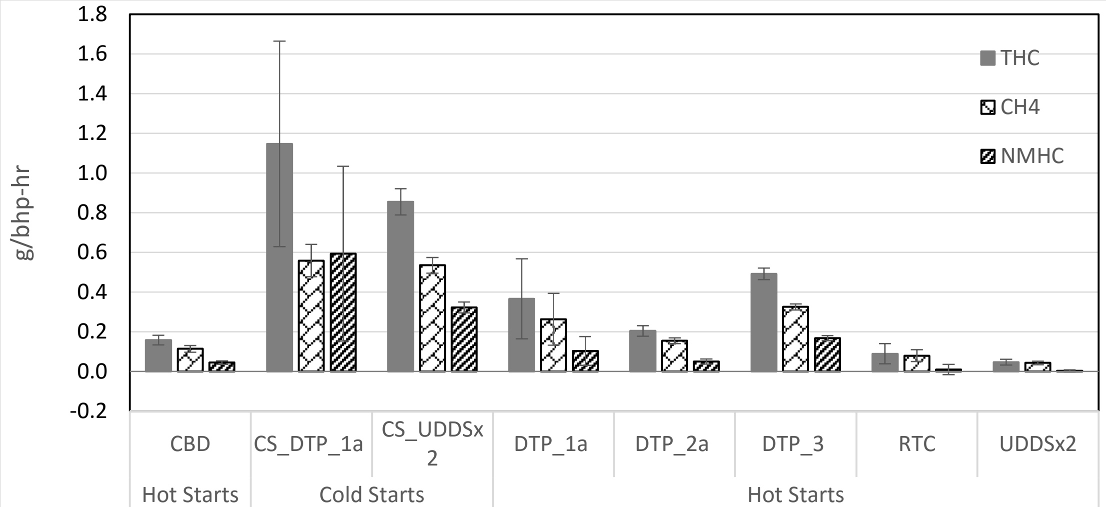
Table 7 shows the 10th, 50th, and 90th percentile statistics for the concentration of ambient NOx and dilute exhaust NOx for M1 and M5, and raw exhaust NOx concentrations for M3 in ppm units. The 90th percentile ambient and dilute NOx concentrations for M1 were 0.234 ppm and 0.632 ppm, while for M5 were 0.090 ppm and 0.115 ppm. As Table 7 shows, the 90th percentile of cycle average dilute NOx exhaust concentrations in M1 is 0.632 compared to 0.115 for M5. This is consistent with the higher readings for M1 compared to M5 shown above in Table 1. As discussed above, the exact nature of discrepancy is not understood and will require further investigation.

**Table 7** Cycle averaged raw, dilute, and ambient measured concentrations (ppm) statistics

| Percentile | M1 Ambient | M1 Dilute | M5 Ambient | M5 Dilute | Raw |
|---|---|---|---|---|---|
| 90th | 0.234 | 0.632 | 0.090 | 0.115 | 6.533 |
| 50th | 0.070 | 0.168 | 0.026 | 0.064 | 0.554 |
| 10th | 0.021 | 0.033 | 0.008 | 0.006 | 0.070 |

## 3.2 THC, NMHC, $CH_4$, CO and $NH_3$ emissions

The hydrocarbon emissions (THC, $CH_4$, and NMHC) are presented in Figure 5. The HC are highest for the cold start tests compared to the hot tests where the regional port cycle (DTP3) showed the highest HC emissions. For all the hot tests, NMHC was below the standard, but just above the reported certification value, except for the regional port cycle. The NMHC emissions were typically lower then $CH_4$ emissions, as one would expect for a NG fueled vehicle. The $CH_4$ emissions were lower than the certification, FEL level of 0.65 g/bhp-hr. Also the $CH_4$ emissions for ISL G NZ in this study with RTC cycles is significantly lower than previously tested NG reuse haulers with the 2010 certified NG 8.9 liter engine (0.18 g/mi vs 6.8 g/mi) . The lower $CH_4$ emissions may be a result of the closed crankcase ventilation (CCV) improvement over previous versions of this engine. Because methane in the crankcase emissions can be redirected back to the combustion room to be burned as fuel again with the CCV system.




| | CBD | CS_DTP_1a | CS_UDDSx 2 | DTP_1a | DTP_2a | DTP_3 | RTC | UDDSx2 |
|---|---|---|---|---|---|---|---|---|
| | Hot Starts | Cold Starts | | Hot Starts | | | | |
| THC | 0.1586 | 1.1465 | 0.8547 | 0.3660 | 0.2048 | 0.4921 | 0.0896 | 0.0465 |
| CH4 | 0.1140 | 0.5584 | 0.5348 | 0.2630 | 0.1551 | 0.3253 | 0.0798 | 0.0433 |
| NMHC | 0.0450 | 0.5939 | 0.3230 | 0.1040 | 0.0502 | 0.1684 | 0.0099 | 0.0032 |

