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Ultra-Low NOx Near-Zero Natural Gas Vehicle Evaluation ISX12N 400

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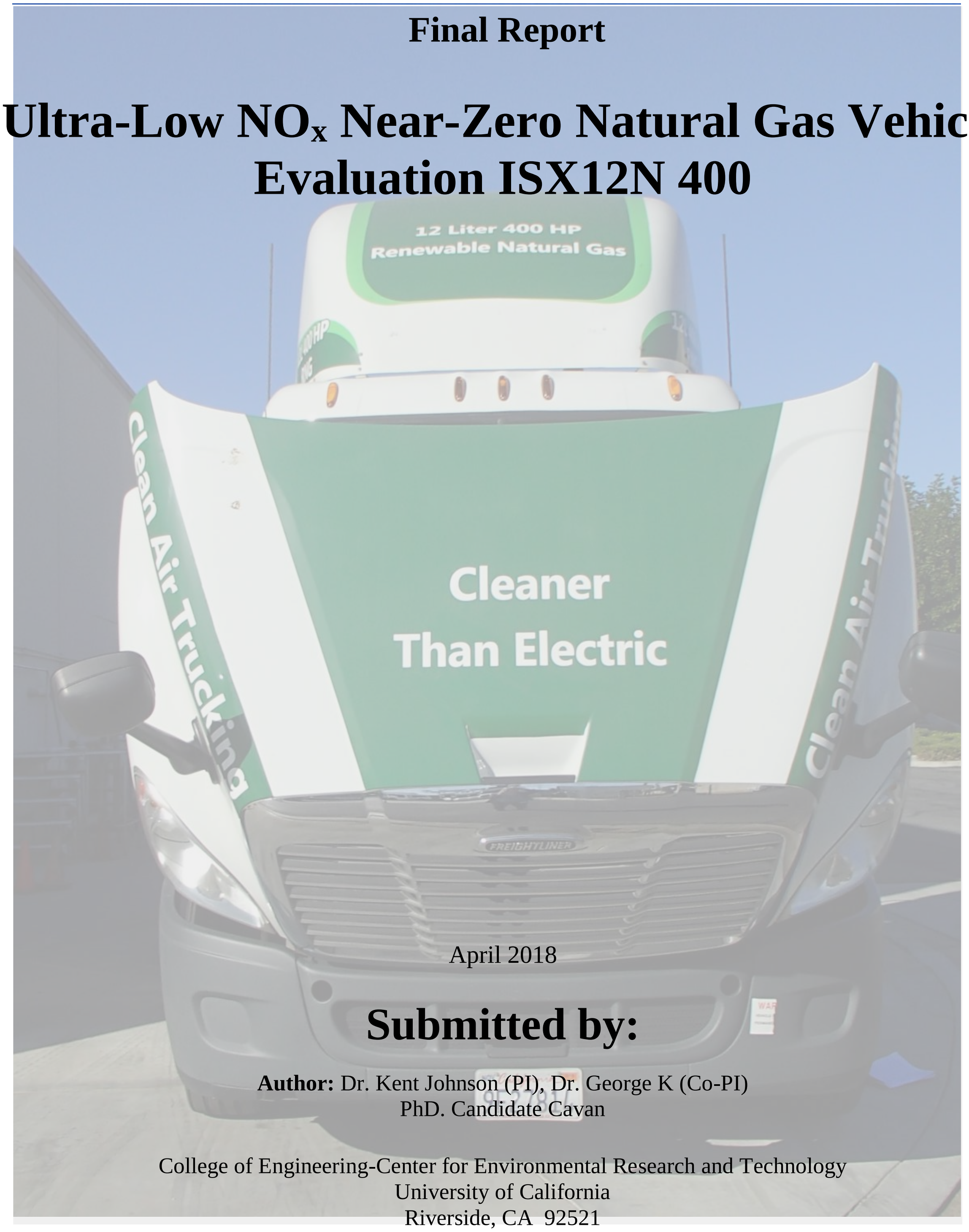
Final Report

Ultra-Low NO_x Near-Zero Natural Gas Vehicle Evaluation ISX12N 400



April 2018

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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 a 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 is 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 ISX12N 400 NG engine met and exceeded the target NO_x emissions of 0.02 g/bhp-hr and maintained those emissions during in-use duty cycles found in the South Coast Air Basin. The other gaseous and particulate matter were below the standards and/or similar to previous levels. Particle number, ammonia emissions, and methane emissions were higher than current 2010 certified diesel engines on similar drive cycles. These higher emissions should be considered for health and environmental impact studies. In general, it is expected NG vehicles could play a significant role in achieving the NO_x inventory goals given the 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
CH_4	methane
CLD	chemiluminescent detection
CO	carbon monoxide
CO_2	carbon dioxide
CNG	compressed natural gas
CPC	condensation particle counter
CPC_CS	CPC with a catalytic stripper
CWI	Cummins Westport Inc.
FE	Fuel economy
FID	flame ionization detector
GDE	gallons diesel equivalent
g/bhp-hr	grams per brake horsepower hour
lpm	liters per minute
LNG	liquid natural gas
MEL	mobile emission laboratory
NG	natural gas
NO_x	nitrogen oxides
N_2O	nitrous oxides
NH_3	ammonia
NMHC	non methane hydrocarbons
NZ	near zero
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
QCL	quantum cascade laser
RPM	revolutions per minute
scfm	standard cubic feet per minute
THC	total hydrocarbons
UCR	University of California at Riverside

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, their 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 this project was to evaluate Cummins West Ports (CWI) ISX12N (Near-zero) 11.9 liter ultra-low NO_x natural gas (NG) truck. The evaluation included regulated and non-regulated emissions, ultrafines, global warming potential, and fuel economy during in-use testing. This report presents a summary of the results and conclusions for the CWI ultra-low NO_x NG 11.9L truck (ISX12N).

Approach: The testing was performed on UC Riverside's chassis dynamometer with their 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 drayage port cycles (near dock, local, and regional), the urban dynamometer driving schedule, and three cycles designed by CARB (called HHDDT cycles).

Measuring NO_x at 90% of the 2010 certification level (~ 0.02 g/bhp-hr is approaching the detection limit of the dilute CVS method. Previously, advanced NO_x measurement methods were evaluated by UCR and the raw measurement method was recommended and utilized (Johnson et al 2016). The raw NO_x chemiluminescence measurement method was also used for this study with the addition of a new spectroscopy method not susceptible to interferences from NH_3 emissions. In addition to the regulated emissions, the laboratory was equipped to measure particle size distribution, particle number (both solid and total), equivalent black carbon, ammonia, and nitrous oxide emissions. The measurements were collected to investigate the benefit of the ISX12N engine and aftertreatment system compared to other approaches.

Results: The ISX12N NG engine showed NO_x emissions below the CARB optional low NO_x standard (0.02 g/bhp-hr) and averaged between 0.0012 and 0.02 g/bhp-hr for the various hot start tests, see Figure ES-1. The NO_x emissions were well controlled at low loads (Creep and Near Dock cycles) as well as during cruise conditions (Regional and HHDDT Cruise) where diesel vehicles tend to have much higher emissions at light loads but perform well at cruise conditions. This suggests stoichiometric NG engines are a good choice for regional NO_x mitigation strategies where light loads are common.

The NO_x emissions reported are the result of emission spikes during de-accelerations from consistent points with-in the test cycle, see Figure ES-2. More than 90% of the NO_x emissions resulted from these transient de-accelerations. The variability in the emissions is a result of the magnitude of the NO_x spike. This suggests possible driver behavior may impact the overall NO_x in-use performance of the vehicle where more gradual de-accelerations are desired, such as with hybrid applications.

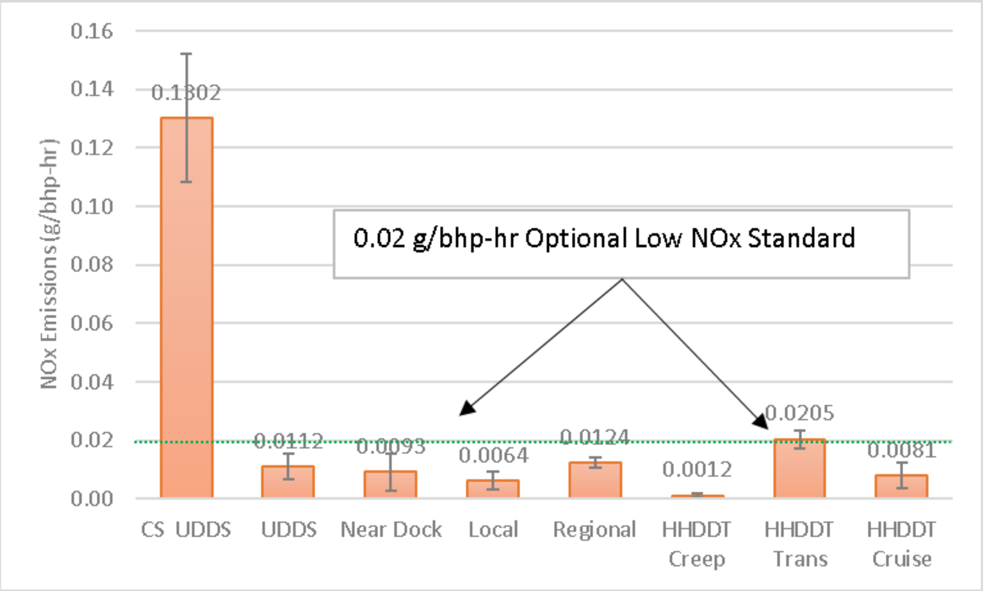

Figure ES-1 Cycle averaged NO_x emissions for the ISX12N 400 equipped truck

Cold start NOx emissions represent a significant part of the total NO_x emissions reported. The cold start emissions averaged 0.130 g/bhp-hr (around ten times higher than the hot UDDS) where the hot/cold weighted emissions was 0.028 g/bhp-hr which is above the certified 0.02 g/bhp-hr emission factor. More than 90% of the NO_x emissions occurred in the first 50 seconds of the cold UDDS test. Once the catalyst warmed up, the remaining portions of the cold UDDS test showed low NO_x emissions similar to the hot UDDS test. It is expected the real impact of the cold start emissions is much lower than 1/7 weighting factor required by the regulations and would be represented by 50 seconds divided by the actual shift time (typically more than 3600 seconds). More research is needed to understand cold start emissions and their impact regionally. The cold start emissions suggest hybrid stop-start technology may need electrically heated catalyst to minimize potential warm-start emissions during long periods of electric only operation.

The other emissions such as carbon monoxide, particulate matter, nitrous oxide, and ammonia also showed some differences compared to similar stoichiometric 2010 certified and NZ certified NG vehicles tested by UCR. For example, the PM for the ISX12N was slightly higher than the NZ and 2010 certified NG engine (0.002 g/bhp-hr vs 0.001 g/bhp-hr), the ammonia was slightly lower ~50 ppm vs ~200 ppm, and N_2O was about the same. 95% of the N_2O cold start emissions resulted in the first 50 seconds. The methane emissions were notably lower in both NZ engines tested compared to the 2010 certified NG 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 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.

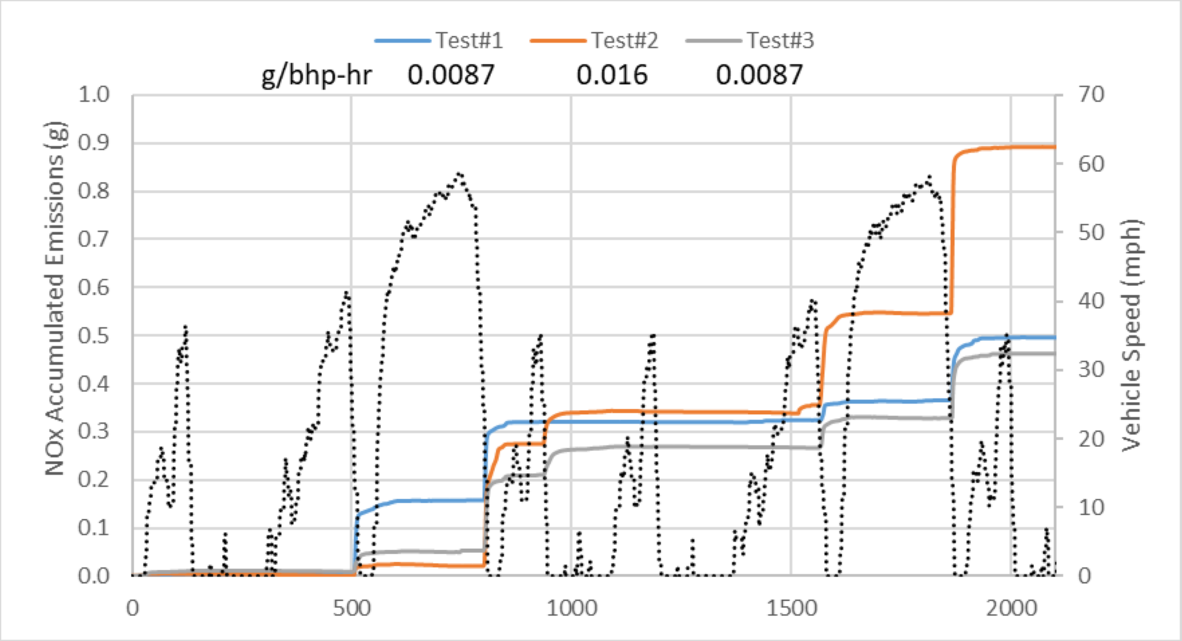

Figure ES-2 Real-time NO_x accumulated mass for the three UDDS hot cycles

[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 (0.0112 g/bhp-hr).

The Particle Number (PN) emissions for the ISX12N averaged from 2e14 #/mi for low power cycles (Near Dock and ARB Creep) to ~8e12 #/mi for the ARB Cruise and Regional port cycles (2.5 nm D50). The particle size distribution showed a peak concentration at 60 nm for all the hot start tests. On average about 50% of the particle number emissions were solid particles for all the test cycles evaluated. The ISX12N #/mi PN emissions were similar to the 2010 certified and the NZ certified engine (~8e12 #/mi). As such, PN emissions from NG vehicles tends to be higher (by about 80x) compared to a diesel's equipped with diesel particulate filters (~1e11 #/mi).

Summary: In general the ISX12N NG engine hot start emissions were within the 0.02 g/bhp-hr certification standard for all the cycles tested, but the cold start combined emissions were high. The optional Low NO_x emission factor was maintained for the full range of hot-start duty cycles found in the South Coast Air Basin unlike other heavy-duty diesel fueled technologies. The other gaseous and PM emissions were similar if not lower to previous studies. It is expected NG vehicles with the ISX12N 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. Unregulated particle number and ammonia emissions, and regulated methane emissions were higher than current 2010 certified diesel engines. These emissions should be considered when evaluating environmental and health impacts.

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.

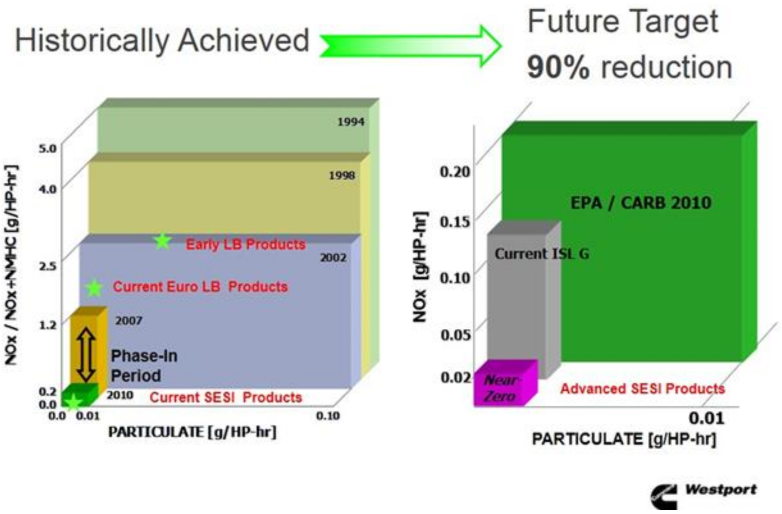

Figure 1-1 Engine dynamometer NO_x and PM certification emissions standards (source CWI)

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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.

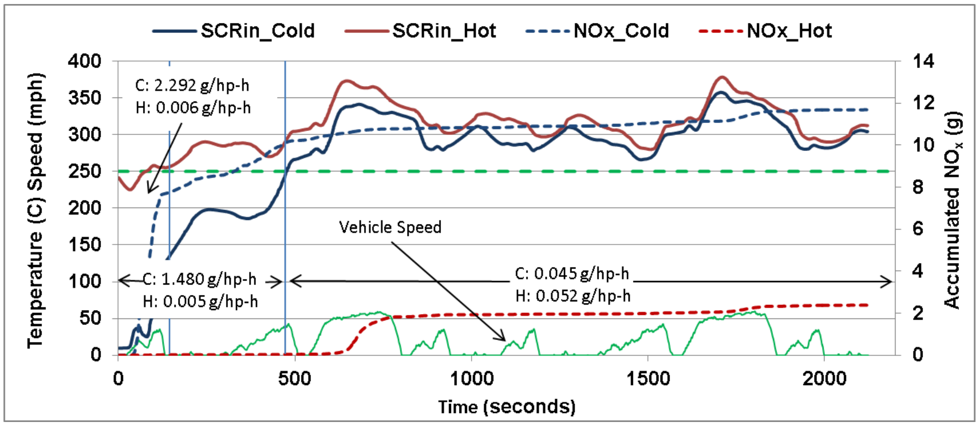
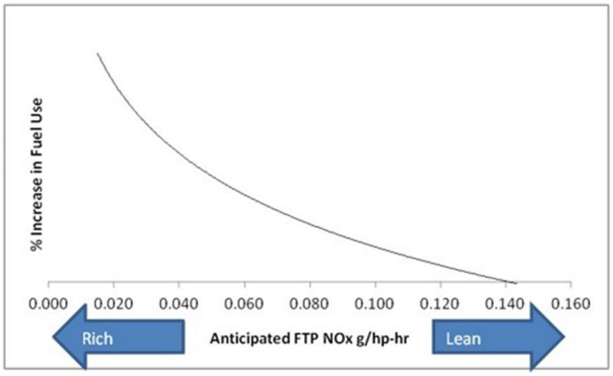


Figure 1-2 In-use emissions from a heavy duty truck tested on UCR's chassis dyno

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 ISX12N NG ultra-low NO_x NG vehicle emissions, global warming potential, and fuel economy during in-use conditions. Given the low NO_x concentrations expected, advanced measurements were utilized to quantify NO_x emissions at and below 0.02 g/bhp-hr emissions levels for NG engines. 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 ISX12N 400 Cummins Westport Inc. (CWI) 11.9 liter Natural Gas engine (SN = 75053847), see Table 2-1 for specifics and Appendix F for additional details. The engine was developed to meet CARB's optional ultra-low NO_x standard of 0.02 g/bhp-hr (90% below the 2010 NO_x emissions standard), see Figure F1 Appendix F.

Table 2-1 Summary of selected main engine specifications

Mfg	Model	Year	Eng. Serial No	Rated Power (hp @ rpm)	Disp. (liters)	Adv NO_x Std g/bhp-h [1]	PM Std. g/bhp-h
CWI	Alpha X12N	2018	75053847	400 @ 1800	11.9	0.02	0.01

[1] The family JCEXH0729XBC represents a 0.02 g/bhp-hr NO_x standard, see Appendix F Figure 1 for details.

2.1.2 Test Fuel

California liquid natural gas (LNG) 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. The samples were analyzed and presented in Table 2-2. The station LNG fuel varied in methane from 95.9 to 89.3 mole percent.

