Final Report

Ultra-Low NO_x Natural Gas Vehicle Evaluation ISL G NZ

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Abstract

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 diesels, 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 NOx inventory requirements.

Although the 2010 certification standards were designed to reduce NO_x emissions, the in-use NO_x emissions are actually much higher than certification standards. The main reason is a result of the poor performance of aftertreatment systems for diesel vehicles during low duty cycle operation. Recent studies by UCR suggest 99% of the operation within 10 miles of the ports represented by up to 1 g/bhp-hr. Thus, a real NO_x success will not only be providing a solution that is independent of duty cycle, but one that also reduces the emissions an additional 90% from the current 2010 standard.

The ISL G NZ 8.9 liter NG engine met and exceeded the target NOx emissions of 0.02 g/bhp-hr and maintained those emissions during a full ration of duty cycles found in the South Coast Air Basin. The other gaseous, particulate matter, particle number and selected non regulated emissions were similar to previous levels. It is expected NG vehicles could play a role in the reduction of the south coast NOx inventory problem given their near zero emission factors demonstrated.

Acronyms and Abbreviations

ARB	Air Resources Board
bs	brake specific
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
lpm	liters per minute
MEL	mobile emission laboratory
NO_x	nitrogen oxides
N_2O	nitrous oxides
OEM	original equipment manufacturer
PM	particulate matter
$PM_{2.5}$	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
GDE	gallons diesel equivalent
NG	natural gas
LNG	liquid natural gas

Executive Summary

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 diesels, with the recent penetration of natural gas (NG) engines in refuse collection, transit, and local delivery where vehicles are centrally garaged and fueled. As emissions and greenhouse gas regulations continue to tighten, new opportunities to use advanced fleet specific heavy duty vehicles with improved fuel economy are becoming available. 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.

Although the 2010 certification standards were designed to reduce NO_x emissions, the in-use NO_x emissions are actually much higher than certification standards. The main reason is a result of the poor performance of aftertreatment systems for diesel vehicles during low duty cycle operation. Recent studies by UCR suggest 99% of the operation within 10 miles of the ports are up to 1 g/bhp-hr NO_x. Stoichiometric natural gas engines with three-way catalysts tend to have better low duty cycle NO_x emissions than diesel engines with SCR aftertreatment systems. Thus, a real NO_x success will not only be providing a solution that is independent of duty cycle, but one that also reduces the emissions an additional 90% from the current 2010 standard.

Goals: The goals of project are to evaluate the ISL G NZ (near zero) 8.9 liter ultra-low NO_x NG vehicle emissions, global warming potential, and fuel economy during in-use conditions. This report presents a summary of the results and conclusions of ultra-low NO_x NG vehicle evaluation.

Approach: The testing was performed on UC Riverside's chassis dynamometer integrated with its mobile emissions laboratory (MEL) located in Riverside CA just east of the South Coast Air Quality Management District (AQMD). The cycles selected for this study are representative of operation in the South Coast Air Basin and included the urban dynamometer driving schedule, the near dock, local, and regional port cycles, the AQMD refuse cycle, and the central business district cycle.

One of the difficulties in quantifying NO_x emissions at 90% of the 2010 certification level (~ 0.02 g/bhp-hr), is the measurement method is approaching its detection limit. 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 range of conditions tested.

In addition to the regulated emissions, the laboratory was equipped to measure particle size distribution, particle number, soot PM mass, ammonia, and nitrous oxide emissions to investigate any dis-benefit resulting from the ISL G NZ engine and aftertreatment system.

Results: The ISL G NZ 8.9 liter NG engine showed NO_x emissions below the proposed 0.02 g/bhp-hr emission target and averaged between 0.014 and 0.002 g/bhp-hr for the various hot start tests, see Figure ES-1. The NO_x emissions (g/bhp-hr) decreased as the duty cycle was decreased which was the opposite trend for the diesel vehicles (where emissions increased as duty cycle decreased). The large error bars (represented by 1 standard deviation) may suggest measurement variability, but when the real-time data was investigated, one can see the variability was a result of test-to-test differences from a few isolated NO_x events during rapid throttle tip-in at idle, see Figure ES-2. This suggests possible driver behavior may impact the overall NO_x in-use performance of the vehicle where more gradual accelerations are desired. This is also evident with the more gradual accelerations of the near dock and local port cycles which showed smaller error bars and lower average emission factors, see Figure ES-1.

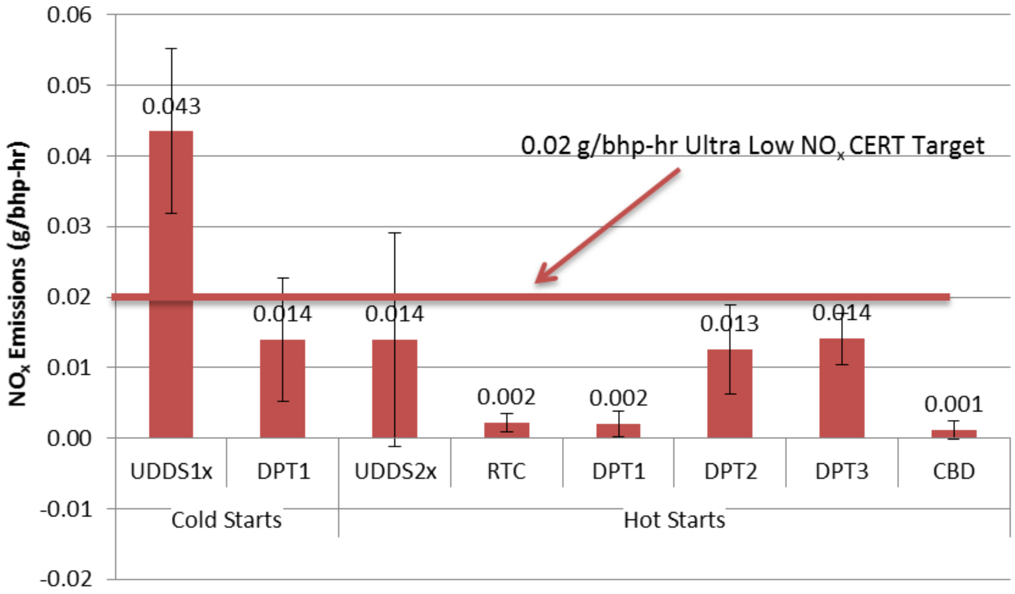

Figure ES-1 Cycle averaged NO_x emissions for the ISL G NZ 8.9 liter equipped vehicle

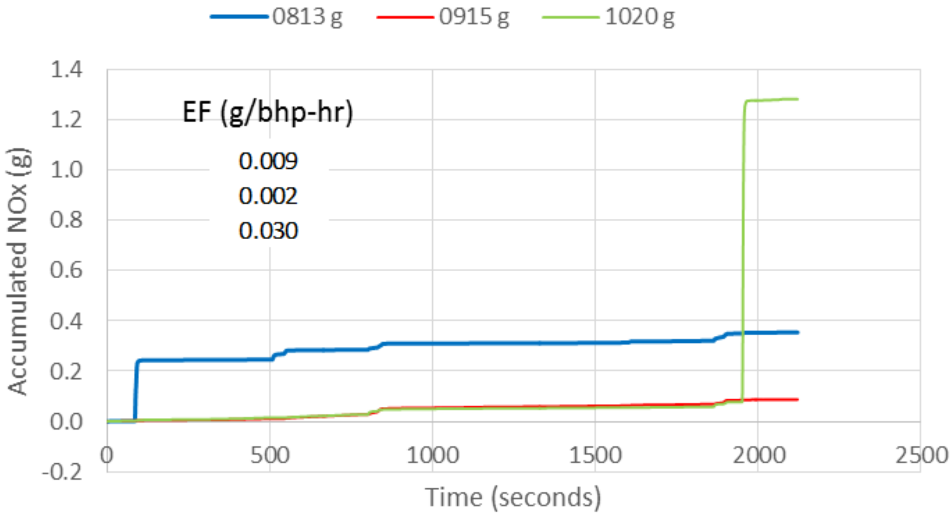

Figure ES-2 Real-time NO_x accumulated mass for the three UDDS hot cycles

[1] Individual accumulated and integrated EF for the UDDS cycle is shown in the figure above. The average of these tests is represented in Figure ES-1, UDDS cycle (0.14 g/bhp-hr).

Cold start emissions represented a significant part of the total NO_x emissions where 90% of the NO_x emissions occurred in the first 200 seconds of the cold UDDS test. Once the catalyst was warmed up, the remaining portions of the cold UDDS test showed low NO_x emissions similar to the hot UDDS test. The hot/cold UDDS weighted emission was 0.0181 g/bhp-hr (weighted as $1/7^{th}$ of the hot cycle) which is below the 0.02 g/bhp-hr standard. Once the TWC catalyst lights off, its NO_x reduction potential remains at a high performance unlike diesel SCR equipped engines where low duty cycles (associated with SCR temperatures below 250C) will cause the SCR performance to decline.

The other emission such as carbon monoxide, particulate matter, particle number, particle size distribution, nitrous oxide, and ammonia were similar to previous versions of the same stoichiometric 8.9 liter engine certified to 0.2 g/bhp-hr NO_x. For example PM was typically below 0.001 g/bhp-h (90% below the standard), ammonia was typically above 200 ppm. This suggests the reduced NO_x emissions did not come at the expense of an increase in other species. The methane emissions were notably lower than the 0.2 g/bhp-hr NOx version of the same engine. The lower methane emissions may be a result of the closed crankcase ventilation system. The fuel economy also appeared to be similar to previous versions of the same engine displacement where the UDDS showed the lowest CO_2 emissions and were below the current FTP standard of 555 g/bhp-hr for both the cold start and hot start tests during in-use chassis testing.

Summary: In general the ISL G NZ 8.9 liter engine hot/cold emissions were within the 0.02 g/bhp-hr certification standard for all the cycles tested. Ironically these emissions factors were maintained for the full range of hot-start duty cycles found in the South Coast Air Basin unlike other heavy duty diesel fueled technologies and certification standards. The other gaseous and PM emissions were similar to previous levels. It is expected NG vehicles with the ISL G NZ could play a role in the reduction of the south coast NO_x inventory in future years given the near zero emission factors demonstrated on each test cycle. Additional research is needed to see if the on-road behavior is similar to test cycles and if there are any deviations as the vehicles age.

1 Background

1.1 Introduction

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 diesels, although there is increasing 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. At the same time 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. Thus, an approach to reduce emissions also needs lower fuel consumption to the extent possible.

1.2 NO_x Emissions

Although the 2010 certification standards were designed to reduce NO_x emissions, the in-use NO_x emissions are actually much higher than certification standards for certain fleets. The magnitude is largely dependent on the duty cycle. Since engines are certified at moderate to high engine loads, low load duty cycle can show different emission rates. For diesel engines low load duty cycles have a significant impact in the NO_x emissions. The NO_x cold start emissions for the first 100 seconds were over 2.2 g/hp-h where for the same time frame with the hot cycle it was 0.006 g/hp-h[1], see Figure 1-1. The cold start emissions were ten times higher than the certification standard and much higher than the corresponding hot start emissions. Additionally the stabilized emission of the two systems over the same time period was very similar at 0.05 g/hp-h (about 75% below the standard). The main cause for the high NO_x emissions is low selective catalytic reduction (SCR) inlet temperatures resulting from low power operation.

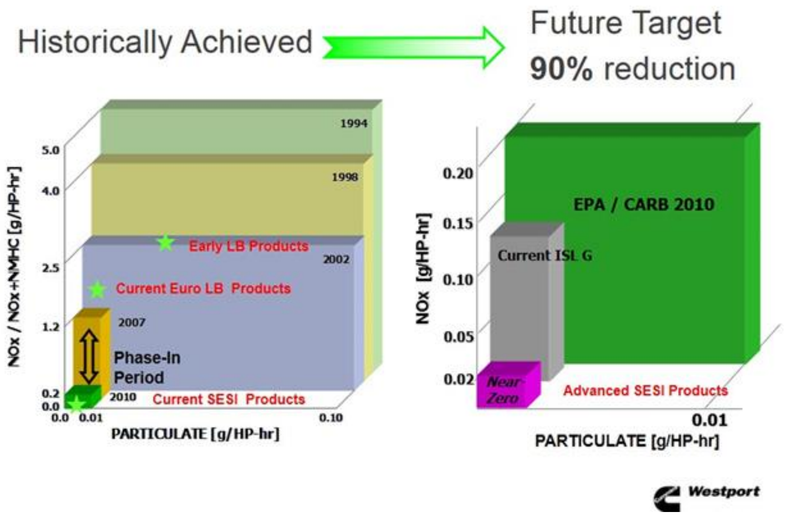

Figure 1-1 Engine dynamometer NO_x and PM certification emissions standards (source CWI)

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[1] Wayne Miller, Kent C. Johnson, Thomas Durbin, and Ms. Poornima Dixit 2013, In-Use Emissions Testing and Demonstration of Retrofit Technology, Final Report Contract #11612 to SCAQMD September 2013.

These same trucks were tested on cycles designed to simulate port activity[2]. The port driving schedule represents near dock (2-6 miles), local (6-20 miles), and regional (20+ miles) drayage port operation. The SCR was inactive for 100% of the near dock cycle, 95% of the local cycle, and 60% of the regional cycle, see Figure 1-2. The NO_x emissions were on the order of 0.3 to 2 g/hp-h (1 to 9 g/mi) as much as 10 times higher than the 2010 standards. It has been show that the SCR system also becomes inactive even after hours of operation due to low loads and lean compression ignition combustion. Thus, the current diesel 2010 solution for low duty cycle activity (like at ports) is very poor where a NG solution can make significant improvements for NO_x emissions, and a reduction in carbon emissions (carbon dioxide), but at a slight penalty in equivalent gallon diesel fuel economy.

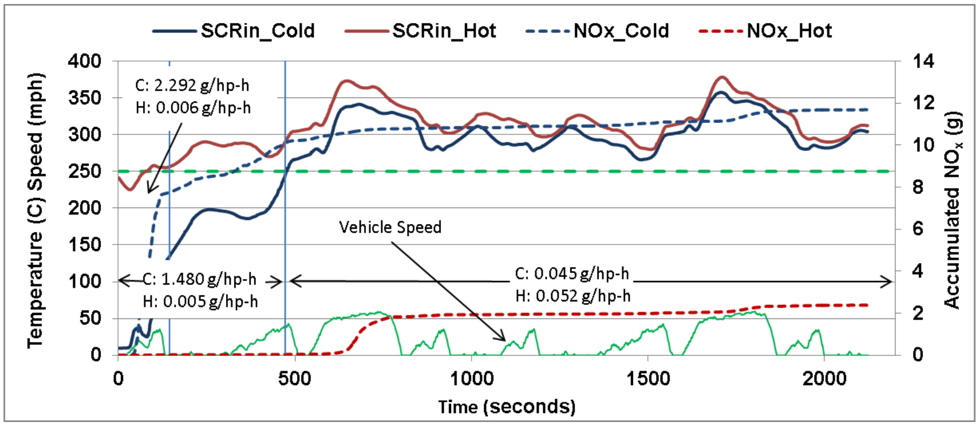
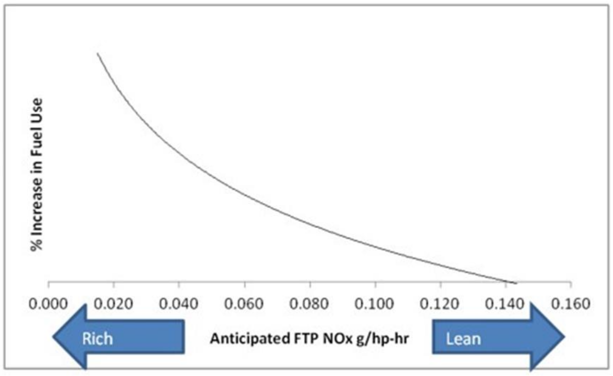


Figure 1-2 In-use emissions from a heavy duty truck tested on UCR's chassis dyno

1.3 Fuel economy

Fuel consumption and emissions are a tradeoff due to the science of combustion. Figure 1-3 shows the NO_x emissions change with changes in fuel consumption for a typical spark ignited engine. As NO_x is reduced from 0.14 to 0.02 g/hp-h fuel consumption increases a known amount. This is a result of the stoichiometric combustion of fuels. Advanced catalysts can be used to reduce NO_x from its baseline levels, but trying to reduce NO_x within a fixed SI combustion system will come at a penalty of increased fuel consumption.



(Source CWI)

Figure 1-3 NOx emissions versus fuel consumption tradeoffs during certification testing

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[2] Patrick Couch, John Leonard, TIAX Development of a Drayage Truck Chassis Dynamometer Test Cycle, Port of Long Beach/ Contract HD-7188, 2011

1.4 Objectives

The goals of project are to evaluate the ISL G NZ 8.9 liter ultra-low NO_x NG vehicle emissions, global warming potential, and fuel economy during in-use conditions. Given the low NO_x concentrations expected, additional measures were implemented to quantify NO_x emissions at and below 0.02 g/bhp-hr emissions levels. This report is a summary of the approach, results, and conclusions of ultra-low NO_x NG vehicle evaluation.

2 Approach

The approach for this demonstration vehicle evaluation includes in-use testing on a chassis dynamometer, emissions measurements with UCRs mobile emission laboratory (MEL), improvements to the NO_x measurement method and a representative selection of in-use test cycles. One of the difficulties in quantifying NO_x emissions at the levels proposed in this project (90% lower than the 2010 certification level ~ 0.02 g/bhp-hr) is the measurement methods are approaching their detection limit to accurately quantify NO_x emissions. This section describes the test article, laboratories and the upgrades performed to quantify NO_x emissions at and below 90% of the 2010 emission standard.

2.1 Test article

2.1.1 Engine

The test article is the ISL G NZ 320 Cummins Westport Inc. (CWI) Natural Gas engine (SN = 73779339), see Table 2-1 for specifics and Appendix F for additional details. The engine was initially certified as a 0.2 g/bhp-hr NO_x 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 ARB website, see Figure F-1 Appendix F. CWI developed this engine as a ultra-low NO_x demonstration engine where the NO_x emissions have been further reduced to 0.02 g/bhp-hr (90% below the 2010 NO_x emissions standard). A second, recently released EO for the near zero configuration with engine family GCEXH0540BH, also on the CARB website and provided from CWI shows the lower NO_x standard is 0.02 g/bhp-hr and the actual certified value was 0.01 g/bhp-hr, see Figure F4 Appendix F. This evaluation is to quantify the in-use NO_x emissions in relationship to the 0.02 g/bhp-hr demonstration level.

Table 2-1 Summary of selected main engine specifications

Mfg	Model	Year	Eng. Family	Rated Power (hp @ rpm)	Disp. (liters)	Adv NO_x Std g/bhp-h [1]	PM Std. g/bhp-h
CWI	ISL G NZ	2014	ECEXH0540LBH	320 @ 2100	8.9	0.02	0.01

[1] The family ECEXH0540LBH is on the engine label given its year of manufacture. The engine tested was produced under the ECEX… label but was later certified and upgraded to the GCEX… label. The engine tested is thus, based on the GCEX label and represents a 0.02 g/bhp-hr NO_x standard, see Appendix F Figure 4 for details.

2.1.2 Test Fuel

California pipeline fuel was used for this study which represents typical Natural Gas available in Southern California. The fuel properties were measured during the emissions testing and are presented in Table 2-2. Fuel samples were collected from the vehicle prior to testing. Three vehicle refuelings (Agua Mansa Station, Riverside CA) were required to complete the work and three fuel samples were collected. Due to sample container issues, only the November 20th sample collected was analyzed as presented in Table 2-2. It is expected the pump NG fuel was consistent over the five days of testing.

Table 2-2 Fuel properties for the local NG test fuels utilized

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

1 Based on these fuel properties the HHV is 1-42.5 BTU/ft3 and the LHV is 939.9 BTU/ft3 with a H/C ratio of 3.905, a MON of 132.39 and a carbon weight fraction of 0.745 and a SG = 0.58, see Appendix E for laboratory results. Note these results meets the US EPA 40 CFR Part 1065.715fuel specification for NG fueled vehicles.

2.1.3 Vehicle inspection

Prior to testing, the vehicle was inspected for proper tire inflation and condition, vehicle condition, vehicle securing, and the absence of any engine code emission faults. The vehicle inspection and securing met UCR's specifications. Cummins Westport Inc. had a service person on site to make sure fault codes were absent prior to and during emissions testing. All tests were performed with-in specification and without any engine code faults. Thus, the results presented in this report are representative of a properly operating vehicle, engine, and aftertreatment system.

2.1.4 Test cycles

The test vehicle utilized an 8.9 liter NG engine which is available for three typical vocations in the South Coast Air Basin, 1) goods movement, 2) bus, and 3) refuse[3]. The engine was provided to UCR in its refuse hauler application which is one of the more common uses for the 8.9 liter engine, see Figure 2-4. In order to characterize emissions from this engine over the rage of in-use applications, goods movement and bus cycles were also tested. UCR tested the vehicle following the three port cycles (Near Dock, Local, and Regional), the Urban Dynamometer Driving Schedule (UDDS), the Central Business District (CBD) bus cycle, and the AQMD Refuse cycle, see Appendix B for details. These cycles are representative of Sothern California driving. Some cycles are short (less than 15 minutes) where double or triple cycles (2x or 3x) cycles are recommended in order capture enough PM mass to quantify emissions near 1 mg/bhp-hr. The UDDS was performed twice (UDDSx2) and the CBD was performed three times (CBDx3) where the emissions represent the average of the cycle.

Table 4 Summary of statistics for the various proposed driving cycles

Day	Distance (mi)	Average Speed (mph)	Duration (sec)
Near Dock	5.61	6.6	3046
Local	8.71	9.3	3362
Regional	27.3	23.2	3661
UDDSx2	11.1	18.8	2122
CBDx3	3.22	20.2	560
AQMD Refuse	4.30	7.31	2997

[1] Hot UDDS was performed as a double cycle (2x) and a single (1x) for the cold tests. The CBD was performed as a triple (3x) test. The refuse cycle includes a compaction element where no distance is accumulated, but emissions are counted with a simulated compaction cycle, see Appendix B for details.

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[3] Cummins Westport, California Energy Commission Merit Review- ISL G Near Zero, December 2, 2015

2.1.5 Work calculation

The reported emission factors presented are based on a g/bhp-hr and g/mi basis (g/mi are provided in Appendix E). 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 ISL G NZ 320 engine lug curve is provided in Figure 2-1.

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

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)

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

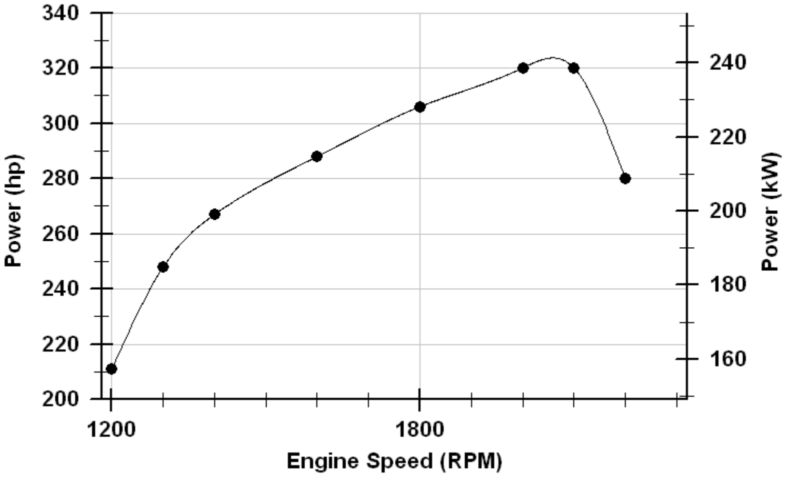

Figure 2-1 Published ISLG 8.9 Natural Gas engine power curve

Figure 2-2 and Figure 2-3 show the measured power and work for each of the tests performed on the refuse vehicle. The engine is certified on the FTP type of cycle where the average power is around 82 Hp and estimated at 24.7 bhp-h, also shown in Figure 2-2 and Figure 2-3. The UDDS, regional (DPT3) and the CBD test cycles represent power near (but lower) than the FTP certification cycle. The near dock (DPT1), local (DPT2), and refuse (RTC) cycles showed much lower power with the DPT1 being the lowest (as shown by previous studies). Previous testing of the low power from the DPT1 cycle resulted in high diesel NO_x emissions because the SCR operating temperatures were never obtained.

The measured work for the all the cycles (except the CBD (lower), RTC, and the regional (DPT3 much higher)) were close to the certification FTP estimated work (Note the hot-UDDS was higher because a double cycle was performed where the cold-UDDS was performed as a single UDDS test). In general the cycles selected are representative of in-use conditions and certification testing. It is expected the results from this study will be very representative for real world emission factors for the test article.

