CALIFORNIA ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Developing, Demonstrating and Testing Advanced Ultra-Low-Emission Natural Gas Engines in Port Yard Trucks

Appendices A-E

Gavin Newsom, Governor

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ABSTRACT

This project demonstrated two pre-commercial liquefied natural gas (LNG)-powered Capacity TJ9000 yard tractors with low-NOx 6.7-liter natural gas engines (B6.7N) from Cummins Westport Inc. (CWI) at Everport Terminals (Port of Los Angeles). In parallel, the University of California, Riverside (UCR) conducted chassis dynamometer emissions testing on both types of LNG yard tractors and a baseline diesel tractor. UCR performed multiple emissions tests on the B6.7N unit with gas blends of variable composition to evaluate the potential benefits of the gas composition sensor.

As described in these Appendices, both types of LNG yard tractors emitted lower emissions of nitrogen oxides (NOx) than the baseline diesel tractor. The emissions for the LNG YTs were comparable to the emissions that they were certified to or less for most of the cycles. For NOx, PM, total particle number, or solid particle number emissions, the test fuels did not show consistent trends over the different cycles, while CO and NH_3 emissions showed higher emissions for lower methane index fuels.

Keywords: Liquefied natural gas; near-zero-emission, CWI ISB6.7 G; yard tractors; development and demonstration; gas composition sensor; chassis dynamometer emission testing; marine terminal operator; cargo-handling equipment.

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EXECUTIVE SUMMARY

The lack of consistent fuel quality in remote locations and other areas of the United States remains an issue in terms of expanding the marketplace and lowering the capital costs for natural gas (NG) engines. Even in California, where fuel quality is more stringently controlled, there is the potential for increasing on-site production of renewable natural gas (RNG) for heavy-duty vehicles (HDVs) that are domiciled nearby, or off-road vehicles such as yard tractors (YT).

To understand the impact of variable-quality natural gas (whether fossil or RNG) on the latest-technology near-zero emission (NZE) natural gas engines, the University of California, Riverside (UCR) designed and led two tasks for this project. The first task included a bench-top laboratory analysis of a fuel quality sensor partially developed as part of this project. The second task included an evaluation of a YT equipped with an NZE engine certified to an optional low NOx standard (OLNS) on a low methane index fuel to determine how susceptible the engine was to engine knock under representative in-use conditions. The second task also included the evaluation of various natural gas blends on the OLNS/NZE demonstration YT as well as comparison to other YTs operating at the port. This report describes the emissions, fuel blend, and knock sensitivity testing results of this effort. This includes a comparison between different YTs operating at the Everport Terminal at the Port of Los Angeles (POLA), which included a OLNS 6.7L LNG YT, a NZE 8.9L LNG YT and a diesel YT, as shown in Table ES-1, and a comparison of the emissions impacts for different NG blends (In Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI, as shown in Table ES-2) on the OLNS-certified 6.7L LNG YT.

Table ES-1: Summary of Vehicles to be Tested at UCR Chassis Dynamometer

ID	Engine Mfg	Chassis Mfg	Fuel	Model	Year	Disp.	Engine Hours	Cert Level (NOx)	Cert Level (PM)
6.7L NG	CWI [1]	Capacity	Varies	B6.7N 240	2019	6.7	969	0.1	0.01
L9N	CWI	Capacity	As-Received LNG from Clean Energy	L9N 250	2018	8.9	315.2	0.02	0.01
6.7L Diesel	CWI	Capacity	As-Received Diesel from Everport	QSB6.7 225	2014	6.7	1976	0.2	0.01

[1] The B6.7 N 240 is the demonstration engine installed in a YT chassis and also the engine utilized for the demonstration of the MI sensor. CWI = Cummins Westport Inc.

Source: University of California, Riverside

The OLNS YT was also recalibrated to a NZE-certification level of 0.02 NOx g/bhp-hr to evaluate the effectiveness of the NZE calibration in this application, and to evaluate if the engine would be susceptible to engine when operated on an extreme low MI fuel on the NZE calibration. Testing was conducted over several different cycles designed from data collected on YT operating at the port, as shown in Table ES-3. This included a lightly loaded yard tractor cycle in both a cold start (YT_26K_CS) and hot start condition (YT_26K_2x), a heavily loaded yard tractor cycle in both a cold start (YT_72K_CS) and hot start condition (YT_72K_2x), a Central Business District (CBD) bus cycle, and an 8-mode steady state cycle.