**Figure 5** Hydrocarbon emission factors (g/bhp-hr)

Figure 6 shows the CO emissions on a g/bhp-hr basis. The CO emissions ranged between 1.3 to 5.3 g/bhp-hr for the regional (DPT3) and cold start near dock (DPT1) test cycles, respectively. The corresponding distance specific emissions (not shown) ranged from 4.2 to 24.3 g/mi for the regional (DPT3) and the cold start UDDS test cycles. The CO emissions of all the cycles tested in this study are below the U.S. EPA & California 2015 CO emission standard for heavy-duty engines, which is 15.5 g/bhp-hr.

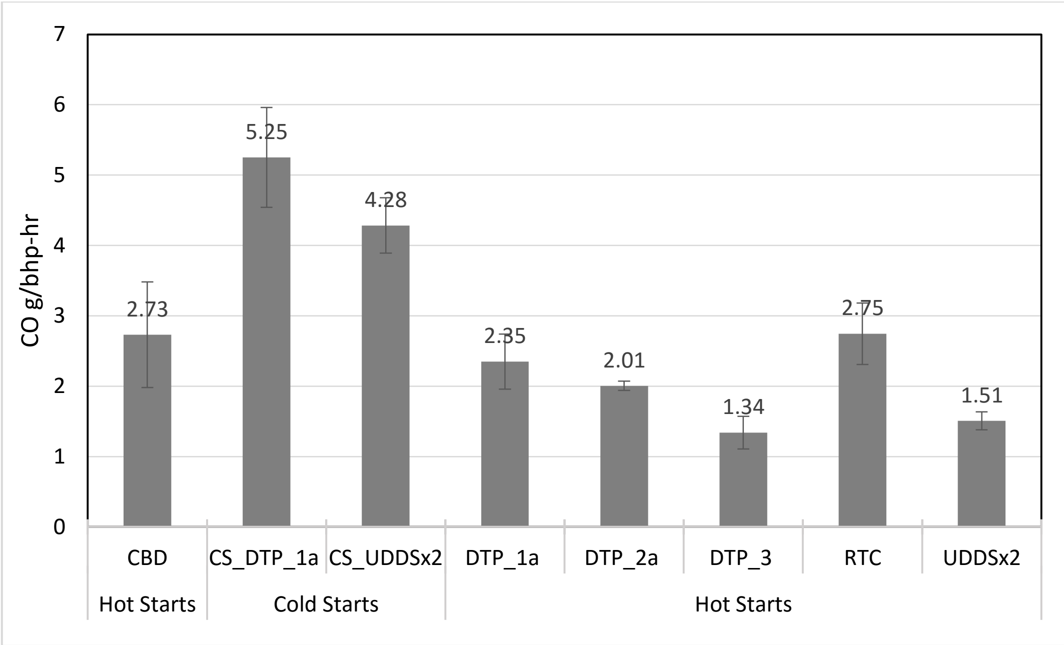



**Figure 6** CO emission factors (g/bhp-hr)

Figure 7 shows the $NH_3$ emissions on a g/bhp-hr basis. The average $NH_3$ emissions ranged between 0.12 to 0.93 g/bhp-hr for all the cycles. For the CBD and DTP 1 cycles which have the lowest duty and NOx emissions, the $NH_3$ emissions are the highest, which is reasonable due to the operation characters of TWC discussed in section 3.5, ‘Emission factors compared with a previous ISL G 8.9 engine certified as 0.2 g/bhp-hr’.