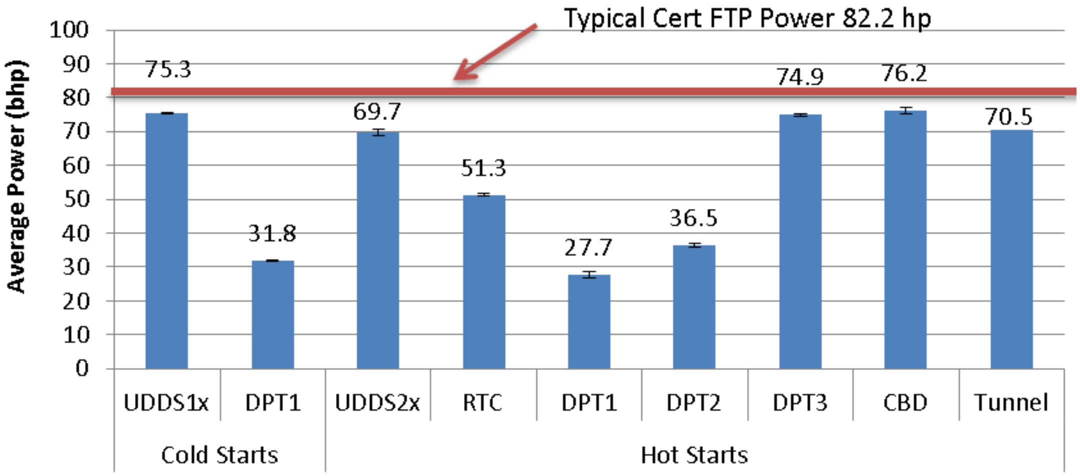

Figure 2-2 Power from the various tests with 1 stdev error bars

[1] The tunnel blank (TB) was performed without the vehicle operating. To calculate a work specific TB comparison, the TB test utilized the power and work value of a single hot-UDDS test to provide context of the measurement detection limits.

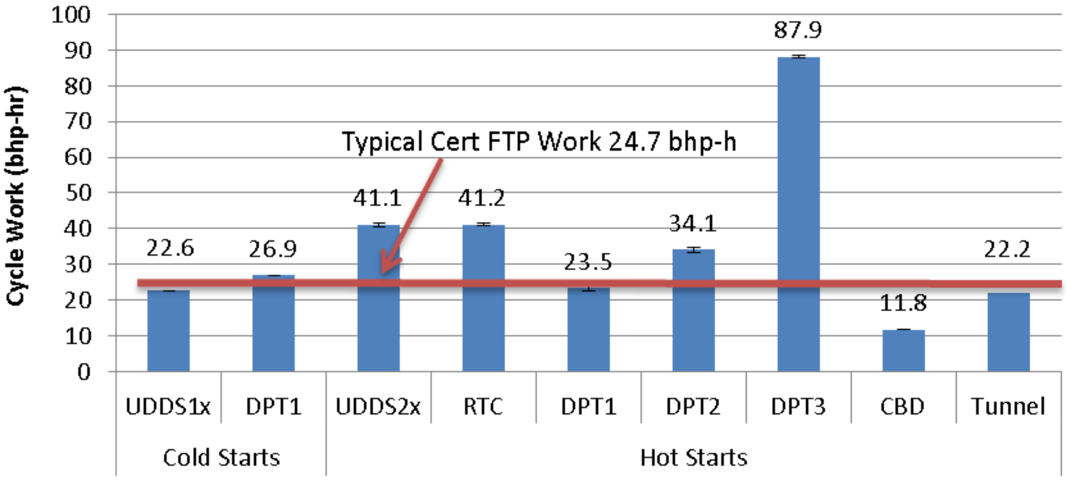

Figure 2-3 Work from the various tests with 1 stdev error bars

[1] The TB was performed without the vehicle operating. To calculate a work specific TB comparison, the TB test utilized the power and work value of a single hot-UDDS test to provide context of the measurement detection limits.

2.2 Laboratories

The testing was performed on UC Riverside's chassis dynamometer integrated with its mobile emissions laboratory (MEL) located in Riverside CA just east of the South Coast Air Quality

Management District (AQMD). This section describes the chassis dynamometer and emissions measurement laboratories used for evaluating the in-use emissions from the demonstration vehicle. Due to challenges of NO_x measurement at 0.02 g/bhp-hr, additional sections are provided to introduce the measurement improvements.

2.2.1 Chassis dynamometer

UCR's chassis dynamometer is an electric AC type design that can simulate inertia loads from 10,000 lb to 80,000 lb which covers a broad range of in-use medium and heavy duty vehicles, see Figure 2-4. The design incorporates 48" rolls, vehicle tie down to prevent tire slippage, 45,000 lb base inertial plus two large AC drive motors for achieving a range of inertias. The dyno has the capability to absorb accelerations and decelerations up to 6 mph/sec and handle wheel loads up to 600 horse power at 70 mph. This facility was also specially geared to handle slow speed vehicles such as yard trucks where 200 hp at 15 mph is common. See Appendix D for more details.

2.2.1.1 Test weight

The ISL G NZ 320 engine is installed in a refuse hauler chassis with a GVW of 62,000 lb, VIN 3BPZX20X6FF100173. The representative test weight for refuse haulers operating in the south coast air basin is 56,000 lb[4]. The testing weight of 56,000 lb was also utilized during previous testing of refuse haulers with diesel and NG engines by UC Riverside and WVU [4 and 5]. For this testing program UCR utilized a testing weight of 56,000 lb for all test cycles (refuse, CBD, UDDS, and port cycles).

Figure 2-4 UCR's heavy duty chassis eddy current transient dynamometer

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[4] Wayne Miller, Kent C. Johnson, Thomas Durbin, and Ms. Poornima Dixit 2014, In-Use Emissions Testing and Demonstration of Retrofit Technology, Final Report Contract #11612 to SCAQMD September 2014.

[5] Daniel K Carder, Mridul Gautam, Arvind Thiruvengada,m Marc C. Besch (2013) In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines, Final Report Contract #11611 to SCAQMD July 2014.

2.2.1.2 Coast down

UCR utilizes a calculation approach for the coast down settings of the chassis dynamometer. This approach is also used by other testing facilities and has been shown to be representative of in-use operation, see Appendix G for a more detailed discussion. The test weight of 56,000 lb resulted in a power of 117.42 Hp at 50 mph with the calculated dynamometer loading coefficients of A = 397.73642, B = -2.43E-14 and C = 0.193166. See calculation methods in Appendix G for more details.

2.2.2 Emissions measurements

The proposed NO_x measurement (at 0.02 g/bhp-hr) are approaching the detection limits for the traditional dilute CVS measurement method. This section discussed the traditional and upgraded methods recommended for the ultra-low NO_x evaluation. This section also provides a section on the calculations utilized, additional measurements needed (ie. Trace analyzers and exhaust flow) and an evaluation of the upgraded methods in comparison to the tradition methods.

2.2.2.1 Traditional method

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 2-4. The accuracy of MEL's measurements has been checked/verified against ARB's[6] and Southwest Research Institute's [7], [8] heavy-duty diesel laboratories. MEL routinely measures Total Hydrocarbons (THC), Methane (CH_4), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x), and Particulate Matter (PM) emissions from diesel engines. Design capabilities and details of MEL are described in Cocker et al[4,9]. Samples can be collected for more detailed analyses such as hydrocarbon speciation, carbonyl emissions, polynuclear aromatic hydrocarbons, etc.

The traditional NO_x 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

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[6] Cocker III, D. R., Shah, S. D., Johnson, K. C., Zhu, X., Miller, J. W., Norbeck, J. M., Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 2. Sampling for Toxics and Particulate Matter, Environ. Sci. Technol. **2004**, 38, 6809-6816

[7] Cocker III, D. R, Shah, S. D., Johnson, K. C., Miller, J. W., Norbeck, J. M., Measurement Allowance Project – On-Road Validation. Final Report to the Measurement Allowance steering Committee.

[8] Johnson, K.C., Durbin, T.D., Cocker, III, D.R., Miller, W.J., Bishnu, D.K., Maldonado, H., Moynahan, N., Ensfield, C., Laroo, C.A. (2009) On-road comparison of a portable emission measurement system with a mobile reference laboratory for a heavy-duty diesel vehicle, Atmospheric Environment 43 (2009) 2877–2883

[9] Cocker III, D. R, Shah, S. D**.**, Johnson, K. C., Miller, J. W., Norbeck, J. M., *Development and Application of a Mobile Laboratory for Measuring Emissions From Diesel Engines I. Regulated Gaseous Emissions*, Environmental Science and Technology. **2004**, 38, 2182-2189

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 (EEPS) model 3090, 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) from Unisearch Associates Inc. LasIR S Series, and a batched low level nitrous oxide (N_2O) emissions with a Fourier Transform Infrared Spectrometer (FTIR). The PN measurement system used a low cut point CPC (2.5 nm D50) because of the large PN concentrations reported below the PMP protocol CPC 23 nm measurement system (10, 11, and 12). The EEPS spectrometer displays measurements in 32 channels total (16 channels per decade) and operates over a wide particle concentration range, including down to 200 particles/cm3.

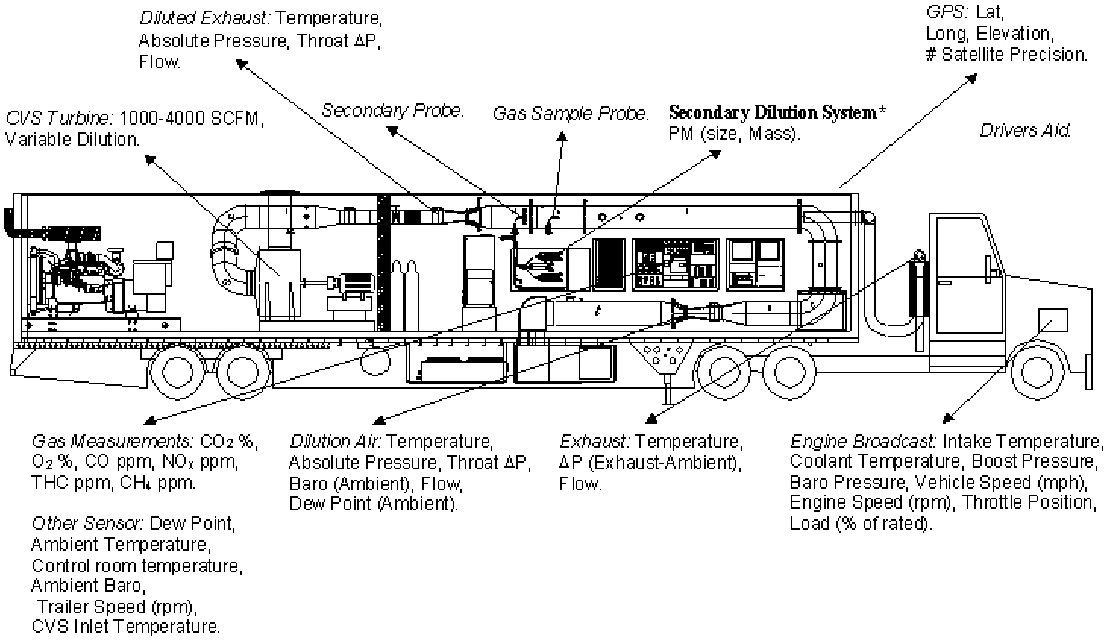


Figure 2-5 Major Systems within UCR's Mobile Emission Lab (MEL)

2.2.2.2 NO_x Method upgrades

Three NO_x 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 below.

Raw NOx measurements

The raw NO_x measurements utilized a 300 HCLD CAI analyzer which sampled raw exhaust through a low volume heated filter and heated sample line. The low volume design was considered to improve the response time of the analyzer with the exhaust flow measurement. The heated filter was acid treated to minimize NH_3 interference with the NO_x measurement. A real-time high speed exhaust flow meter (100 Hz model EFM-HS Sensors Inc) was used to align NO_x

concentration with real time exhaust flow measurements. The EFM-HS was correlated with UCR dual CVS system prior to testing to improve the accuracy between the raw and dilute CVS methods and eliminate exhaust flow biases from propagating through the comparison.

Trace level NOx analyzer

A trace level chemiluminescence NO-NO_2-NO_x 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 with-in CE-CERT's atmospheric research laboratories for ambient NO_x quantification for several years. This analyzer was calibrated and integrated specially for this ultra-low NO_x project. The span on the instrument was set to 600 ppb and 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 and showed a T_{10-90} and a T_{90-10} 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 NO_x emissions below 1 ppm with an ambient trace type NO_x analyzer.

2.2.2.3 Calculation upgrades

The calculations for the traditional and improved methods are presented in this section. The calculations are in agreement with 40 CFR Part 1065, but are presented in a condensed version to draw observation differences without the details of working in molar flow rates as per 40 CFR Part 1065.

Table 2-3 NO_x measurement methods traditional and upgraded

Type	Analyzer	Meth. ID	Description
Traditional	600 HCLD dil 600 HCLD amb	M1	Modal NO_x with ambient bag correction
Traditional	600 HCLD dil 600 HCLD amb	M2	Dilute bag NO_x with ambient bag correction
Upgrade	300 HCLD raw	M3	Raw NO_x no ambient bag correction
Upgrade	600 HCLD dil TECO amb	M4	Modal dilute NOx with ambient real time correction
Upgrade	TECO dil TECO amb	M5	Trace analyzer dilute bag with trace ambient bag correction

Traditional Methods:

The traditional NO_x 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.

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

Where:

NO_{x_m1}	the Method 1 NO_x measurement method (g/cycle)
Q_{cvs_i}	is the instantaneous CVS flow
ρ_{NOx}	is the density of NO_x from 40 CFR Part 1065
C_{m_i}	is the instantaneous NO_x concentration measured with the dilute NO_x 600 HCLD CAI analyzer
C_a	is the ambient bag NO_x concentration measured by the 600 HCLD CAI analyzer
DF_i	instantaneous dilution factor

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

Where:

NO_{x_m2}	the Method 2 NO_x measurement method (g/cycle)
Q_{cvs_ave}	is the average CVS flow
ρ_{NOx}	is the density of NO_x from 40 CFR Part 1065
C_d	is the dilute bag NO_x concentration measured with the dilute NOx 600 HCLD CAI analyzer
C_a	is the ambient bag NO_x concentration measured by the 600 HCLD CAI analyzer
DF_{ave}	average dilution factor

Upgraded Methods:

The upgraded NOx measurement methods are presented in the next three equations. These upgrades included new analyzers, sample lines, sample filters, and exhaust flow measurement systems. For Method 3 (M3) there is no ambient correction. For Method 4 (M4) the real time dilute NOx is corrected for ambient real time NOx 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).

$$NO_{x\_m3} = \sum_{i=1}^{n} (Q_{exh_i} * \Delta t_{\_i}) * \rho_{NO_x} * \left(C_{m\_i}\right)$$

Where:

NO_{x_m3}	the Method 3 NO_x measurement method (g/cycle)
Q_{exh_i}	is the instantaneous exhaust flow measured in the tail pipe
ρ_{NOx}	is the density of NO_x from 40 CFR Part 1065
C_{m_i}	is the dilute bag NO_x concentration measured with the dilute NO_x 300 HCLD CAI analyzer

$$NO_{x\_m4} = \sum_{i=1}^{n} (Q_{cvs_i} * \Delta t_{\_i}) * \rho_{NO_x} * \left(C_{m\_i} - C_{a\_adv\_i} * \left(1 - \frac{1}{DF_i}\right)\right)$$

Where:

NO_{x_m4}	the Method 4 NO_x measurement method (g/cycle)
Q_{cvs_i}	is the instantaneous CVS flow
ρ_{NOx}	is the density of NO_x from 40 CFR Part 1065

C_{m_i} is the dilute bag NO_x concentration measured with the dilute NO_x 600 HCLD CAI analyzer
C_{a_adv} is the trace ambient bag NOx concentration measured by the TECO trace NO_x analyzer
DF_i instantaneous dilution factor

$$NO_{x\_m5} = (Q_{cvs\_ave} * \Delta t) * \rho_{NO_x} * \left(C_{d\_adv} - C_{a\_adv} * \left(1 - \frac{1}{DF_{\_ave}} \right) \right)$$

Where:

NO_{x_m5} the Method 5 NO_x measurement method (g/cycle)
Q_{cvs_ave} is the average CVS flow
ρ_{NOx} is the density of NO_x from 40 CFR Part 1065
C_{d_adv} is the dilute bag NO_x concentration measured by the TECO trace NO_x analyzer
C_{a_adv} is the ambient bag NO_x concentration measured by the TECO trace NO_x analyzer
DF_{ave} average dilution factor

2.2.3 Method evaluation

One of the main contributing factors to the issue with the traditional CVS sampling system is the magnitude of the ambient concentration has on the calculation. Table 2-4 lists the 10th, 50th, and 90th average ambient, dilute modal, and raw tailpipe measured percentile concentrations. The 50th percentile raw, dilute, and ambient NO_x concentration were 0.55 ppm, 0.17 ppm, and 0.07 ppm respectively.

As discussed previously, the ambient concentration is subtracted from the dilute concentration prior to calculating the mass based emissions. This subtraction is typically a larger number minus a small number. At the 0.02 g/bhp-hr emission level, the ambient concentration is now at the same levels as the dilute measured value. The ambient concentration was found to be 54% of the total measured dilute concentration at the 50th percentile measured concentration, see Table 2-4. The ambient corrected NOx concentration (C_{a_cor}) utilized in the dilution measurements is the product of ambient NO_x concentration and an inverse ratio of the dilution factor, see equation below. If we divide the C_{a_cor} by the dilute NOx measured we get a ratio that is representative of the ambient percent of total NOx. Figure 2-6 shows the ratio in a histogram plot and more than half the data is above 0.6 suggest that most of the measurements meeting the 0.02 g/bhp-hr were only twice that of ambient concentrations. This ratio gives the reader a feel for the influence ambient has at and below 0.02 g/bhp-hr NOx emissions.

Table 2-4 Cycle averaged raw, dilute, and ambient measured concentrations (ppm) statistics

Percentile	Amb	Dilute ^{1}	Raw ^{1}	C_{a_cor}/Dil %
10th	0.234	0.632	6.533	105%
50th	0.070	0.168	0.554	54%
90th	0.021	0.033	0.070	10%

[1] With the cold starts removed, the dilute and raw 10th, 50th, and 90th would be 0.326, 0.146, and 0.031 ppm for the dilute concentration and 2.115, 0.450, and 0.069 ppm for the raw concentration, respectively.

The results show a 10th, 50th and 90th percentile (C_{a_cor}/C_d) ratio of 10%, 54% and 105%, respectively. This suggest more than ½ of the measurements were sampled where the dilute concentration was 50% of the ambient corrected (C_{a_cor}) concentration. The low concentrations measured by dilute methods will impact all the methods except for M3 that utilizes the raw sampling approach where no dilution correction is needed.

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

Where:

C_{a_cor}	is the ambient NOx concentration factor used in M1
C_a	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)

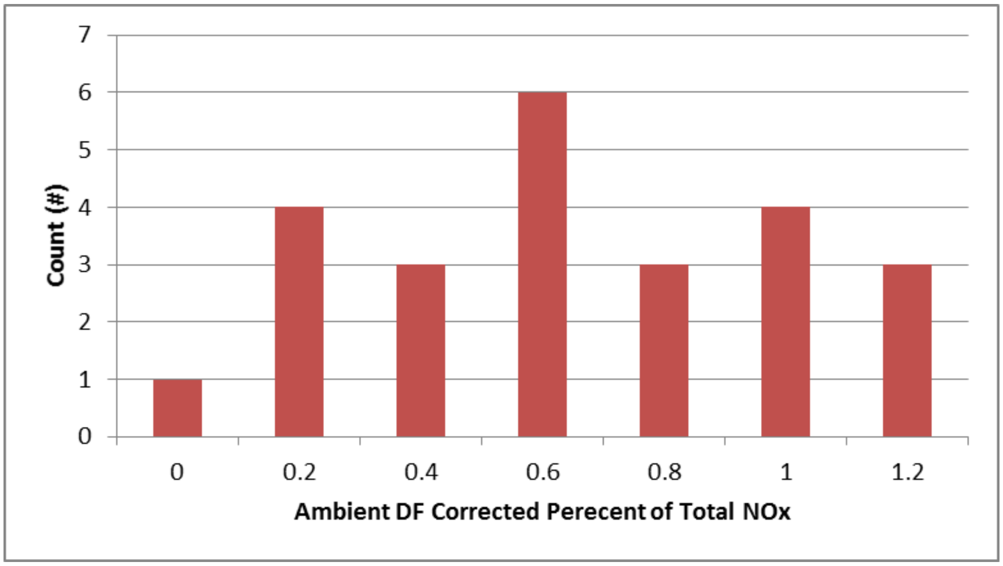


Figure 2-6 Ambient fraction of dilute NO_x concentration distribution

The real-time concentrations for each cycle is also important where observations suggest a few NO_x spikes of 20-30 times the average values were the basis of the cycle average concentrations. Section 4 provides additional discussions on the real-time transient NO_x measurements. It is important to understand that the real-time NO_x spikes will impact the M1, M3, and M4 measurements since these utilize real-time signals where M2 and M5 are integrated bag signals.

The average mean difference in average emissions between the methods is shown in Table 2-5 with M1 as the reference method. For M2 the average NO_x emissions was very similar to M1 (only 5% higher on average, but varied from higher to lower from cycle to cycle). M3 was slightly lower (-18% on average), but was consistently lower except for the CBD tests. Further investigation of the CBD tests shows one of the M1 tests had a negative emission rate due a high ambient bag concentration compared to the modal dilute concentration. This negative value was not an outlier, but a real measurement difficulty at these emission levels. The M4 average NO_x emission rate was notably higher (and relatively more variable) and for M5 the average was significantly lower for all tests compared to the M1 traditional method.

The M4 utilized real time ambient concentrations for real time correction of the background calculation. The trace analyzer utilized show some short term drift that didn't appear to be related to ambient concentration changes. Additional investigation is needed, but is outside the scope of this effort. The researchers suggest the M4 method will have more variability as a result and could be the cause for the higher mean difference.

The M5 utilized the trace NO_x analyzer for bag measurements. Surprisingly the M5 method showed a much lower mean value. Investigations were carried out to see about analyzer drift or stability and no issues were found during the bag analysis time spans.

Table 2-5 NO_x emission average percent difference from Method 1

Trace	M2	M3	M4	M5
UDDS1x	-17%	-40%	96%	-87%
DPT1	31%	-42%	-8%	-99%
UDDS2x	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 is provided in Table 2-6. The two tailed paired t-test and f-test results suggest the two traditional methods do not have statistically different means or different variances at 95% confidence, see Table 2-6 (M2 p-value >> 0.05 for both). The upgraded methods showed a different result that varies. The M3 (raw exhaust flow approach) mean difference is not statistically significant at 95% confidence (M3 p-value > 0.06) but is at the 90% confidence. The M4 (RT ambient correction) and M5 (trace bag evaluation) upgraded methods both have statistically different means (p-value < 0.05 for both).

Table 2-6 Comparison to traditional Method 1 measurement (modal dilute NO_x)

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

Each of the added methods (M3, M4, and M5) may have some possible implementation issues that need to be considered in order to evaluate the comparative results. The M3 measurement showed good alignment between the measured NOx signal and the exhaust flow signal. The majority of the NOx mass emissions resulted from a few large spikes, as discussed in Section 4. These NOx spikes were found to represent more than 80% of the total emission factor. Closer inspection shows that the NOx concentration and exhaust flow spike occurred simultaneously and were usually a result of a rapid acceleration from idle.

For the M4 approach (real-time NOx ambient correction) the analyzer had a slight zero stability issue over the 20-40 minute test cycle not found during the short 3 minute bag analysis. As such, the drift may be the result of the M4 poor method comparison.

The low M5 method may represent the best approach with very accurate bag measurements for both the ambient and dilute bag measurements with a trace type NOx analyzer with a larger sample cell. The drift issue suggested for the M4 measurement didn’t appear to be a factor during the short bag analysis, but additional tests should be performed to evaluation. As such, this method may have performed the best, but additional testing is suggested to evaluate this method on future testing opportunities at 0.02 g/bhp-hr.

In summary the M1, M2, and M3 appear to be the most reliable where the M3 results are more consistent at the extremely low concentrations measured. M4 and M5 require further investigation with lower zero drift instrumentation.

3 Results

This section describes the results from the ISL G NZ 8.9 liter ultra-low NO_x NG engine. The results are organized by gaseous emissions followed by PM, particle size distribution, greenhouse gases, and fuel economy. The emission factors presented in g/bhp-hr for comparison to the certification standard. Emissions in g/mile are provided in Appendix E. Error bars are represented by single standard deviations due to the relatively large magnitude of the error bars in relationship to the low emission levels measured for several species (three repeats were performed where the 95% confidence interval multiplier for the single standard deviation is 3.182).