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

Property	Molar % #1/#2	Property	Molar % #1/#2
Methane	95.9 / 89.3	Pentane	<0.001
Ethane	1.53 / 4.31	Carbon dioxide	0.00
Propane	0.032/0.079	Oxygen	0.45 / 0.08
Butane	<0.003	Nitrogen	2.0 / 6.26

[1] Based on these fuel properties, the HHV is 1042.5 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 1065.715 fuel specification for NG fueled vehicles. #1 fuel was used on 1/30, 1/31, and 2/1 and test fuel #2 was used on 2/2 and 2/5 as listed in Appendix A.

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 fault codes. The vehicle inspection and securing met UCR's specifications. The vehicle arrived at UCR with an active engine fault. Cummins Westport Inc. had a Cummins Cal Pacific technician service the engine fault which turned out to be a faulty oxygen sensor. The technician replaced the oxygen sensors prior to testing and the engine fault was cleared and the vehicle was driven to make sure adaptive learning were complete. No engine faults were found during or after testing was completed.

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. At the time of testing the vehicle had 56,424 miles accumulated.

2.1.4 Test cycles

The test vehicle utilized an ISX12N NG engine which is primarily a goods movement engine in the South Coast Air Basin. As such, UCR tested the vehicle following the three drayage type port cycles (Near Dock, Local, and Regional), the Urban Dynamometer Driving Schedule (UDDS), and the Heavy-Heavy Duty Diesel Truck (HHDDT) transient test cycles. These cycles are representative of Sothern California driving vocations. Some cycles are very short (less than 30 minutes) where double or triple (2x or 3x) cycles are recommended in order capture enough PM mass to quantify emissions near 1 mg/bhp-hr. The average speed of the cycles varies from 1.75 mph (HHDDT_CREEP) to 39.6 mph with an overall top speed on just under 70 mph (HHDDT_Cruise), see Table 2-3 and Appendix B for details.

Table 2-3 Summary of statistics for the test cycles performed

Day	Distance (mi)	Average Speed (mph)	Duration (sec)
UDDS_CS	5.55	18.8	1061
UDDSx2	11.1	18.8	2122
Near Dock	5.61	6.6	3046
Local	8.71	9.3	3362
Regional	27.3	23.2	3661
HHDDT_Creepx3	0.372	1.75	768
HHDDT_Transx3	8.55	15.4	2004
HHDDT_Cruise	23.1	39.9	2083

[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.

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 signals from the engine ECM referred to as J1939 actual torque, friction torque, and reference torque (1770.15 ft-lb). 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 ISX12N 400 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)

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

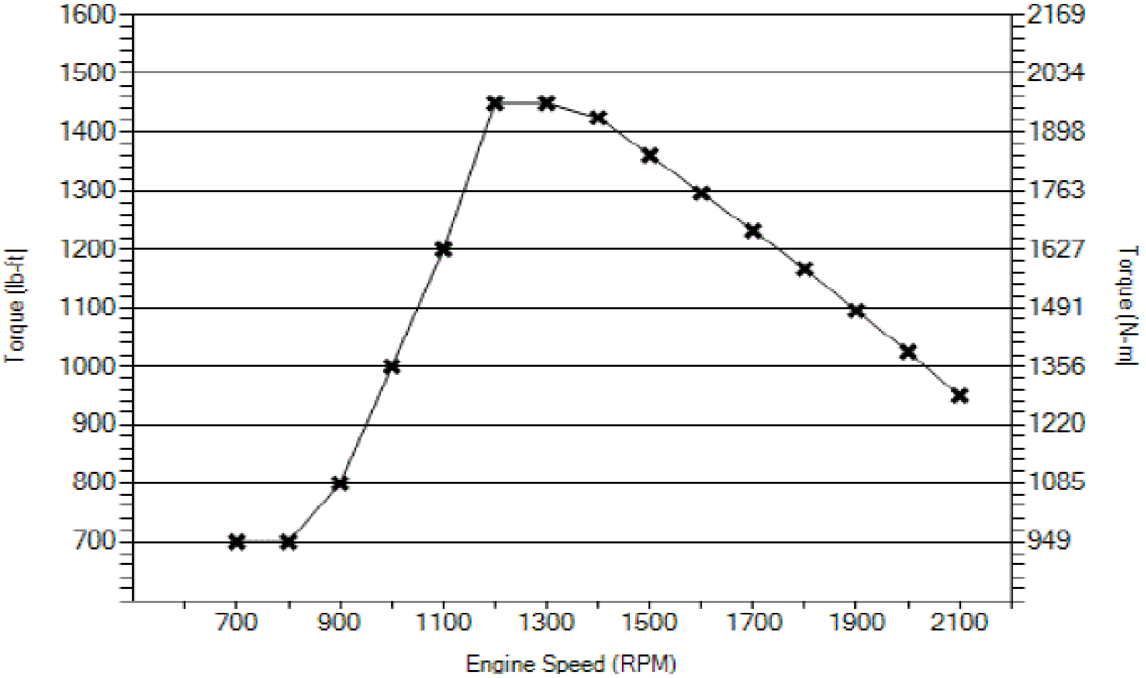

Figure 2-1 Published ISX12N Natural Gas engine torque curve

Figure 2-2 and Figure 2-3 show the measured power and work for each of the tests performed on the heavy duty truck. Heavy duty engines are certified on the FTP type of cycle where the average power is around 100 Hp and estimated at 33 bhp-hr (25% of rated). The UDDS and HHDDT Cruise test cycles represent power near the FTP certification cycle. The other cycles showed lower power with the HHDDT_Creep and Near Dock being the lowest (as shown by previous studies). One concern for low power operation is higher NOx emissions as diesels aftertreatment systems are not active. The TWC stoichiometric engine does not have this limitation and performed well for all the cycles and is a success for NG engines. This will be discussed in the result section.

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.

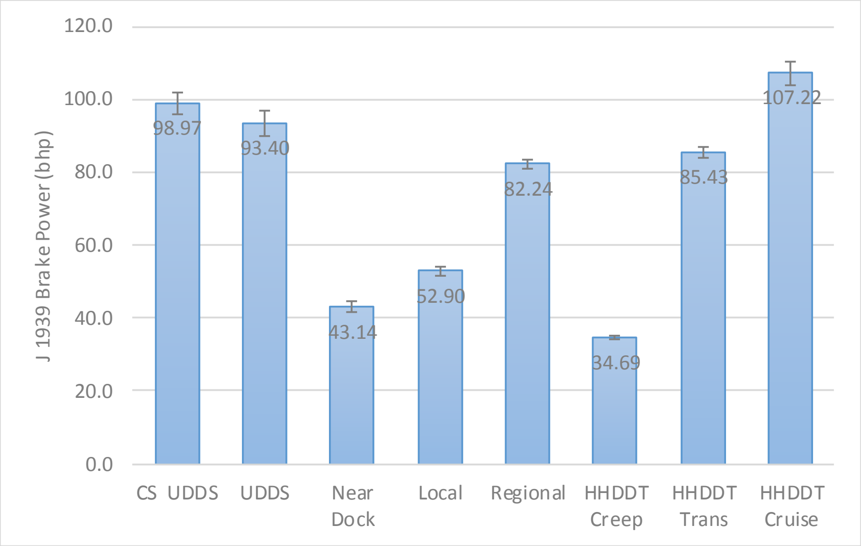

Figure 2-2 Power from the various tests with 1 stdev error bars

[1] Error bars represent 1 standard deviation with a sample size of 3 (n=3). The error bars were higher than usual due to ECM drop out. The engine CAN logging had some difficulties that caused more variability in the engine load. The engine load will add to the uncertainty (around 3%) of the final results, but do not impact the overall message of the low emission factors.

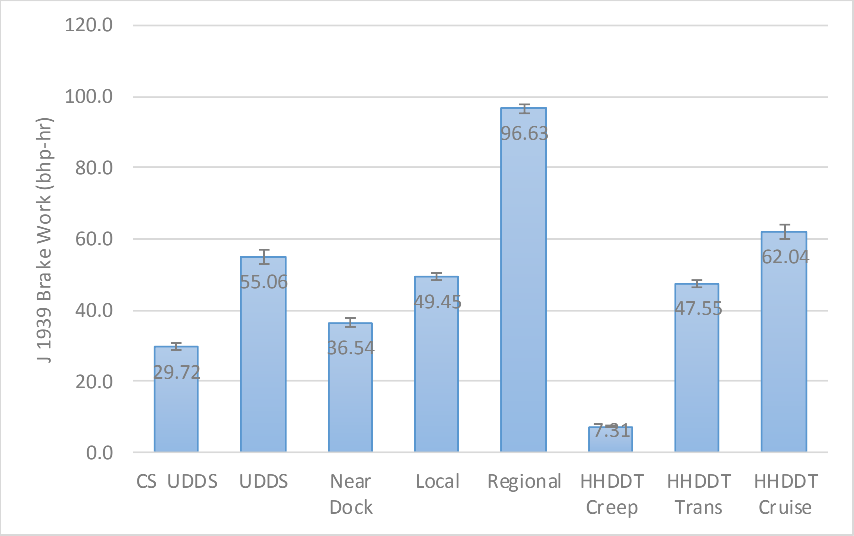

Figure 2-3 Work from the various tests with 1 stdev error bars

[1] Error bars represent 1 standard deviation with a sample size of 3 (n=3). The error bars were higher than usual due to ECM drop out. The engine CAN logging had some difficulties that caused more variability in the engine load. The engine load will add to the uncertainty (around 3%) of the final results, but do not impact the overall message of the low emission factors.

2.2 Laboratory

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 previous measurement improvements and new measurement improvements for the emissions testing performed in this report.

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. 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 ISX12N 400 engine is installed in a heavy duty truck with a GVWR of 52,000 lb, VIN 1FUJGBD97FLFY9734. The representative test weight for goods movement operating in the south coast air basin is 69,500 lb[3]. The testing weight of 69,500 lb was also utilized during previous testing of several goods movement NG and diesel trucks by UC Riverside and WVU [4 and 4]. For this testing program, UCR utilized a testing weight of 69,500 lb for all test cycles (UDDS, port, and ARB HHDDT).

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 selected test weight of 69,500 lb resulted in a power of 107.34 Hp at 50 mph with the calculated dynamometer loading coefficients of A = 493.6193, B = -3.3409E-14 and C = 0.124575. See calculation methods in Appendix G for more details.

2.2.2 Emissions measurements

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

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[3] 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.

[4] 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.

of MEL's measurements has been checked/verified against ARB's[5] and Southwest Research Institute's[6,7] 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, 8]. Samples can be collected for more detailed analyses such as hydrocarbon speciation, carbonyl emissions, polynuclear aromatic hydrocarbons, etc.

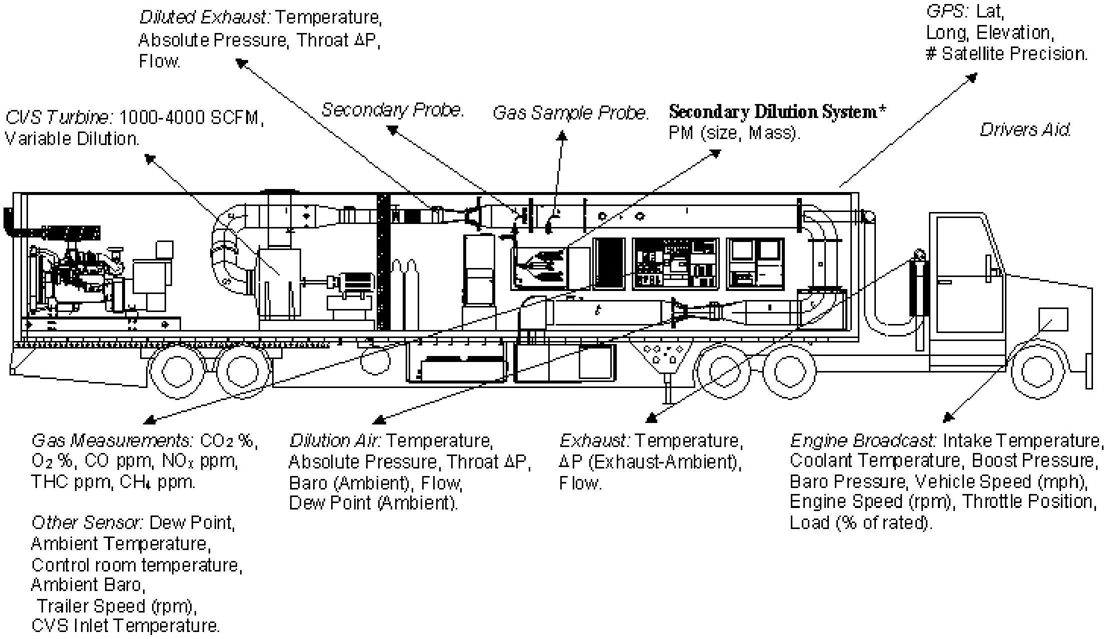

Figure 2-4 Major Systems within UCR's Mobile Emission Lab (MEL)

2.2.3 Low NOx Measurements

The optional low NO_x standard (< 0.02 g/bhp-hr) is approaching the measurement detection limits for the traditional dilute CVS measurement method. In the previous Low NOx evaluation with the ISL G Near Zero (NZ) 8.9L engine, UCR evaluated five methods two from the tradition approach and three new methods, see Table 2-4 for summary of methods. The previous results showed more than ½ of the measurements for the Ultra Low NOx NG engine had a dilute concentration 50% of the ambient corrected concentration. The low diluted concentrations measured impact all the methods except for M3 (raw) such that variability and means were different. Although there were no statistical differences in that study, it was suggested the traditional (M1 and M2) and raw (M3)

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[5] 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

[6] 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.

[7] 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

[8] 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

measurement were recommended[9]. For details on the methods, calculations and evaluation see (5). Method 4 and 5 were not used during this study.

Chemiluminescence Detection (CLD) is the laboratory method for dilute and raw NOx measurement. The CLD analyzer measures the light (lumens) emitted by the reaction with NO and Ozone (O3). Similarly NH3 will also react with O3 to emit light thus adding the response in a NOx analyzer unless care is taken. Many in the industry add acid treaded filters to mask the effect, but it is uncertain how well they work during high NH3 concentration and low NO concentrations. As such, UCR integrated a quantum cascade laser (QCL) measurement method to evaluate the impact of ultra-low NOx measurement in the presence of large amounts of NH3. The QCL is a spectroscopy method which can measure NO and NO2 and is not sensitive to NH3 cross interference.

Table 2-4 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

This section discussed the traditional, raw and added QCL NOx measurement methods recommended for the ultra-low NO_x evaluation. This section also provides a section on the other real time measurement methods utilized for particle number.

2.2.3.1 Traditional method

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

2.2.3.2 Method upgrades

Two NO_x upgrade methods were considered for this project. These included 1) real-time raw CLD sampling and exhaust flow measurements and 2) real-time raw QCL sampling and exhaust flow measurements. The raw CLD sampling was setup in the previous program and the QCL was added to the measurements from this program. The new measurement methods 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

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[9] Johnson, K., Jiang, Y., and Yang, J., Final Report Ultra-Low NOx Natural Gas Vehicle Evaluation ISL G NZ, SC AQMD, November 2016.

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.

Quantum Cascade Laser spectroscopy (QCL)

UCR utilized the MEXA-ONE-QL-NX Quantum Cascade Laser (QCL) analyzer for the direct, simultaneous real-time measurement of the four relevant nitrogen-containing exhaust gas components NO, NO_2, N_2O and NH_3. The analyzer combines a light source based on the new quantum cascade technology (efficient lasers in the mid-infrared spectral region) with a precisely adjusted dual path cell to measure low concentrations with maximum sensitivity. The detection limit complies with current European legal requirements. Furthermore, the MEXA-ONE-QL-NX offers wide measuring ranges of up to 5000 ppm (for NO). By using extremely narrowband light sources and measuring under reduced pressure the cross-sensitivity to other exhaust gas components can be drastically minimized. The complete measuring system - including filtration - is specifically developed for the measurement of NH3 and thus guarantees a very fast NH3 rise time (T10-T90) of less than 5 seconds. The MEXA-ONE-QL-NX can be operated as a stand-alone analyzer or integrated into the MEXA-ONE software interface for user-friendly and simplified system operation.

2.2.3.3 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. The calculations are provided in the previous report and are not repeated here.

Table 2-5 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
Previous	300 HCLD raw	M3	Raw NO_x no ambient bag correction
Upgrade	QCL raw	M3b	Raw NO, NO_2, N_20, and NH_3

2.2.3.4 Method evaluation

The evaluation of the methods in this report include the dilute, raw CLD and raw QCL. For the dilute CVS measurements, one of the main contributing factors is the magnitude of the ambient concentration has on the calculation. As discussed previously, the 50th percentile raw, dilute, and ambient NO_x concentration were 0.55 ppm, 0.17 ppm, and 0.07 ppm respectively. This analysis will not be repeated here, but is expected to be similar since emission levels were similar and the same configuration for the dilute CVS was utilized.

The raw accumulated CLD NO_x emissions is compared to the raw accumulated QCL NO_x emissions in Figure 2-5. The two NO_x measurement methods CLD and QCL track well and there is no obvious deviation for the CLD NOx measurement resulting from the high NH_3 emissions, see Figure 2-5. In addition, the integrated results between the raw CLD and raw QCL show the CLD is slightly lower (20%) than the QCL when all the integrated results are pooled together, see Figure 2-7 and Figure 2-8. If there were an interference for the CLD it would have increased the measurement not reduced it. Thus, both the real time figure and the integrated results suggest the CLD interferences from the high concentration NH_3 is not causing a measurable impact on the CLD measurement when acid treated filters are used and replaced on a daily basis in the presence of 50 to 300 ppm raw NH_3.

The comparison between the integrated NO_x measurement methods showed no statistical differences in means between the different methods except between raw CLD and raw QCL, see Table 2-6. The two tailed paired t-test between raw CLD and raw QCL was 0.02 suggesting the means are statistically different and the raw CLD NOx was on average 20% lower than the QCL NOx. There were not differences in variability or in means for the rest of the comparisons.