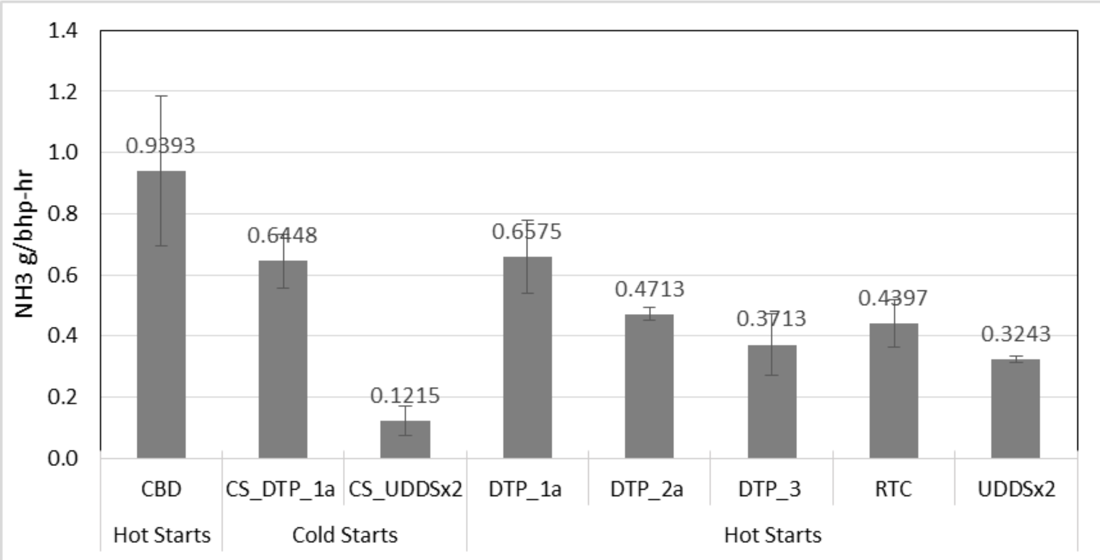



**Figure 7** $NH_3$ emission factors (g/bhp-hr)

## 3.3 PM mass, particle number and particle size distributions

The PM emissions for all the tests including the cold start tests was typically 90% below the certification standard and close to UCR tunnel blank value of 0.42 g/bhp-hr, see Figure 8. The first regional PM filter weight was statistically higher than the other three (80, 21, 20 µg), which the possibility that something may have burned off the exhaust system that may have been an artifact of previous vehicle operation. If the first PM results was eliminated, the DPT3 emission rate would be reduced from 1.01 mg/bhp-hr to 0.5 mg/bhp-hr. In either case, all the emission rates were well below the certification standard of 10 mg/bhp-hr.

Low PM results are expected for a NG fueled engine where previous studies showed similar PM emissions well below 10 mg/bhp-hr. The low levels of PM mass emissions are attributed to the fact that natural gas is primarily comprised of $CH_4$, which is the lowest molecular weight HC and has a simpler structure compared to diesel or gasoline fuels [22]. That means products of the reaction have simpler structure, which mainly including methanol, formaldehyde, ethane, benzene. The main source of PM in natural gas engines is considered to be the entry of engine lubricating oil into the combustion chamber [22].

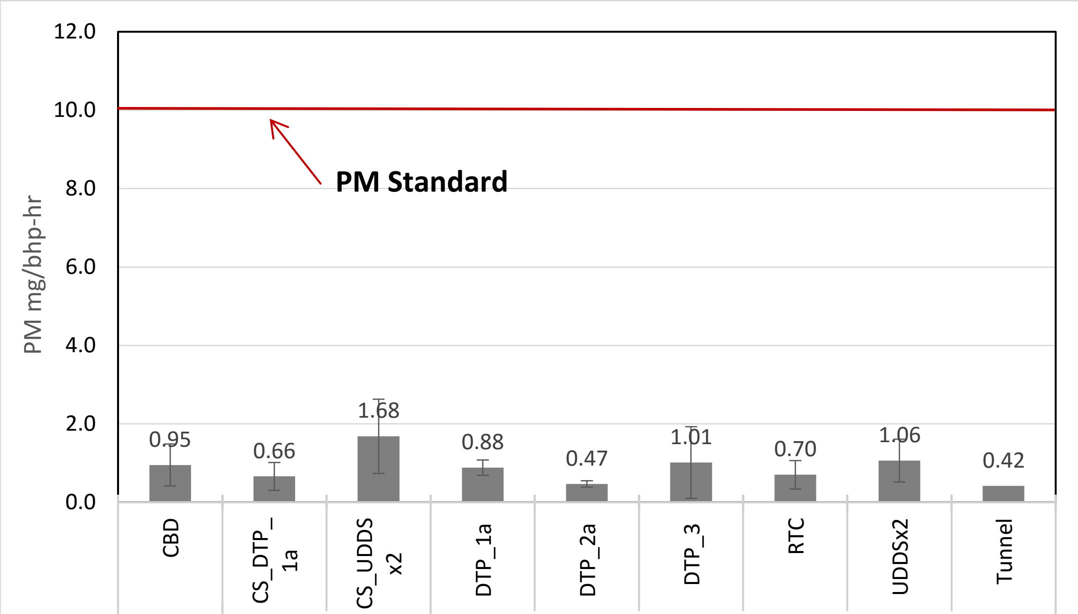



**Figure 8** PM emission factors (g/bhp-hr)

The results of soot emission presented in Figure 9, indicated that soot comprises only 0.5%-10.3% of the total PM emissions. It is found that during the cold start UDDS cycle, which has the highest PM mass emission (1.68 mg/bhp-hr), soot emissions were only 0.048 mg/bhp-hr.