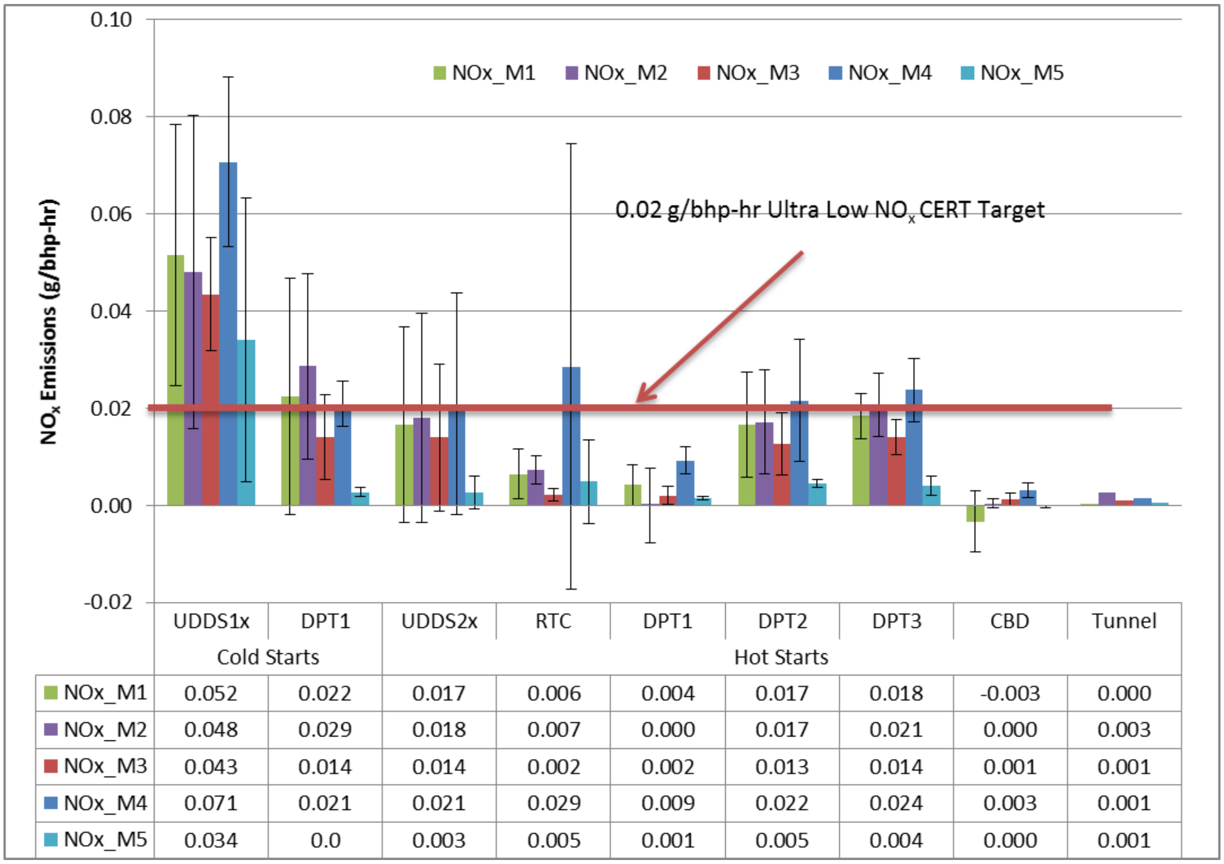
The UDDS cycle is the representative test cycle for comparisons to the engine certification FTP cycle where the other cycles (port, refuse, and bus) provide the reader a feel for the in-use comparability to low duty cycles, cruise conditions, and other vocational specifics of the real world. As such, the results will be presented in each sub-section within the context of the test cycle.

3.1 Gaseous emissions

3.1.1 NOx emissions

The NO_x emissions are presented in Figure 3-1 for each of the methods evaluated and for all the test cycles performed. The NO_x emissions were below the demonstration 0.02 g/bhp-hr emissions targets for the UDDS, DPT1 (hot and cold), and the CBD for all measurement methods. The local and regional port cycles (DPT2 and DPT3) NO_x emissions were below the improved methods but at and below the standard for the traditional methods. The cold start emissions were higher than the hot tests when comparing between like tests (UDDS cold vs hot and DPT1 cold vs hot) and averaged at 0.043 g/bhp-hr for the UDDS test cycle (M3).

In general, the NO_x emissions are below the ISL G NZ 2016 NO_x certification standard of 0.02 g/bhp-hr for all tests and below the in-use NTE standard of 0.03 g/bhp-hr. The reported certification value listed on the ARB EO is 0.01 g/bhp-hr which is slightly lower than the M3 measurements (0.014 g/bhp-hr) shown for the UDDS hot test cycle, Figure 3-1. Deeper investigation shows one of the three hot UDDS tests was statistically higher (M3 = 0.009, 0.002, 0.030 g/bhp-hr). A similar trend was also found for the other four methods where the third point was much higher than the other two points. If the third point was eliminated the average for the hot UDDS would be just under the EO certification value reported by CWI (M3 = 0.005 g/bhp-hr). The test-to-test variability shown by the large error bars in Figure 3-1 was investigated where real-time analysis suggest the variability is not from low measurement issues, but appears to be the results of the vehicle variability. Section 4 provides a discussion on real-time investigation.

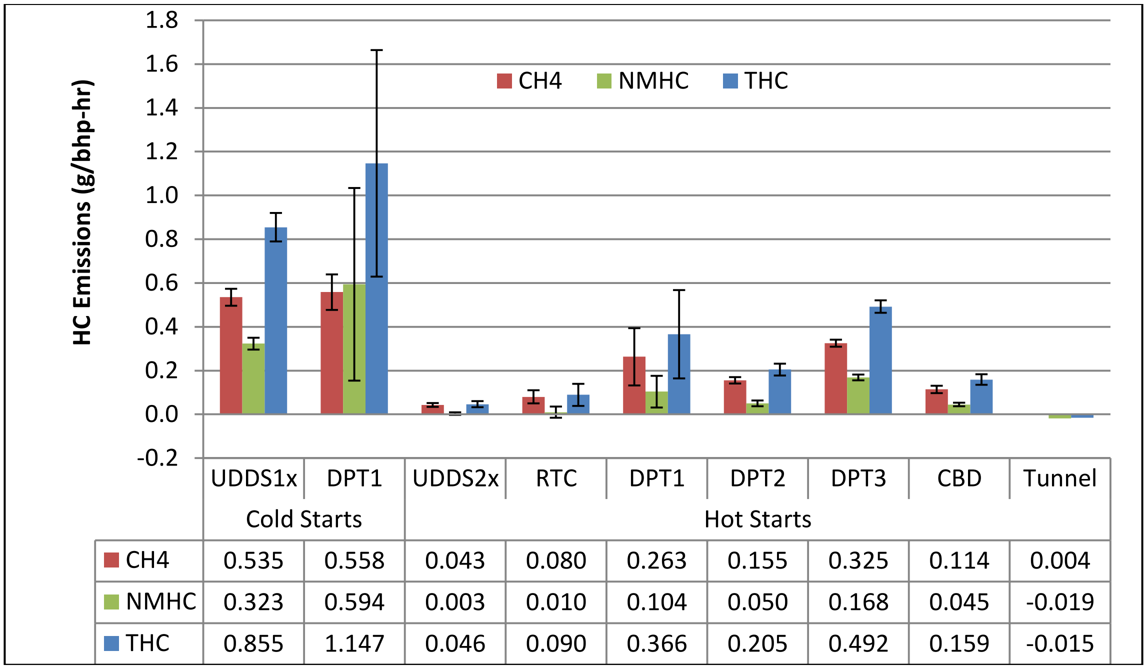


	UDDS1x	DPT1	UDDS2x	RTC	DPT1	DPT2	DPT3	CBD	Tunnel
	Cold Starts		Hot Starts						
NOx_M1	0.052	0.022	0.017	0.006	0.004	0.017	0.018	-0.003	0.000
NOx_M2	0.048	0.029	0.018	0.007	0.000	0.017	0.021	0.000	0.003
NOx_M3	0.043	0.014	0.014	0.002	0.002	0.013	0.014	0.001	0.001
NOx_M4	0.071	0.021	0.021	0.029	0.009	0.022	0.024	0.003	0.001
NOx_M5	0.034	0.0	0.003	0.005	0.001	0.005	0.004	0.000	0.001

Figure 3-1 Measured NOx emission for the various test cycles

3.1.2 Other gaseous emissions

The hydrocarbon emissions (THC, CH_4, and NMHC) are presented in Figure 3-2. The HC are highest for the cold start tests compared to the hot tests where the regional port cycle (PDT3) showed the highest HC emissions. For all the hot tests the NMHC was below the standard but just above the reported certification value except for the regional port cycle. The NMHC was typically lower than CH_4 emission as one would expect for a NG fueled vehicle. The CH_4 emissions are lower than the certification results presented in Appendix F Figure F-4 (0.04 vs the FEL level of 0.65 g/bhp-hr). Also the CH_4 emissions for the refuse hauler are significantly lower (6.4 g/mi vs 0.26 g/mi) than previously tested NG reuse haulers with the 2010 certified NG 8.9 liter engine. The lower CH_4 emissions may be a result of the closed crankcase ventilation (CCV) improvement over previous versions of this engine, see Appendix F for details.



	UDDS1x	DPT1	UDDS2x	RTC	DPT1	DPT2	DPT3	CBD	Tunnel
	Cold Starts		Hot Starts						
🟥 CH4	0.535	0.558	0.043	0.080	0.263	0.155	0.325	0.114	0.004
🟩 NMHC	0.323	0.594	0.003	0.010	0.104	0.050	0.168	0.045	-0.019
🟦 THC	0.855	1.147	0.046	0.090	0.366	0.205	0.492	0.159	-0.015

Figure 3-2 Hydrocarbon emission factors (g/bhp-hr)

Figure 3-3 shows the CO emissions on a g/bhp-hr basis and Figure 3-4 shows the un-regulated NH_3 emissions on a g/bhp-hr basis. The CO emissions ranged between 1.3 to 5.3 g/bhp-hr for the cold start near dock (PDT1) and regional (DPT3) test cycles, respectively. The distance specific emissions ranged from 4.2 to 24.3 g/mi for the regional (PDT3) and the cold start UDDS test cycles. Previous testing of the ISG vehicle show similar CO emissions ranging from 14.4 to 19.2 g/mi (CBD and UDDS test cycles and same test weights).

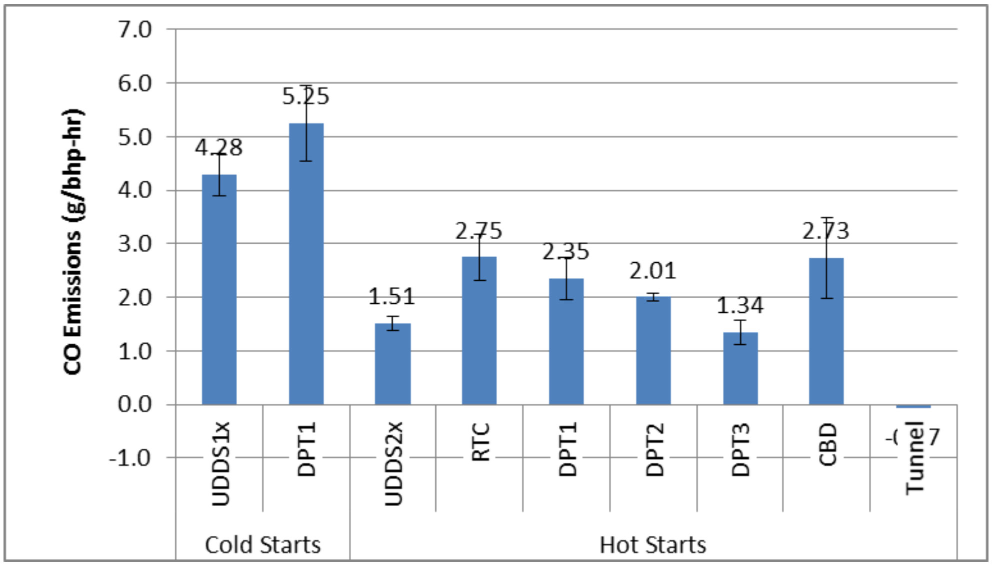


Figure 3-3 CO emission factors (g/bhp-hr)

The NH_3 emissions ranged from 0.43 to 0.94 g/bhp-hr for the hot UDDS and regional (DPT3) cycles. The distance specific emissions varied from 1.16 g/mi to 5.27 g/mi for the regional and CBD test cycles. The NH_3 emissions are slightly higher than previous ISL G vehicle where the NH_3 ranged from 1.17 to 2.8 g/mi for the UDDS and RTC cycle as compared to 1.19 and 4.09 g/mi for the ISL G NZ, respectively. The NH_3 concentration varied from 118 ppm (UDDS) to 305 ppm (CBD), see Figure 3-5.

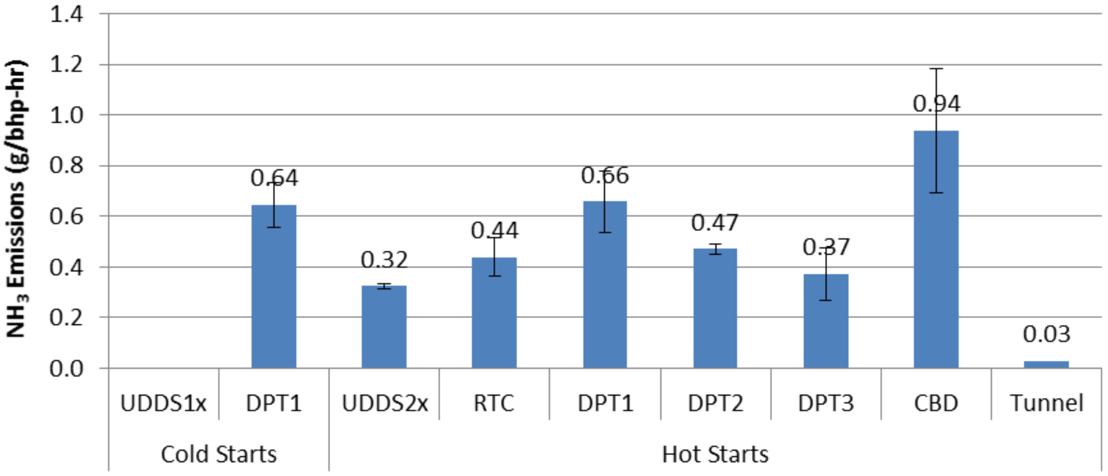


Figure 3-4 Ammonia emission factors (g/bhp-hr)

[1] 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.

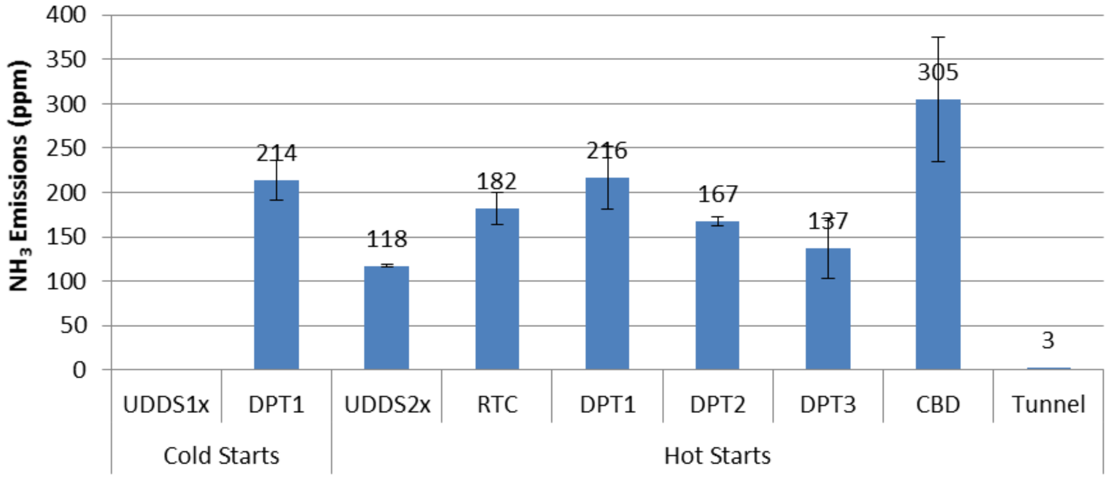


Figure 3-5 Ammonia measured tail pipe concentration (ppm)

[1] 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.

3.2 PM emissions

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 (based on UDDS sample time and work), see Figure 3-6. The first regional PM filter weight was statistically higher than the other three (80, 21, 20 ug) where it is suggested something may have burned off the exhaust system that test that may be artifact of previous vehicle operation. If the first PM results 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 EF 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 measured filter weights were 13 ug with a single standard deviation of 3 ug where the tunnel blank was measured at 5 ug (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 detection capability more than vehicle performance between cycles.

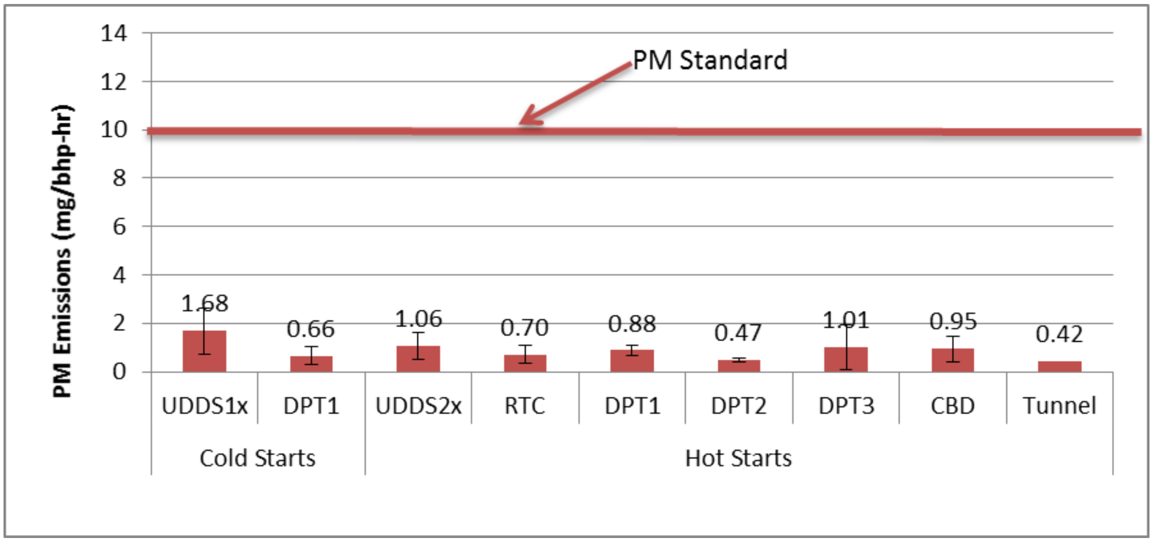


Figure 3-6 PM emission factors (mg/bhp-hr)

[1] Tunnel PM emission factor was based on a tunnel blank and test conditions of the UDDS 2x load conditions for the ISL G NZ test engine.

3.3 PN emissions

The PN emissions (CPC 3772) are shown in Figure 3-7 and Table 3-1 for the test cycles performed. The PN were highest for the high speed regional cycle (DPT3) on a total # basis, but were highest on a #/mi basis for the cold start near dock cycle (PDT1). Since the UDDS cycle is representative of the FTP certification cycle, comparisons to the hot UDDS cycle are presented in Table 3-2 (#/mi basis). The statistical analyses in Table 3-2 were conducted using a 2-tailed, 2 sample equal variance t-test. For the statistical analyses, results are considered to be statistically significant for $p < 0.05$, or marginally statistically significant for $0.05 < p < 0.1$. The near dock port cycle (DPT1) and the UDDS cold start showed statistically significant mean differences where the regional port cycle (DPT 3) showed marginally significant mean difference to the UDDS hot test. The cold start UDDS showed about three times the PN compared to the hot UDDS. The regional cycle showed about 82% more PN compared to the UDDS cycle and the near dock (DPT 1) showed 92% fewer PN. The trash compaction cycle (RTC) and the local port cycle (PDT 2) had similar PN emission rates and did not show statistically different means.

During previous studies with 0.2 g/bhp-hr certified NO_x ISL G engine tested on the near dock and regional port cycles, the PN emissions were $1.9\times10^{12} \pm 3.8\times10^{11}$ #/mi (11) which was about

92% lower than the ISL G NZ UDDS test cycle results, but about the same as the near dock port cycle. In a second study with the ISL G 8.9 liter engine, the PN emissions were $4\text{x}10^{12}$ for the CBD test cycle (10) which agrees well with the results in this study for the near dock and CBD test cycles. During a similar refuse hauler application of the ISL G engine, the PN emissions for the RTC cycle were $2.5\text{x}10^{13}$, $5.8\text{x}10^{12}$, and $2.0\text{x}10^{12}$ #/mi for the curbside, transit, and compaction portions of the RTC test cycle, respectively (12) which compare well with the PN from the ISL G NZ results. Late model diesel engines equipped with DPFs show PN emissions that range from $1.3\text{x}10^{11}$ to $0.7\text{x}10^{11}$ for on-road UDDS and cruise type of tests (18). In general the PN emissions for the ISL G NZ are mixed in comparison to the ISL G with some higher and some about the same. The ISL G NZ and ISL G both show higher PN emissions compared to diesel vehicles equipped with DPFs.

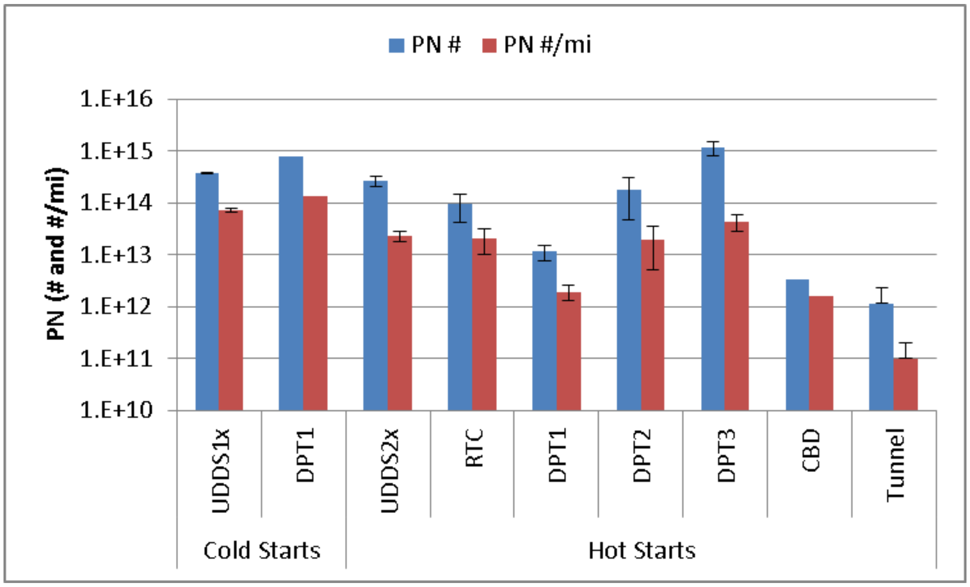


Figure 3-7 Particle number emissions (# and #/mi)

[1] Note the PN presented are based on CVS dilute measurements without sample conditioning (no volatile particle catalytic stripper system) and a D50 of 3 nm (CPC 3776). These PN values will be higher than those presented by the PMP system which uses a 3790A counter (24 nm D50 cut diameter and a volatile particle catalytic stripper system).

Table 3-1 PN Emissions from the ISL-G NZ 8.9 liter engine for various cycles

	PN #		PN #/mi	
Trace	ave	stdev	ave	stdev
CS_UDDS1x	3.80E+14	1.90E+13	7.25E+13	5.22E+12
CS_DPT1	7.87E+14		1.36E+14	
UDDS2x	2.66E+14	6.21E+13	2.37E+13	5.39E+12
RTC	9.49E+13	5.20E+13	2.12E+13	1.12E+13
DPT1	1.16E+13	3.83E+12	1.96E+12	6.25E+11
DPT2	1.83E+14	1.35E+14	2.01E+13	1.50E+13
DPT3	1.16E+15	3.46E+14	4.30E+13	1.51E+13
CBD	3.42E+12		1.62E+12	
Tunnel	1.15E+12	1.15E+12	1.02E+11	1.02E+11

[1] CS stands for cold start and Tunnel stands for tunnel blank. Stdev is a single standard deviation.