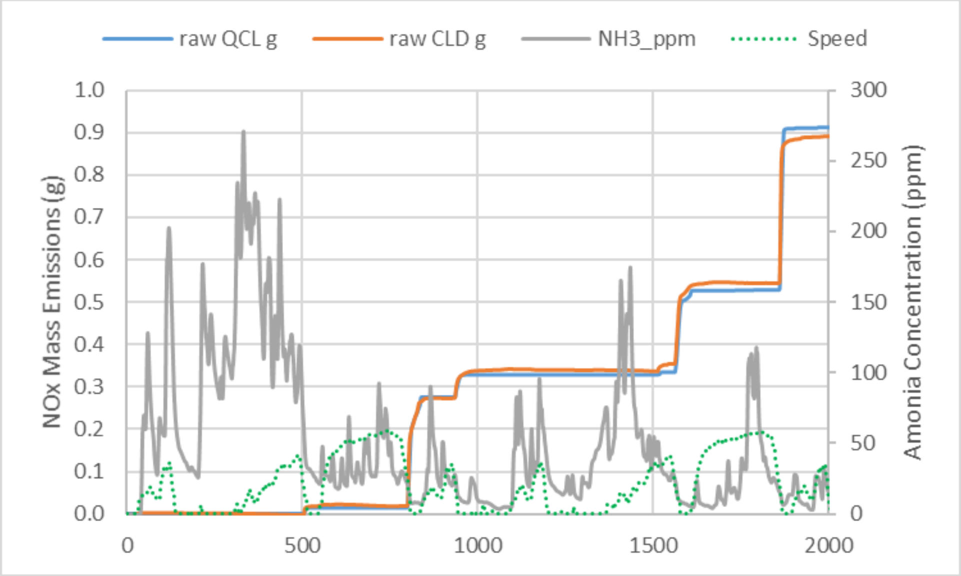


Figure 2-5 Real time raw (CLD and QCL) accumulation NOx with NH3 concentration

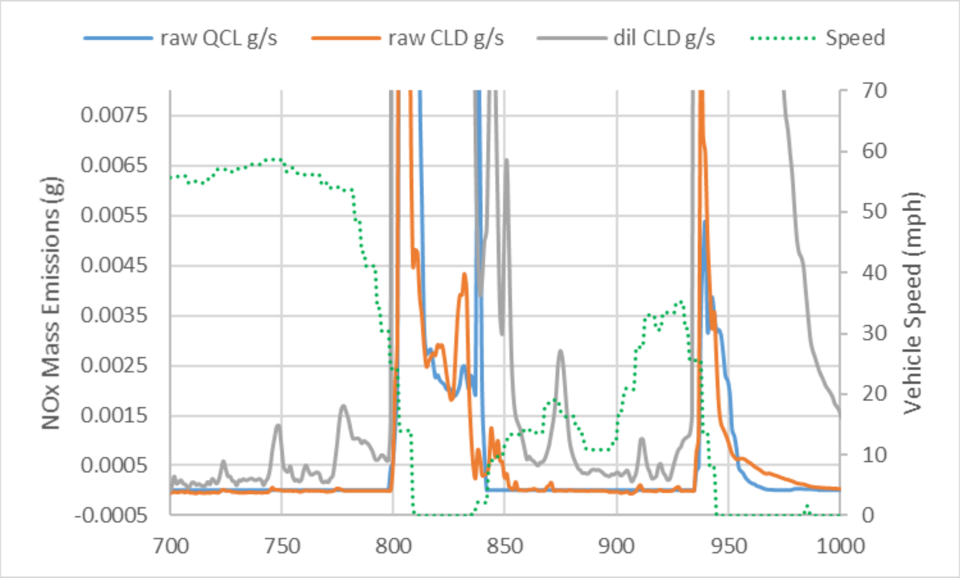
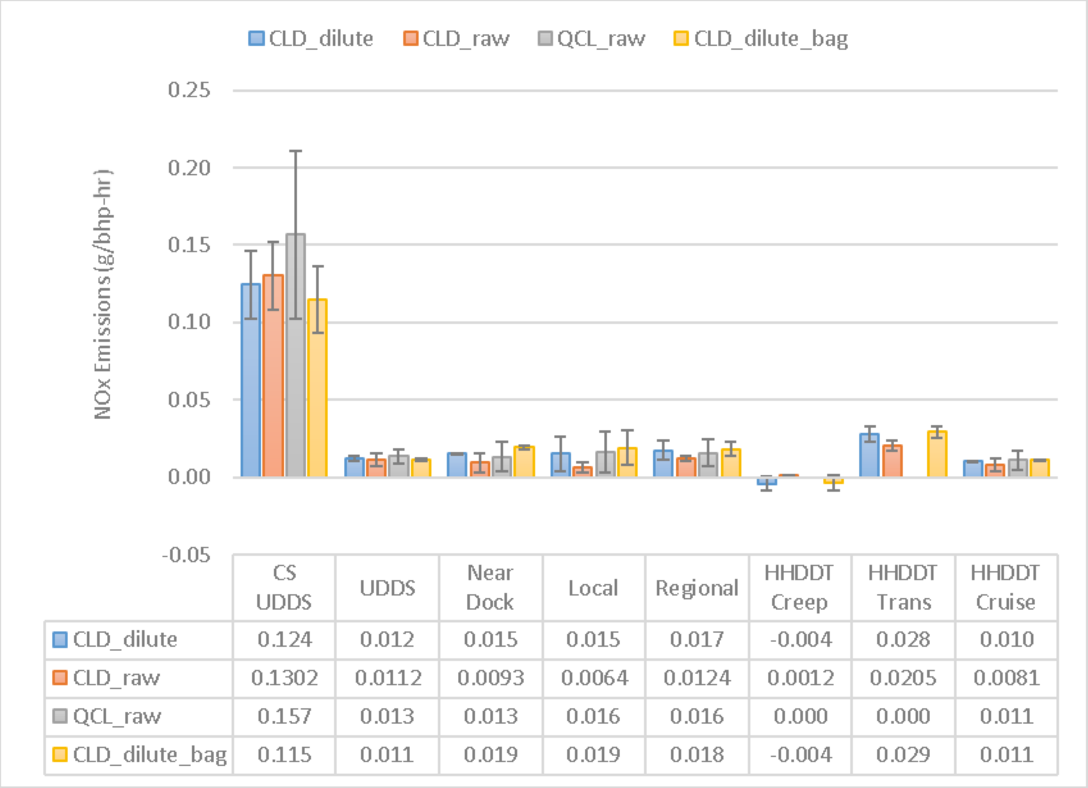


Figure 2-6 Real time raw (CLD and QCL) and dilute CLD NO$_x$ measurements



	CS UDDS	UDDS	Near Dock	Local	Regional	HHDDT Creep	HHDDT Trans	HHDDT Cruise
CLD_dilute	0.124	0.012	0.015	0.015	0.017	-0.004	0.028	0.010
CLD_raw	0.1302	0.0112	0.0093	0.0064	0.0124	0.0012	0.0205	0.0081
QCL_raw	0.157	0.013	0.013	0.016	0.016	0.000	0.000	0.011
CLD_dilute_bag	0.115	0.011	0.019	0.019	0.018	-0.004	0.029	0.011

Figure 2-7 Measured NOx emission for the hot and cold start test cycles

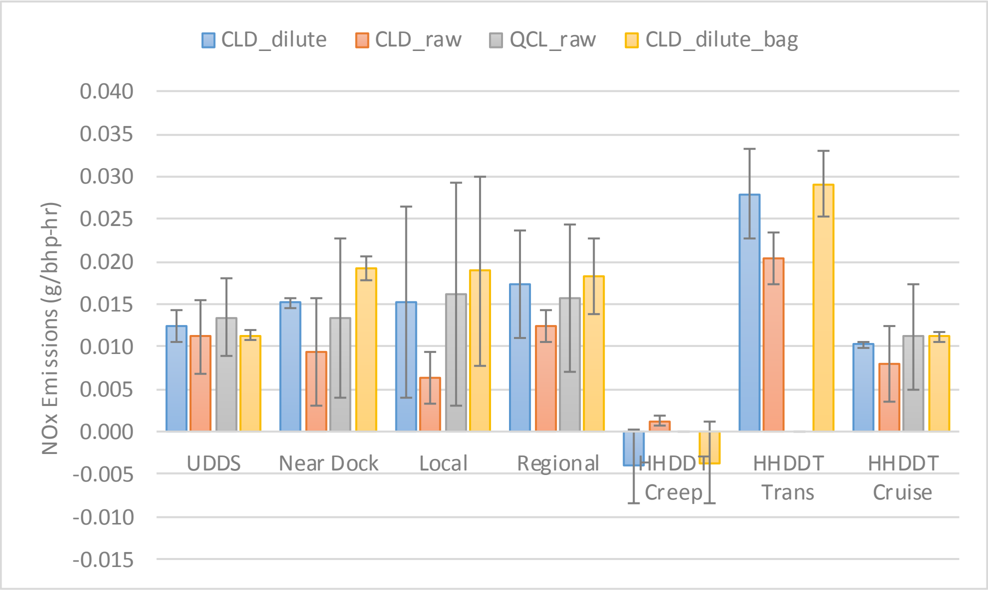


Figure 2-8 Measured NOx emission for the hot start only test cycles

Table 2-6 NO_x measurement methods t and f test (paired, two tailed) statistics

		t.test		f.test	
Array 1	Array 2	aves	all	aves	all
raw CLD	dil CLD	0.226	0.128	0.599	0.777
dil CLD	raw QCL	0.374	0.268	0.374	0.241
raw CLD	raw QCL	0.085	0.021	0.725	0.360
dil CLD	bag CLD	0.955	0.921	0.808	0.661
raw CLD	bag CLD	0.533	0.249	0.454	0.470
raw QCL	bag CLD	0.493	0.405	0.256	0.117

2.2.4 NH_3, PN, PSD, and BC Measurements

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), a PN measurement system with a catalytic stripper (CPC_CS), soot PM mass with AVL's Micro Soot Sensors (MSS 483) which reports equivalent black carbon (eBC), and ammonia (NH_3) emissions with an integrated real-time tunable diode laser (TDL) from Unisearch Associates Inc.

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/cm^3.

3 Results

This section describes the results from the ISX12N NG ultra-low NO_x NG engine. The results are organized by gaseous emissions followed by PM, particle number (PN), particle size distribution (PSD), 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.

The UDDS cycle is the representative test cycle for comparisons to the engine certification FTP cycle where the other cycles (port and CARB HHDDT) 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

The results section is organized similar to the 2015 report on the ISL9N NZ NG engine. This includes utilizing similar scaling for each of the figures and the organization of the sections. The goal was to be able to compare the reports side-by-side to draw conclusions between the two demonstrations.

3.1.1 NOx emissions

The NO_x emissions are presented in Figure 3-1 for the raw CLD method for all the test cycles performed (hot and cold). NO_x emissions were below the demonstration 0.02 g/bhp-hr emissions targets for the all the hot start tests (Note rounding the HHDDT results becomes 0.02 g/bhp-hr). The NOx emissions did not increase with decreasing load as is common with diesel engines (similar result for the ISL G NZ 8.9L engine). As discussed previously this is a result of the stoichiometric fuel control and TWC aftertreatment system. The port emissions ranged from 0.012 to 0.006 g/bhp-hr and the ARB HHDDT varied from 0.001 to 0.02 g/bhp-hr. The cold start emissions were higher than the hot tests when comparing between like tests (UDDS cold vs hot) and averaged at 0.130 g/bhp-hr for the UDDS test cycle. The previous ISL9N NZ engine showed a lower cold start 0.043 vs 0.13 g/bhp-hr) and about the same hot start emissions compared to the ISX12N engine.

In general, the NO_x emissions are below the ISX12N 2018 optional low NO_x certification standard of 0.02 g/bhp-hr for all tests but one 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 (0.0112 g/bhp-hr) shown for the UDDS hot test cycle, Figure 3-1. Deeper investigation shows all the tests had similar NOx spikes resulting from de-acceleration, more discussion is presented in a later section. The same NOx spike was also found for the other measurement methods. The test-to-test variability shown by the 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.

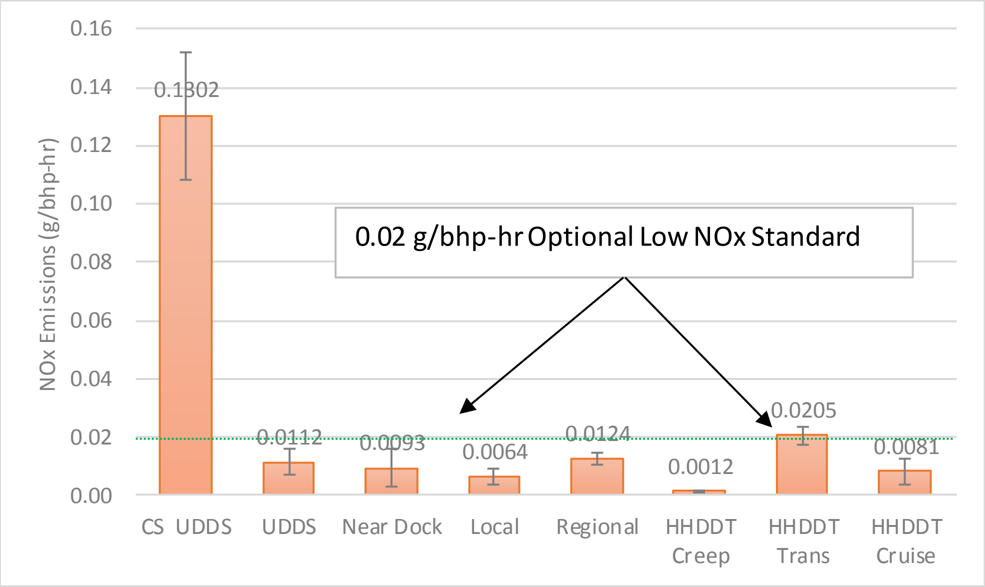
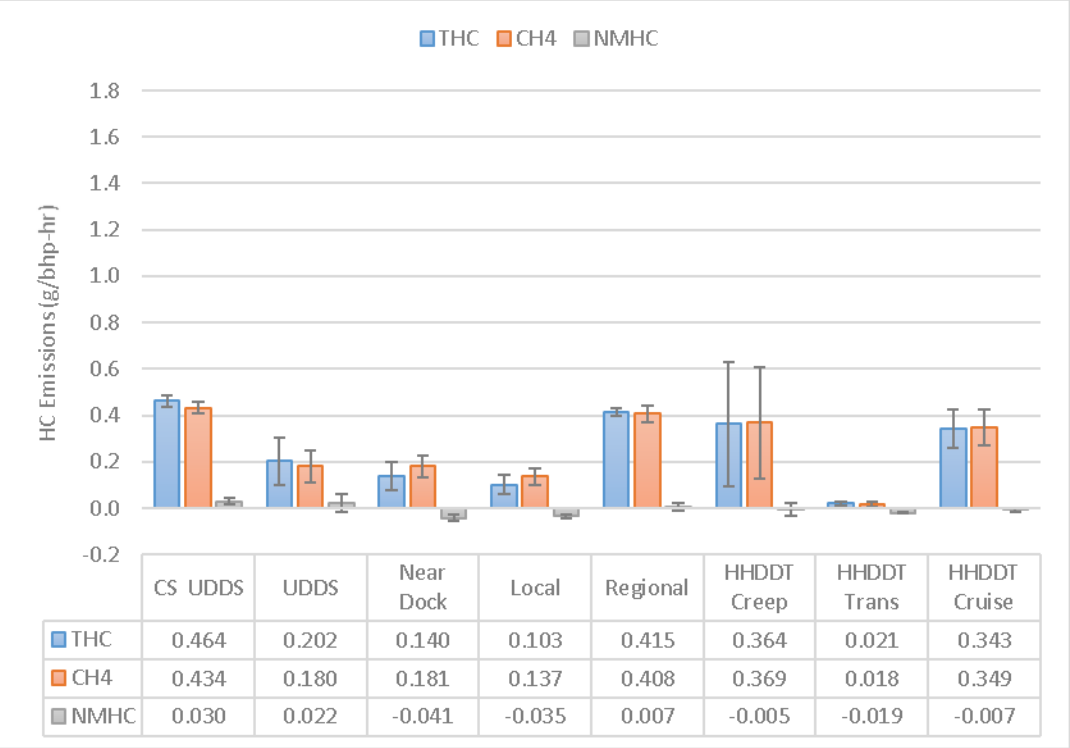


Figure 3-1 Measured NOx emission for the hot and cold start test cycles

3.1.2 Other gaseous emissions

The hydrocarbon emissions (THC, CH_4, and NMHC) are presented in Figure 3-2. The THC were relatively consistent between test cycles and ranged between 0.4 b/bhp-hr (CS_UDDS) and 0.01 g/bhp-hr (HHDDT Trans). The regulated HC species (NMHC) ranged from less than zero (truncated to zero) to 0.03 g/bhp-hr for the CS_UDDS. For all the tests (hot and cold) the NMHC was below the standard (0.14 g/bhp-hr) and above the reported certification value in the EO (0.004 g/bhp-hr), Appendix F Figure F-4. The NMHC was typically lower than CH_4 emission as one would expect for a NG fueled vehicle. Also the CH_4 emissions for the heavy duty truck are significantly lower (6.4 g/mi vs 0.9 g/mi UDDS) than previously tested NG trucks with the 2010 certified ISL G 8.9 L engine. The lower CH_4 emissions may be a result of the closed crankcase ventilation (CCV) improvement over previous versions of this engine.



	CS UDDS	UDDS	Near Dock	Local	Regional	HHDDT Creep	HHDDT Trans	HHDDT Cruise
THC	0.464	0.202	0.140	0.103	0.415	0.364	0.021	0.343
CH4	0.434	0.180	0.181	0.137	0.408	0.369	0.018	0.349
NMHC	0.030	0.022	-0.041	-0.035	0.007	-0.005	-0.019	-0.007

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. Figure 3-5 shows the NH_3 emissions in concentration. The CO emissions ranged between 0.23 (HHDDT_Trans) to 1.93 g/bhp-hr (CS_UUDS). The distance specific emissions ranged from 0.38 g/mi (Cruise) to 2.7 g/mi (Creep) which is lower than previous testing of NG vehicles from CWI (both the 2010 certified and the optionally low NOx engine tested by UCR in 2015). Previous testing of the ISL G (2010 certified engine) showed CO emissions ranging from 14.4 to 19.2 g/mi (CBD and UDDS test cycles).

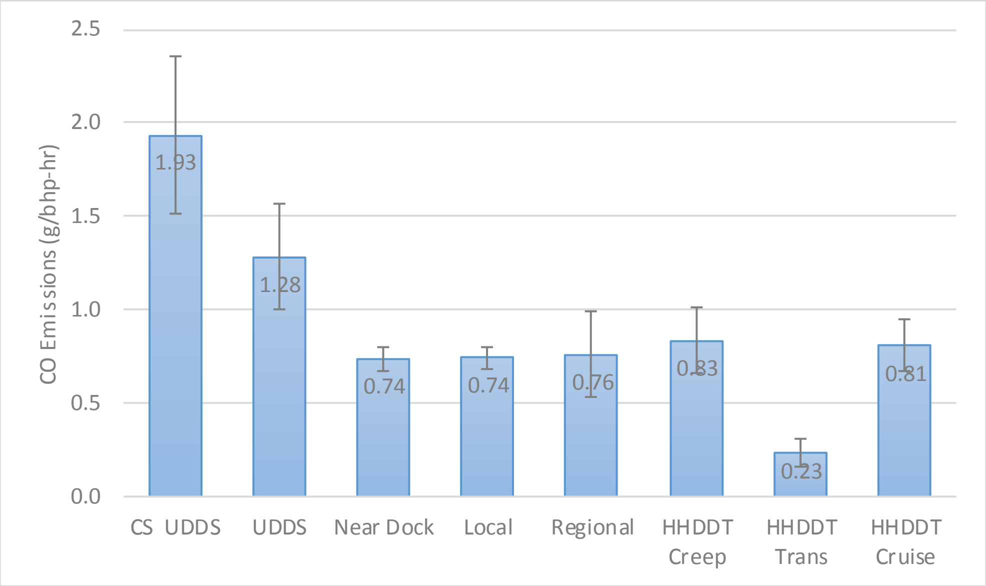


Figure 3-3 CO emission factors (g/bhp-hr)

The NH_3 emissions ranged from 0.038 (Trans) to 0.18 g/bhp-hr (CS_UUDS). The distance specific emissions varied from 0.015 g/mi (Local) to 0.34 g/mi (Creep) for the regional and CBD test cycles. The NH_3 emissions are much lower than previous ISL G (2010 certified) and NZ vehicles where the NH_3 ranged from 1.17 to 2.8 g/mi for the UDDS and RTC (2010 certified) and from 1.19 and 4.09 g/mi for the NZ certified, respectively. The ISX12N NH_3 emissions varied from 20.1 ppm (Trans) to 54.8 ppm (Near Dock) which is almost a magnitude of order lower than before, see Figure 3-5.

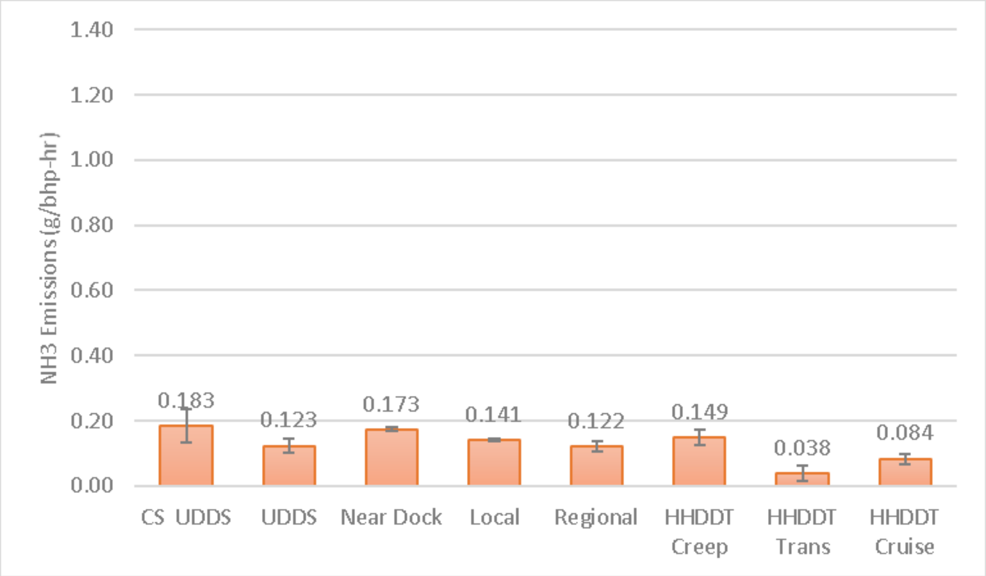


Figure 3-4 Ammonia emission factors (g/bhp-hr)

[1] NH_3 are based on the QCL system sampling from the raw exhaust. Similar results were found with UCR's integrated TDL.