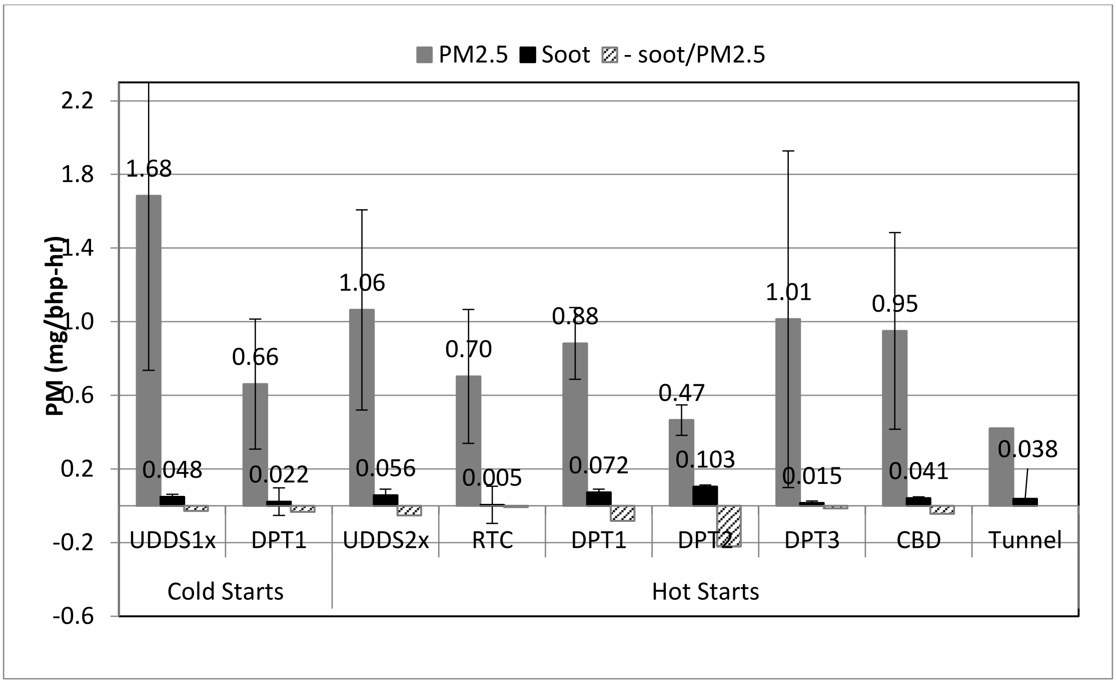



**Figure 9** soot emission factors (g/bhp-hr)

## 3.4 Greenhouse gases and fuel economy

The greenhouse gases include $CO_2$ and $CH_4$ are reported here to characterize the vehicles global warming potential (GWP). The GWP calculations are based on the intergovernmental panel on climate change (IPCC) values of 25 times $CO_2$ equivalent for $CH_4$ and 298 times $CO_2$ equivalent for nitrous oxide ($N_2O$). The global warming potential is provided in Table 8 on a g/bhp-hr basis. The $CH_4$ emissions are low and represent 5% for the cold start tests and around 1-2% for the hot start tests.

Greenhouse gases from vehicles are also found in PM emissions for their absorption of solar radiation. The main species of the PM responsible for solar absorption is called black carbon (BC). BC is a short lived climate forcer and is not grouped with the $CO_2$ equivalent method, and is tread here separately. UCR quantified the BC emissions (referred to as equivalent black carbon eBC) from the vehicle with its AVL micro soot sensor 483 (MSS) which measures the PM soot or eBC. Table 8 also lists the soot PM for each cycle and the ratio of soot/total PM emissions. The results suggest less than 10% of the PM measured for all the cycles except the regional port cycle are BC and during the regional cycle up to 22% of the total PM measured is BC. Additional analysis showed that the measured average concentration ranged between 2-3 ug/m$^3$ when corrected for water interferences (as reported by manufacturer) the concentration was~ 1ug for all tests. The low concentrations are at the detection limits of the MSS instrument and suggests the measured BC cannot be quantified accurately, but may suggest BC is not significate for the ISL G NZ NG engine.

**Table 8** Global warming potential for the ISLG NZ vehicle tested (g/bhp-hr)

| Trace | $CO_2$ | $CH_4$ | GWP ($CO_{2\,eq}$) | $CO_2$ /GWP | Soot | Soot/$PM_{2.5}$ |
|---|---|---|---|---|---|---|
| CS UDDS1x | 546.8 | 0.53 | 578.5 | 0.95 | 0.05 | 3% |
| CS DPT1 | 627.0 | 0.56 | 667.7 | 0.94 | 0.02 | 3% |
| UDDS2x | 548.9 | 0.04 | 555.0 | 0.99 | 0.06 | 5% |
| RTC | 577.0 | 0.08 | 584.0 | 0.99 | 0.01 | 1% |
| DPT1 | 649.8 | 0.26 | 661.4 | 0.98 | 0.07 | 8% |
| DPT2 | 597.0 | 0.16 | 608.9 | 0.98 | 0.1 | 22% |
| DPT3 | 549.3 | 0.33 | 564.4 | 0.97 | 0.01 | 1% |
| CBD | 576.1 | 0.11 | 589.0 | 0.98 | 0.04 | 4% |