Table 3-2 Statistical comparison to the UDDSx2 test cycle

Cycle	t-test	f-test	mean % dif
CS UDDS	0.012	0.870	206%
RTC	0.492	0.388	-11%
DPT1	0.002	0.027	-92%
DPT2	0.721	0.230	-15%
DPT3	0.104	0.227	82%

[1] Unpaired two tailed sample equal variance t-test and mean % difference from the UDDSx2 test cycle

3.4 Ultrafines

The ultrafine PSD (as measured by the EEPS) are shown in Figure 3-8 on a log-log scale concentration basis as measured in the dilute CVS. The cold start UDDS and the regional (DPT3) cycles showed the highest particle number concentration at 10 nm particle diameter of all the traces. The higher PSD for the cold UDDS and regional cycle are a result of PN spikes under different conditions. The cold start UDDS PSD PN spike occurred during the cold portion and for the hot regional cycle (DPT3) the spike occurred during the cruise. The secondary peak at 105 nm particle diameter was highest for the same two cycles and the CBD. DPT1 showed the lowest PSD and was typically below the tunnel blank concentrations. During previous testing on the ISL G 8.9 liter engine the PSD showed a similar bi-modal PSD at 10 nm and 110 nm (10, 11, and 12). Diesel vehicles equipped with a DPF only show a single mode of operation (when not in a DPF regeneration) for the same UDDS and port cycles tested on the ISL G NZ vehicle (2).

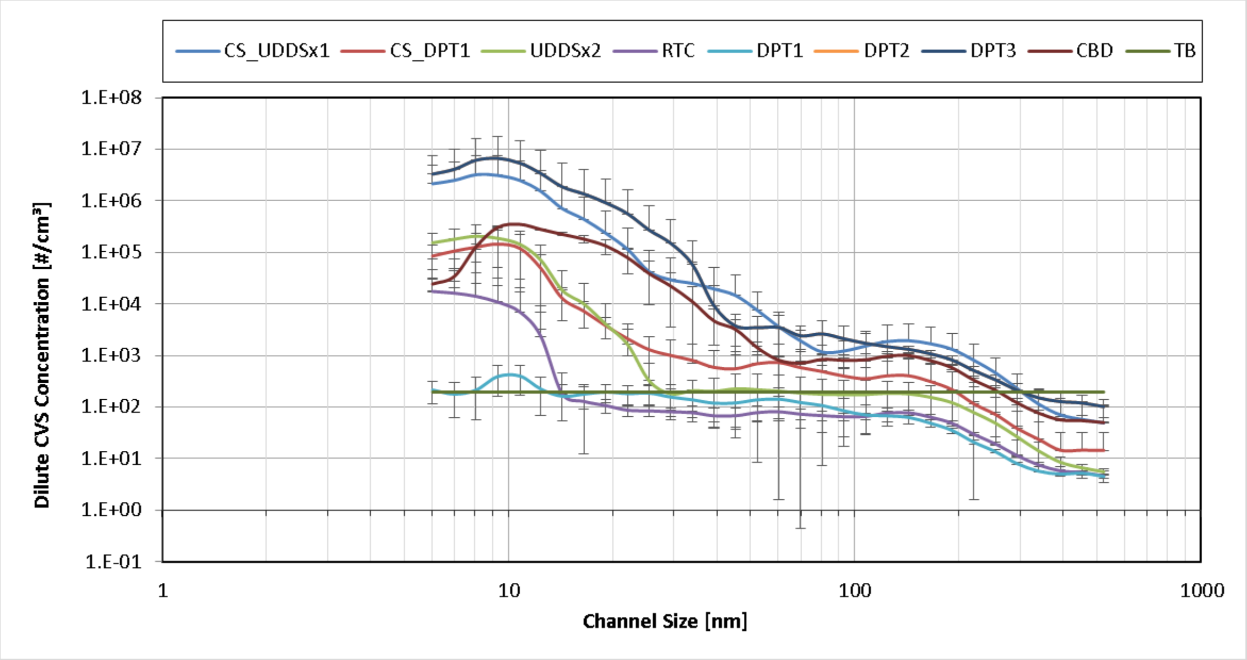


Figure 3-8 EEPS ultrafine PSD measurements for each of the test cycles

3.5 Greenhouse gases

The greenhouse gases include CO_2, CH_4 and N_2O and 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), IPCC fourth assessment report - 2007. The global warming potential is provided in Table 3-3 on a g/bhp-hr basis (see Appendix E for g/mi basis). The CH_4 and N_2O 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 treated 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 3-3 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/m3 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 significant for the ISL G NZ NG engine.

Table 3-3 Global warming potential for the ISLG NZ vehicle tested (g/bhp-hr)

Trace	CO_2	CH_4	N_2O	GWP ($CO_{2\,eq}$)	CO_2 /GWP	Soot	Soot/$PM_{2.5}$
UDDS1x	546.8	0.53	0.062	578.5	0.95	0.05	3%
DPT1	627.0	0.56	0.090	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	0.027	608.9	0.98	0.1	22%
DPT3	549.3	0.33	0.024	564.4	0.97	0.01	1%
CBD	576.1	0.11	0.034	589.0	0.98	0.04	4%

[1] N_20 samples were not collected on the hot UDDS, RTC, and DPT1 due to scheduling details. PM Soot measurements were near the detection limits of the MSS-483 measurement system. The MSS soot signal was corrected for a 1 ug/1% water interference factor as reported by AVL.

3.6 Fuel economy

The fuel economy of the NG vehicle is evaluated by comparing the CO_2 emissions between cycles where the higher the CO_2 the higher the fuel consumption. CO_2 is also regulated by EPA with a standard as performed with the FTP and SET test cycles. The certification like cycle (UDDS) showed the lowest CO_2 emissions and were below 555 g/bhp-hr (FTP standard) for both the cold start and hot start tests. The NG vehicle CO_2 emissions varied slightly between cycles where only the near dock cycle (DPT1) showed a statistically higher CO_2 emission rate. The average CO_2 for all the cycles was 584 g/bhp-hr, and 565 g/bhp-hr with the PDT1 cycle removed. The CO_2 standard and certification value is 555 g/bhp-hr and 465 g/bhp-hr respectively for this displacement engine, see Figure F1 Appendix F. The standard is the target and the certification value is the value measured by the manufacturer. It is suggested the higher in-use CO_2 value (ie in the chassis vs on a test stand) could be a result of additional losses in the chassis where the certification test occurs with the engine on a test stand.

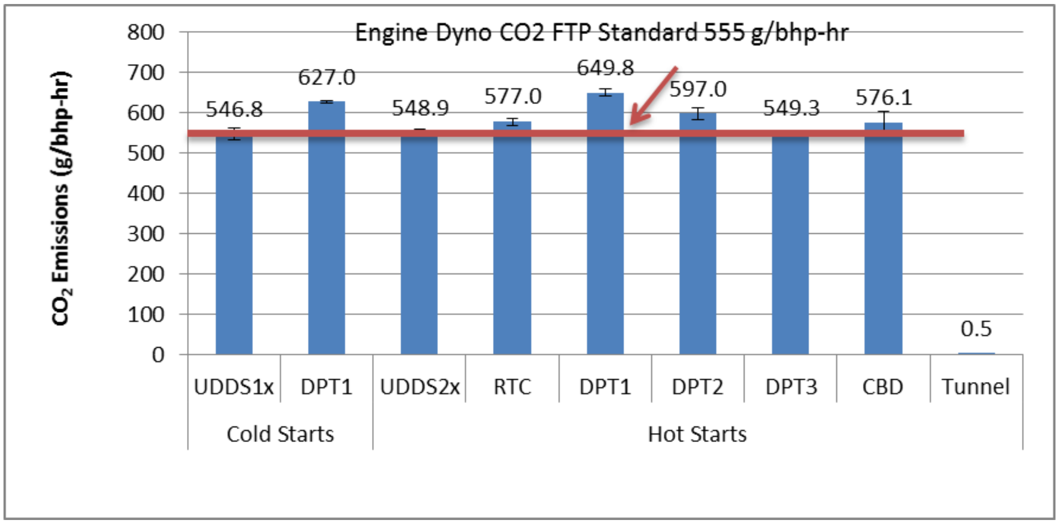


Figure 3-9 CO_2 emission factors (g/bhp-hr)

The ISL G-NZ MPG on a diesel gallon equivalent (MPG_{de}) basis (assuming 2863gNG/gallon diesel (14)) ranges from 4.5 MPG_{de} for the regional port cycle (DPT3) to 2.5 MPG_{de} for the CBD cycle. During previous testing, the previous ISL G 8.9 L fuel economy was found to be 2365 g/mi on a chassis dynamometer at 56,000 GVW following the UDDS test cycle.

4 Discussion

This section discusses investigation into the real-time data to characterize the impact of the cold start and transient NO_x emissions.

4.1 Transient emissions

Figure 4-1 shows the real-time NO_x mass emission rate (g/sec) for the three repeated UDDS cycles. Test 0813 and 1020 had large NO_x spikes, one near the beginning of the test and one near the end of the test where test ID 0915 had only small spikes which are not apparent in Figure 4-1. This indicates that NOx emissions are essentially zero except during sharp accelerations. Figure 4-2 shows the accumulated NO_x emissions as a function of time. The results in Figure 4-2 show the impacts the large and small spikes have on the accumulated NO_x emissions. Test 0915 and 1020 were very similar except for the large spike near the end of the 1020 test.

Figure 4-3 shows the percent of total NOx accumulate as a function of time. The one large spike for test 1020 represented 90% of the total emissions. If the single NOx spike did not occur, the EF for the triplicate cycle would have been close to 0.005 g/bhp-hr instead of the 0.014 g/bhp-hr reported. Figure 4-4 shows the real time NOx emission rate (g/s) exhaust flow, engine RPM, and engine power at the time where the spike occurred. The NOx spike appears to be occurring at the transition from idle to loaded conditions. The figure shows that NOx emission rate and exhaust flow are lined up well suggesting there is not a measurement issue but a real event. In general the transient nature of the emissions suggest the NOx emission are low and are typically below 0.02 g/bhp-hr when good control of the engine stoichiometry is maintained.

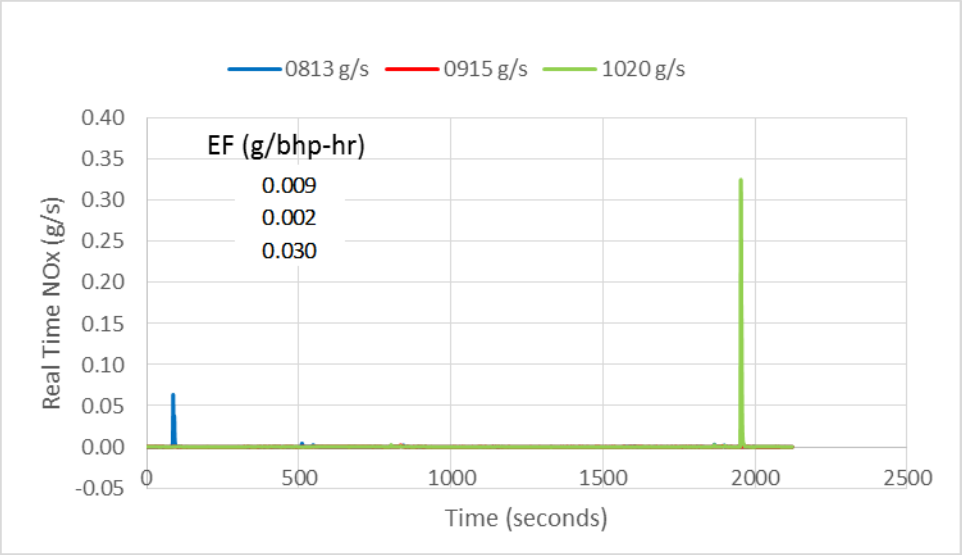


Figure 4-1 Real-time mass rate NOx emissions (g/sec) UDDS cycles

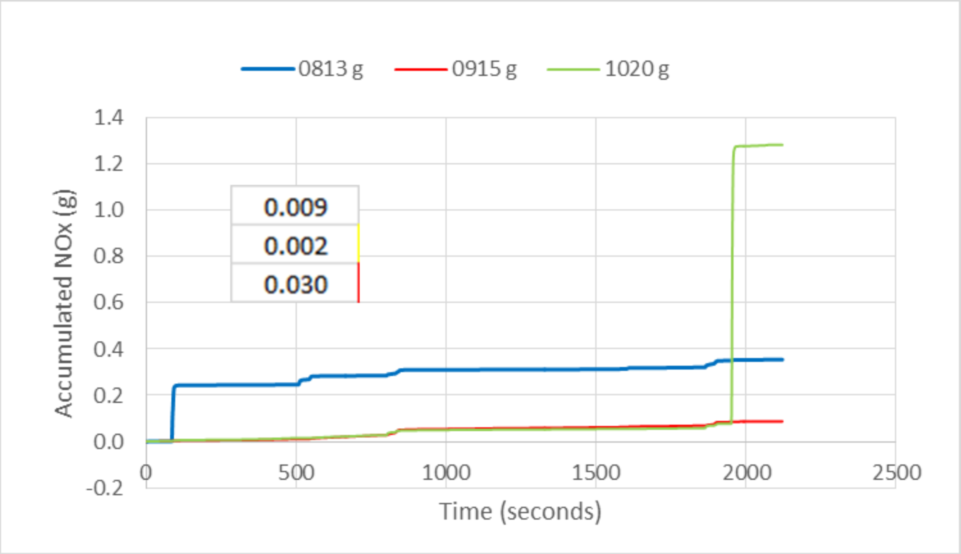


Figure 4-2 Accumulated mass NOx emissions UDDS cycles

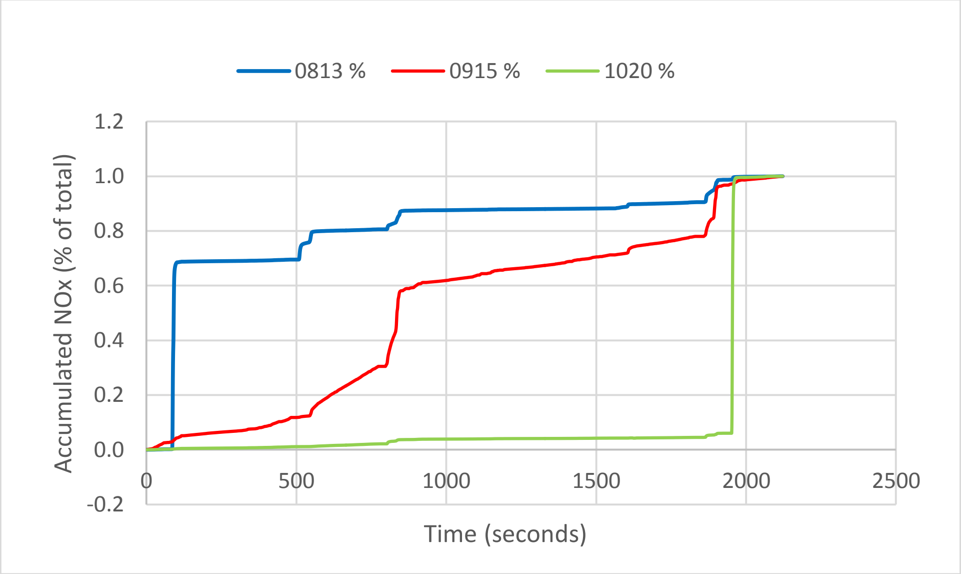


Figure 4-3 Real time NOx emissions (percent of total)

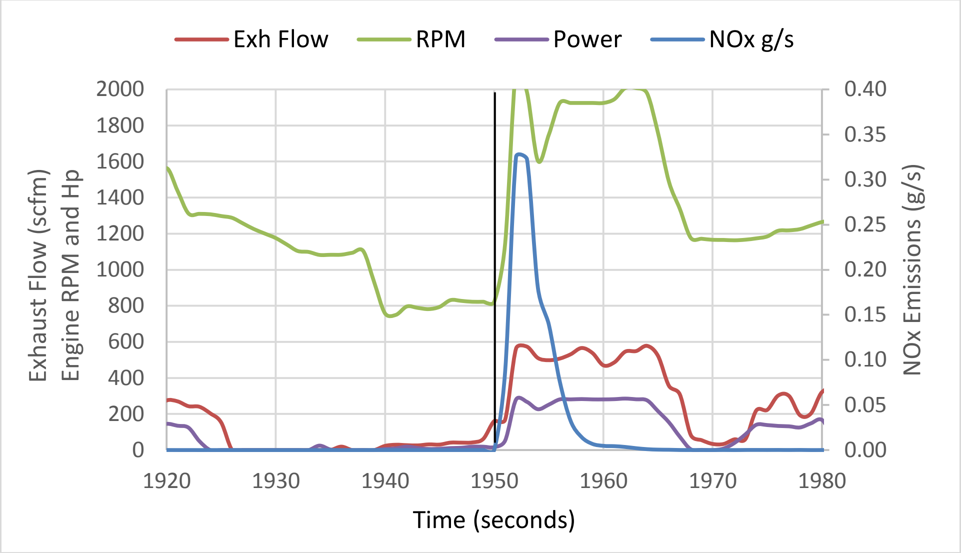


Figure 4-4 Real time NOx emissions large spike evaluation

4.2 Cold start emissions

Cold start emissions represented a significant part of the total emissions as one would expect. Figure 4-5 shows the accumulated NO_x (g) and exhaust temperature as a function of time. 90% of the NO_x emissions occurred in the first 200 seconds of the cold start test. The remaining part of the cold UDDS test was very similar to the hot UDDS test. The UDDS hot/cold weighted emissions is 0.0181 g/bhp-hr (weighted as $1/7^{th}$ of the hot cycle). Given that the cold start lasted 200 seconds out of 1080 seconds (total cycle length) the weighted cold start emissions ($1/7^{th}$ of the hot test) are, thus, based on 200sec/1080sec/7 = 2.6%. This suggests 2.6% of this vehicles in-use emissions are represented by a cold start as defined by how the certification process computes its impact for the regulation process. Also unique to the NG solution, once the catalyst performance is achieved it remains at this high performance unlike the diesel SCR equipped engines where low duty cycle will cause the NOx emissions to increase again.

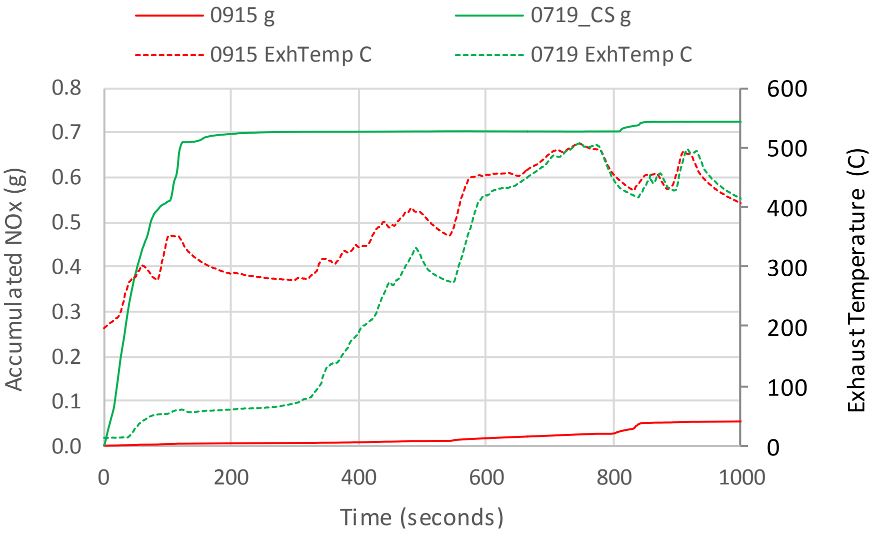


Figure 4-5 Accumulated NOx emissions hot vs cold UDDS comparison

5 Summary and Conclusions

The testing was performed on UC Riverside's chassis dynamometer integrated with its mobile emissions laboratory (MEL) located in Riverside CA just east of the South Coast Air Quality Management District (SCAQMD). The cycles selected for this study are representative of operation in the South Coast Air Basin and included the urban dynamometer driving schedule, the near dock, local, and regional port cycles, the AQMD refuse cycle, and the central business district cycle.

One of the difficulties in quantifying NO_x emissions at the levels proposed in this research (90% below the 2010 certification level ~ 0.02 g/bhp-hr) is the dilute measurement methods are too close to the detection limit to quantify NO_x emissions at the 5% accuracy expected from the emissions industry. 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; however, the raw sampling approach was the most accurate and precise over the range of conditions tested.

In general the ISL G NZ 8.9 met and exceeded the target NO_x emissions of 0.02 g/bhp-hr and maintained those emissions during a range of duty cycles found in the South Coast Air Basin. It is expected NG vehicles could play a role in the reduction of the south coast NOx inventory problem given their near zero emission factors demonstrated

The main conclusions can be summarized as (conclusions are based on the Method 2 results unless noted otherwise):

1. The ILS G NZ 8.9 liter NG engine showed NO_x emissions below the 0.02 g/bhp-hr emission target and averaged between 0.014 and 0.002 g/bhp-hr for hot start tests.
2. The cold start tests ranged from 0.043 to 0.014 g/bhp-hr for the UDDS and DPT2 cycles. The UDDS hot/cold weighted emissions was 0.0181 g/bhp-hr for all test cycles performed which is below the certified 0.02 g/bhp-hr emission factor.
3. The NO_x emissions did not increase with lower power duty cycles and showed the opposite trend where the lower power duty cycles showed lower NO_x emissions unlike the diesel counterparts
4. The large NO_x error bars suggest measurement variability, but real-time data shows the variability is isolated to a few NO_x events during rapid tip-in events from accelerations from idle. This suggests possible driver behavior may impact the overall NO_x in-use performance of the vehicle and more gradual accelerations are desired for minimum emissions.
5. This suggests possible driver behavior may impact the overall NO_x in-use performance of the vehicle where more gradual accelerations are desired.
6. The other gaseous and PM emissions were similar to previously measured levels from the 0.2 g/bhp-hr ISL G engine and should not add to any unknown impacts for the use of the NZ engine in the heavy duty fleet.

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Appendix A. Test Log

This Appendix contains detailed test logs recorded during engine and chassis dynamometer testing. The testing was performed on Vehicle ID 2015_016, Project Low NOx 2015, Vehicle VIN = 3BPZX20X6FF100173 with the test mode in Conventional mode. The chassis and vehicle operators were Eddie and Don for all the testing and the instrument operators were Mark, Jade, Danny and Joey.

Date	Test Time	Test Cycle	Test ID	Hp @ 50	Weight	A	B	C
11/16/2015	14:43	Refuse	201511161358	117.42	56000	397.73642	-2.43E-14	0.193166
11/16/2015	14:56	Compaction Cycle	201511161358	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	7:33	UDDS_CS_1x	201511180727	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	8:17	UDDS_x2	201511180813	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	9:22	UDDS_x2	201511180915	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	10:23	UDDS_x2	201511181020	117.42	56000	397.73642	-2.43E-14	0.193166
11/18/2015	12:14	RTC_DPF_NG	201511181280	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	7:22	UDDS_CS_1x	201511190719	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	7:48	Compaction Cycle	warmup	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	8:13	RTC_DPF_NG	201511190809	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	8:54	RTC_DPF_NG	201511190809	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	9:35	RTC_DPF_NG	201511190929	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	10:16	RTC_DPF_NG	201511190929	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	10:58	DTP_1	201511191051	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	12:58	DTP_1	201511191255	117.42	56000	397.73642	-2.43E-14	0.193166
11/19/2015	14:16	DTP_1	201511191412	117.42	56000	397.73642	-2.43E-14	0.193166
11/20/2015	7:19	DTP_1_CS	201511200716	117.42	56000	397.73642	-2.43E-14	0.193166
11/20/2015	8:41	DTP_2	201511200838	117.42	56000	397.73642	-2.43E-14	0.193166
11/20/2015	10:04	DTP_2	201511200959	117.42	56000	397.73642	-2.43E-14	0.193166
11/20/2015	11:24	DTP_2	201511201122	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	7:24	DTP_1_CS	201511230717	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	8:45	DTP_3	201511230840	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	10:18	DTP_3	201511231015	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	12:35	DTP_3	201511231225	117.42	56000	397.73642	-2.43E-14	0.193166
11/23/2015	2:10	CBD	201511231408	117.42	56000	397.73642	-2.43E-14	0.193166

Date	Test Time	Test Cycle	Test ID	Hp @ 50	Weight	A	B	C
11/25/2015	8:27	UDDS_CS_1x	201511250820	117.42	56000	397.73642	-2.43E-14	0.193166
11/25/2015	9:13	CBD	201511250907	117.42	56000	397.73642	-2.43E-14	0.193166
11/25/2015	9:48	CBD	201511250946	117.42	56000	397.73642	-2.43E-14	0.193166

Appendix B. Test Cycle Description

The test vehicle utilizes an 8.9 liter NG engine which is available for three typical vocations in the South Coast Air Basin, 1) goods movement, 2) transit bus, and 3) refuse. As such UCR tested the vehicle following the three drayage type port cycles (Near Dock, Local, and Regional), the Urban Dynamometer Driving Schedule (UDDS), the Central Business District (CBD) bus cycle, and the AQMD Refuse cycle. These cycles are representative of Sothern California driving vocations used. Some cycles are very short (less than 30 minutes) where double or triple cycles (2x or 3x) cycles are recommended in order capture enough PM mass to quantify emissions near 1 mg/bhp-hr.