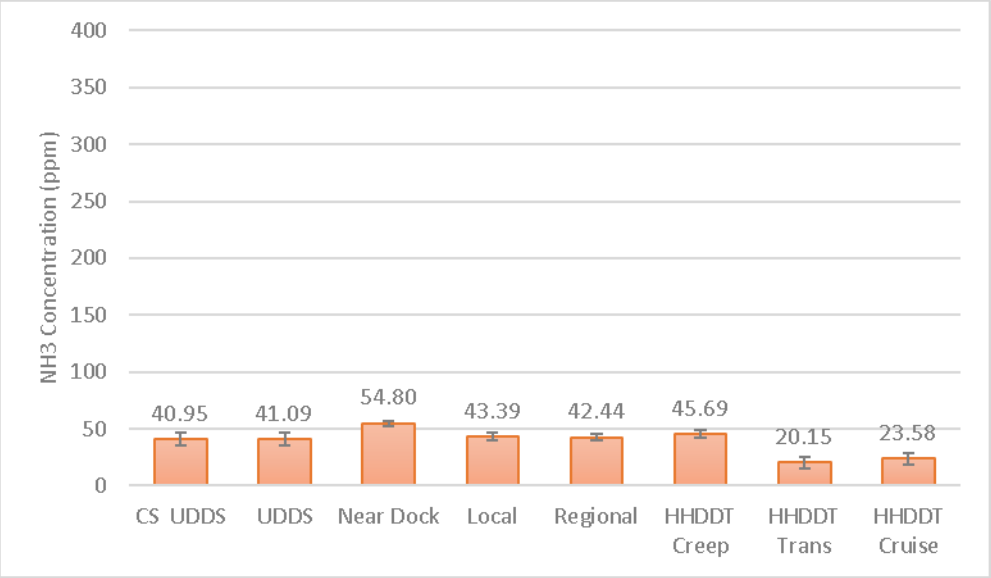


Figure 3-5 Ammonia measured tail pipe concentration (ppm)

[1] NH_3 are based on the QCL system sampling from the raw exhaust. Similar results were found with UCR's integrated TDL.

3.2 PM emissions

The PM emissions for all the tests including the cold start tests was typically 80% below the certification standard (0.010 g/bhp-hr), see Figure 3-6. The total PM emissions reported as PM2.5 ranged from 0.004 g/bhp-hr (CS_UDDS) to 0.001 g/bhp-hr (Regional). The emissions are slightly higher than the previous NZ demonstration and it is suggested this may be a result of some added oil consumption. A discussion in the Ultrafine Section will be utilized to facilitate this discussion. In general, the 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 51 ug with a single standard deviation of 23 ug where the tunnel blank ranged from 5 - 8 µg. As such, the PM emission rates were low and near the quantification limit of PM filters (ten times the LDL = 10*6 µg = 60 µg/filter), see Figure 3-7. The shown variability may be a result of measurement detection more than vehicle performance between cycles.

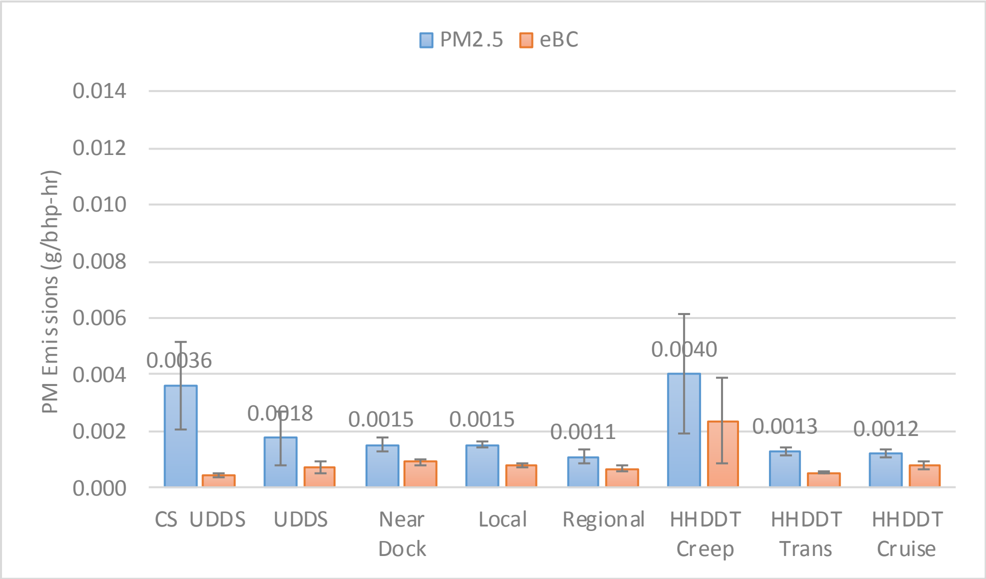


Figure 3-6 PM emission factors (g/bhp-hr)

[1] Creep, transient and cruise cycles were shorter than the port cycles and thus had more variability due to the filter weight. See figure below.

The soot or elemental carbon denoted as equivalent black carbon (eBC) ranged from 0.0004 g/bhp-hr (CS_UDDS) to 0.0024 g/bhp-hr (Creep). The Creep cycle emissions were only large because the work (denominator) was so small. When you consider the MSS-483 measured concentration the emissions were more consistent between the hot tests and averaged 0.079 mg/m3 (LDL is 0.002 mg/m3 for the MSS-483).

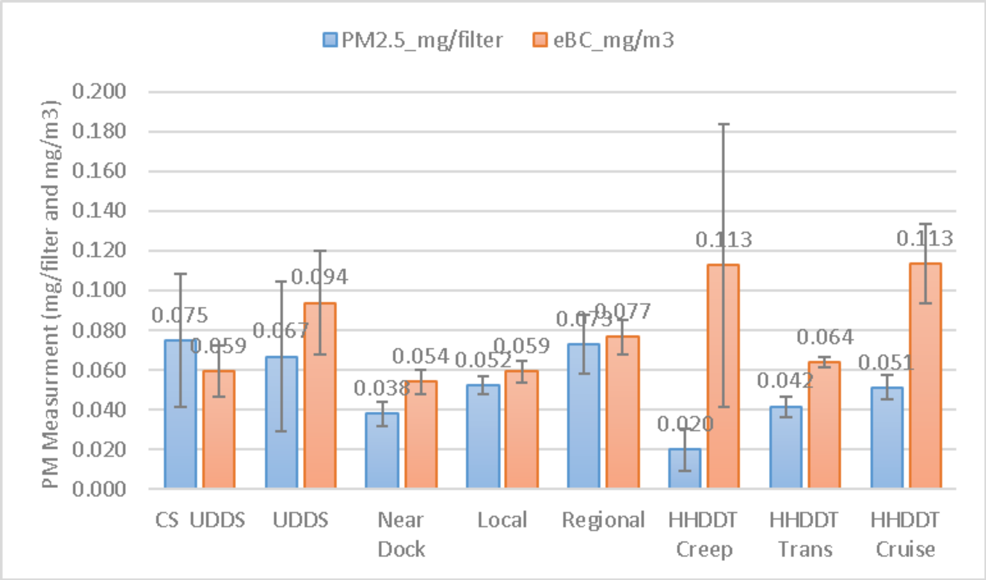


Figure 3-7 PM emission measurements filter weights and eBC concentration

[1] Tunnel blanks were 5-8 ug during this project and filter weights below 0.05 mg are near quantification limits (10*LDL = 0.050 mg/filter). When close to the quantification limits the variability may be a result of measurement detection and not test article. eBC concentrations were also near quantification limits (10 * LDL = 10*0.002 or 0.020 mg/m3).

3.3 PN emissions

The PN emissions utilizing a low cut point CPC (3772) are shown in Figure 3-8 and Table 3-1 for both total and solid (with a catalytic stripper) number per mile. The total PN (CPC_total) were highest (2e14) for the Creep cycle (HHDDT_Creep) and lowest on the Regional and Cruise cycles (~8e12). Since the UDDS cycle is representative of the FTP certification like cycle, comparisons to the hot UDDS are considered. The cold start total PN was higher than the hot cycle and showed a trend of increasing total PN (#/mi) as you decrease load. When you look at the measured concentration (Figure 3-9), the PN emissions are relatively flat suggesting the PN emissions are at a constant rate from the exhaust so slow traffic will experience higher PN emissions from the vehicle.

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 $1.9 \times 10^{12} \pm 3.8 \times 10^{11}$ #/mi (11) which was about 92% lower than the ISX12N UDDS test cycle results, but about the same as the near dock port cycle. In a second study with the ISL G NZ 8.9 liter engine, the PN emissions were 4×10^{12} for the CBD test cycle (10) which agrees well with the results in this study for the near dock test cycles. During a similar refuse hauler application of the ISL G engine, the PN emissions for the RTC cycle were 2.5×10^{13}, 5.8×10^{12}, and 2.0×10^{12} #/mi for the curbside, transit, and compaction portions of the RTC test cycle, respectively (12) which compare well with the PN from the ISX12N results. Late model diesel engines equipped with DPFs show PN emissions (with similar D50 cut points of 2.5 nm) ranged from 1.3×10^{11} to 0.7×10^{11} for on-road UDDS and cruise type of tests (18). In general the PN emissions for the ISX12N are mixed in comparison to the ISL G with some higher and some about the same. The ISX12N and ISL G both show higher (10x to 1000x higher) PN emissions compared to diesel vehicles equipped with DPFs.

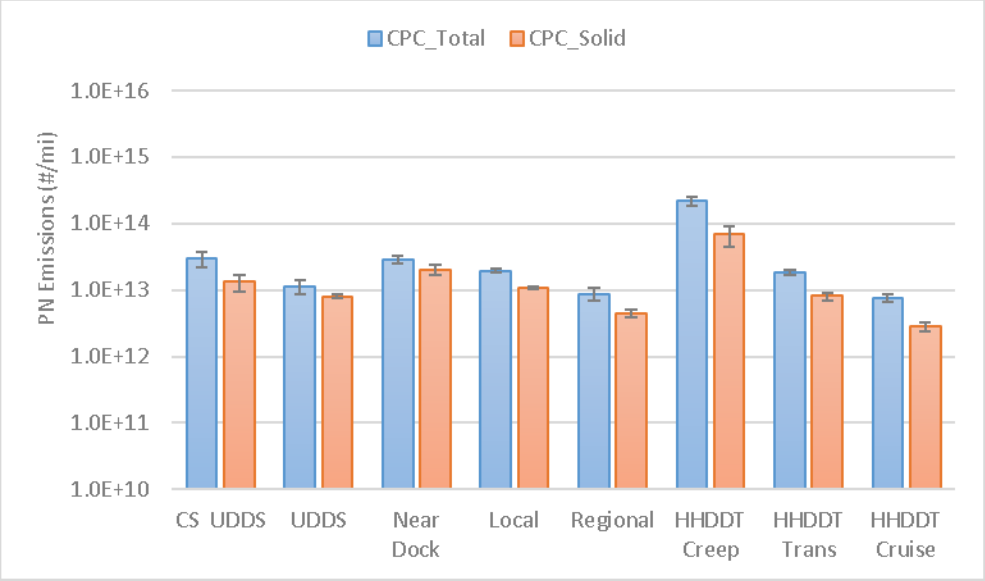


Figure 3-8 Particle number emissions solid and total (#/mi)

[1] Note the PN presented are based on CVS dilute measurements with and without sample conditioning using a catalytic stripper (CS). These data represent total particles (without CS) and solid particles (with CS). The CPCs used were based on a D50 of 2.5 nm (CPC 3776). These PN values may be higher than those presented by the PMP system which uses a 3790A counter (24 nm D50 cut diameter) and a volatile particle CS system.

Table 3-1 PN Emissions from the ISX12N engine for various cycles

Trace	Power	Distance	Total_PN #/mi		Solid_PN #/mi	
n/a	bhp	mi	ave	stdev	ave	stdev
CS UDDS	99.0	5.7	3.0E+13	7.8E+12	1.3E+13	3.9E+12
UDDS	93.4	11.4	1.1E+13	2.7E+12	8.0E+12	4.8E+11
Near Dock	43.1	5.8	2.9E+13	4.2E+12	2.0E+13	3.3E+12
Local	52.9	8.9	1.9E+13	1.3E+12	1.1E+13	6.6E+11
Regional	82.2	27.6	8.7E+12	1.9E+12	4.4E+12	5.6E+11
HHDDT Creep	34.7	0.4	2.2E+14	3.4E+13	6.8E+13	2.3E+13
HHDDT Trans	85.4	8.9	1.8E+13	1.6E+12	8.1E+12	1.1E+12
HHDDT Cruise	107.2	23.2	7.6E+12	1.0E+12	2.8E+12	4.0E+11

[1] CS stands for cold start and Stdev is a single standard deviation (n=3)

The solid particles are also considered in this study which were not considered in the previous study of the NA engine. The solid particles are quantified by removing the semi-volatiles with a catalytic stripper in front of the CPC. The solid PN were lower than the total PN as expected where the solid PN fraction represented on average 50% of the total PN, see Figure 3-10. The percent solid particle was highest for the near dock and lowest for the regional cycle (71% vs 52%) suggesting as duty cycle increases in load the fraction of solid particles reduces. The opposite trend was observed for the CARB HHDDT cycles.

Figure 3-11 shows a comparison between the EEPS measurement system and the total and solid PN CPC measurement systems for selected test cycles. The EEPS and total CPC PN were in agreement where their correlation resulted in a slope of 0.56 (EEPS slightly lower than the CPCs) with an R^2 of 0.995.

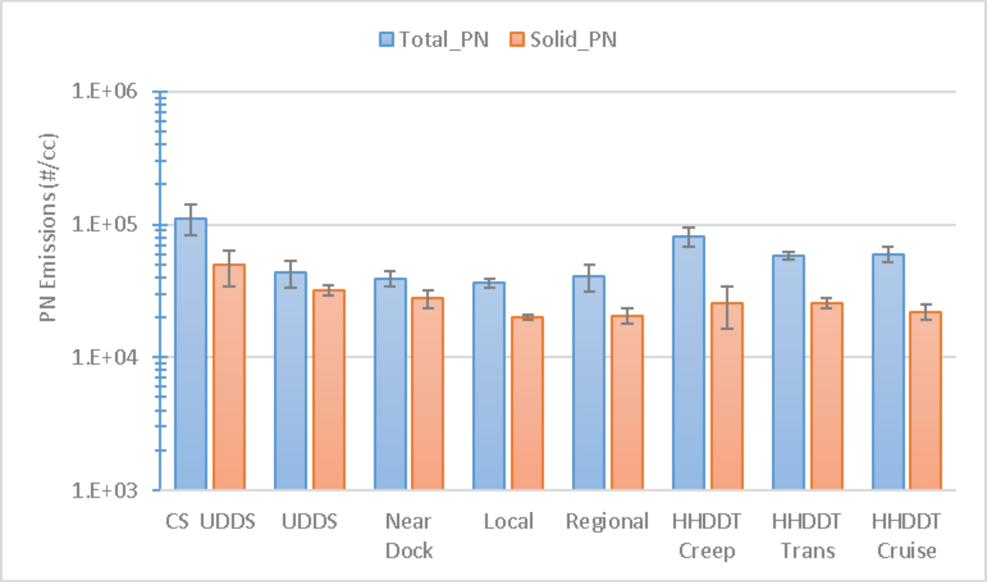


Figure 3-9 Particle number emissions solid and total (#/cc)

[1] Note the PN presented are based on CVS dilute measurements with and without sample conditioning using a catalytic stripper (CS).

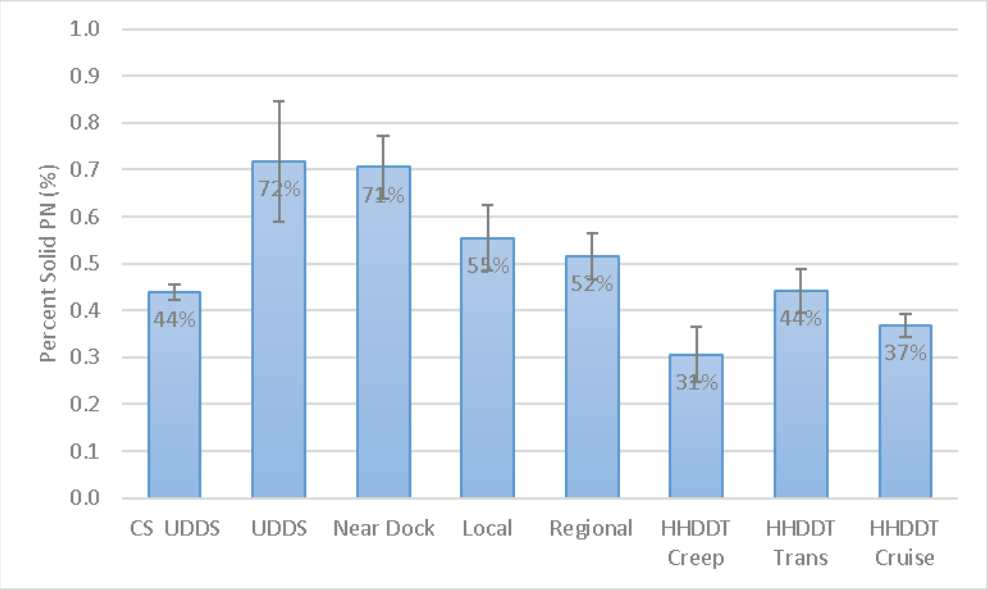


Figure 3-10 Percent solid particle number from CPC data (%)

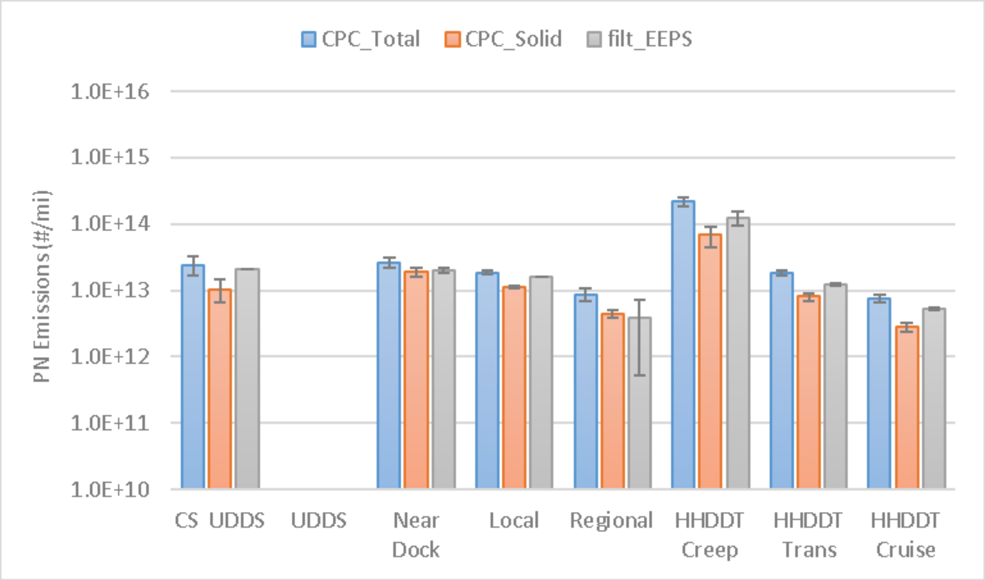


Figure 3-11 EEPS comparisons for PN (#/mi)

[1] EEPS #/mile estimate using traditional inversion matrix provided with EEPS. Note

3.4 Ultrafines

The ultrafine PSD (as measured by the EEPS) are shown in Figure 3-12 on a log-log scale concentration basis as measured in the dilute CVS. The cold start UDDS cycle showed the highest particle number concentration at ~10 nm particle diameter where all the hot tests (UDDS, Port, and HHDDT) all showed very similar PSD. The higher PSD for the cold UDDS and regional cycle are a result of a PN spike near the last hill of the UDDS test cycle.