The fuel economy of the NG vehicle is evaluated by comparing the $bsCO_2$ emissions between cycles, where the higher the $bsCO_2$ the higher the fuel consumption. $bsCO_2$ is also regulated by EPA with a standard for FTP and SET test cycles. The certificate cycles (UDDS) showed the lowest $bsCO_2$ emissions that were below 555 g/bhp-hr (FTP standard) for both the cold start and hot start tests, see Figure 10. The NG vehicle $bsCO_2$ emissions only varied slightly between cycles with only the near dock cycle (DPT1) showed a statistically higher $bsCO_2$ emission rate. The average $bsCO_2$ for all the cycles was 584 g/bhp-hr, and 565 g/bhp-hr with the DTP 1 cycle removed. The bs$CO_2$ standard level and certification values are 555 g/bhp-hr and 465 g/bhp-hr respectively for this displacement engine.

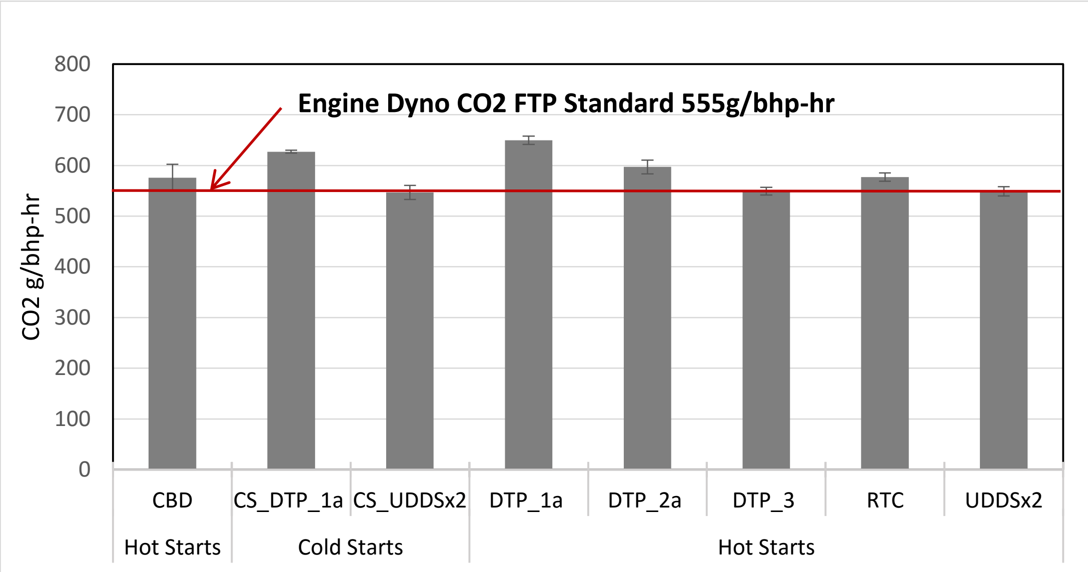



**Figure 10** $CO_2$ emission factors (g/bhp-hr)

The fuel economy on a g/mi per gallon (MPG) on a diesel gallon equivalent (DGE) assuming 2863g NG/gallon diesel ranges from 5 $MPG_{de}$ for the RTC cycles to 2 $MPG_{de}$ for CBD cycles, see Figure 11. The results show that during vehicle operation over the regional drayage cycle that lower $CO_2$ emissions and higher fuel economy were observed compared to other cycles. Regional type operation is characterized by extended freeway cruise and longer steady-state high speed vehicle operation. On the contrary the CBD and DTP 1 cycles, characterized by extended idling and creep mode operation, with higher percentages of low speed transients resulted in the highest $CO_2$ emissions and lowest fuel economy compared to other cycles. Higher power demand during transient activities results in frequent rich mode fueling contributing to higher CO emissions and a lower fuel economy.