Drayage Truck Port (DTP) cycle

TIAX, the Port of Long Beach and the Port of Los Angeles developed the port cycle. Over 1,000 Class 8 drayage trucks at these ports were data logged for trips over a four-week period in 2010. Five modes were identified based on several driving behaviors: average speed, maximum speed, energy per mile, distance, and number of stops. These behaviors are associated with different driving conditions such as queuing or on-dock movement, near-dock, local or regional movement, and highway movements (see Table B-1 for the phases). The data was compiled and analyzed to generate a best fit trip (combination of phases). The best-fit trip data was then additionally filtered (eliminating accelerations over 6 mph/s) to allow operation on a chassis dynamometer.

The final driving schedule is called the drayage port tuck (DPT) cycle and is represented by 3 modes where each mode has three phases to best represent near dock, local, and regional driving as shown in Table B-1, B-2 and Figure B-1. The near-dock (DTP-1) cycle is composed of phase 1, 2, and 3a from Table B-1. This gives the complete near-dock cycle listed in Table B-2. Similarly, for the Local and Regional cycles (DPT-2 and DPT-3) the main difference is phase 3, which changes to 4 and 5 respectively. Phase 1 and 2 remain the same for all three cycles where creep and low speed transient are considered common for all the port cycles. For this testing it is recommended to perform phase 1 through 5 individually and to calculate the weighted emissions from the combined phases for an overall weighing impact.

Table B-1. Drayage Truck Port cycle by phases

Description	Phase #	Distance mi	Ave Speed mph	Max Speed mph	Cycle length
Creep	1	0.0274	0.295	4.80	335
low speed transient	2	0.592	2.67	16.8	798
short high speed transient	3	4.99	9.39	40.6	1913
Long high speed transient	4	8.09	13.07	46.4	2229
High speed cruise	5	24.6	35.04	59.3	2528

Table B-2. Drayage Truck Port cycle by mode and phases

Description	Distance mi	Ave Speed mph	Max Speed Mph	Mode 1	Mode 2	Mode 3
Near-dock PDT1	5.61	6.6	40.6	Creep	Low Speed Transient	Short High Speed Transient
Local PDT2	8.71	9.3	46.4	Creep	Low Speed Transient	Long High Speed Transient
Regional PDT3	27.3	23.2	59.3	Creep	Low Speed Transient	High Speed Cruise

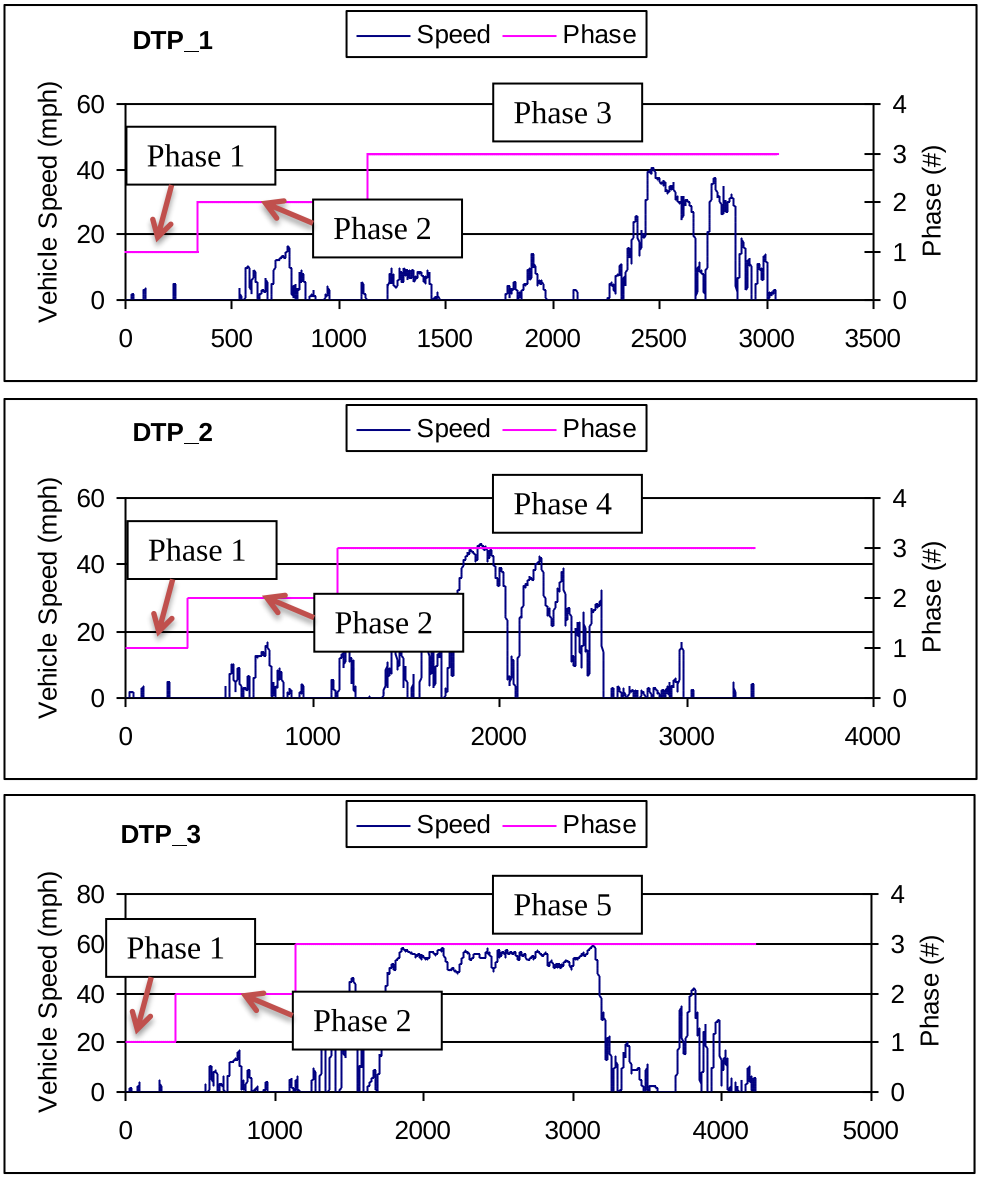

Figure B-1 Drayage truck port cycle near dock, local, and regional

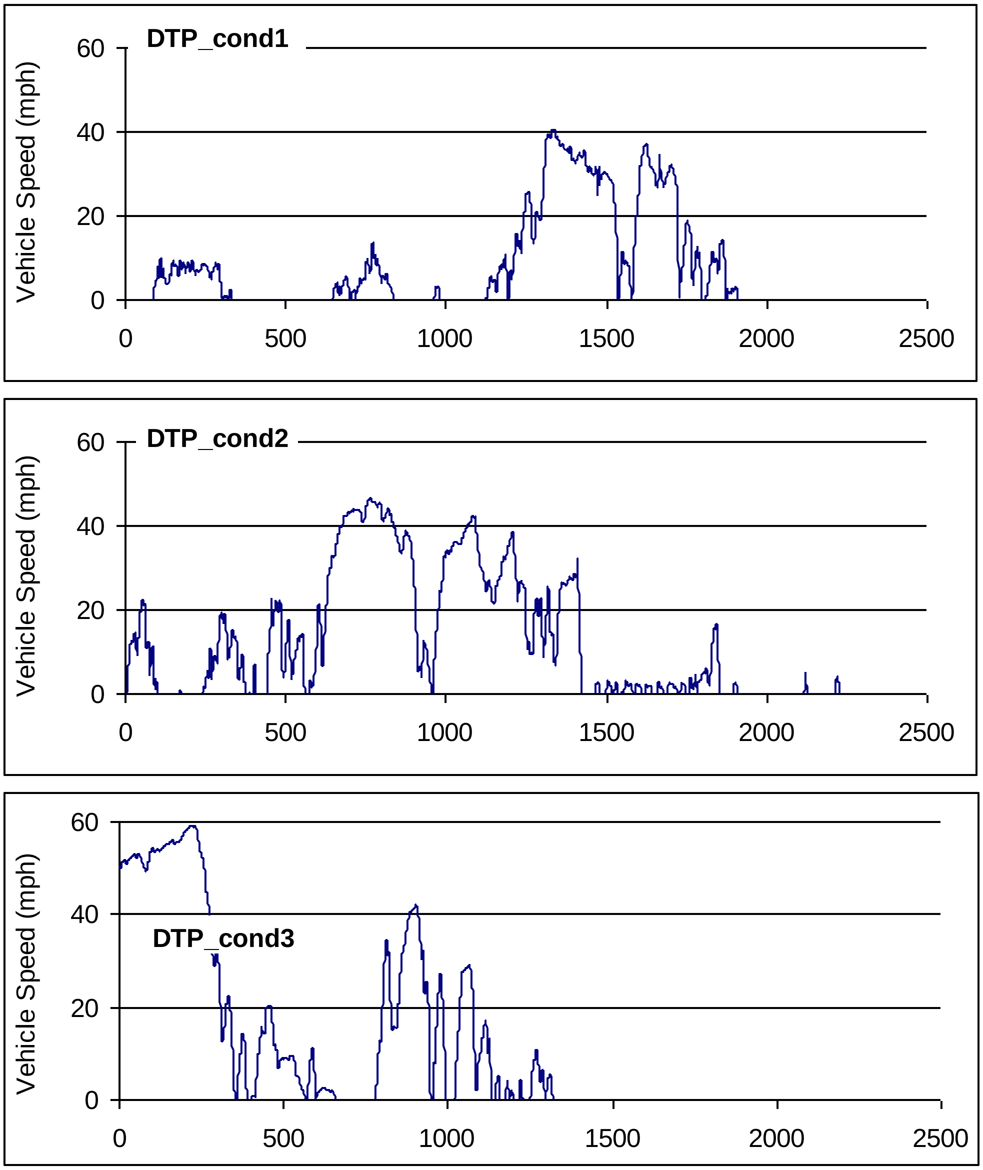

Figure B-2 Drayage truck port cycle conditioning segments consisting of phase 3 parts

Urban Dynamometer Driving Schedule (UDDS) description

The Federal heavy-duty vehicle Urban Dynamometer Driving Schedule (UDDS) is a cycle commonly used to collect emissions data on engines already in heavy, heavy-duty diesel (HHD) trucks. This cycle covers a distance of 5.55 miles with an average speed of 18.8 mph, sample time of 1061 seconds, and maximum speed of 58 mph. The speed/time trace for the HUDDS is provided below in Figures B-3. This cycle was used for all cold start tests as a single test and was performed in duplicate for all hot tests. Duplicates were used to accumulate sufficient mass for the gravimetric measurement method.

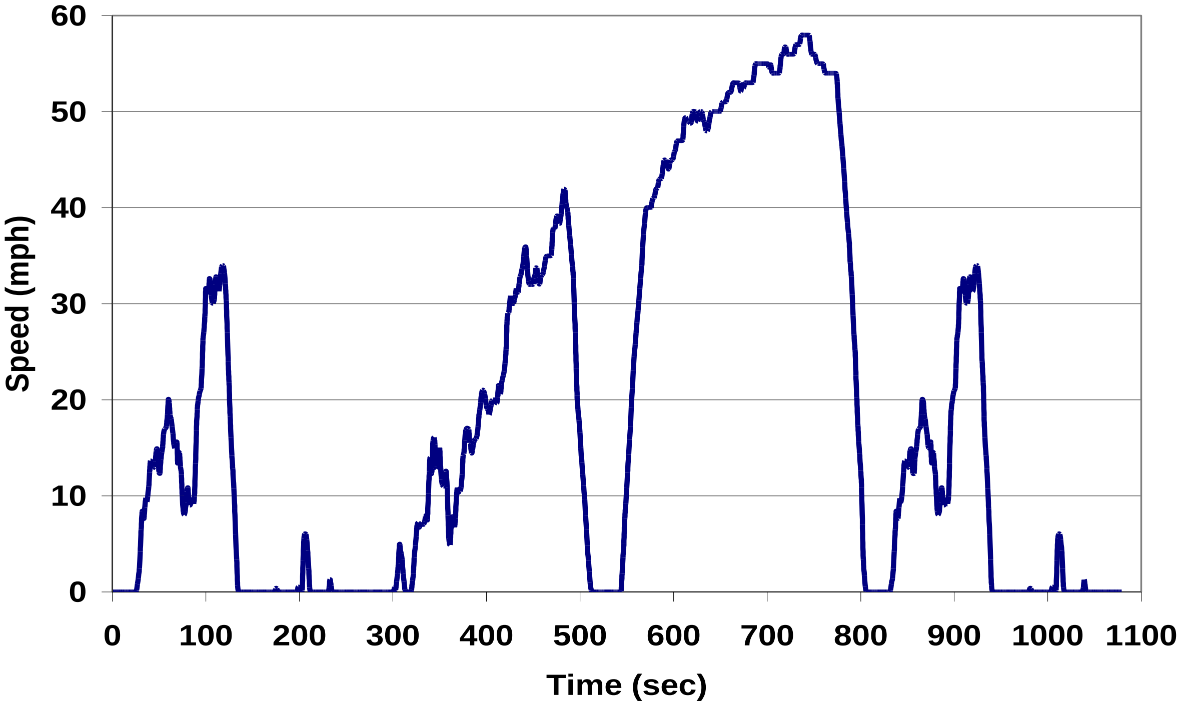

Figure B-3. Speed/Time Trace for a 1xHUDDS cycle for the chassis dynamometer.

The AQMD refuse truck cycle

The AQMD refuse truck cycle (AQMD-RTC) is the same as the WHM-RTC in that the cycle consists of a transport, curbside and compaction operation, with the main difference being the length of time and arrangement of the individual modes. The duration of the AQMD-RTC transport and curbside is 2127 seconds, representing a distance of 4.56 miles and the compaction adds another 760 seconds for a total of 2887 seconds. Figure A-4 shows the vehicle speed vs. time trace for the cycle preparation, transport (phase 1) and curbside (phase 2) portion of the cycle. The curb side pick-up mode is representative of multiple short idle times with frequent stop-and-go operation. The cycle is characterized by frequent accelerations and decelerations. The frequent stop-and-go operation could lead to lower catalytic activity and higher mass tailpipe emissions rates.

Real-world compaction operation was obtained from ECU engine load. It was observed that the engine load varied from 80 to 20 hp in a cyclical manner. The compaction cycle is simulated with the vehicle operating at steady-state speed of 30 mph with an intermittent engine of 80 hp and 20 hp. The total duration of the compaction cycle (phase 3) is 880 seconds, see Figure A-5 for the vehicle speed vs. time trace and axle power loading of the compaction cycle. The emissions are collected for only the stabilized speed which occurs 80 seconds into the trace and ends 40 seconds before the end of the trace for a total of 760 seconds.

Since, the compaction operation does not accrue any driving miles in real-world, the emissions from the compaction cycle are represented on a time-specific basis. Further, in order to represent the distance-specific emissions of the refuse truck operation as a whole, the total mass of emissions from the compaction cycle is added to the transport and curbside emissions divided by the distance of the transport and curbside portion. Thus, it is expected the distance specific emissions on the refuse cycle will be higher than the transport plus curbside emissions since the compaction cycle didn't accumulate any distance.

UCR's MEL was configured with the conditioning and transport plus triple curbside into a signal cycle where the sampling was started at second 526 (Start of Transport Phase 1). After completing Phase 2 (Curbside), the compaction cycle was loaded and the driver brought the vehicle speed up to 30 mph and then the dyno was put in a load cycle mode that oscillated from 20 to 80 hp as shown in Figure B-5.

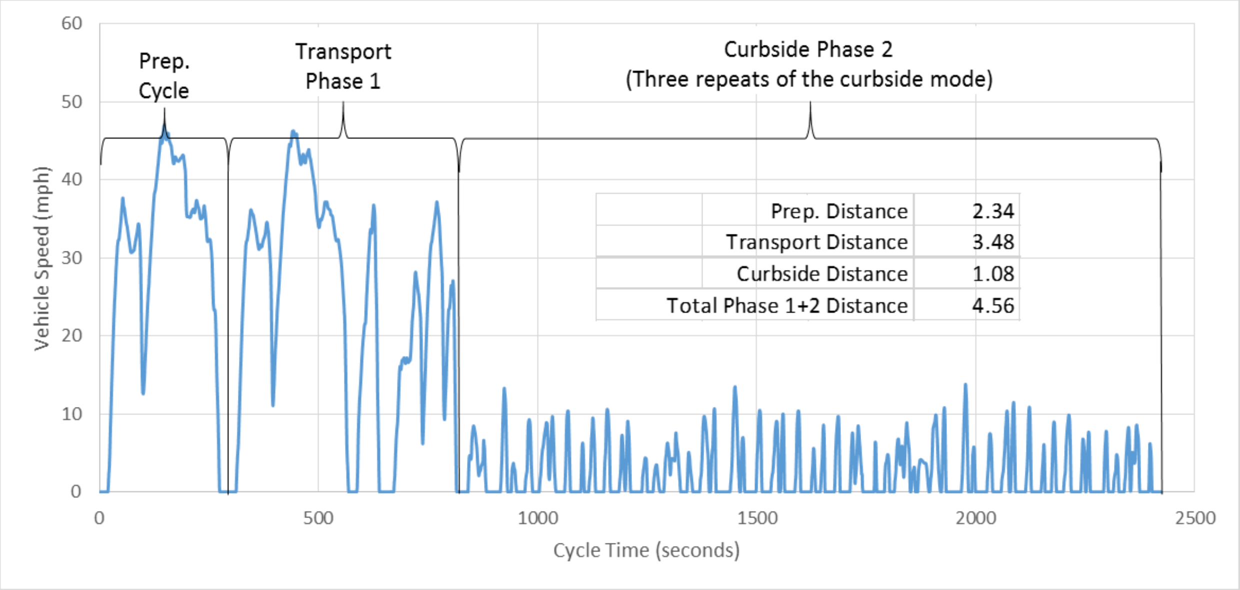

Figure B-4 Speed trace for AQMD refuse truck driving cycle

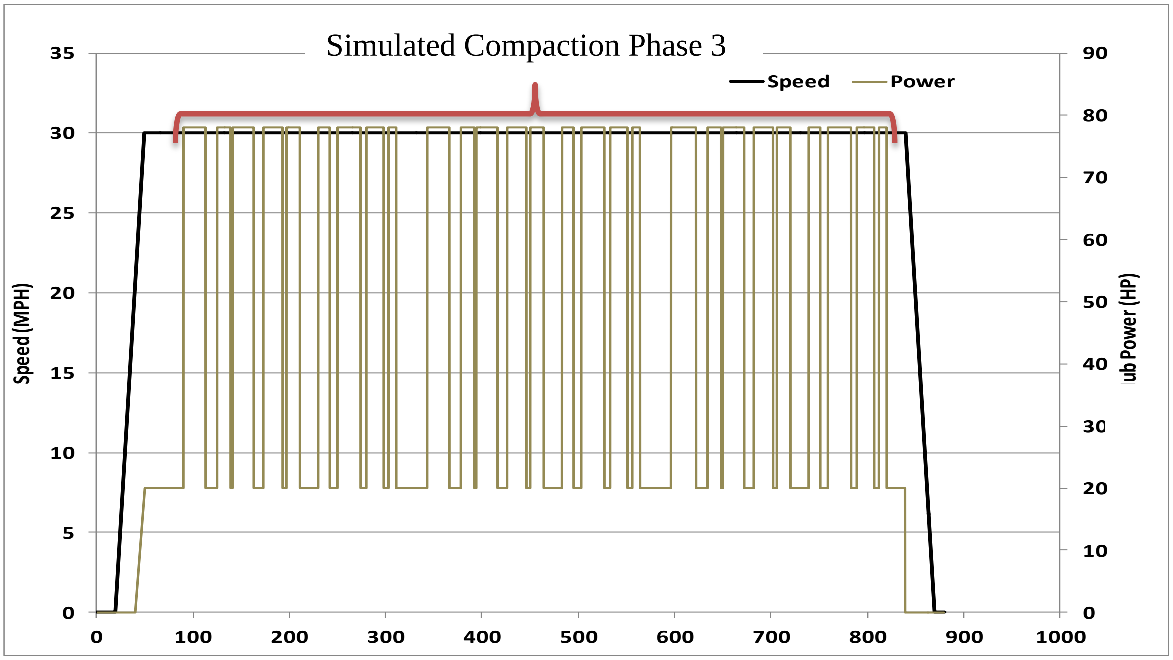

Figure B-5 Speed trace for AQMD refuse truck compaction cycle

Central Business District (CBD) Cycle

The Central Business District (CBD) Cycle is a chassis dynamometer testing procedure for heavy-duty vehicles (*SAE J1376*). The CBD cycle represents a “sawtooth” driving pattern, which includes 14 repetitions of a basic cycle composed of idle, acceleration, cruise, and deceleration modes. The following are characteristic parameters of the cycle:

- Duration: 560 s
- Average speed: 20.23 km/h
- Maximum speed: 32.18 km/h (20 mph)
- Driving distance: 3.22 km
- Average acceleration: 0.89 m/s^2
- Maximum acceleration: 1.79 m/s^2

Vehicle speed over the duration of the CBD cycle is shown in Figure A-1.

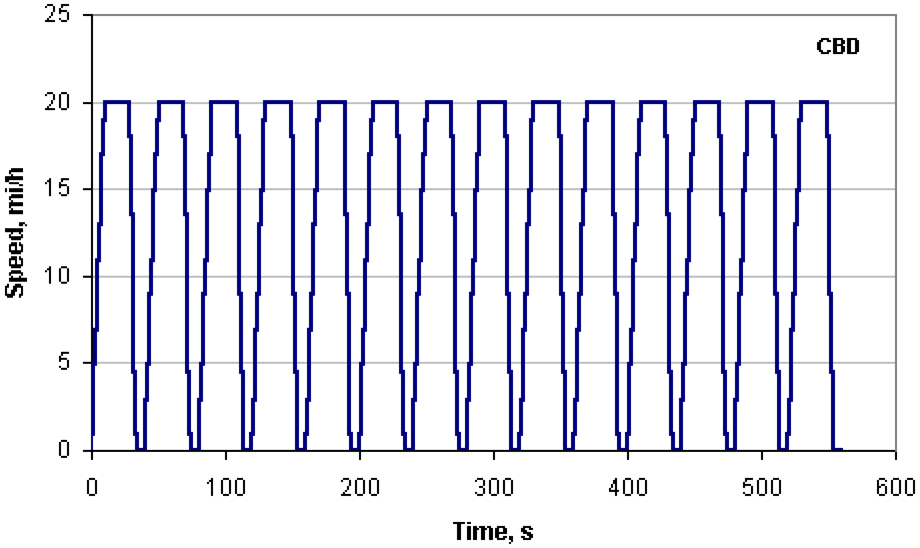

Figure B-6. CBD Driving Cycle

The standard CBD test cycle will be used for bus testing where three cycles will be combined for a triple CBD for a total sample time of 30 minutes. Performing the CBD cycle three times in one test allows for additional sample volumes to be collected for all batched type analysis (filters, DNPH, BETEX and N_2O). Preconditioning is defined as performing a previous triple CBD and a 20 minute soak to improve repeatability between hot repeats. Emissions analyses for gaseous emissions will also be collected over the triple CBD cycles. This cycle is shown in Figure A-2. The triple CBD cycle will be repeated in triplicate for repeatability metrics as described earlier.