Although it is hard to see from the figure, there is a secondary peak at 60 nm particle diameter which was not evident during the previous testing of the NZ technology. The PN at 60 nm is ~

4E5 #/cc where previously it was < 1E4 and ranged from 5E3 to 1E2 at similar CVS sample conditions. The higher PM mass (average filter weights of 50 vs 20 ug) suggests there may be higher PM mass emissions. It is suspected the PM emissions from NG vehicles is from the lubrication oil. 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 ISX12N vehicle (2).

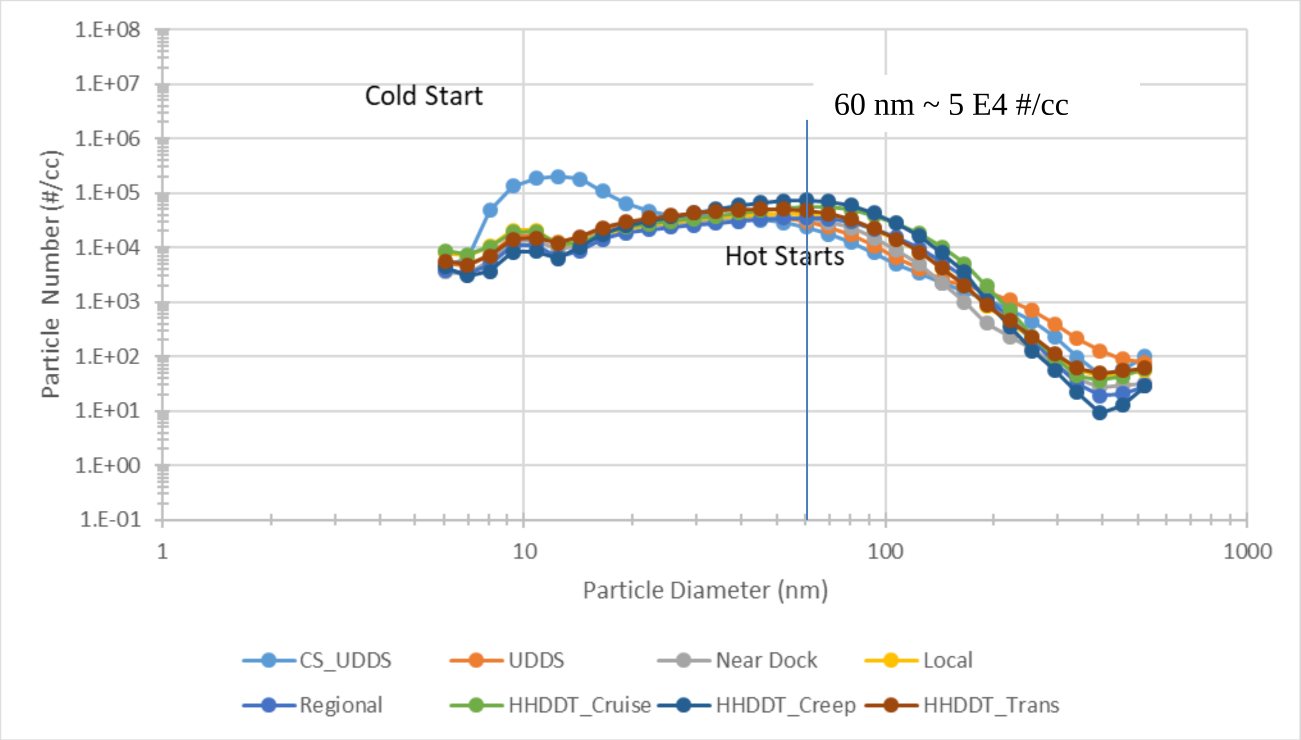


Figure 3-12 EEPS ultrafine PSD CVS measurements for each of the test cycles

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 3-2 on a g/bhp-hr basis (see Appendix E for g/mi basis). The CH_4 and N_2O emissions are low and represent less than 3% for the cold start tests and around 1% for the hot start tests.

N_2O showed up to 1% contribution to the GWP for the cold start, but less than 0.02% for all the hot starts where CH4 represented from 2% to 0.1% for the various cycles. The higher cold start N_2O emissions was a result of a large N_20 spike at the start of the test, see Figure 3-13. N_2O reached 200 ppm for the first 50 seconds and this one spike represented 95% of the total N20 emissions for the full test cycle. This observation was only possible due to the advanced QCL technology developed by Horiba. The hot start UDDS did not result in a large N_20 spike during a warm start with the catalyst temperature of approximately 350 C (see Figure 3-14). Others have shown (Huai et al, 2003) that N_20 emissions can exist from a warm start gasoline TWC controlled vehicle. NG cold start and warm start N$_2$0 emissions may be a concern if frequent cranking events occur. Analysis of the vehicle activity is needed to truly assess the impact of NG emissions on the region.

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 3-2 lists the soot PM for each cycle and the ratio of soot/total PM emissions. The results suggest around 10% of the cold start PM is eBC and up around 50% of the hot start cycles are eBC. Additional analysis showed that the measured average concentration ranged between 59 ug/m3 which is an order of magnitude higher than for the previous NZ technology tested. The higher concentrations suggests there is more PM and eBC for the ISX12N compared to the ISL9N.

Table 3-2 Global warming potential for the ISX12N truck tested (g/bhp-hr)

Trace	CO$_2$	CH$_4$	N$_2$0	GWP (CO$_2$ eq)	eBC	eBC/PM$_{2.5}$
CS UDDS	540.5	0.434	0.0192	557.1	0.0004	12%
UDDS	534.1	0.180	0.0000	538.6	0.0007	42%
Near Dock	608.5	0.181	0.0001	613.0	0.0009	59%
Local	611.3	0.137	0.0001	614.7	0.0008	53%
Regional	555.4	0.408	0.0005	565.7	0.0007	62%
HHDDT Creep	612.0	0.369	0.0001	621.2	0.0024	59%
HHDDT Trans	548.7	0.018	0.0001	549.2	0.0005	42%
HHDDT Cruise	534.4	0.349	0.0003	543.3	0.0008	64%

[1] N$_2$0 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.

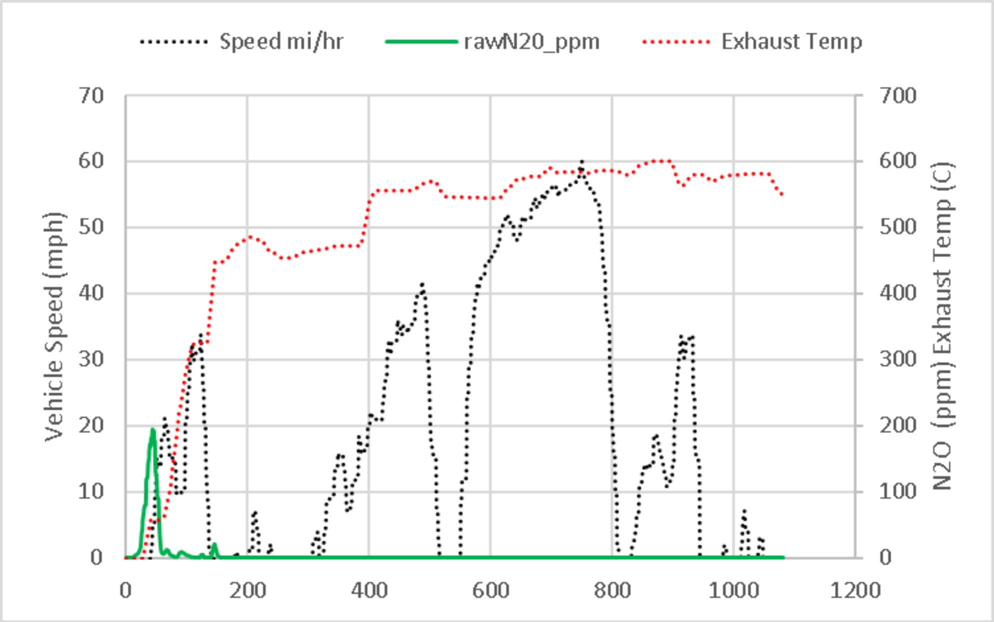


Figure 3-13 QCL N$_2$0 Results during a cold start

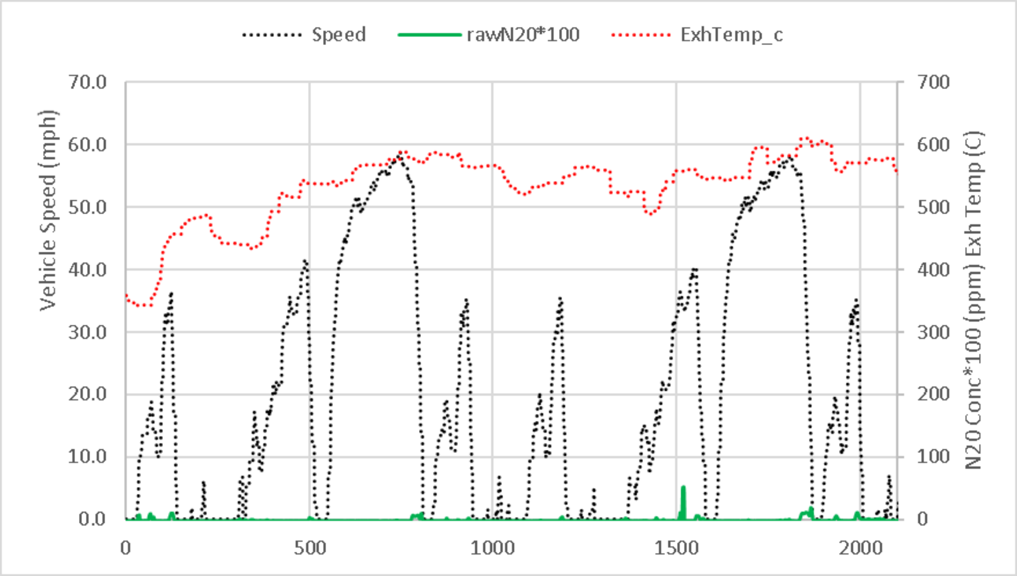


Figure 3-14 QCL N$_2$0 Results during a hot start (N$_2$0 Multiplied by 100)

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 the light loaded cycles (Near Dock, Local, and Creep) showed a higher CO_2 emission compared to the FTP standard. The average CO_2 for all the cycles was 568 g/bhp-hr, and 542 g/bhp-hr with the low power cycles removed. The CO_2 standard and certification value is 555 g/bhp-hr and 502 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 (for a particulate engine rating which is defined in 1065) 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.

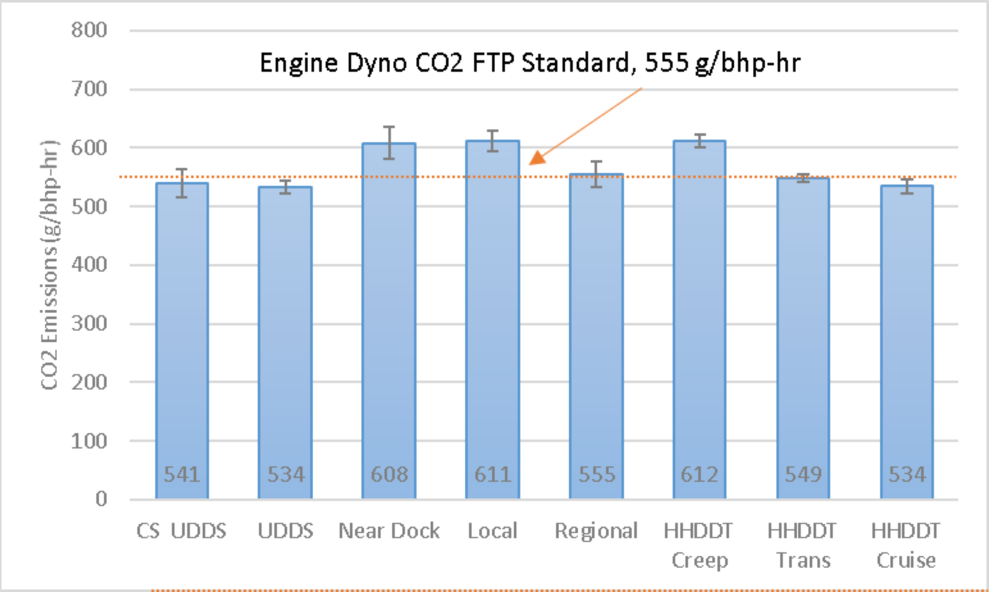


Figure 3-15 CO_2 emission factors (g/bhp-hr)

The ISX12N MPG on a diesel gallon equivalent (MPG_{de}) basis (assuming 2863gNG/gallon diesel (14)) ranges from 5.48 MPG_{de} (Cruise) to < 1 MPG_{de} (Creep). For the UDDS test cycle the MPG was 3.0 MPG_{de} where during previous testing, the ISL G 8.9 L (2010 certified) fuel economy was found to be ~ 2.3 MPG_{de} on a chassis dynamometer at similar test weights.

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 accumulated mass emission (g) for the three repeated UDDS cycles (test #1, 2, and 3). All the spikes occur at similar times within the test cycle. Variability occurs because the magnitude is different, see Figure 4-1. Interesting all the spikes occur during de-accelerations. This suggests that NOx emissions are essentially zero (estimated at less than < 0.0007 g/bhp-hr) except during sharp de-accelerations. This also suggests > 99% of the hot running emissions from the ISX12N NZ technology is a result of the transient nature of the truck. It is interesting that the previous ISL9N NZ transient NOx emissions showed emissions spikes on accelerations not de-accelerations. It is unclear what changed in the design to cause this.

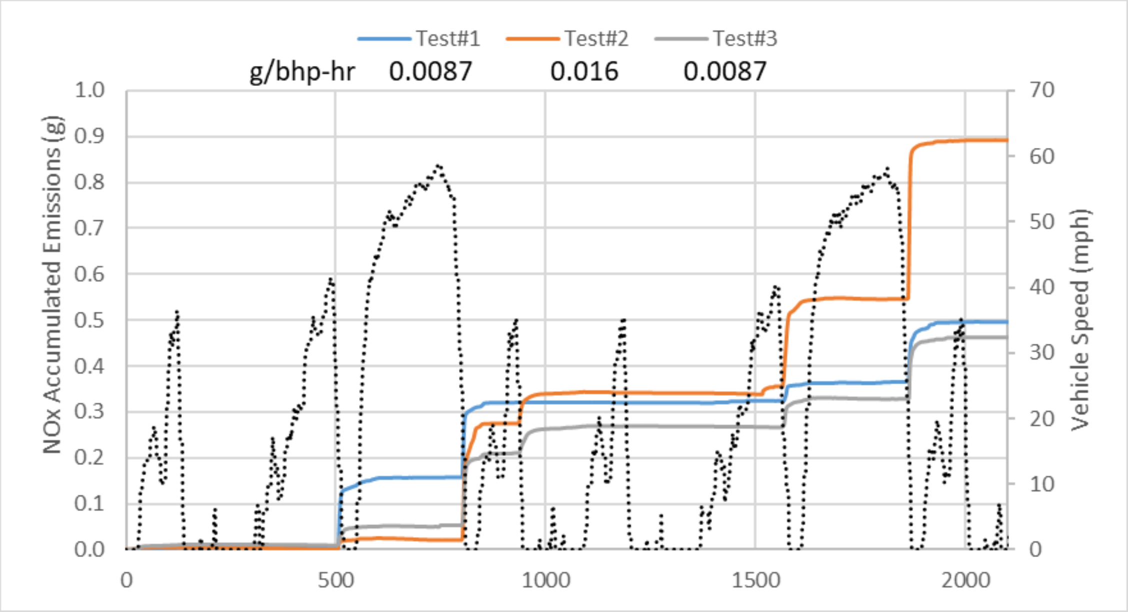


Figure 4-1 Accumulated NOx emissions (g) hot start UDDS cycles

4.2 Cold start emissions

Cold start emissions represented a significant part of the total emissions as one would expect, but it is unclear what the real impact from these cold start emissions is on the true regional inventory. Figure 4-2 shows the accumulated NO_x (g) emissions and truck speed as a function of time. Approximately 90% of the NO_x emissions (for all three CS_UDDS tests) occurred in the first 100 seconds of the cold start test. The remaining part of the cold UDDS test was very similar to the hot UDDS test where emissions spikes occurred at de-accelerations. The UDDS hot/cold weighted emissions is 0.028 g/bhp-hr (weighted as 1/7th of the hot cycle based on CFR recommendations).

Given that the cold start lasted 50 seconds out of 1080 seconds (total cycle length) the real weighted cold start emissions in-use for a 4 hr shift will be much less at be represented by 50/14000 or 0.3%. This suggests 0.3% of this vehicles in-use emissions are represented by a cold start as defined by a 4 hour shift. 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. Catalyst conditions were on average 15C for the cold start tests and above 300C for the warm starts (20 minute soaks). It is uncertain what the true warm start emissions will be from regional NG truck usage and will depend on their usage.

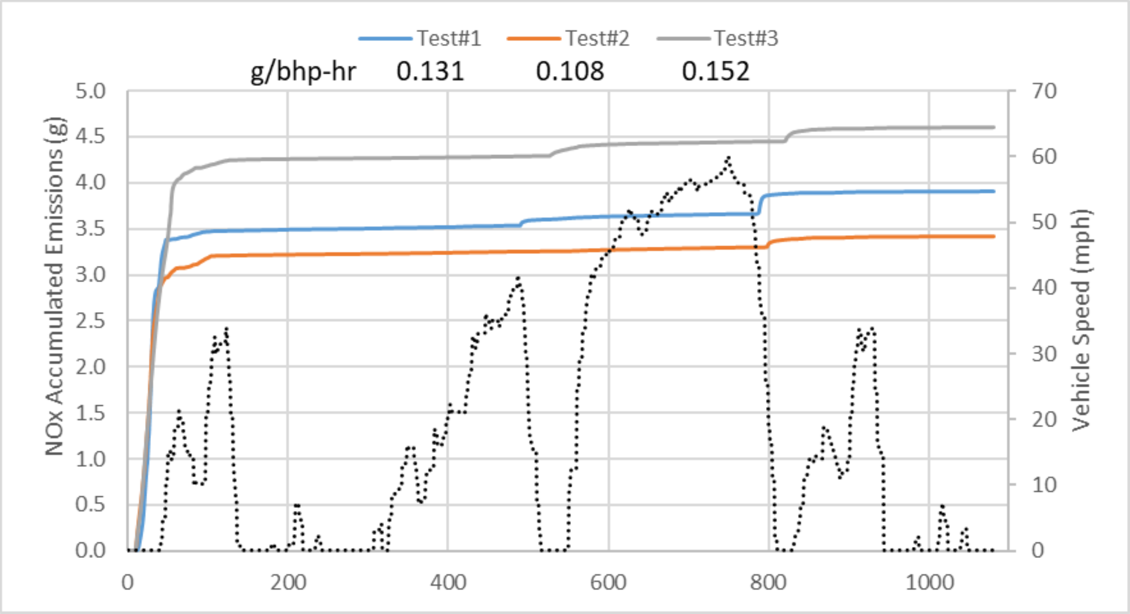


Figure 4-2 Accumulated NOx emissions (g) cold start UDDS cycles

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, and CARB's heavy duty transient cycles.