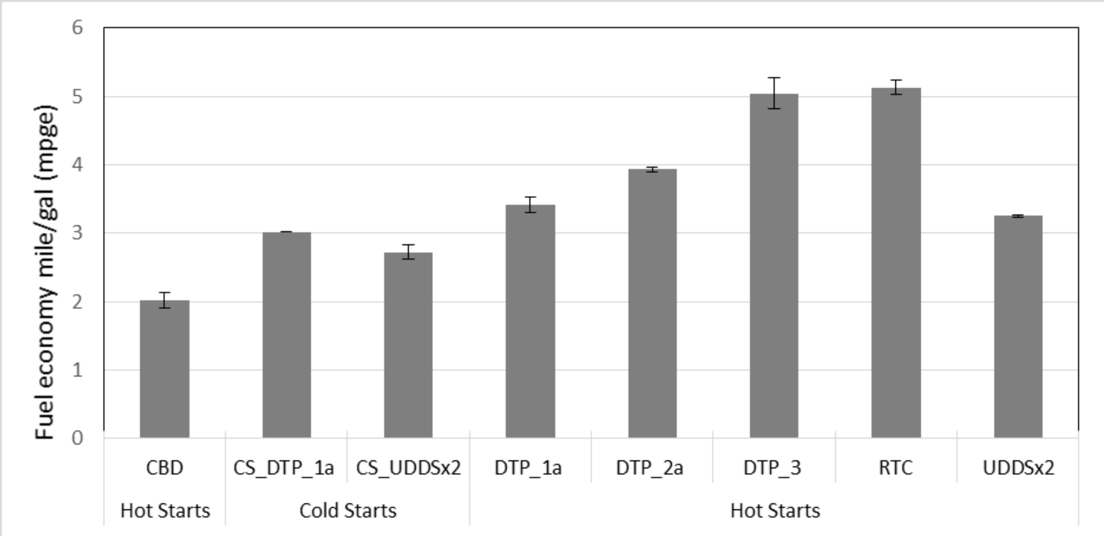



**Figure 11** Fuel economy (mile/gal)

## 3.5 Emission factors compared with a previous ISL G 8.9 engine certified as 0.2 g/bhp-hr

The cycle-based emission factors for the ISL G near zero (NZ) engine in this study can be compared to those from previous studies for the ISL G with NOx standard as 0.2 g/bhp-hr. This includes studies conducted by UCR [14, 23] and West Virginia University (WVU) [24]. The UCR studies included a class 8 heavy-duty truck fitted with a 2012 model year (MY) ISL G engine [25], a refuse hauler with a 2011 ISL G engine [23], and a transit bus equipped with a 2009 MY ISL G [14]. Studies by WVU include those by Gautam et al. The Gautam et al. [24] study included a 2008 ISL G equipped transit bus, a 2008 ISL G LNG equipped refuse haulers, and three 2008-2011 ISL G CNG and LNG-equipped goods movement trucks [24]. Comparisons between the ISL G and ISL G NZ engines were made for the DTP1 cycle for the class 8 trucks, for the RTC cycle for the refuse haulers, and for the CBD for the transit buses. Additionally, some comparisons were made over a UDDS cycle for different refuse haulers. To make these comparisons, g/bhp-hr units were used for NOx emissions, g/mi units were used for CO, $CO_2$, and $NH_3$ emissions, and mg/mi units were used for PM emissions. For the ISL G NZ engine in this section, the results of NOx emissions in bhp-hr unit were calculated from M3, which is the raw exhaust method without any ambient correction. Table 9 shows the data of emission factors of the ISL G NZ engine in this study compared with previous ISL G engines and Figure 12 shows the difference in percentage. N.A. in the table means the data is not available.

**Table 9** Emission factors of the ISL G NZ engine compared with previous ISL G engines

| Study | Cycle | Vehicle Type | Engine | Catalyst | NOx g/bhp-hr | CO g/mi | $CO_2$ g/mi | $NH_3$ g/mi | PM mg/mi | THC g/mi | NMHC g/mi |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Karavalakis et al | RTC | Waste Hauler | ISL G 8.9 | TWC | 0.203 | 10.73 | 9295 | 0.29 | 5.90 | 1.516 | 0.04 |
| Gautam et al | | Waste Hauler | ISL G 8.9 | TWC | 0.110 | 36.55 | 2261 | 0.31 | 5.74 | N.A. | 0.09 |
| 2015 Ultra Low NOx | | Waste Hauler | ISL G 8.9 NZ | TWC | 0.002 | 6.03 | 1268 | 0.97 | 1.55 | 0.196 | 0.02 |
| Karavalakis et al | DTP 1 | Class 8 HD Truck | ISL G 8.9 | TWC | 0.34 | 4.24 | 2129 | 0.59 | 2.89 | 4.24 | 0.19 |
| Gautam et al | | Goods Movement Truck | ISL G 8.9 | TWC | 0.12 | 6.07 | 2500 | 0.24 | 8.96 | N.A. | 0.11 |
| 2015 Ultra Low NOx | | Waste Hauler | ISL G 8.9 NZ | TWC | 0.002 | 6.93 | 1909 | 1.94 | 2.58 | 1.073 | 0.31 |
| Karavalakis et al | CBD | Transit Bus | ISL G 8.9 | TWC | 0.023 | 8.058 | 1710 | 1.49 | 4.75 | 0.370 | 0.14 |
| Gautam et al | | Transit Bus | ISL G 8.9 | TWC | 0.056 | 9.13 | 1709 | 1.50 | 0.97 | N.A. | 0.06 |
| 2015 Ultra Low NOx | | Waste Hauler | ISL G 8.9 NZ | TWC | 0.001 | 15.32 | 3225 | 5.27 | 5.34 | 0.888 | 0.25 |
| Gautam et al | UDDS | Waste Hauler | ISL G 8.9 | TWC | 0.060 | 26.88 | 2365 | 0.89 | 12.6 | N.A. | 0.051 |
| 2015 Ultra Low NOx | | Waste Hauler | ISL G 8.9 NZ | TWC | 0.014 | 5.50 | 2005 | 1.19 | 3.88 | 0.170 | 0.012 |