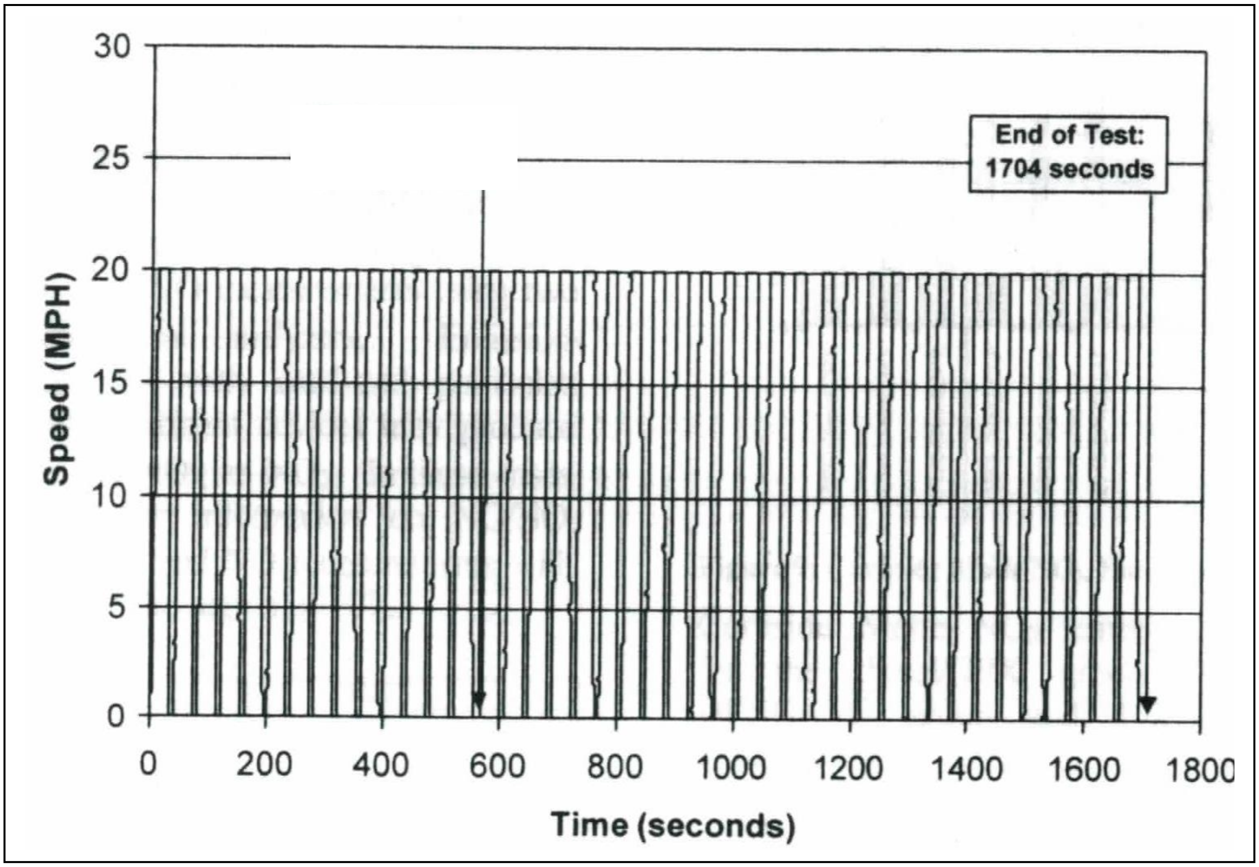

Figure B-7. Triple CBD Cycle

Appendix C. UCR Mobile Emission Laboratory

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. The details for sampling and measurement methods of mass emission rates from heavy-duty diesel engines are specified in Code of Federal Regulations (CFR): Protection of the Environment, Section 40, Part 1065. UCR's unique heavy-duty diesel mobile emissions laboratory (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 C-1. The accuracy of MEL's measurements have been checked/verified against ARB's[10] and Southwest Research Institute's[11,12] heavy-duty diesel laboratories. MEL routinely measures Total Hydrocarbons (THC), Methane, Carbon Monoxide, Carbon Dioxide, Nitrogen Oxides, and Particulate Matter (PM) emissions from diesel engines. Design capabilities and details of MEL are described in Cocker et al[1,13]. Samples can be collected for more detailed analyses such as hydrocarbon speciation, carbonyl emissions, polynuclear aromatic hydrocarbons, etc.

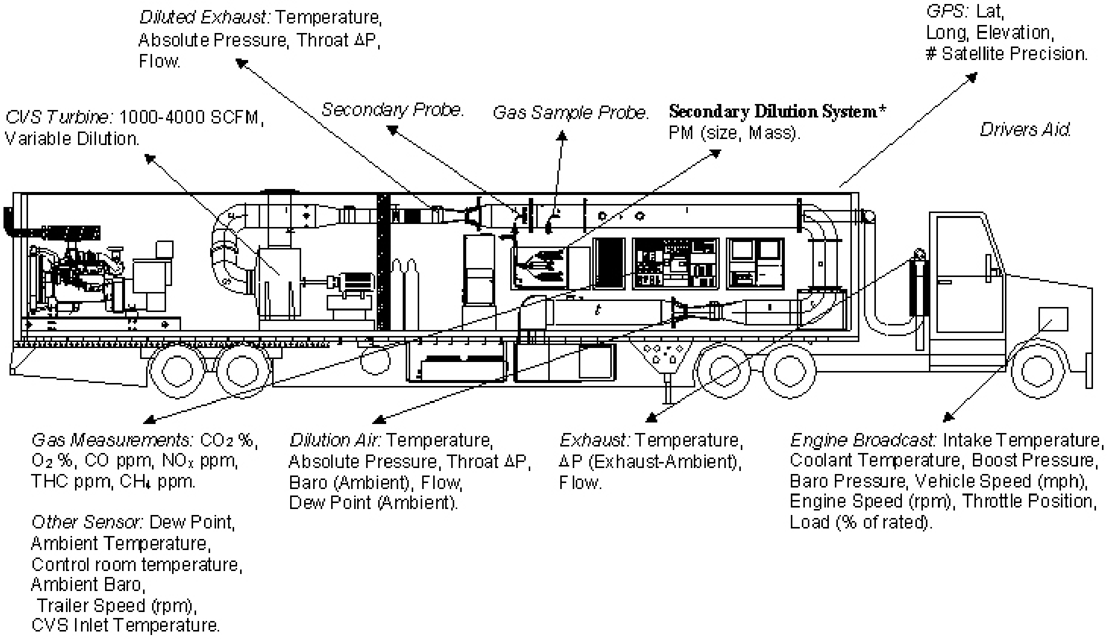

Figure C-1: Major Systems within UCR's Mobile Emission Lab (MEL)

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[10] Cocker III, D. R., Shah, S. D., Johnson, K. C., Zhu, X., Miller, J. W., Norbeck, J. M., Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 2. Sampling for Toxics and Particulate Matter, Environ. Sci. Technol. **2004**, 38, 6809-6816

[11] Cocker III, D. R, Shah, S. D., Johnson, K. C., Miller, J. W., Norbeck, J. M., Measurement Allowance Project – On-Road Validation. Final Report to the Measurement Allowance steering Committee.

[12] Johnson, K.C., Durbin, T.D., Cocker, III, D.R., Miller, W.J., Bishnu, D.K., Maldonado, H., Moynahan, N., Ensfield, C., Laroo, C.A. (2009) On-road comparison of a portable emission measurement system with a mobile reference laboratory for a heavy-duty diesel vehicle, Atmospheric Environment 43 (2009) 2877–2883

[13] Cocker III, D. R, Shah, S. D., Johnson, K. C., Miller, J. W., Norbeck, J. M., *Development and Application of a Mobile Laboratory for Measuring Emissions From Diesel Engines I. Regulated Gaseous Emissions*, Environmental Science and Technology. **2004**, 38, 2182-2189

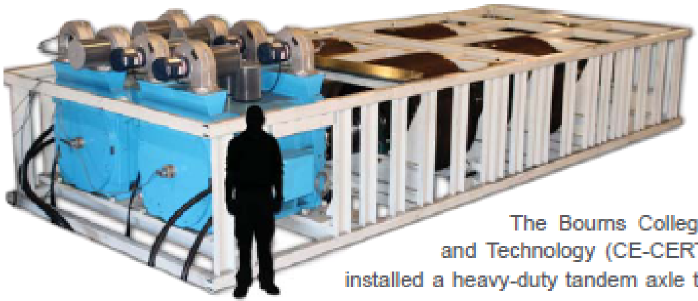
Appendix D. Heavy-Duty Chassis Dynamometer Laboratory

UCR’s chassis dynamometer is an electric AC type design that can simulate inertia loads from 10,000 lb to 80,000 lb which covers a broad range of in-use medium and heavy duty vehicles, see Figure D-1. The design incorporates 48” rolls, axial loading to prevent tire slippage, 45,000 lb base inertial plus two large AC drive for achieving a range of inertias. The dyno has the capability to absorb accelerations and decelerations up to 6 mph/sec and handle wheel loads up to 600 horse power at 70 mph. This facility was also specially geared to handle slow speed vehicles such as yard trucks where 200 hp at 15 mph is common.

The chassis dynamometer was designed to accurately perform the new CARB 4 mode cycle, urban dynamometer driving schedule (UDDS), refuse drive schedule (WHM), bus cycles (CBD), as well as any speed vs time trace that do not exceed the acceleration and deceleration rates. The load measurement uses state of the art sensing and is accurate to 0.05% FS and has a response time of less than 100 ms which is necessary for repeatable and accurate transient testing. The speed accuracy of the rolls is ± 0.01 mph and has acceleration accuracy of ± 0.02 mph/sec which are both measured digitally and thus easy to maintain their accuracy. The torque transducer is calibrated as per CFR 1065 and is a standard method used for determining accurate and reliable wheel loads.

Figure D-1. UCR’s heavy duty chassis eddy current transient dynamometer

Mustang Advanced Engineering delivers a newly designed 48" Electric AC Heavy-Duty Truck Chassis Dynamometer with dual, direct-connected 300-hp AC motors to The University of California - Riverside, College of Engineering - Center for Environmental Research and Technology (CE-CERT).



The science of measuring emissions from mobile and other sources has evolved significantly over the past several years. The most important changes in the nature of emissions measurement science has been a shift to examining emissions from diesel sources and to understanding emissions under in-use driving conditions.

The Bourns College of Engineering – Center for Environmental Research and Technology (CE-CERT) at The University of California Riverside has recently installed a heavy-duty tandem axle truck chassis dynamometer in the facility's research area. Designed and manufactured by Mustang Advanced Engineering, the development of this chassis dynamometer design was based on targeting vehicles in the medium to heavy-duty diesel vehicle range. Heavy-duty applications that can be tested at the facility include on-highway trucks, buses, waste haulers, yard tractors, and more - under test conditions representative of their specific in-use operations. The facility couples the new heavy-duty chassis dynamometer from Mustang Advanced Engineering with CE-CERT's Mobile Emissions Laboratory (MEL), to perform precise vehicle simulation and in-operation emissions measurements.

The first research conducted on the new facility will be a comparison of federally mandated diesel fuel formulas versus the stricter formulation required in California. The program calls for 10 heavy-duty trucks to be tested with several different fuels.

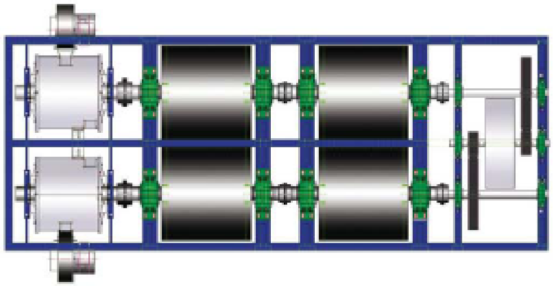
The new dynamometer will simulate on-road driving conditions for any big rig using its 48" precision rollers with dual, direct connected, 300 horsepower motors attached to each roll set. The dynamometer applies the appropriate loading to a vehicle to simulate factors such as the friction of the roadway and wind resistance that it would experience under typical driving conditions. An additional large inertia weight was incorporated into the dynamometer to increase the base mechanical inertia and enable the dynamometer to provide precise on-road simulation for a wide range of vehicle weights. The driver accelerates and decelerates according to a driving trace which specifies the speed and time over a wide range of vehicle simulation cycles. As the on-road driving conditions are being simulated on the dynamometer, emissions measurements will be collected with CE-CERT's Mobile Emissions Laboratory (MEL).

"This adds new capabilities in California that are only available at a limited number of facilities around the country," said Tom Durbin, who with J. Wayne Miller, are the principle investigators for the project. At both the state and federal levels, scientific requirements for emissions testing are trending away from steady state engine testing in favor of transient conditions found in typical driving, Durbin explained. "This addition will significantly expand our laboratory and measurement capabilities and help us continue our role as leading experts in the field of emissions research," said CE-CERT Director Matthew Barth.

CE-CERT's new heavy-duty chassis dynamometer will allow the testing of a variety of heavy vehicles under loaded and transient in-use conditions with corresponding emissions measurements. The dynamometer configuration is capable of meeting the inertia simulation range requirements of 10,000 to 80,000 lb for each of the cycles listed below. This includes acceleration rates up-to 6 mph/sec, as found in the UDDS Section D Drive Schedule and deceleration rates of up to 7 mph/sec as required for the WHM Refuse Drive Schedule. The dynamometer can also provide a load in excess of 600 HP @ 70 mph. The dynamometer also has the ability to continuously handle 200 Hp @ 15 mph for applications such as yard tractors.

The Dynamometer system is designed to meet the Heavy Duty Drive Schedules for diesel trucks in the weight range of 10,000 to 80,000 lb with acceleration rates for the following cycles:

- CARB HHDDT Cruise Mode Drive Schedule
- UDDS (Urban Dynamometer Drive Schedule)
- CARB 50 mph HHDDT Cruise Cycle
- HHDDT Transient Mode Drive Schedule
- WHM Refuse Drive Schedule
- Bus cycles such as, the CBD, OC Bus cycle, NY bus cycle
- In-use cycles for applications such as yard tractors.



"As part of our strategic plan, Mustang has developed a cost effective series of diesel, petroleum and hybrid certification grade dynamometer systems to address the needs of the global emissions and R&D market. There is a clear and present demand for a full performance cost effective dynamometer systems that offer all of the capabilities and confidence of a certification system at a price point that makes it no longer cost-prohibitive for organization to perform critical emissions studies, hybrid system calibration development, performance evaluation and other cutting edge research technologies. Researchers are in need of dynamometer systems to develop the next generation technologies which mimic the capabilities of the certification requirements, but at a fraction of the cost of a true certification system. That is what we are developing with this series of dynamometers and universities are lining up for them", said Executive Vice President, Donald Ganzhorn.

Appendix E. Additional Test Data and Results

This appendix includes some additional results not presented in the main report, but can be used to support the assumptions and decisions made for the results presented. Following Tables E-1 through E-4 are fuel sample analysis reports.

Table E-1 Average emission factors for all cycles (g/bhp-hr)

	Duration	Engine		Ave Modal Emission Factor (g/bhp-hr)							PM (mg/bhp-hr)		NOx Emissions (mg/bhp-hr)				
Trace	sec	bhp	bhp-hr	THC	CH_4	NMHC	CO	N_2O	CO_2	NH_3	$PM_{2.5}$	Soot	M1	M2	M3	M4	M5
CS_UDDS	1081	75.3	22.6	0.85	0.53	0.32	4.28	0.062	546.8		1.7	0.05	51.5	48.0	43.5	70.7	34.1
CS_DPT1	3049	31.8	26.9	1.15	0.56	0.59	5.25	0.090	627.0	0.64	0.7	0.02	22.5	28.6	14.0	20.9	2.7
UDDS	2122	69.7	41.1	0.05	0.04	0.00	1.51	-	548.9	0.32	1.1	0.06	16.6	18.0	13.9	20.9	2.6
RTC	2889	51.3	41.2	0.09	0.08	0.01	2.75	-	577.0	0.44	0.7	0.00	6.4	7.2	2.2	28.6	4.9
DPT1	3049	27.7	23.5	0.37	0.26	0.10	2.35	-	649.8	0.66	0.9	0.07	4.2	0.0	2.0	9.2	1.4
DPT2	3365	36.5	34.1	0.20	0.16	0.05	2.01	0.027	597.0	0.47	0.5	0.10	16.6	17.2	12.6	21.6	4.5
DPT3	4228	74.9	87.9	0.49	0.33	0.17	1.34	0.024	549.3	0.37	1.0	0.01	18.4	20.8	14.1	23.7	4.1
CBD	560	76.2	11.8	0.16	0.11	0.05	2.73	0.034	576.1	0.94	0.9	0.04	-3.3	0.4	1.2	3.1	-0.2
Tunnel	1134	70.5	22.2	-0.01	0.00	-0.02	-0.07		0.5	0.03	0.4	0.04	0.2	2.6	1.0	1.4	0.6

Table E-2 Standard deviation of the emission factors for all cycles (g/bhp-hr)

	Duration	Engine		Stdev Modal Emission Factor (g/bhp-hr)							PM (mg/bhp-hr)		NOx Emissions (mg/bhp-hr)				
Trace	sec	bhp	bhp-hr	THC	CH_4	NMHC	CO	N_2O	CO_2	NH_3	$PM_{2.5}$	Soot	M1	M1	M1	M1	M1
CS_UDDS	0.0	0.2	0.1	0.07	0.04	0.03	0.39	-	14.1		0.9	0.01	26.9	32.3	11.7	17.5	29.2
CS_DPT1	0.0	0.1	0.1	0.52	0.08	0.44	0.71	-	2.9	0.09	0.4	0.07	24.4	19.2	8.7	4.7	0.9
UDDS	0.0	1.1	0.6	0.01	0.01	0.01	0.13	-	9.1	0.01	0.5	0.03	20.1	21.6	15.1	22.8	3.5
RTC	0.0	0.4	0.3	0.05	0.03	0.03	0.44	-	8.1	0.08	0.4	0.10	5.1	2.9	1.3	45.9	8.6
DPT1	0.0	1.1	0.9	0.20	0.13	0.07	0.39	-	8.3	0.12	0.2	0.02	4.1	7.8	1.9	2.8	0.4
DPT2	0.0	0.7	0.6	0.03	0.01	0.01	0.06	0.004	13.7	0.02	0.1	0.01	10.8	10.7	6.3	12.5	0.8
DPT3	0.0	0.3	0.4	0.03	0.02	0.01	0.23	0.003	7.7	0.10	0.9	0.01	4.7	6.5	3.6	6.5	1.9
CBD	0.0	0.8	0.1	0.02	0.02	0.01	0.75	0.012	25.9	0.24	0.5	0.01	6.3	1.0	1.3	1.5	0.3
Tunnel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table E-3 Average emission factors for all cycles (g/mi)

	Vehicle			Ave Modal Emission Factor (g/mi)							PM (mg/mi)		NOx Emissions (mg/mi)				
Trace	sec	bhp	mi	THC	CH_4	NMHC	CO	N_2O	CO_2	NH_3	$PM_{2.5}$	Soot	M1	M1	M1	M1	M1
CS_UDDS	1081	75.3	5.2	3.70	2.31	1.40	18.5	0.27	2367	-	7.3	0.21	223	208	189	306	164
CS_DPT1	3049	31.8	5.8	5.29	2.58	2.74	24.3	0.41	2895	2.98	3.1	0.10	104	132	65	96	13
UDDS	2122	69.7	11.2	0.17	0.16	0.01	5.5	-	2005	1.19	3.9	0.20	61	66	51	77	10
RTC	2889	51.3	4.4	0.82	0.74	0.09	25.4	-	5348	4.09	6.5	0.02	61	67	20	274	47
DPT1	3049	27.7	5.9	1.45	1.04	0.41	9.4	-	2589	2.64	3.5	0.29	17	-1	8	37	6
DPT2	3365	36.5	9.1	0.77	0.58	0.19	7.5	0.10	2236	1.77	1.7	0.39	63	65	48	81	17
DPT3	4228	74.9	28.1	1.54	1.02	0.53	4.2	0.07	1718	1.16	3.2	0.05	58	65	44	74	13
CBD	560	76.2	2.1	0.89	0.64	0.25	15.3	0.19	3226	5.27	5.3	0.23	-19	2	7	17	0
Tunnel	1134	70.5	6.0	-0.07	0.02	-0.08	-0.3	-	1.9	0.10	1.6	0.14	1	10	4	5	2

Table E-4 Standard deviation of the emission factors for all cycles (g/mi)

	Vehicle			Stdev Modal Emission Factor (g/mi)							PM (mg/mi)		NOx Emissions (mg/mi)				
Trace	sec	bhp	bhp-hr	THC	CH_4	NMHC	CO	N_2O	CO_2	NH_3	$PM_{2.5}$	Soot	M1	M1	M1	M1	M1
CS_UDDS	0	0.2	0.1	0.22	0.13	0.09	1.4	-	93	-	4.2	0.06	118	141	53	79	156
CS_DPT1	0	0.1	0.0	2.37	0.37	2.02	3.4	-	3	0.39	1.6	0.35	112	88	40	22	4
UDDS	0	1.1	0.1	0.05	0.03	0.02	0.4	-	8	0.06	2.0	0.12	75	81	56	85	13
RTC	0	0.4	0.1	0.44	0.26	0.23	3.4	-	146	0.78	3.2	0.96	49	30	12	444	83
DPT1	0	1.1	0.1	0.77	0.50	0.28	2.0	-	88	0.61	0.6	0.08	17	31	7	11	2
DPT2	0	0.7	0.1	0.11	0.06	0.05	0.3	0.01	16	0.11	0.3	0.04	41	41	24	47	3
DPT3	0	0.3	0.1	0.08	0.04	0.04	0.7	0.01	27	0.31	2.8	0.04	14	20	11	20	6
CBD	0	0.8	0.0	0.14	0.10	0.05	4.4	0.07	187	1.44	3.1	0.04	36	5	7	9	0
Tunnel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Atmospheric Analysis & Consulting, Inc.

Laboratory Analysis Report
ASTM-D3588 (BTU and F-Factor)

CLIENT	**University of Riverside**	**SAMPLING DATE**	**11/20/2015**
PROJECT NO.	**160033**	**ANALYSIS DATE**	**1/11/2016**

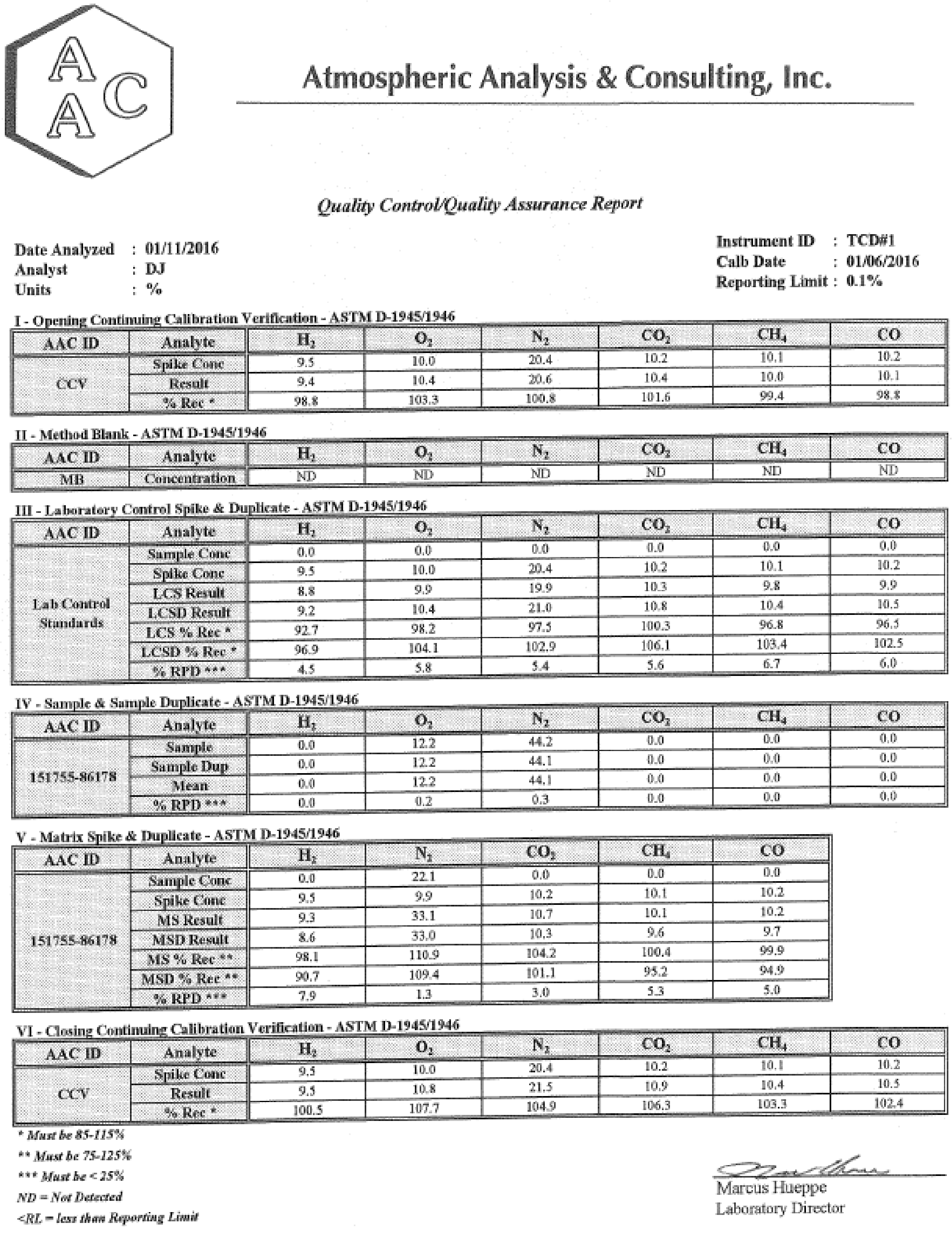
	Client ID:	CNG 1501	
	AAC ID:	160033-86526	
	Component	**Mole %**	**Weight %**
FIXED GASES	H_2	0.00	0.00
	O_2	0.00	0.00
	N_2	0.63	1.04
	CO	0.00	0.00
	CO_2	0.35	0.90
	CH_4	94.65	89.77
	He	NM	NM
	Ar	NM	NM
HYDROCARBONS	C_2 (as Ethane)	3.8675	6.8752
	C_3 (as Propane)	0.4110	1.0715
	C_4 (as Butane)	0.0757	0.2602
	C_5 (as Pentane)	0.0112	0.0480
	C_6 (as Hexane)	0.0025	0.0126
	C_{6+} (as Hexane)	0.0032	0.0163
TRS	TRS as H2S	NM	NM
H2O	Moisture content	NM	NM

All results have been normalized to 100% on a dry weight basis.