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 close to the detection limit to quantify NO_x emissions at the 5% accuracy expected from the emissions industry. During previous testing of a NZ engine, UCR upgraded its NO_x measurement methods where it was suggested high ammonia emissions may contribute to the NO_x measurement. In this study it was demonstrated with a spectroscopy method that the low NO_x measurements are accurate even in the presence of high concentrations of NH_3. In summary the improved methods proved to be accurate and reliable where raw sampling was determined to be the most accurate and precise over the range of conditions tested.

In general the ISX12N 400 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 high NOx inventory given the near zero emission factors demonstrated

The main conclusions can be summarized as (conclusions are based on the raw measurement method):

1. The ISX12N 400 11.9 liter NG engine showed NO_x emissions that ranged from 0.012 to 0.006 g/bhp-hr (port cycles) and from 0.001 to 0.02 g/bhp-hr for ARB's transient truck cycles.
2. The cold start emissions averaged 0.130 g/bhp-hr for the UDDS test cycle. The UDDS hot/cold weighted (1/7 cold start weighted) emissions was 0.028 g/bhp-hr which is above the certified 0.02 g/bhp-hr emission factor. It is expected the impact of the cold start emissions real in-use emissions could be lower and depend on the real fraction of time a NG truck operates in cold mode vs hot operation.
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 real time NO_x emissions show consistent NOx spikes resulting during transient de-accelerations. The cause for variability was the result of the magnitude of the spikes. More than 90% of the hot running emissions resulted from these NOx spikes. This suggests possible driver behavior may impact the overall NO_x in-use performance of the vehicle and more gradual de-accelerations are desired for minimum emissions.
5. Total PN averaged from 2e14 #/mi for the ARB Creep cycle and lowest on the Regional and Cruise cycles (~8e12 #/mi).
6. The solid PN averaged about 50% for all the test cycles.
7. PN is higher (20x) for NG vehicles (8e12 #/mi) compared to diesels equipped with a DPF (1e11 #/mi). It is unclear what impact this will have locally and regionally.

8. NH_3 emissions appeared to be lower for the ISX12N compared to the previous testing of the ISL G NZ 8.9L engine.
9. PM mass was low for the ISX12N truck, but seemed slightly higher than the previous ISL G NZ 8.9L engine tested.

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Appendix A. Test Log

This Appendix contains detailed test logs recorded during testing. The testing was performed on Vehicle ID 2018_002, Project Low NOx 2018, at a test weight of 69,000 lb. The chassis and vehicle operators were Lauren and Don for all the testing and the instrument operators were Cavan and Lauren. The QCL was operated every day with some startup issues on 1/30/2019 which were fixed and then selected tests repeated and then issues on 2/5/2018 (during the creep and transient test cycles). Unfortunately the 2/5/2018 issues were not realized until the data was analyzed. The results were not representative of the exhaust and thus the data were removed from the report. The creep loads and conditions matches the Near Dock cycle and the Transient conditions match the Local cycle. The N20 emissions were utilized from these cycles for the GHG analysis to estimate impacts from N20 emissions where necessary. Additionally NH3 emissions were based on UCR's TDL measurement with the QCL as a backup measurement. The QCL NOx measurements matched the CLD measurements and the report is based on the CLD measurements.

Table A-1 Summary log for all testing, preparations, and conditioning tests performed in this report.

Date	Test Time	Vehicle	CE-CERT Vehicle Number	Project	Dyno Cycle	MEL Cycle	Fuel	Dyno/MEL/ECM_Snapshot file Name	Technician/Driver	Weight/ Hp @ 50	Vehicle Weight	A	B	C
1/30/2018	11:57:00 AM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	UDDS_CS	UDDS_CS	LNG	201801301146	Mark/Don	107.34	69,500	493.6193	-3.3E-14	0.124575
1/30/2018	12:47:00 PM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	UDDSx2	UDDSx2	LNG	201801301245	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
1/30/2018	1:49:00 PM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	UDDSx2	UDDSx2	LNG	201801301347	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
1/31/2018	7:15:00 AM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	UDDS_CS	UDDS_CS	LNG	201801310712	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
1/31/2018	8:01:00 AM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	UDDSx2	UDDSx2	LNG	201801310759	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
1/31/2018	9:04:00 AM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	UDDSx2	UDDSx2	LNG	201801310901	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
1/31/2018	10:41:00 AM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	DTP1 (Cycle 1)	DTP1	LNG	201801311038	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
1/31/2018	11:59:00 AM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	DTP2 (Cycle 1)	DTP2	LNG	201801311156	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
1/31/2018	1:25:00 PM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	DTP3 (Cycle 1)	DTP3	LNG	201801311325	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/1/2018	8:21:00 AM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	DTP 1 (Cycle 2)	DTP 1	LNG	201802010818	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/1/2018	9:39:00 AM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	DTP 1 (Cycle 3)	DTP 1	LNG	201802010937	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/1/2018	11:37:00 AM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	DTP2 (Cycle 2)	DTP2	LNG	201802011134	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/1/2018	1:19:00 PM	1FUJGBD97FLFY9734	2018_002	CWI-Low Nox	DTP2 (Cycle 3)	DTP2	LNG	201802011303	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/2/2018	7:23:00 AM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	UDDS CS	UDDS CS	LNG	201802020720	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/2/2018	8:34:00 AM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	DTP3 (Cycle 2)	DTP3	LNG	201802020830	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/2/2018	10:14:00 AM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	DTP3 (Cycle 3)	DTP3	LNG	201802021011	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/2/2018	12:03:00 PM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	HHDDT Cruise (Cycle 1)	HHDDT Cruise	LNG	201802021200	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/2/2018	1:07:00 PM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	HHDDT Cruise (Cycle 2)	HHDDT Cruise	LNG	201802021305	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/2/2018	2:12:00 PM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	HHDDT Cruise (Cycle 3)	HHDDT Cruise	LNG	201802021410	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/5/2018	7:53:00 AM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	HHDDT Creep x3 (Cycle 1)	HHDDT Creep x3	LNG	201802050750	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/5/2018	8:36:00 AM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	HHDDT Creep x3 (Cycle 2)	HHDDT Creep x3	LNG	201802050834	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/5/2018	9:19:00 AM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	HHDDT Creep x3 (Cycle 3)	HHDDT Creep x3	LNG	201802050913	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/5/2018	10:11:00 AM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	HHDDT Transient_x3 (Cycle 1)	HHDDT Transient_x3	LNG	201802051004	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/5/2018	11:13:00 AM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	HHDDT Transient_x3 (Cycle 2)	HHDDT Transient_x3	LNG	201802051108	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575
2/5/2018	12:14:00 PM	1FUJGBD97FLFY9735	2018_002	CWI-Low Nox	HHDDT Transient_x3 (Cycle 3)	HHDDT Transient_x3	LNG	201802051211	Lauren/Don	107.34	69500	493.6193	-3.3E-14	0.124575

Appendix B. Test Cycle Description

The test vehicle utilizes an ISX12N NG engine which is primarily a goods movement engine in the South Coast Air Basin. As such, UCR tested the vehicle following the three drayage type port cycles (Near Dock, Local, and Regional), the Urban Dynamometer Driving Schedule (UDDS), and the HHDDT transient test cycles. These cycles are representative of Sothern California driving vocations used. Some cycles are very short (less than 30 minutes) where double or triple (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

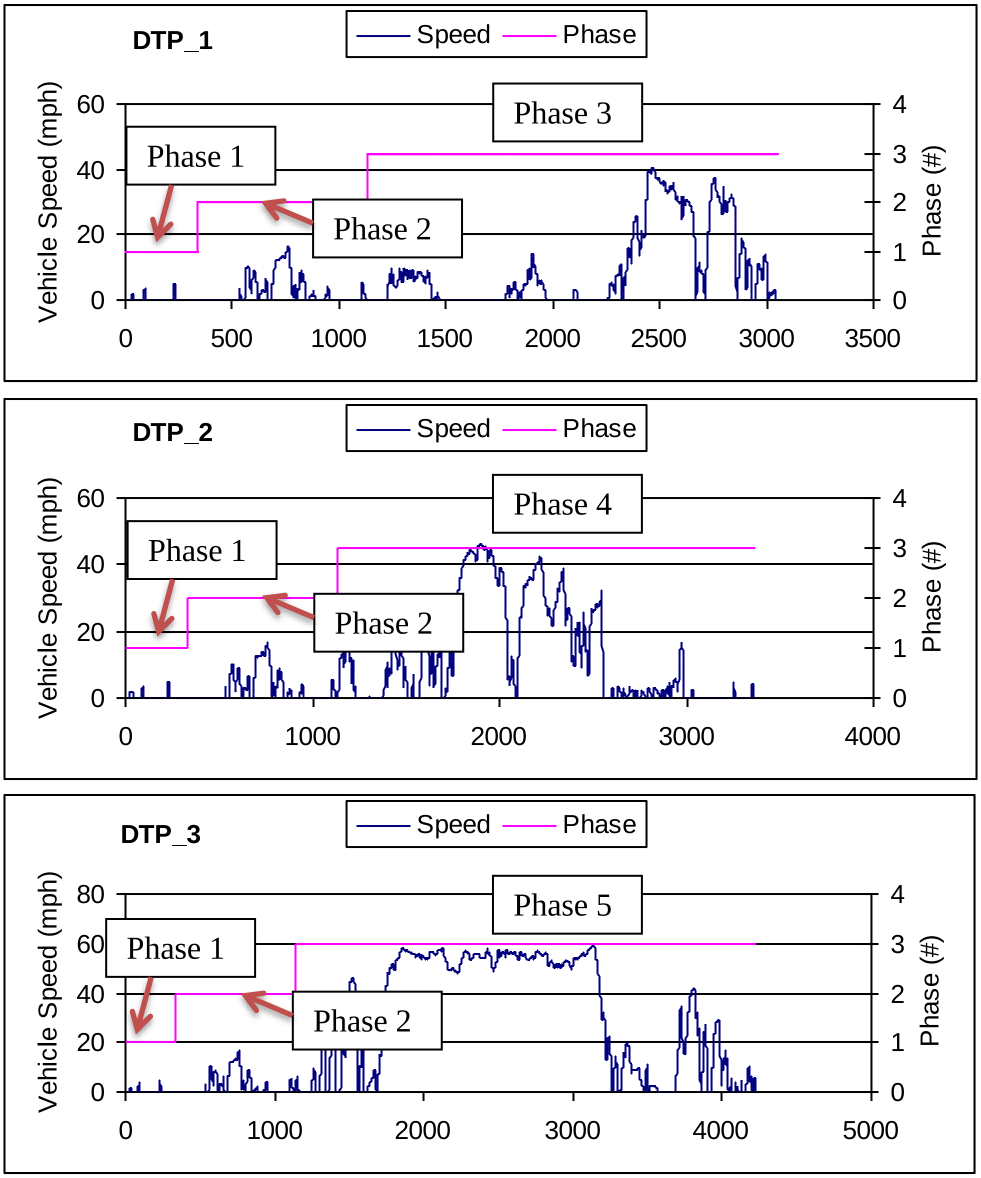


Figure B-1 Drayage truck port cycle near dock, local, and regional

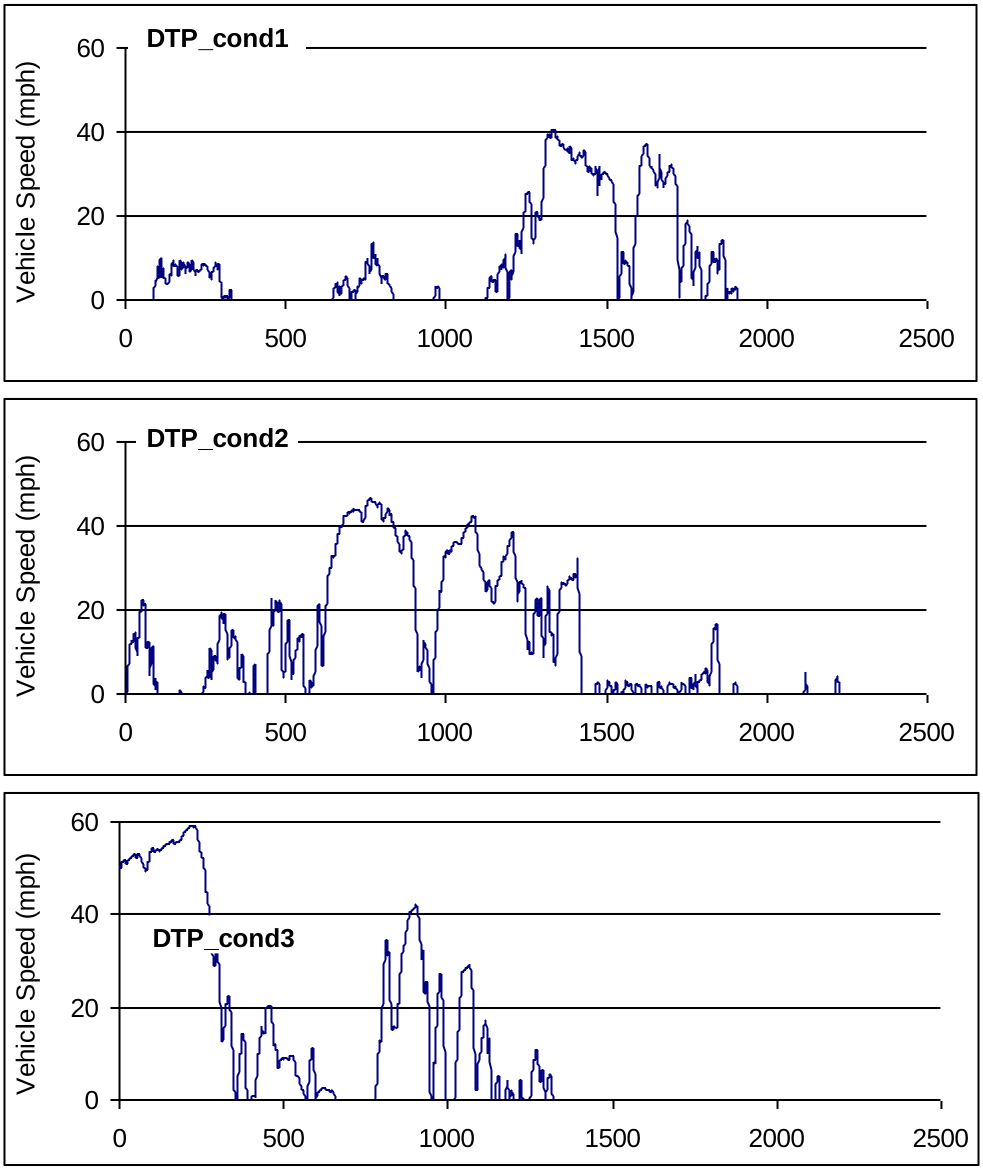


Figure B-2 Drayage truck port cycle conditioning segments consisting of phase 3 parts

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.

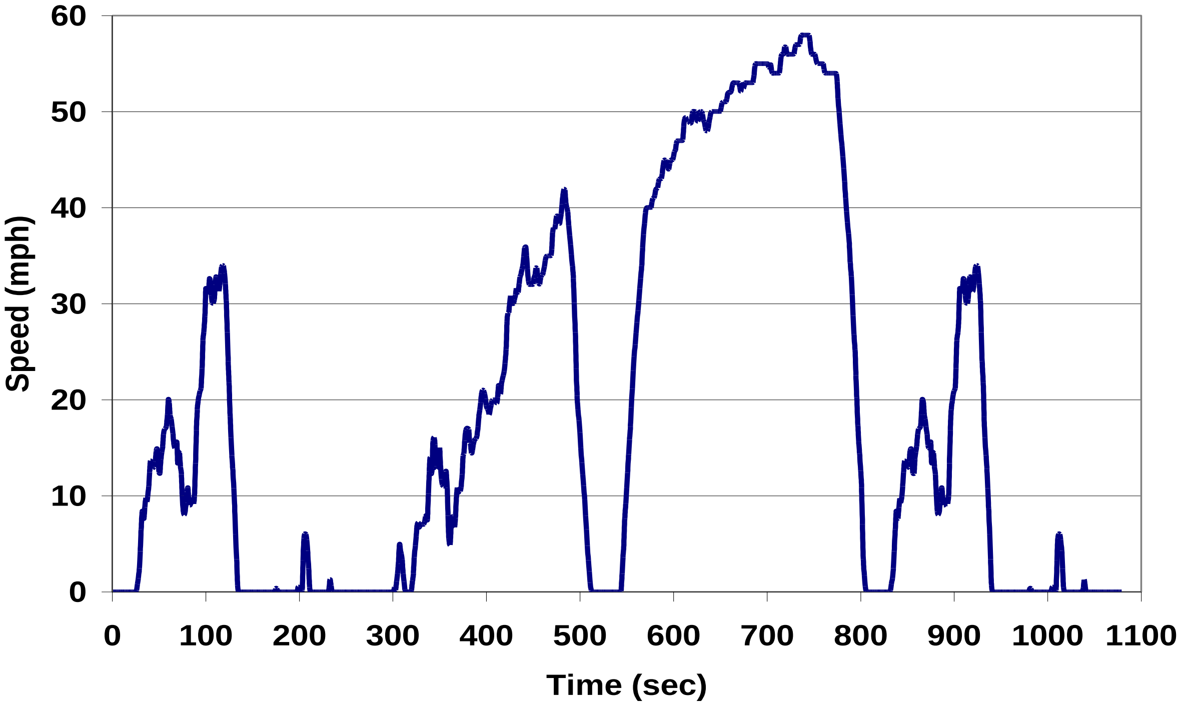


Figure B-3. Speed/Time Trace for a 1xHUDDS cycle.

ARB Cycles HHDDT:

The other three cycles tested were the ARB Creep, Transient, and Cruise cycles denoted HHDDT_Creep, HHDDT_Transient, and HHDDT_Cruise. The details of the cycle are summarized in Table B-3 and are presented in Figure B-4, 5, and 6. The creep and transient were performed as 3x cycles. The cruise was performed as a 1x cycle. The triple cycle operation was performed in order to obtain sufficient PM mass on the integrated filter which typically needs around 20 minutes.