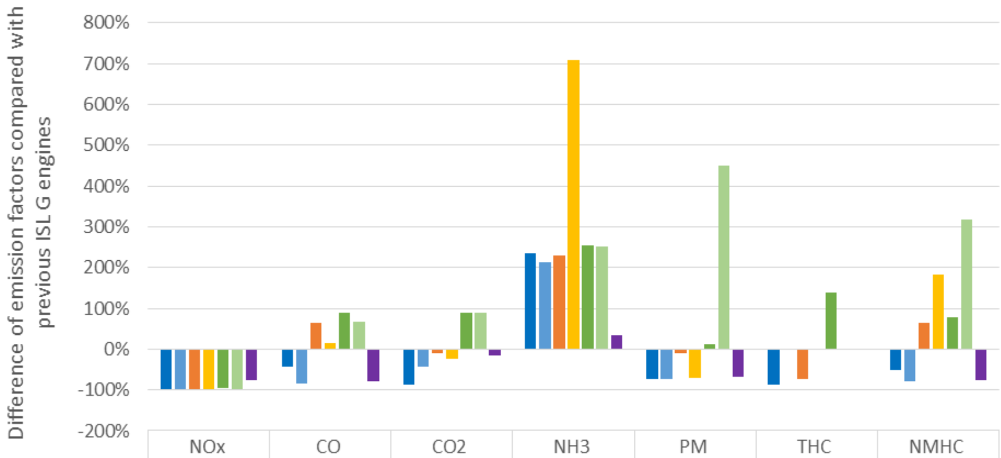
For all the vehicle types and cycles except UDDS, the ISL G NZ engine significantly reduced NOx emissions compared with previous ISL G engines by approximately 98%-99%, while for UDDS cycles NOx emissions were reduced by about 77%, see Figure 12. The lower NOx emissions of the ISL G NZ engine can be attributed for three main factors. Firstly, a larger TWC was used for the ISL G NZ engine, which can provide a larger catalytic surface area and greater reduction efficiencies. Another important change for the ISL G NZ engine is that the engine operates with a slightly different air-fuel ratio from previous ISL G engines. This allows the catalytic converter efficiency to be further optimized in terms of NOx reductions in comparison with the reductions of other pollutants. Finally, an improvement in the closed crankcase ventilation system (CCV) can reduce the NOx emissions by 10%.

For CO emissions, there is a 14% to 90% increase for the CBD and DPT1 cycles compared to previous ISL G engines, but a 43% to 83% decrease for the RTC cycle. The increases in CO emissions suggest a richer air-fuel ratio is being used to increase the TWC efficiency for reducing NOx emissions for the ISL G NZ engine, although it is not consistent over all cycles. For richer air-fuel ratios, more CO is produced during combustion.

PM/NMHC emissions are at very low emission levels for both the ISL G NZ and the ISL G. So even though there are some differences between these two engines, they are relatively minor on an absolute basis.

THC emissions were approximately 75%-87% lower than those for the older ISL G NG engine for the RTC and DTP 1 cycles, but not for the CBD cycles. Reductions in THC emissions or the ISL G NZ engine could be due to an increase in the efficiency of the larger catalyst in reducing $CH_4$ or to improvements in the CCV system, although this was not consistent for all cycles.

In comparing with previous ISL G engines, there was a significant increase of the $NH_3$ emissions for the DTP1 and CBD cycles, from 34% to 708%, see Figure 12. Previous study by Heeb and Forss et al. indicated that post-TWC catalyst NO and $NH_3$ emissions are anticorrelated, with the highest $NH_3$ but lowest NO emissions found for fuel-rich combustion (air-fuel ratio<1) [26]. The air-to-fuel ratio, which is strongly correlated to transient vehicle operation, is an important parameter, not only affecting the engine-out exhaust gas composition, but also the catalyst performance itself. Fuel-rich combustion ($\lambda<1$), generally more prevalent when the vehicle accelerates, favors the formation of $NH_3$ in the TWC catalyst, which may be a byproduct of the fact that the TWC can reduce NOx to $N_2$, which can react with the hydrogen from $H_2O$ and $CH_4$ to produce $NH_3$. In additional, the larger size TWC could facilitate the reactions on the catalyst that form $NH_3$. Differences in air-fuel ratio for the ISL G NZ engine could also lead to higher ammonia emissions.