Fuel Gas Specifications

Atomic Breakdown - (scf/lb) / %		*HHV Btu/lb*	23286
Carbon (C)	74.1	*LHV Btu/lb*	20987
Hydrogen (H)	24.2	*HHV Btu/dscf*	1038
Oxygen (O)	0.7	*LHV Btu/dscf*	936
Nitrogen (N)	1.0	*F-Factor*	8645
Helium (He)	0.00	*Relative Denisty*	0.5841
Argon (Ar)	0.00	*C2-C6+ Weight %*	8.2837
Sulfur (S)	0.00	*MW lb/lb-mole*	16.915
Motor Octane Number	131.32	*Methane Number*	94.17

Marcus Hueppe
Laboratory Director



Atmospheric Analysis & Consulting, Inc.

Quality Control/Quality Assurance Report

Date Analyzed : 01/11/2016
Analyst : DJ
Units : %

Instrument ID : TCD#1
Calb Date : 01/06/2016
Reporting Limit : 0.1%

I - Opening Continuing Calibration Verification - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
CCV	Spike Conc	9.5	10.0	20.4	10.2	10.1	10.2
	Result	9.4	10.4	20.6	10.4	10.0	10.1
	% Rec *	98.8	103.3	100.8	101.6	99.4	98.8

II - Method Blank - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
MB	Concentration	ND	ND	ND	ND	ND	ND

III - Laboratory Control Spike & Duplicate - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
Lab Control Standards	Sample Conc	0.0	0.0	0.0	0.0	0.0	0.0
	Spike Conc	9.5	10.0	20.4	10.2	10.1	10.2
	LCS Result	8.8	9.9	19.9	10.3	9.8	9.9
	LCSD Result	9.2	10.4	21.0	10.8	10.4	10.5
	LCS % Rec *	92.7	98.2	97.5	100.3	96.8	96.5
	LCSD % Rec *	96.9	104.1	102.9	106.1	103.4	102.5
	% RPD ***	4.5	5.8	5.4	5.6	6.7	6.0

IV - Sample & Sample Duplicate - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
151755-86178	Sample	0.0	12.2	44.2	0.0	0.0	0.0
	Sample Dup	0.0	12.2	44.1	0.0	0.0	0.0
	Mean	0.0	12.2	44.1	0.0	0.0	0.0
	% RPD ***	0.0	0.2	0.3	0.0	0.0	0.0

V - Matrix Spike & Duplicate - ASTM D-1945/1946

AAC ID	Analyte	H_2	N_2	CO_2	CH_4	CO
151755-86178	Sample Conc	0.0	22.1	0.0	0.0	0.0
	Spike Conc	9.5	9.9	10.2	10.1	10.2
	MS Result	9.3	33.1	10.7	10.1	10.2
	MSD Result	8.6	33.0	10.3	9.6	9.7
	MS % Rec **	98.1	110.9	104.2	100.4	99.9
	MSD % Rec **	90.7	109.4	101.1	95.2	94.9
	% RPD ***	7.9	1.3	3.0	5.3	5.0

VI - Closing Continuing Calibration Verification - ASTM D-1945/1946

AAC ID	Analyte	H_2	O_2	N_2	CO_2	CH_4	CO
CCV	Spike Conc	9.5	10.0	20.4	10.2	10.1	10.2
	Result	9.5	10.8	21.5	10.9	10.4	10.5
	% Rec *	100.5	107.7	104.9	106.3	103.3	102.4

** Must be 85-115%*
*** Must be 75-125%*
**** Must be < 25%*
ND = Not Detected
<RL = less than Reporting Limit

Marcus Hueppe
Laboratory Director

Atmospheric Analysis & Consulting, Inc.

Quality Control/Quality Assurance Report

Date Analyzed : 01/11/2015
Analyst : DJ
Units : ppmv

Instrument ID : FID #3
Calb Date : 01/06/16
Reporting Limit : 0.5 ppmv

I - Opening Continuing Calibration Verification - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
CCV	Spike Conc	102.0	98.6	95.2	100.8	99.6	98.8
	Result	105.4	103.9	100.1	105.8	104.5	104.7
	% Rec *	103.3	105.3	105.1	104.9	104.9	106.0

II - Method Blank - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
MB	Concentration	ND	ND	ND	ND	ND	ND

III - Laboratory Control Spike & Duplicate - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
Lab Control Standards	Sample Conc	0.0	0.0	0.0	0.0	0.0	0.0
	Spike Conc	102.0	98.6	95.2	100.8	99.6	98.8
	LCS Result	101.2	99.8	96.9	102.3	101.8	102.8
	LCSD Result	102.4	101.4	98.2	103.9	104.2	108.0
	LCS % Rec *	99.2	101.2	101.8	101.5	102.2	104.1
	LCSD % Rec *	100.4	102.9	103.2	103.1	104.6	109.4
	% RPD ***	1.2	1.6	1.3	1.6	2.3	5.0

IV - Sample & Sample Duplicate - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
151755-86178	Sample	2.6	0.0	0.0	0.0	0.0	0.0
	Sample Dup	2.6	0.0	0.0	0.0	0.0	0.0
	Mean	2.6	0.0	0.0	0.0	0.0	0.0
	% RPD ***	0.8	0.0	0.0	0.0	0.0	0.0

V - Matrix Spike & Duplicate - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
151755-86178	Sample Conc	1.3	0.0	0.0	0.0	0.0	0.0
	Spike Conc	51.0	49.3	47.6	50.4	49.8	49.4
	MS Result	53.4	50.2	49.2	51.9	51.6	52.4
	MSD Result	53.1	50.9	49.3	52.2	55.1	53.3
	MS % Rec **	102.2	101.9	103.5	103.0	103.6	106.1
	MSD % Rec **	101.5	103.2	103.6	103.7	110.7	107.8
	% RPD ***	0.7	1.3	0.2	0.6	6.6	1.6

VI - Closing Continuing Calibration Verification - ASTM D-1945/1946

AAC ID	Analyte	Methane	Ethane	Propane	Butane	Pentane	Hexane
CCV	Spike Conc	102.0	98.6	95.2	100.8	99.6	98.8
	Result	101.3	99.5	96.4	101.3	99.3	98.4
	% Rec *	99.3	100.9	101.2	100.5	99.7	99.6

** Must be 85-115%*

*** Must be 75-125%*

**** Must be < 25%*

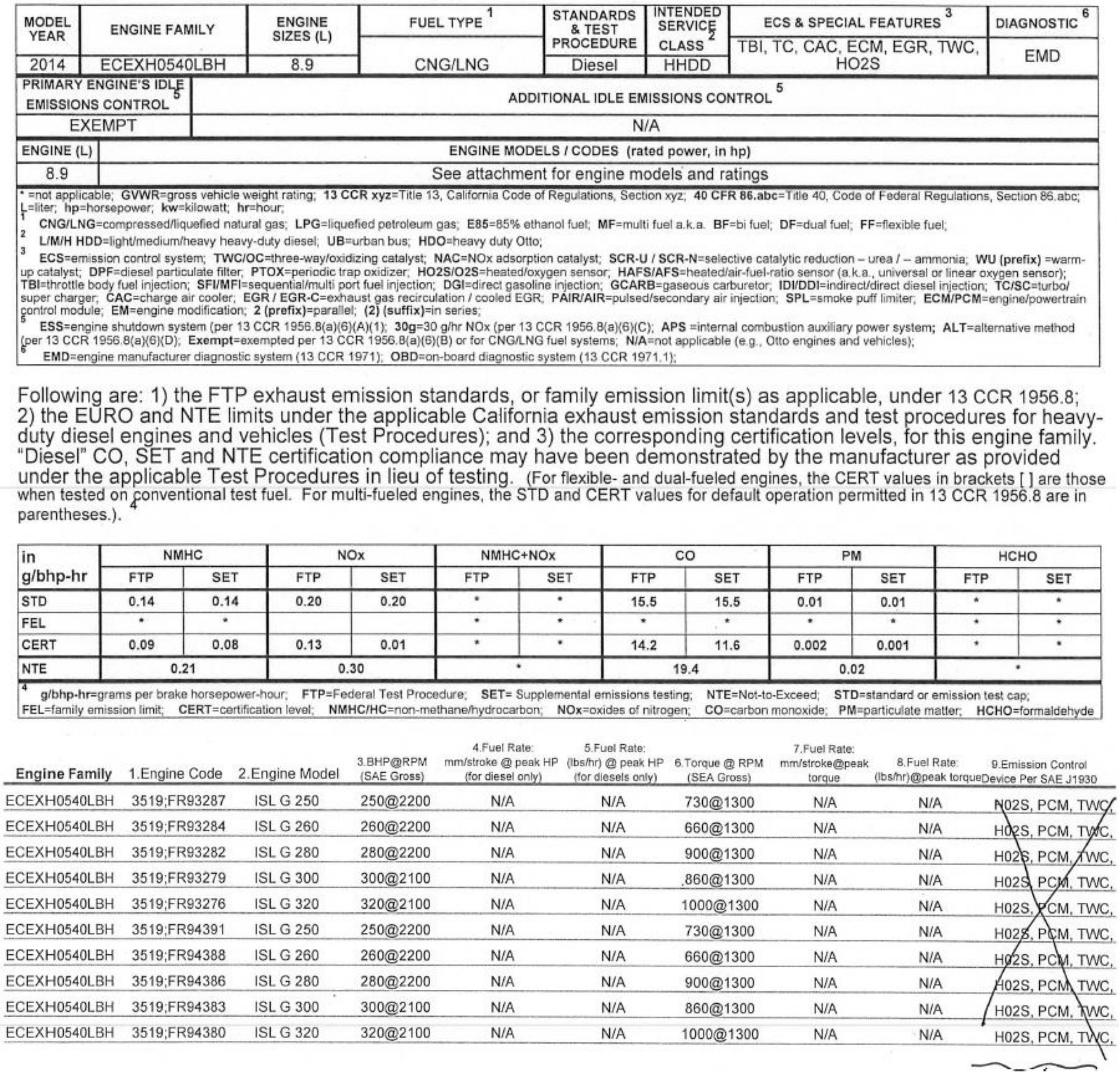
ND = Not Detected

<RL = less than Reporting Limit

Marcus Hueppe
Laboratory Director

Appendix F. Engine certification data, labels, and upgrades

This appendix includes the engine executive order Figure F-1 as listed on the ARB website for the family number listed on the engine name plate see Figure F-2 and F-3, Family number ECEXH0540LBH. The ISL G NZ certification is provided in the recently released documents as presented in Figure F-4, 5, and 6.



MODEL YEAR	ENGINE FAMILY	ENGINE SIZES (L)	FUEL TYPE[1]	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS[2]	ECS & SPECIAL FEATURES[3]	DIAGNOSTIC[6]
2014	ECEXH0540LBH	8.9	CNG/LNG	Diesel	HHDD	TBI, TC, CAC, ECM, EGR, TWC, HO2S	EMD

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

ENGINE (L)	ENGINE MODELS / CODES (rated power, in hp)
8.9	See attachment for engine models and ratings

* =not applicable; **GVWR**=gross vehicle weight rating; **13 CCR xyz**=Title 13, California Code of Regulations, Section xyz; **40 CFR 86.abc**=Title 40, Code of Federal Regulations, Section 86.abc; **L**=liter; **hp**=horsepower; **kw**=kilowatt; **hr**=hour;

[1] **CNG/LNG**=compressed/liquefied natural gas; **LPG**=liquefied petroleum gas; **E85**=85% ethanol fuel; **MF**=multi fuel a.k.a. **BF**=bi fuel; **DF**=dual fuel; **FF**=flexible fuel;

[2] **L/M/H HDD**=light/medium/heavy heavy-duty diesel; **UB**=urban bus; **HDO**=heavy duty Otto;

[3] **ECS**=emission control system; **TWC/OC**=three-way/oxidizing catalyst; **NAC**=NOx adsorption catalyst; **SCR-U / SCR-N**=selective catalytic reduction – urea / – ammonia; **WU (prefix)** =warm-up catalyst; **DPF**=diesel particulate filter; **PTOX**=periodic trap oxidizer; **HO2S/O2S**=heated/oxygen sensor; **HAFS/AFS**=heated/air-fuel-ratio sensor (a.k.a., universal or linear oxygen sensor); **TBI**=throttle body fuel injection; **SFI/MFI**=sequential/multi port fuel injection; **DGI**=direct gasoline injection; **GCARB**=gaseous carburetor; **IDI/DDI**=indirect/direct diesel injection; **TC/SC**=turbo/super charger; **CAC**=charge air cooler; **EGR / EGR-C**=exhaust gas recirculation / cooled EGR; **PAIR/AIR**=pulsed/secondary air injection; **SPL**=smoke puff limiter; **ECM/PCM**=engine/powertrain control module; **EM**=engine modification; **2 (prefix)**=parallel; **(2) (suffix)**=in series;

[5] **ESS**=engine shutdown system (per 13 CCR 1956.8(a)(6)(A)(1); **30g**=30 g/hr NOx (per 13 CCR 1956.8(a)(6)(C); **APS** =internal combustion auxiliary power system; **ALT**=alternative method (per 13 CCR 1956.8(a)(6)(D); **Exempt**=exempted per 13 CCR 1956.8(a)(6)(B) or for CNG/LNG fuel systems; **N/A**=not applicable (e.g., Otto engines and vehicles);

[6] **EMD**=engine manufacturer diagnostic system (13 CCR 1971); **OBD**=on-board diagnostic system (13 CCR 1971.1);

Following are: 1) the FTP exhaust emission standards, or family emission limit(s) as applicable, under 13 CCR 1956.8; 2) the EURO and NTE limits under the applicable California exhaust emission standards and test procedures for heavy-duty diesel engines and vehicles (Test Procedures); and 3) the corresponding certification levels, for this engine family. "Diesel" CO, SET and NTE certification compliance may have been demonstrated by the manufacturer as provided under the applicable Test Procedures in lieu of testing. (For flexible- and dual-fueled engines, the CERT values in brackets [ ] are those when tested on conventional test fuel. For multi-fueled engines, the STD and CERT values for default operation permitted in 13 CCR 1956.8 are in parentheses.).[4]

in g/bhp-hr	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET
STD	0.14	0.14	0.20	0.20	*	*	15.5	15.5	0.01	0.01	*	*
FEL	*	*			*	*	*	*	*	*	*	*
CERT	0.09	0.08	0.13	0.01	*	*	14.2	11.6	0.002	0.001	*	*
NTE	0.21		0.30		*		19.4		0.02		*	

[4] **g/bhp-hr**=grams per brake horsepower-hour; **FTP**=Federal Test Procedure; **SET**= Supplemental emissions testing; **NTE**=Not-to-Exceed; **STD**=standard or emission test cap; **FEL**=family emission limit; **CERT**=certification level; **NMHC/HC**=non-methane/hydrocarbon; **NOx**=oxides of nitrogen; **CO**=carbon monoxide; **PM**=particulate matter; **HCHO**=formaldehyde

Engine Family	1.Engine Code	2.Engine Model	3.BHP@RPM (SAE Gross)	4.Fuel Rate: mm/stroke @ peak HP (for diesel only)	5.Fuel Rate: (lbs/hr) @ peak HP (for diesels only)	6.Torque @ RPM (SEA Gross)	7.Fuel Rate: mm/stroke@peak torque	8.Fuel Rate: (lbs/hr)@peak torque	9.Emission Control Device Per SAE J1930
ECEXH0540LBH	3519;FR93287	ISL G 250	250@2200	N/A	N/A	730@1300	N/A	N/A	~~H02S, PCM, TWC,~~
ECEXH0540LBH	3519;FR93284	ISL G 260	260@2200	N/A	N/A	660@1300	N/A	N/A	~~H02S, PCM, TWC,~~
ECEXH0540LBH	3519;FR93282	ISL G 280	280@2200	N/A	N/A	900@1300	N/A	N/A	~~H02S, PCM, TWC,~~
ECEXH0540LBH	3519;FR93279	ISL G 300	300@2100	N/A	N/A	860@1300	N/A	N/A	~~H02S, PCM, TWC,~~
ECEXH0540LBH	3519;FR93276	ISL G 320	320@2100	N/A	N/A	1000@1300	N/A	N/A	~~H02S, PCM, TWC,~~
ECEXH0540LBH	3519;FR94391	ISL G 250	250@2200	N/A	N/A	730@1300	N/A	N/A	~~H02S, PCM, TWC,~~
ECEXH0540LBH	3519;FR94388	ISL G 260	260@2200	N/A	N/A	660@1300	N/A	N/A	~~H02S, PCM, TWC,~~
ECEXH0540LBH	3519;FR94386	ISL G 280	280@2200	N/A	N/A	900@1300	N/A	N/A	~~H02S, PCM, TWC,~~
ECEXH0540LBH	3519;FR94383	ISL G 300	300@2100	N/A	N/A	860@1300	N/A	N/A	~~H02S, PCM, TWC,~~
ECEXH0540LBH	3519;FR94380	ISL G 320	320@2100	N/A	N/A	1000@1300	N/A	N/A	~~H02S, PCM, TWC,~~

Figure F-1 Engine certification order for the ISL G (not ISL G NZ) NG engine (ARB source)

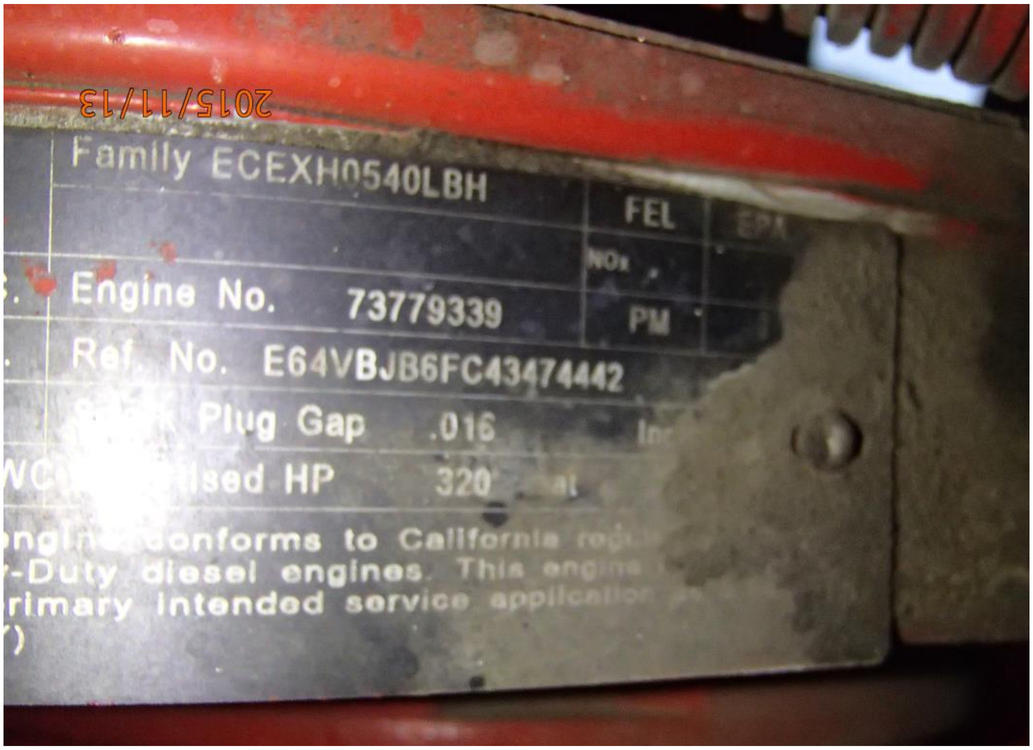


Figure F-2 Engine label for the ISL G NZ 320 NG engine

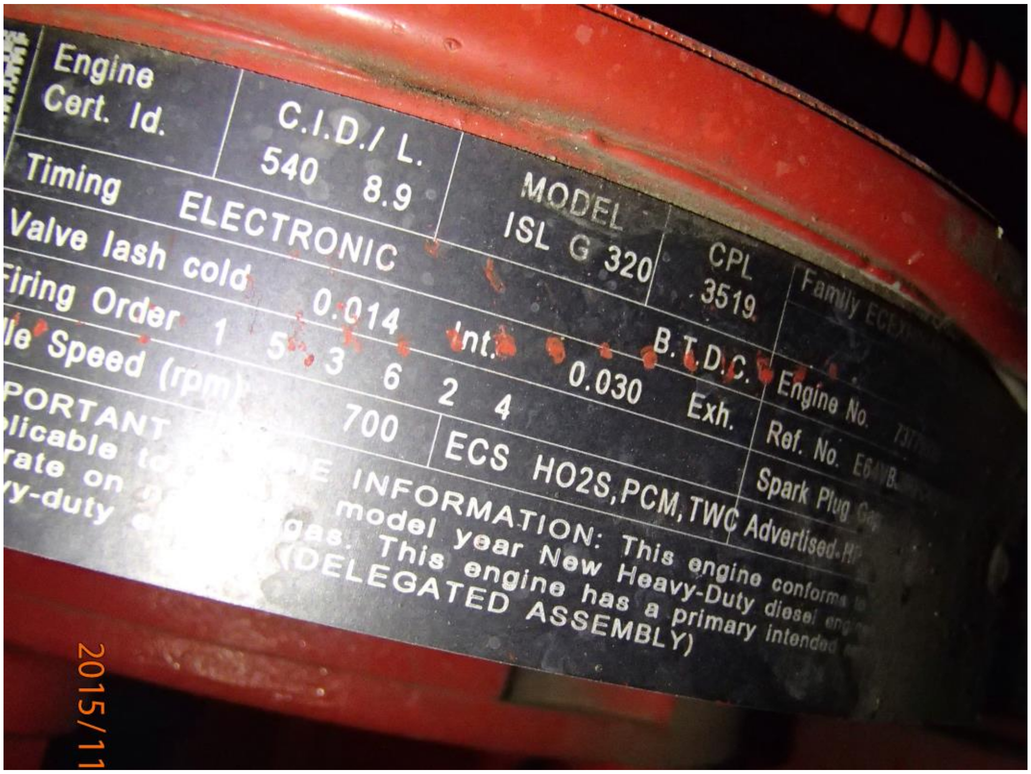
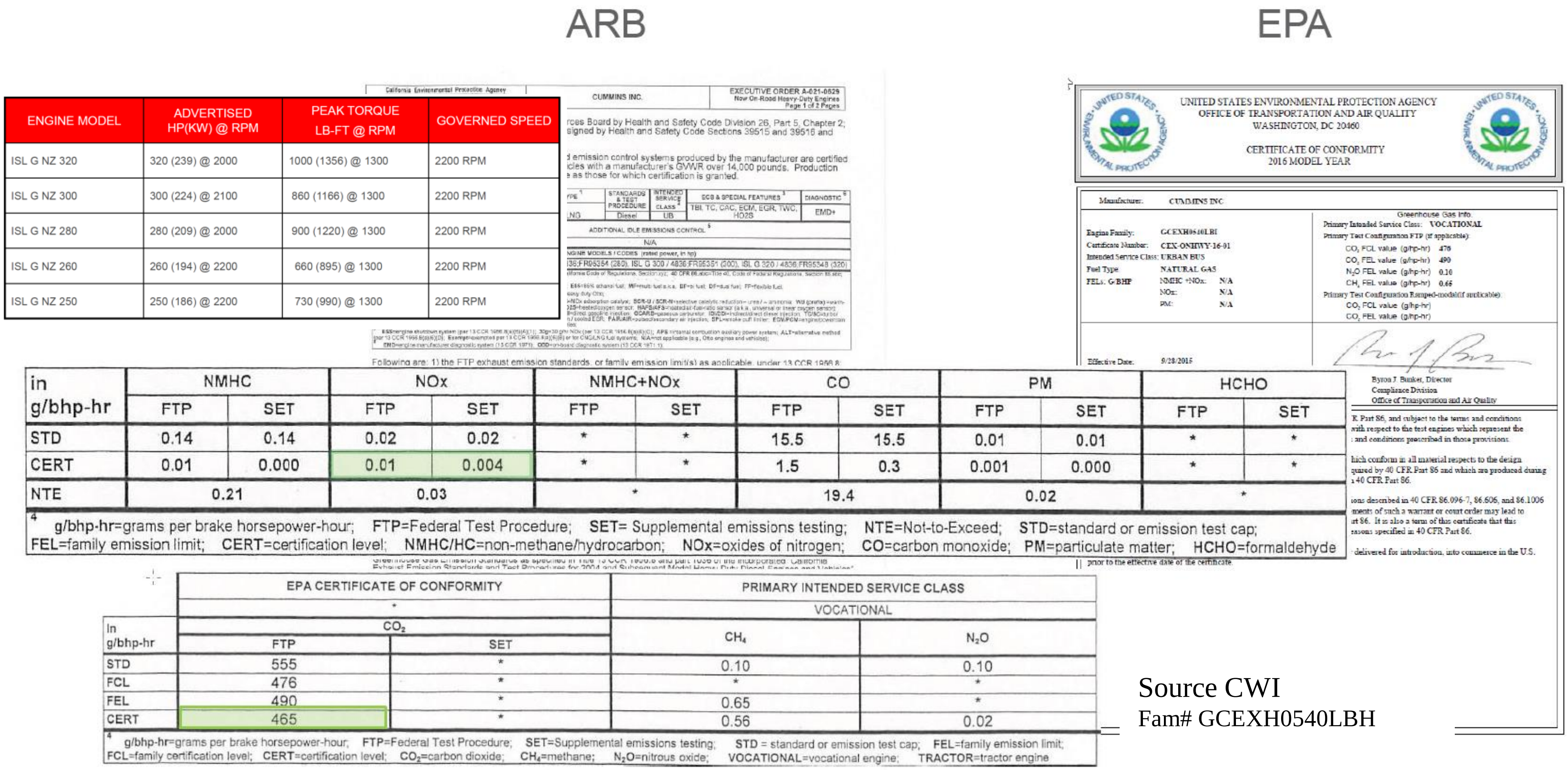


Figure F-3 Engine label for the ISL G NZ 320 NG engine



ARB

EPA

ENGINE MODEL	ADVERTISED HP(KW) @ RPM	PEAK TORQUE LB-FT @ RPM	GOVERNED SPEED
ISL G NZ 320	320 (239) @ 2000	1000 (1356) @ 1300	2200 RPM
ISL G NZ 300	300 (224) @ 2100	860 (1166) @ 1300	2200 RPM
ISL G NZ 280	280 (209) @ 2000	900 (1220) @ 1300	2200 RPM
ISL G NZ 260	260 (194) @ 2200	660 (895) @ 1300	2200 RPM
ISL G NZ 250	250 (186) @ 2200	730 (990) @ 1300	2200 RPM

California Environmental Protection Agency

CUMMINS INC.