Table B-3 Summary of cycle statistics

Cycle	Total Time Sec	Total Time (Hour)	Average Speed	Distance	Max Acceleration	Max Speed
Creep	256	0.071	1.75	0.124	2.30	8.24
Transient	668	0.186	15.4	2.85	2.90	47.5
Cruise	2083	0.579	39.9	23.1	2.14	59.3

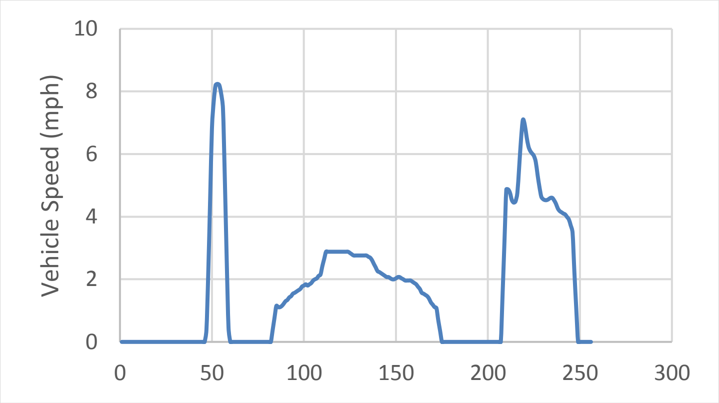


Figure B-4 Speed/Time Trace for a HHDDT_CREEP cycle (performed as 3x) 759 sec

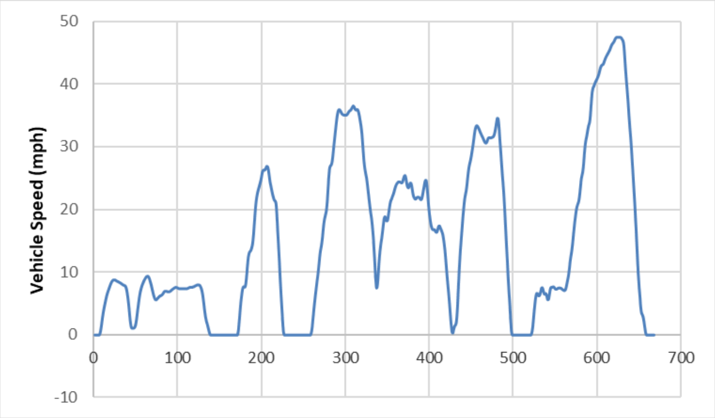


Figure B-5 Speed/Time Trace for a HHDDT_TRANS cycle (performed as 3x) 2004 sec

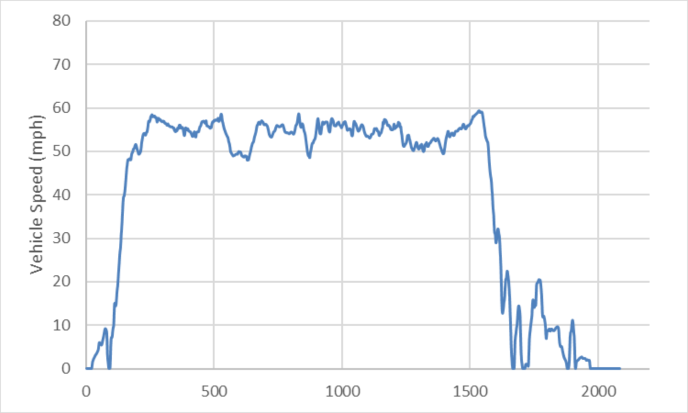
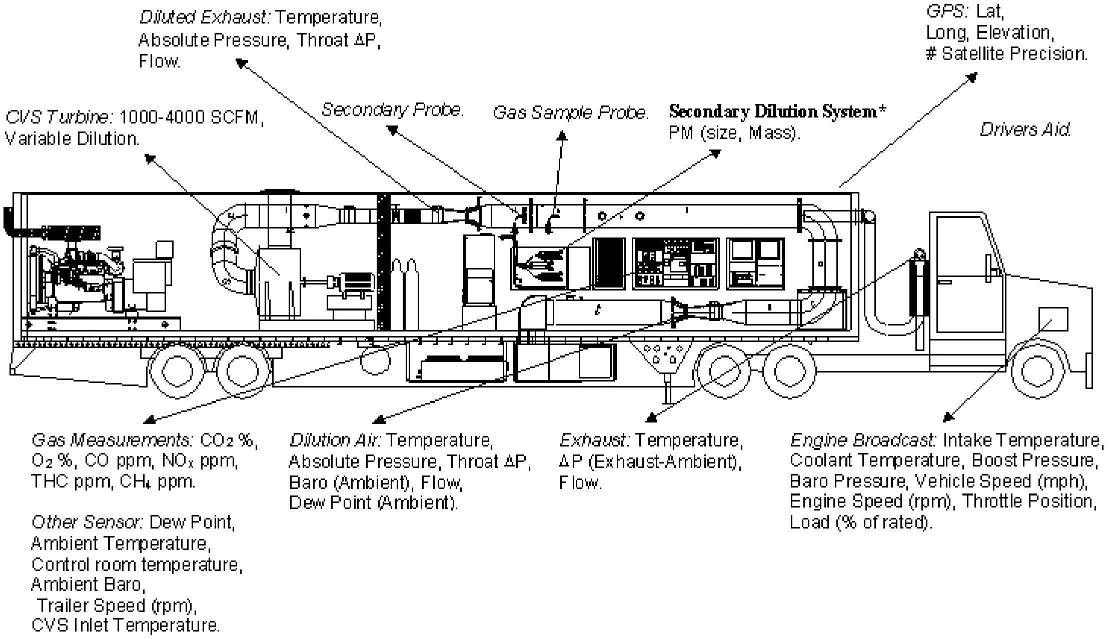


Figure B-6 Speed/Time Trace for a HHDDT_CRUISE cycle (performed as 1x) 2083 sec

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.



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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

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

Appendix D. Heavy-Duty Chassis Dynamometer Laboratory

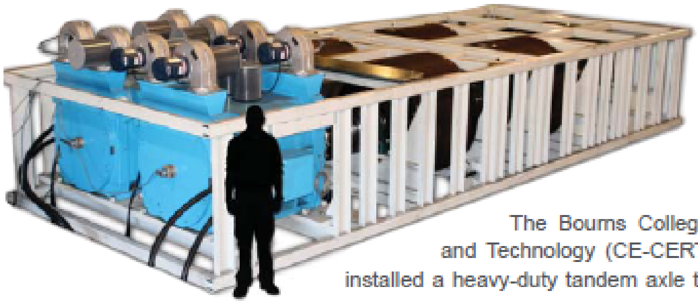
UCR’s chassis dynamometer is an electric AC type design that can simulate inertia loads from 10,000 lb to 80,000 lb which covers a broad range of in-use medium and heavy duty vehicles, see Figure D-1. The design incorporates 48” rolls, axial loading to prevent tire slippage, 45,000 lb base inertial plus 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 Publication “Project Spotlights” March 2010

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.

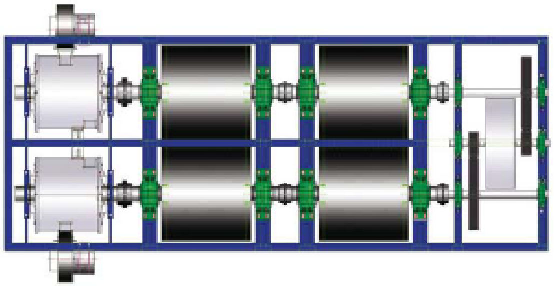
The new dynamometer will simulate on-road driving conditions for any big rig using its 48” precision rollers with dual, direct connected, 300 horsepower motors attached to each roll set. The dynamometer applies the appropriate loading to a vehicle to simulate factors such as the friction of the roadway 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 additional results not presented in the main report. Table E-1 and E-2 are the average and standard deviation tables for the brake specific emissions for the primary measurements. Table E-3 and E-4 are the emission rates on a g/mi basis. Table E-5 and E-6 are the particle number emissions in concentration and #/mi. The last two figures in this Appendix are the fuel samples for the 1st and 2nd fuel test. The QCL was operated every day with some startup issues on 1/30/2019 which were fixed and then selected tests repeated and then issues on 2/5/2018 (during the creep and transient test cycles). Unfortunately the 2/5/2018 issues were not realized until the data was analyzed. The results were not representative of the exhaust and thus the data were removed from the report. The creep loads and conditions matches the Near Dock cycle and the Transient conditions match the Local cycle. The N20 emissions were utilized from these cycles for the GHG analysis to estimate impacts from N20 emissions where necessary. Additionally NH3 emissions were based on UCR's TDL measurement with the QCL as a backup measurement. The QCL NOx measurements matched the CLD measurements and the report is based on the CLD measurements.

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

Trace	Duration	Power	Work	Distance	Temp	Dilute Mass Emissions (g/bhp-hr)								Raw Mass Emissions (g/bhp-hr)					
n/a	sec	bhp	bhp-hr	mi	C	THC	CH4	NMHC	CO	kNOx	PM2.5	eBC	CO2	TDL_NH3	CLD_NOx	QCL_NOx	QCL_NO2	QCL_N2O	QCL_NH3
CS UDDS	1081	98.97	29.72	5.67	15.48	0.464	0.434	0.030	1.93	0.124	0.0036	0.0004	541	0.051	0.1302	0.157	0.000	0.019	0.183
UDDS	2122	93.40	55.06	11.35	18.80	0.202	0.180	0.022	1.28	0.012	0.0018	0.0007	534	0.112	0.0112	0.013	0.000	0.000	0.123
Near Dock	3049	43.14	36.54	5.81	20.28	0.140	0.181	-0.041	0.74	0.015	0.0015	0.0009	608	0.131	0.0093	0.013	0.002	0.000	0.173
Local	3365	52.90	49.45	8.94	27.82	0.103	0.137	-0.035	0.74	0.015	0.0015	0.0008	611	0.211	0.0064	0.016	0.005	0.000	0.141
Regional	4230	82.24	96.63	27.64	24.89	0.415	0.408	0.007	0.76	0.017	0.0011	0.0007	555	0.146	0.0124	0.016	0.000	0.000	0.122
HHDDT Creep	759	34.69	7.31	0.40	15.83	0.364	0.369	-0.005	0.83	-0.004	0.0040	0.0024	612	0.149	0.0012	-	-	-	0.149
HHDDT Trans	2004	85.43	47.55	8.91	24.95	0.021	0.018	-0.019	0.23	0.028	0.0013	0.0005	549	0.038	0.0205	-	-	-	0.038
HHDDT Cruise	2083	107.22	62.04	23.24	29.21	0.343	0.349	-0.007	0.81	0.010	0.0012	0.0008	534	0.062	0.0081	0.011	0.000	0.000	0.084

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

Trace	Duration	Power	Work	Distance	Temp	Dilute Mass Emissions (g/bhp-hr)								Raw Mass Emissions (g/bhp-hr)					
n/a	sec	bhp	bhp-hr	mi	C	THC	CH4	NMHC	CO	kNOx	PM2.5	eBC	CO2	TDL_NH3	CLD_NOx	QCL_NOx	QCL_NO2	QCL_N2O	QCL_NH3
CS UDDS	0	3.10	0.93	0.02	8.31	0.025	0.026	0.012	0.42	0.022	0.002	0.0001	24.0	0.052	0.0220	0.054	0.000	0.007	0.051
UDDS	0	3.37	1.99	0.05	7.21	0.102	0.066	0.040	0.28	0.002	0.001	0.0002	10.9	0.045	0.0044	0.005	0.000	0.000	0.022
Near Dock	0	1.40	1.18	0.05	4.19	0.060	0.048	0.013	0.07	0.001	0.000	0.0001	26.5	0.077	0.0063	0.009	0.001	0.000	0.007
Local	0	1.13	1.06	0.13	1.32	0.042	0.035	0.008	0.06	0.011	0.000	0.0001	17.4	0.088	0.0030	0.013	0.006	0.000	0.003
Regional	0	1.22	1.44	0.12	5.39	0.018	0.037	0.019	0.23	0.006	0.000	0.0001	21.6	0.082	0.0018	0.009	0.000	0.000	0.014
HHDDT Creep	0	0.64	0.13	0.01	3.03	0.269	0.239	0.030	0.18	0.004	0.002	0.0015	10.5	0.023	0.0006	-	-	-	0.023
HHDDT Trans	0	1.69	0.94	0.34	1.66	0.009	0.009	0.001	0.08	0.005	0.000	0.0000	6.8	0.025	0.0030	-	-	-	0.025
HHDDT Cruise	0	3.34	1.93	0.07	0.86	0.084	0.079	0.007	0.14	0.000	0.000	0.0001	11.7	0.070	0.0044	0.006	0.000	0.000	0.016

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

Trace	Duration	Power	Work	Distance	Dilute Mass Emissions (g/mi)								Raw Mass Emissions (g/mi)					
n/a	sec	bhp	bhp-hr	mi	THC	CH4	NMHC	CO	kNOx	PM2.5	eBC	CO2	TDL_NH3	CLD_NOx	QCL_NOx	QCL_NO2	QCL_N2O	QCL_NH3
CS UDDS	1081	98.97	29.72	5.67	2.428	2.271	0.158	10.11	0.650	0.0193	0.0023	2830	0.273	0.681	0.829	0.000	0.102	0.973
UDDS	2122	93.40	55.06	11.35	0.992	0.881	0.112	6.23	0.060	0.0086	0.0035	2590	0.541	0.054	0.065	0.001	0.000	0.585
Near Dock	3049	43.14	36.54	5.81	0.884	1.140	-0.259	4.63	0.095	0.0096	0.0057	3824	0.836	0.058	0.083	0.014	0.001	1.090
Local	3365	52.90	49.45	8.94	0.572	0.762	-0.193	4.11	0.086	0.0085	0.0045	3382	1.177	0.035	0.091	0.030	0.001	0.779
Regional	4230	82.24	96.63	27.64	1.451	1.428	0.024	2.66	0.061	0.0039	0.0024	1941	0.509	0.043	0.055	0.000	0.002	0.427
HHDDT Creep	759	34.69	7.31	0.40	6.644	6.751	-0.108	15.33	-0.074	0.0743	0.0436	11306	2.739	0.023	-	-	-	2.739
HHDDT Trans	2004	85.43	47.55	8.91	0.112	0.095	-0.101	1.22	0.149	0.0069	0.0029	2929	0.204	0.109	-	-	-	0.204
HHDDT Cruise	2083	107.22	62.04	23.24	0.920	0.937	-0.017	2.15	0.027	0.0032	0.0021	1426	0.170	0.022	0.030	0.000	0.001	0.224

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

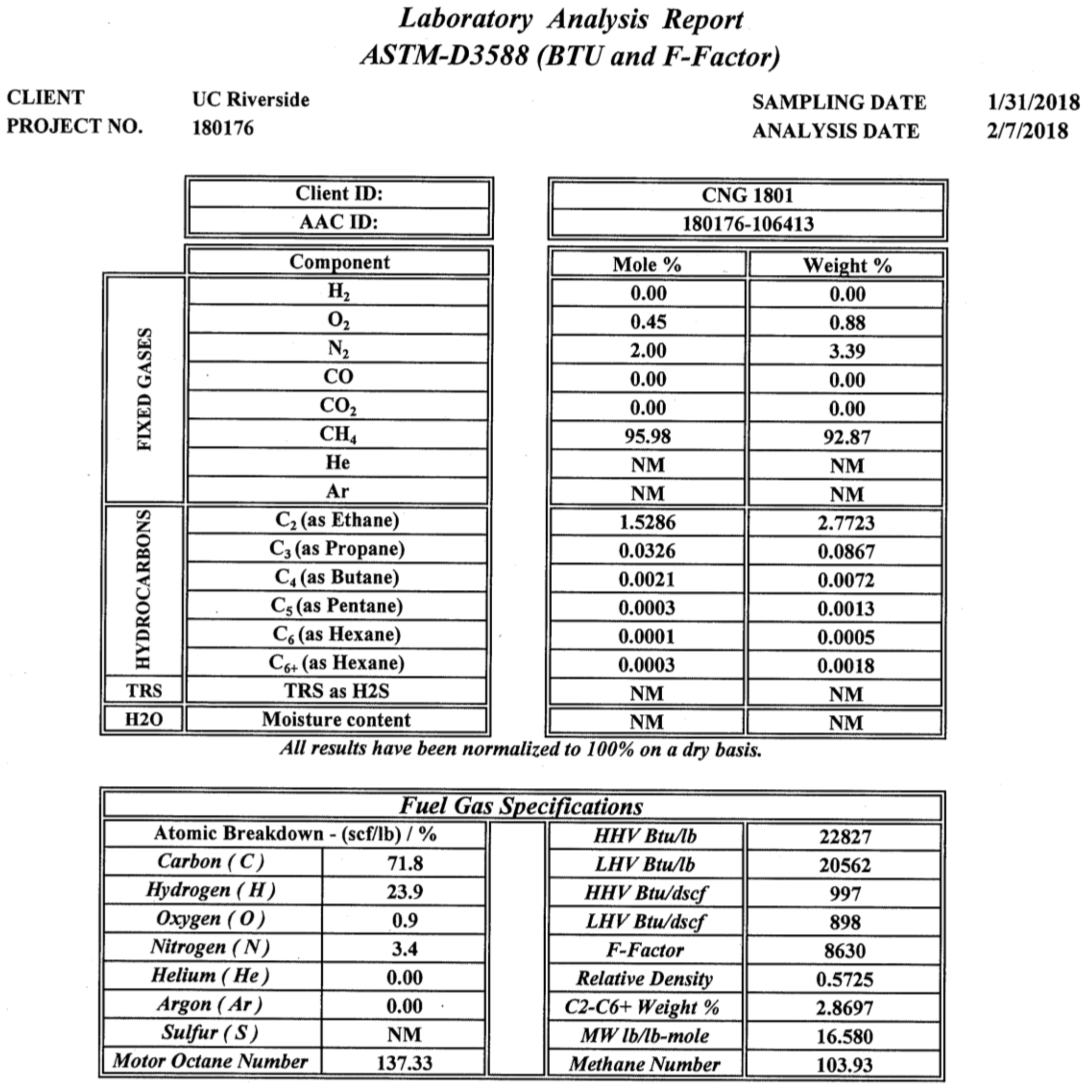
Trace	Duration	Power	Work	Distance	Dilute Mass Emissions (g/mi)								Raw Mass Emissions (g/mi)					
n/a	sec	bhp	bhp-hr	mi	THC	CH4	NMHC	CO	kNOx	PM2.5	eBC	CO2	TDL_NH3	CLD_NOx	QCL_NOx	QCL_NO2	QCL_N2O	QCL_NH3
CS UDDS	0	3.10	0.93	0.02	0.072	0.072	0.067	2.11	0.104	0.0085	0.0005	48.1	0.284	0.107	0.271	0.001	0.035	0.293
UDDS	0	3.37	1.99	0.05	0.517	0.349	0.195	1.53	0.008	0.0049	0.0010	118.8	0.199	0.021	0.023	0.001	0.000	0.120
Near Dock	0	1.40	1.18	0.05	0.398	0.324	0.077	0.53	0.005	0.0016	0.0007	147.4	0.506	0.038	0.057	0.007	0.001	0.073
Local	0	1.13	1.06	0.13	0.251	0.214	0.038	0.45	0.065	0.0009	0.0004	122.4	0.514	0.017	0.075	0.036	0.001	0.015
Regional	0	1.22	1.44	0.12	0.087	0.150	0.064	0.81	0.022	0.0008	0.0003	41.6	0.282	0.006	0.030	0.000	0.000	0.054
HHDDT Creep	0	0.64	0.13	0.01	4.711	4.178	0.540	2.74	0.077	0.0392	0.0274	220.8	0.346	0.011	-	-	-	0.346
HHDDT Trans	0	1.69	0.94	0.34	0.051	0.049	0.008	0.43	0.025	0.0011	0.0002	77.5	0.131	0.018	-	-	-	0.131
HHDDT Cruise	0	3.34	1.93	0.07	0.254	0.241	0.018	0.38	0.002	0.0004	0.0004	14.3	0.196	0.013	0.018	0.000	0.001	0.050

Table E-3 Average emissions particle number results and others (#/mi, #/cc and concentration)

Trace	Power	Distance	Vmix	#/cc			#/mi				NH3_ppm	
n/a	bhp	mi	m3	CPC	CPC_CS	EEPS	Total_PN	Solid_PN	EEPS	% Solid	TDL	QCL
CS_UDDS	99.0	5.67	1519.0	111717	49262	78577	3.0E+13	1.3E+13	1.1E+13	44%	16.08	40.95
UDDS	93.4	11.35	2981.5	43119	31799	29310	1.1E+13	8.0E+12		72%	41.92	41.09
DPT1	43.1	5.81	4285.5	39206	27668	27054	2.9E+13	2.0E+13	1.3E+13	71%	40.07	54.80
DPT2	52.9	8.94	4730.6	36499	20154	33268	1.9E+13	1.1E+13	7.9E+12	55%	62.01	43.39
DPT3	82.2	27.64	5943.6	40502	20585	26985	8.7E+12	4.4E+12	3.9E+12	52%	47.62	42.44
HHDDT_Creep	34.7	0.40	1066.1	81629	25421	46625	2.2E+14	6.8E+13	1.3E+14	31%	45.69	45.69
HHDDT_Trans	85.4	8.91	2814.4	57794	25512	38421	1.8E+13	8.1E+12	1.2E+13	44%	10.15	20.15
HHDDT_Cruise	107.2	23.24	2927.8	60022	22074	41724	7.6E+12	2.8E+12	5.3E+12	37%	21.54	23.58