| | NOx | CO | CO2 | NH3 | PM | THC | NMHC |
|---|---|---|---|---|---|---|---|
| RTC (UCR study) | -99.01% | -43.80% | -86.36% | 234.48% | -73.73% | -87.07% | -50.00% |
| RTC (WVU study) | -98.18% | -83.50% | -43.92% | 212.90% | -73.00% | | -77.78% |
| DTP 1 (UCR study) | -99.41% | 63.44% | -10.33% | 228.81% | -10.73% | -74.69% | 63.16% |
| DTP 1 (WVU study) | -98.33% | 14.17% | -23.64% | 708.33% | -71.21% | | 181.82% |
| CBD (UCR study) | -95.65% | 90.12% | 88.60% | 253.69% | 12.42% | 140.00% | 78.57% |
| CBD (WVU study) | -98.21% | 67.80% | 88.71% | 251.33% | 450.52% | | 316.67% |
| UDDS (WVU study) | -76.67% | -79.54% | -15.22% | 33.71% | -69.21% | | -76.47% |

**Figure 12** Difference of emission factors compared with previous ISL G 8.9 engines

## 4. Conclusion

The emissions for a vehicle equipped with an ISL G 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 heavy-duty engines. The emissions collected in this study include PM, PN, NOx, CO, fuel economy (FE), $NH_3$, and $CO_2$. An important aspect of this study was the accurate characterization of NOx emissions at such low NOx levels. A total of two traditional and three upgraded methods were used for the measurement of NOx. The three upgraded NOx measurement methods included a raw NOx measurement integrated with real time exhaust flow, a real-time ambient correction approach, and a trace level ambient analyzer for accurate bag analysis. The cycles selected for this study are representative of operation in the greater Los Angeles area and included the UDDS, the near dock, local, and regional port cycles, the SCAQMD refuse cycle, and the CBD cycle.

In general, the ISL G 8.9 engine met and exceeded the target NOx emissions of 0.02 g/bhp-hr and maintained those emissions during a full range of duty cycles found in the South Coast Air Basin. It is expected NG vehicles could play a role in the reduction of NOx inventories in areas with severe air quality problems. In terms of NOx emissions measurements, the improved methods varied in their success, with the raw sampling approach showing to be the most accurate and precise over the range of conditions tested.

The main conclusions can be summarized as:

1. The ISL G NZ 8.9 liter NG engine showed a NOx emissions below the proposed 0.02 g/bhp-hr emission target and averaged between 0.014 and 0.002 g/bhp-hr. NOx emissions were significantly reduced by 97%-100% compared with the standard ISL G 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.
2. NOx emissions did not increase with the low duty DPT 1 cycle. The low NOx emissions under low duty conditions is different from diesel engines, which typically cannot achieve high enough exhaust temperatures for the SCR system to work at low loads.
3. The NOx emissions showed relatively large variability from test to test. 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. The real-time data shows the variability is primarily due to a few NOx spikes during rapid tip-in events from an acceleration from idle. This suggests driver behavior may impact the overall NOx in-use performance of the vehicle, with more gradual accelerations is desired.

4. Each of the added enhanced diluted NOx measurement methods (M4, and M5) may have some possible implementation issues that need to be considered. M3, which is the raw exhaust measurement method, may be best to measure ultra-low NOx emissions lower than 0.02 level because no ambient NOx correction factor is needed.
5. The CO emissions ranged between 1.3 to 5.3 g/bhp-hr for the regional (DPT3) and cold start near dock (DPT1) test cycles, respectively, which is solidly below 15.5 g/bhp-hr certification standard. For CO emissions, there is a 14% to 90% increase for the CBD and DPT1 cycles compared to previous ISL G engines, but a 43%-83% decrease for RTC and UDDS cycles. The increases in CO emissions suggest a richer air-fuel ratio is being used to increase the TWC efficiency for reducing NOx emissions for the ISL G NZ engine, although it is not consistent over all cycles.
6. There is a significant increase of the $NH_3$ emission, which is reasonable due to the effect of TWC. TWC is a catalyst that can reduce NOx to $N_2$, which can react with the hydrogen from $H_2O$ and $CH_4$ to produce $NH_3$.
7. THC/$CH_4$ emissions were lower than those for the older ISL G NG engines. For RTC cycles, for example, $CH_4$ emissions were 0.18 g/mi for the ISL G NZ

engine compared to 6.8 g/mi for an older ISL G 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.

8. The PM/NMHC emissions were similar to previous levels and should not add to any unknown impacts for the use of NG fuels in the heavy duty fleet.

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