EXECUTIVE ORDER A-021-0629
New On-Road Heavy-Duty Engines
Page 1 of 2 Pages

rces Board by Health and Safety Code Division 26, Part 5, Chapter 2; signed by Health and Safety Code Sections 39515 and 39516 and

d emission control systems produced by the manufacturer are certified icles with a manufacturer's GVWR over 14,000 pounds. Production e as those for which certification is granted.

YPE [1]	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS [2]	ECS & SPECIAL FEATURES [3]	DIAGNOSTIC [6]
LNG	Diesel	UB	TBI, TC, CAC, ECM, EGR, TWC, HO2S	EMD+

ADDITIONAL IDLE EMISSIONS CONTROL [5]

N/A

NGINE MODELS / CODES (rated power, in hp)

36;FR95354 (280), ISL G 300 / 4836;FR95351 (300), ISL G 320 / 4836;FR95348 (320)

Following are: 1) the FTP exhaust emission standards, or family emission limit(s) as applicable, under 13 CCR 1956.8;

in g/bhp-hr	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET
STD	0.14	0.14	0.02	0.02	*	*	15.5	15.5	0.01	0.01	*	*
CERT	0.01	0.000	0.01	0.004	*	*	1.5	0.3	0.001	0.000	*	*
NTE	0.21		0.03		*		19.4		0.02		*	

[4] g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; SET= Supplemental emissions testing; NTE=Not-to-Exceed; STD=standard or emission test cap; FEL=family emission limit; CERT=certification level; NMHC/HC=non-methane/hydrocarbon; NOx=oxides of nitrogen; CO=carbon monoxide; PM=particulate matter; HCHO=formaldehyde

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF TRANSPORTATION AND AIR QUALITY
WASHINGTON, DC 20460

CERTIFICATE OF CONFORMITY
2016 MODEL YEAR

Manufacturer: CUMMINS INC

Engine Family: GCEXH0540LBH
Certificate Number: CEX-ONHWY-16-01
Intended Service Class: URBAN BUS
Fuel Type: NATURAL GAS
FELs: G/BHP
NMHC +NOx: N/A
NOx: N/A
PM: N/A

Greenhouse Gas Info.
Primary Intended Service Class: VOCATIONAL
Primary Test Configuration FTP (if applicable):
CO_2 FCL value (g/hp-hr) 476
CO_2 FEL value (g/hp-hr) 490
N_2O FEL value (g/hp-hr) 0.10
CH_4 FEL value (g/hp-hr) 0.65
Primary Test Configuration Ramped-modal(if applicable):
CO_2 FCL value (g/hp-hr)
CO_2 FEL value (g/hp-hr)

Effective Date: 9/28/2015

Byron J. Bunker, Director
Compliance Division
Office of Transportation and Air Quality

R Part 86, and subject to the terms and conditions with respect to the test engines which represent the : and conditions prescribed in those provisions.

hich conform in all material respects to the design quired by 40 CFR Part 86 and which are produced during 1 40 CFR Part 86.

ions described in 40 CFR 86.096-7, 86.606, and 86.1006 ments of such a warrant or court order may lead to rt 86. It is also a term of this certificate that this easons specified in 40 CFR Part 86.

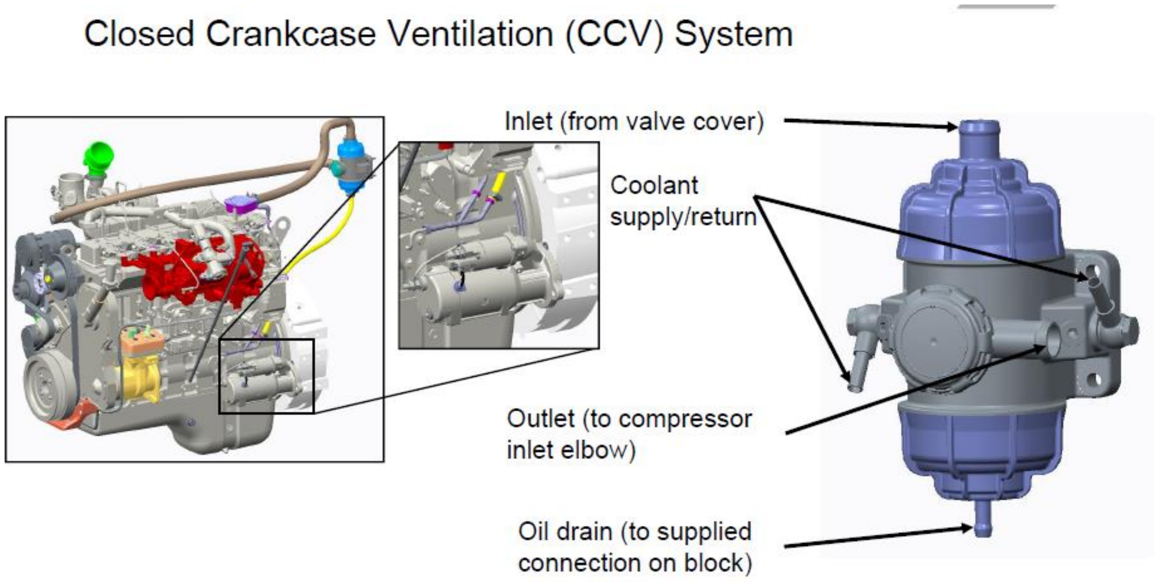
delivered for introduction, into commerce in the U.S. prior to the effective date of the certificate.

In g/bhp-hr	EPA CERTIFICATE OF CONFORMITY		PRIMARY INTENDED SERVICE CLASS	
	*		VOCATIONAL	
	CO_2		CH_4	N_2O
	FTP	SET		
STD	555	*	0.10	0.10
FCL	476	*	*	*
FEL	490	*	0.65	*
CERT	465	*	0.56	0.02

[4] g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; SET=Supplemental emissions testing; STD = standard or emission test cap; FEL=family emission limit; FCL=family certification level; CERT=certification level; CO_2=carbon dioxide; CH_4=methane; N_2O=nitrous oxide; VOCATIONAL=vocational engine; TRACTOR=tractor engine

Source CWI
Fam# GCEXH0540LBH

Figure F-4 2016 ISL G NZ certification executive order with engine ratings (ARB and EPA)



Closed Crankcase Ventilation (CCV) System

Inlet (from valve cover)

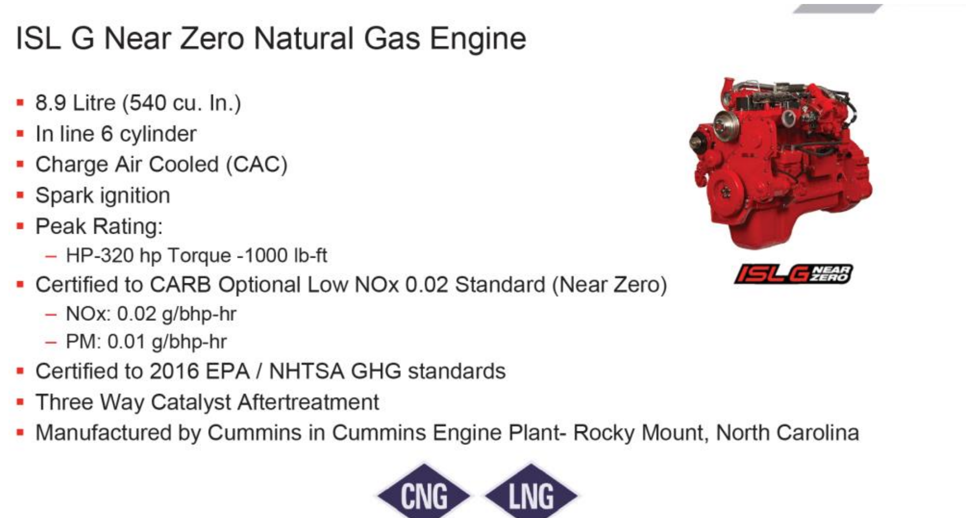
Coolant supply/return

Outlet (to compressor inlet elbow)

Oil drain (to supplied connection on block)

Source CWI

Figure F-5 Cummins methane blow by capture improvement

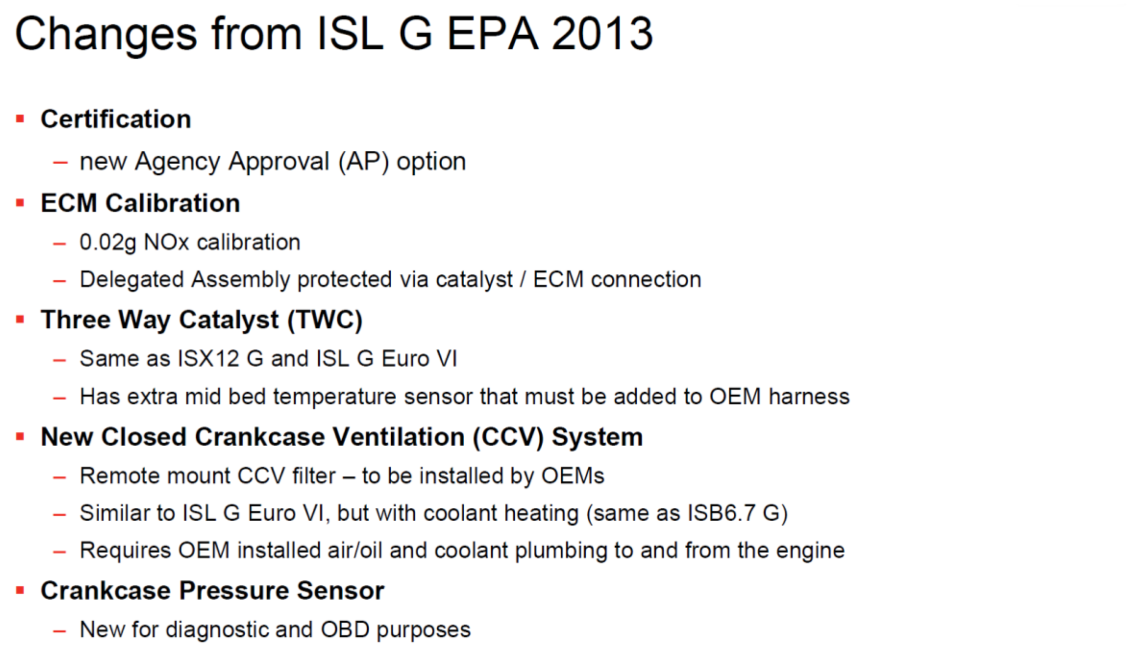


ISL G Near Zero Natural Gas Engine

- 8.9 Litre (540 cu. In.)
- In line 6 cylinder
- Charge Air Cooled (CAC)
- Spark ignition
- Peak Rating:
  - HP-320 hp Torque -1000 lb-ft
- Certified to CARB Optional Low NOx 0.02 Standard (Near Zero)
  - NOx: 0.02 g/bhp-hr
  - PM: 0.01 g/bhp-hr
- Certified to 2016 EPA / NHTSA GHG standards
- Three Way Catalyst Aftertreatment
- Manufactured by Cummins in Cummins Engine Plant- Rocky Mount, North Carolina

Source CWI

Figure F-6 Cummins specifications for the ISL G NZ



Changes from ISL G EPA 2013

- **Certification**
  - new Agency Approval (AP) option
- **ECM Calibration**
  - 0.02g NOx calibration
  - Delegated Assembly protected via catalyst / ECM connection
- **Three Way Catalyst (TWC)**
  - Same as ISX12 G and ISL G Euro VI
  - Has extra mid bed temperature sensor that must be added to OEM harness
- **New Closed Crankcase Ventilation (CCV) System**
  - Remote mount CCV filter – to be installed by OEMs
  - Similar to ISL G Euro VI, but with coolant heating (same as ISB6.7 G)
  - Requires OEM installed air/oil and coolant plumbing to and from the engine
- **Crankcase Pressure Sensor**
  - New for diagnostic and OBD purposes

Source CWI

Figure F-7 ISL G NZ emission enhancements

Appendix G. Coastdown methods

Road load coefficients are important where at 65 mph the aerodynamic term accounts for 53% of the resisting force, rolling resistance 32%, driveline losses 6% and auxiliary loads at 9%. These load fractions vary with speed and the square of the speed where a properly configured dynamometer is needed to simulate the loads from 0 to 70 mph. The method for determining coastdown coefficients was published and evaluated as part of a study submitted to the South Coast Air Quality Management District[14]. Typical coastdown procedures assume that vehicle loading force is a function of vehicle speed, drag coefficient, frontal area and tire rolling resistance coefficient and takes the form of equation 1:

$$M\frac{dV}{dt} = \frac{1}{2}\rho A C_D V^2 + \mu M g cos(\theta) + Mgsin(\theta) \qquad \text{(Equation 1)}$$

Where:
M = mass of vehicle in lb (tractor + payload + trailer+ 125lb/tire)
ρ = density of air in kg/m^3.
A = frontal area of vehicle in square feet, see Figure G-1 below
C_D = aerodynamic drag coefficient (unit less).
V = speed vehicle is traveling in mph.
μ = tire rolling resistance coefficient (unit less).
g = acceleration due to gravity = 32.1740 ft/sec^2.
θ = angle of inclination of the road grade in degrees (this becomes zero).

Assuming that the vehicle loading is characteristic of this equation, speed-time data collected during the coastdown test can be used with static measurements (ZET/NZET mass, air density, frontal area, and grade) to solve for drag coefficient (C_d) and tire rolling resistance coefficient (μ). The frontal area is measured based on the method described in Figure G-1 below. However, experience performing in-use coastdowns is complex and requires grades of less than 0.5% over miles of distance, average wind speeds < 10 mph ± 2.3 mph gusts and < 5 mph cross wind[15]. As such, performing in-use coastdowns in CA where grade and wind are unpredictable are unreliable where a calculated approach is more consistent and appropriate. Additionally vehicles equipped with automatic transmissions have shown that on-road loading is also affected by the characteristics of the vehicle transmission, especially when reverse pumping losses at low speed begin to dominate.

UCR's and others recommend a road load determination method that uses a characteristic coastdown equation, with a measured vehicle frontal area (per SAE J1263 measurement recommendations), a tire rolling resistance μ, and a coefficient of drag (Cd) as listed in Table G-1. If low rolling resistant tires are used then the fuel savings can be employed with a slightly improved coefficient as listed. Similarly if an aerodynamic tractor design is utilized (ie a certified SmartWay design) then a lower drag coefficient can be selected. Table G-1 lists the

---

[14] Draft Test Plan Re: SCAQMD RFP#P2011-6, "In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines", October 2011

[15] EPA Final rulemaking to establish greenhouse gas emissions standards and fuel efficiency standards for medium and heavy duty engines and vehicles, Office of Transportation and Air Quality, August 2011 (Page 3-7) and J1263 coast down procedure for fuel economy measurements

coefficients to use based on different ZET/NZET configurations. Once the coefficients are selected then they can be used in the above equation to calculate coastdown times to be used for calculating the A, B, C coefficients in Equation 2 for the dynamometer operation parameters. From these equations calculate the coastdown times from based on the coefficients in Table G-1 as shown in Table G-2 (65,000 lb, ustd, Cdstd and Table G-1). From Table G-2 one can plot the force (lb) vs average speed bin to get the ABC coefficients for the chassis dynamometer (see Figure G-2). These are the coefficients to enter into the chassis dynamometer then validate via the details of Appendix C. Repeat process until validation criteria is met. Typically one or two iterations is needed to meet the validation criteria.

Table G-1 Constants and parameters for Class 8 heavy duty trucks

Variable	Value	Description
θ	0	no grade in these tests
ρ	1.202	standard air density kg/m^3
μ_{std}	0.00710	standard tires
μ_{adv}	0.00696	low rolling resistant tires
C_{D_std}	0.750	for non-SmartWay tractor
C_{D_adv}	0.712	for SmartWay tractor
g	9.806	nominal value m/sec^2
M	Varies	mass: final test weight kg

[1] The tire rolling resistance, μ, for low rolling resistant tires shows a 1-2% savings (ref SmartWay). As such utilize 0.00686 fpr low rolling resistant tires. In this document the tractors may vary, but the trailers will be assumed similar. As such, if the tractor utilizes the certified SmartWay tractor type then coefficient of drag can be reduced by up to 10% (5% fuel savings) depending on the technology. As such in this guidance document utilize the Cd_adv for SmartWay tractors and Cd_std for non-SmartWay tractors. Additionally, for reference other vocations show higher Cd's, such as the C_D = 0.79 for buses and 0.80 for refuse trucks. Nominal value of gravity is used in this document where actual value can be found by following 40CFR 1065.630 or at http://www.ngs.noaa.gov

$$\frac{dV}{dt} = \frac{1}{2}\frac{\rho A C_D V^2}{M} + \mu g cos(\theta) + \ g sin(\theta) \qquad \text{(Equation 2)}$$

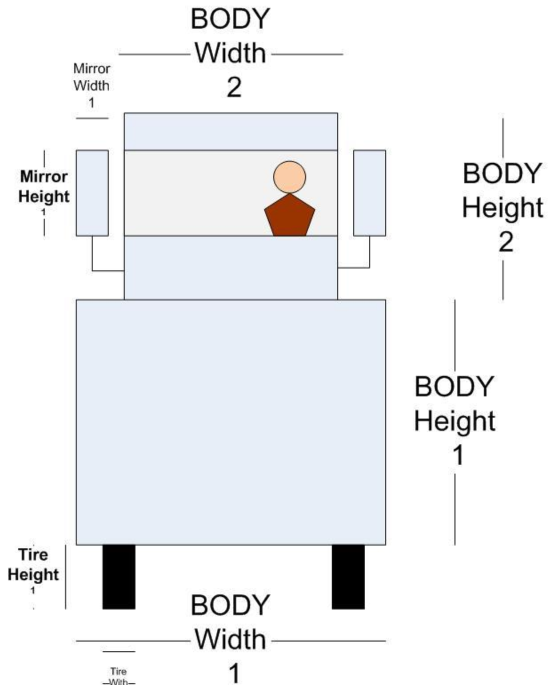


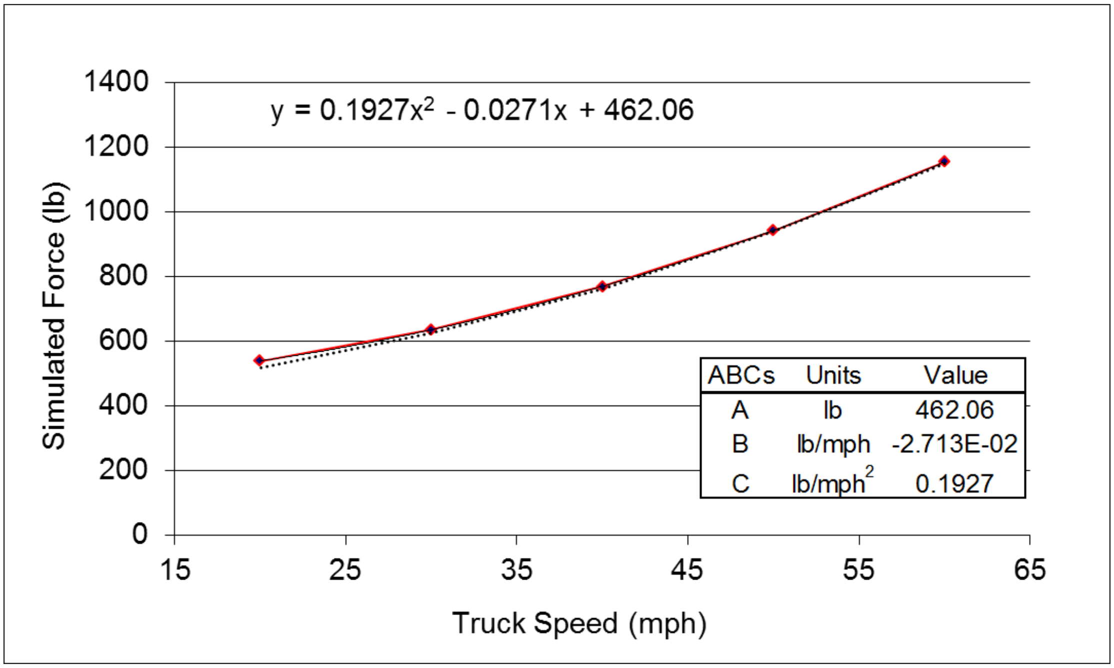
Figure G-1 Vehicle frontal area dimensions method

Using Equation 2 (solution for $\frac{dV}{dt}$ or deceleration), one can calculate the deceleration for each average speed bin (60, 50, … down to 20 mph), see Table G-2. From the deceleration time one can calculate the desired time which is the target for the coast down simulation on the chassis dynamometer. Using the final test weight (M), the total simulated force can be calculated using Equation 1 at each speed bin, see values Table G-2. Plot the simulated force (lb) on the y-axis vs truck speed (mph) on the x-axis. Using a best fit polynomial of order two, calculate the polynomial coefficients A (0th order term), B (1st order term), and C (2nd order term), see Figure G-2. Enter these ABCs into your chassis dynamometer and verify the coast down times match your desired coast down times to within 5%.

The calculation approach is consistent and has proven very reliable for chassis testing heavy duty vehicle and has been used for years by UCR and others. For detailed evaluation of aerodynamic modifications and body styles, UCR recommends investing the time perform in-use coastdowns where sufficient program resources will be needed as per 40 CFR Part 1066, SAE J2263, and J1263.

Table G-2 Desired coastdown times for a Class 8 truck with standard components

Data Point	Avg Speed MPH	Calc Time sec	Decel MPH/Sec	Desired Decel ft/sec^2	Decel Gs	Force lb
65-55	60	25.67	0.38954	0.57	0.018	1154
55-45	50	31.44	0.31806	0.47	0.014	942
45-35	40	38.51	0.25965	0.38	0.012	769
35-25	30	46.68	0.21422	0.31	0.010	635
25-15	20	55.02	0.18177	0.27	0.008	539



ABCs	Units	Value
A	lb	462.06
B	lb/mph	-2.713E-02
C	lb/mph^2	0.1927

Figure G-2 Resulting ABCs based on Table G-2 results