Table E-4 Standard deviation for particle number results and others (#/mi, #/cc and concentration)

Trace	Power	Distance	Vmix	#/cc			#/mi				NH3_ppm	
n/a	bhp	mi	m3	CPC	CPC_CS	EEPS	Total_PN	Solid_PN	EEPS	% Solid	TDL	QCL
CS_UDDS	3.1	0.02	0.6	29525	14821	29525	7.8E+12	3.9E+12	1.5E+13	2%	15.85	6.09
UDDS	3.4	0.05	1.3	10101	2851	10101	2.7E+12	4.8E+11		13%	16.22	6.01
DPT1	1.4	0.05	2.0	5467	4401	2703	4.2E+12	3.3E+12	1.2E+13	7%	27.27	2.03
DPT2	1.1	0.13	0.9	2840	989	5260	1.3E+12	6.6E+11	1.1E+13	7%	28.48	3.26
DPT3	1.2	0.12	2.4	9089	2671	897	1.9E+12	5.6E+11	3.4E+12	5%	20.49	3.18
HHDDT_Creep	0.6	0.01	0.1	14052	8994	11189	3.4E+13	2.3E+13	3.1E+13	6%	6.30	3.15
HHDDT_Trans	1.7	0.34	0.4	3749	2339	1857	1.6E+12	1.1E+12	5.3E+11	5%	11.73	5.33
HHDDT_Cruise	3.3	0.07	0.3	7900	3077	2500	1.0E+12	4.0E+11	3.2E+11	2%	26.14	5.07



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

CLIENT	**UC Riverside**	**SAMPLING DATE**	**1/31/2018**
PROJECT NO.	**180176**	**ANALYSIS DATE**	**2/7/2018**

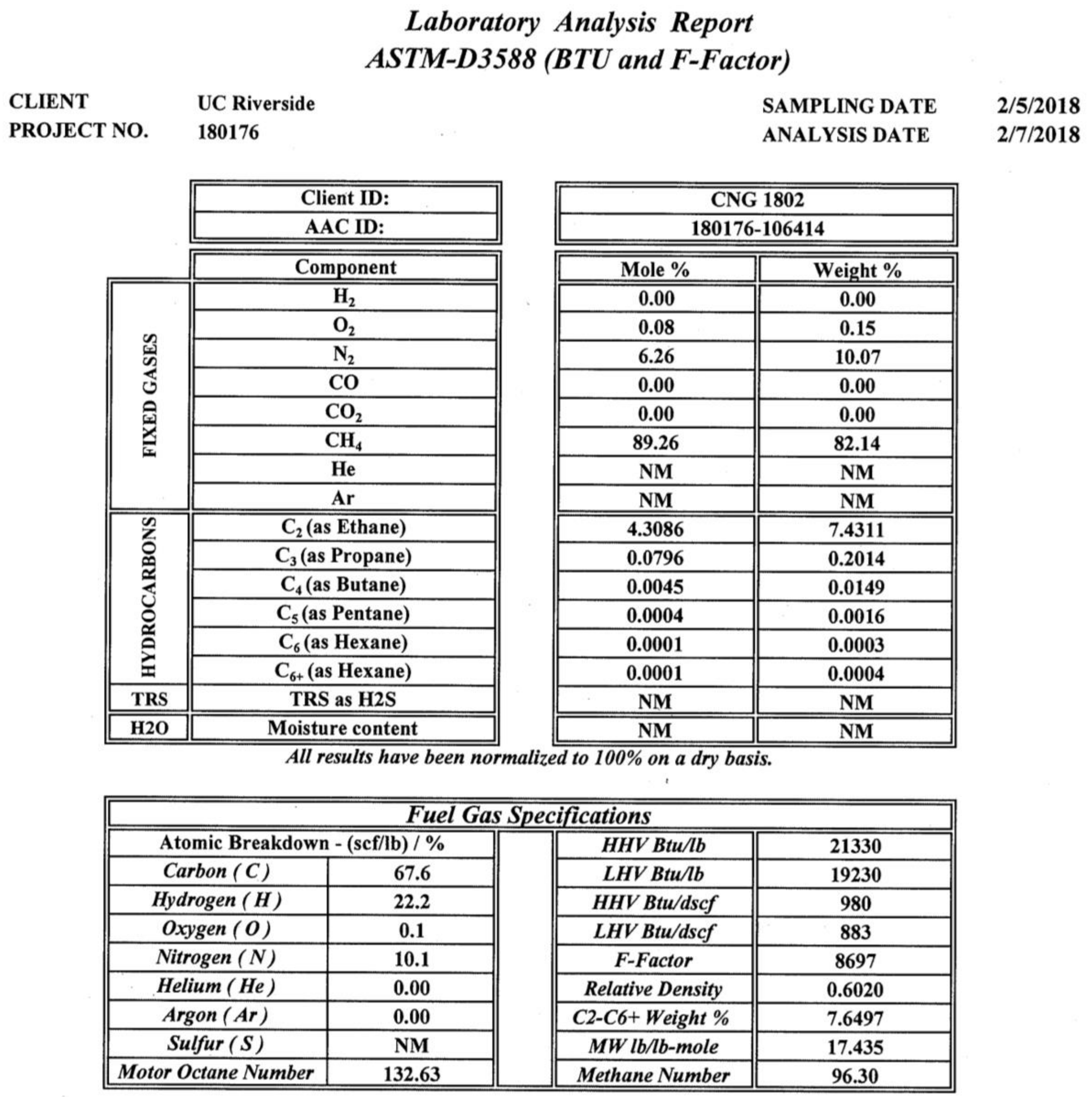
	Client ID:	**CNG 1801**	
	AAC ID:	**180176-106413**	
	Component	**Mole %**	**Weight %**
FIXED GASES	H_2	0.00	0.00
	O_2	0.45	0.88
	N_2	2.00	3.39
	CO	0.00	0.00
	CO_2	0.00	0.00
	CH_4	95.98	92.87
	He	NM	NM
	Ar	NM	NM
HYDROCARBONS	C_2 (as Ethane)	1.5286	2.7723
	C_3 (as Propane)	0.0326	0.0867
	C_4 (as Butane)	0.0021	0.0072
	C_5 (as Pentane)	0.0003	0.0013
	C_6 (as Hexane)	0.0001	0.0005
	C_{6+} (as Hexane)	0.0003	0.0018
TRS	TRS as H2S	NM	NM
H2O	Moisture content	NM	NM

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

Fuel Gas Specifications

Atomic Breakdown - (scf/lb) / %			
Carbon (C)	71.8	*HHV Btu/lb*	22827
Hydrogen (H)	23.9	*LHV Btu/lb*	20562
Oxygen (O)	0.9	*HHV Btu/dscf*	997
Nitrogen (N)	3.4	*LHV Btu/dscf*	898
Helium (He)	0.00	*F-Factor*	8630
Argon (Ar)	0.00	*Relative Density*	0.5725
Sulfur (S)	NM	*C2-C6+ Weight %*	2.8697
Motor Octane Number	137.33	*MW lb/lb-mole*	16.580
		Methane Number	103.93

Fuel Sample #1



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

CLIENT	**UC Riverside**	**SAMPLING DATE**	**2/5/2018**
PROJECT NO.	**180176**	**ANALYSIS DATE**	**2/7/2018**

	Client ID:	**CNG 1802**	
	AAC ID:	**180176-106414**	
	Component	**Mole %**	**Weight %**
FIXED GASES	H_2	0.00	0.00
	O_2	0.08	0.15
	N_2	6.26	10.07
	CO	0.00	0.00
	CO_2	0.00	0.00
	CH_4	89.26	82.14
	He	NM	NM
	Ar	NM	NM
HYDROCARBONS	C_2 (as Ethane)	4.3086	7.4311
	C_3 (as Propane)	0.0796	0.2014
	C_4 (as Butane)	0.0045	0.0149
	C_5 (as Pentane)	0.0004	0.0016
	C_6 (as Hexane)	0.0001	0.0003
	C_{6+} (as Hexane)	0.0001	0.0004
TRS	TRS as H2S	NM	NM
H2O	Moisture content	NM	NM

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

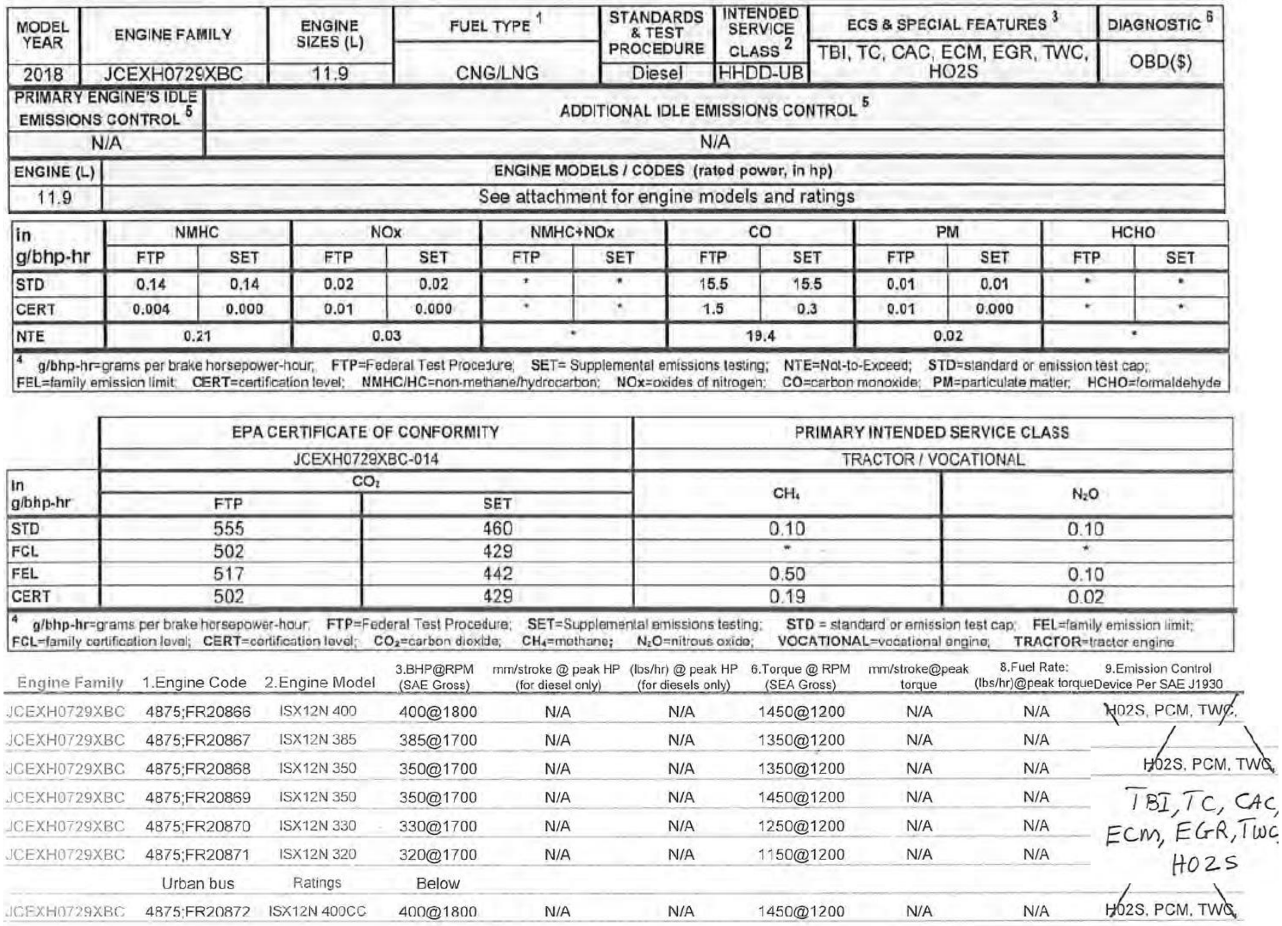
Fuel Gas Specifications

Atomic Breakdown - (scf/lb) / %			
Carbon (C)	67.6	*HHV Btu/lb*	21330
Hydrogen (H)	22.2	*LHV Btu/lb*	19230
Oxygen (O)	0.1	*HHV Btu/dscf*	980
Nitrogen (N)	10.1	*LHV Btu/dscf*	883
Helium (He)	0.00	*F-Factor*	8697
Argon (Ar)	0.00	*Relative Density*	0.6020
Sulfur (S)	NM	*C2-C6+ Weight %*	7.6497
Motor Octane Number	132.63	*MW lb/lb-mole*	17.435
		Methane Number	96.30

Fuel Sample #2

Appendix F. Engine certification family, details, and ratings

This appendix includes the engine executive order Figure F-1 as listed on the ARB website for the family number tested JCEXH0729XBC with engine rating ISX 12N 400. • For model year 2018, the 8.9 liter engine is called the "L9N". Prior to 2018, the engine name was "ISL G" for the 0.2g NOx version and "ISL G Near Zero" for the 0.02g NOx version



MODEL YEAR	ENGINE FAMILY	ENGINE SIZES (L)	FUEL TYPE [1]	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS [2]	ECS & SPECIAL FEATURES [3]	DIAGNOSTIC [6]
2018	JCEXH0729XBC	11.9	CNG/LNG	Diesel	HHDD-UB	TBI, TC, CAC, ECM, EGR, TWC, HO2S	OBD($)

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

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

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	0.004	0.000	0.01	0.000	*	*	1.5	0.3	0.01	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

	EPA CERTIFICATE OF CONFORMITY		PRIMARY INTENDED SERVICE CLASS	
	JCEXH0729XBC-014		TRACTOR / VOCATIONAL	
in g/bhp-hr	CO_2		CH_4	N_2O
	FTP	SET		
STD	555	460	0.10	0.10
FCL	502	429	*	*
FEL	517	442	0.50	0.10
CERT	502	429	0.19	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

Engine Family	1.Engine Code	2.Engine Model	3.BHP@RPM (SAE Gross)	mm/stroke @ peak HP (for diesel only)	(lbs/hr) @ peak HP (for diesels only)	6.Torque @ RPM (SEA Gross)	mm/stroke@peak torque	8.Fuel Rate: (lbs/hr)@peak torque	9.Emission Control Device Per SAE J1930
JCEXH0729XBC	4875;FR20866	ISX12N 400	400@1800	N/A	N/A	1450@1200	N/A	N/A	H02S, PCM, TWC,
JCEXH0729XBC	4875;FR20867	ISX12N 385	385@1700	N/A	N/A	1350@1200	N/A	N/A	
JCEXH0729XBC	4875;FR20868	ISX12N 350	350@1700	N/A	N/A	1350@1200	N/A	N/A	H02S, PCM, TWC,
JCEXH0729XBC	4875;FR20869	ISX12N 350	350@1700	N/A	N/A	1450@1200	N/A	N/A	TBI, TC, CAC, ECM, EGR, TWC HO2S
JCEXH0729XBC	4875;FR20870	ISX12N 330	330@1700	N/A	N/A	1250@1200	N/A	N/A	
JCEXH0729XBC	4875;FR20871	ISX12N 320	320@1700	N/A	N/A	1150@1200	N/A	N/A	
	Urban bus	Ratings	Below						
JCEXH0729XBC	4875;FR20872	ISX12N 400CC	400@1800	N/A	N/A	1450@1200	N/A	N/A	H02S, PCM, TWC,

Figure F-1 Engine certification order for the ISX 12N NG engine (ARB source)

Engine No. 75053847
Model ALPHA X12N
Advertised HP 400 at 1800 RPM
Conf. No. D0L3002BX03
Date of mfg. 08/16
Manufactured by Cummins Engine Company, Inc., U.S.A.
S.O. No. 05923
Ref. No. CAN_AL_KW_TS680
Engine Cert Ident C.I.D. 729/11.9
CPL 4875
Exempt No. 25001
Injection timing code NA
Injector torque Inch-Lbs.
Eff. Date 08-08-16
Exp. Date
Valve lash cold(mm) Int. .018/.457 Exh. .036/.914

Figure F-2 Test engine label

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 coefficients

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[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

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

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

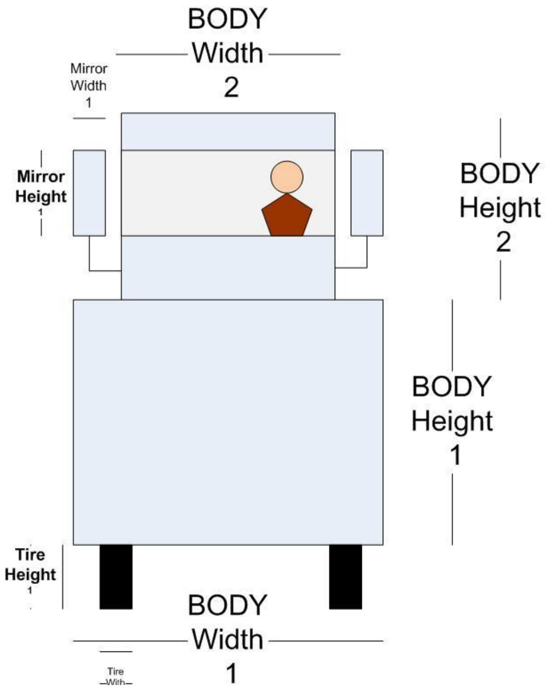

Figure G-1 Vehicle frontal area dimensions method

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

		Desired				
Data Point	Avg Speed MPH	Calc Time sec	Decel MPH/Sec	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

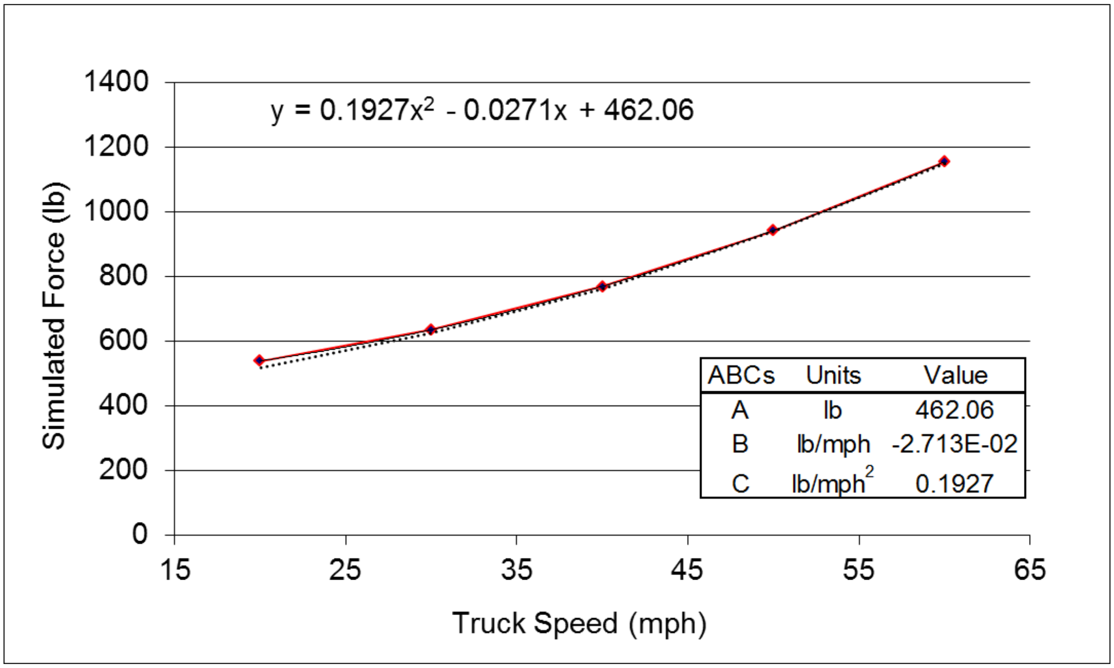

Figure G-2 Resulting ABCs based on Table G-2 results