Table ES-2: Natural Gas Fuel Blends Simulating Pipeline and Renewable Natural Gas Fuels (vol percent)

Fuel	MI	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	O_2	CO_2
In Tank - LNG Pipeline	83.2	93.0	6.72	0.03	-	0.17	<0.1	<0.1
RNG 1	92.6	93.6	-	-	-	3.7	0.5	2.2
RNG 2	101.2	91	-	-	-	1.9	-	7
Extreme Pipeline	70.7	77	12	5	1	-	-	5
Extreme MI (ExMI)	67.5	89.5	-	10.5	-	-	-	-

MI = Methane Index as determined from https://www.cumminswestport.com/fuel-quality-calculator

Source: University of California, Riverside

Table ES-3: Summary of Statistics for Various Proposed Driving Cycles

Day	Test Weight (lb.)	Distance (mi)	Average Speed (mph)	Duration (sec)
YT_72K_CS	72,000	2.37	7.12	1200
YT_72K_2x	72,000	2.37 x 2	7.12	2400
YT_26K_CS	26,000	1.76	5.27	1200
YT_26K_2x	26,000	1.76 x 2	5.27	2400
CBD_3x	35,000	6.0	12.6	1680
SS_Modes	72,000	8.7	18.5	1695

[1] Hot yard tractor (YT) cycles were performed as a double cycle (2x) and a single (1x) for the cold tests. The YT_72K cycles were performed at 69,000 lbs. for the 6.7L LNG YT. The YT_26K_CS test was not performed on the 6.7L LNG YT. The SS-Modes test was not conducted on the 8.9L LNG YT, and the SS_Mode was only run at the 22-mph speed for the 6.7L LNG YT on the Extreme MI fuel. The CBD was performed as a triple (3x) test, see Appendix A for details.

Source: University of California, Riverside

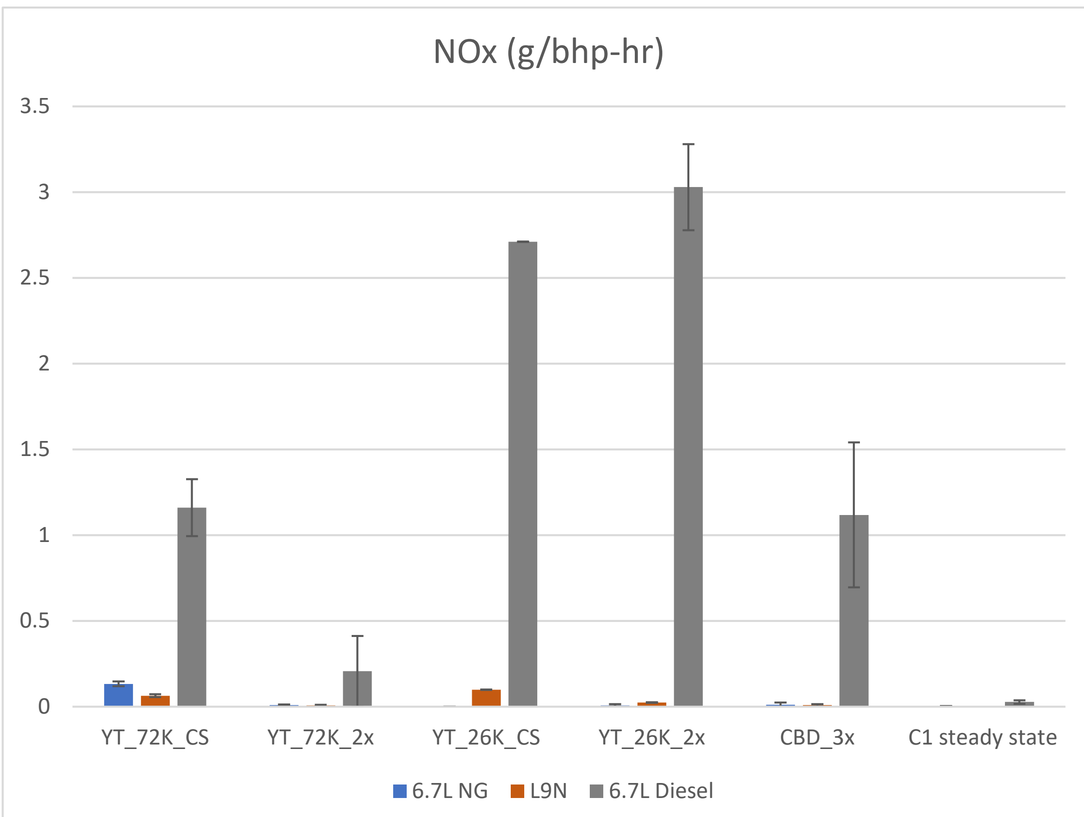
This testing provided a better understanding of the potential impacts of variable-quality NG, the response time for a current technology NG engine to adapt and learn to operate on different qualities of NG, and the basis for the continuing development of sensors and control systems for commercial NG engines. By better quantifying these potential impacts and how the NG engines might adapt to variable-quality NG, future NG engines can be developed to accept wider ranges of LNG/NG properties. These engines could be deployed in many markets throughout the country where pipeline NG has higher levels of ethane, and MIs near 75, or applications in more remote areas where less processed NG or NG from the production site itself might be used in engines.

A summary of the results of this study follows.

Comparison Between Natural Gas and Diesel

NOx emissions for the 6.7L and 8.9L LNG YTs were considerably lower than those for the diesel YT, as shown in Figure ES-1. The emissions for the LNG YTs were comparable to the emissions that they were certified to or less for most of the cycles, i.e., 0.1 g/bhp-hr and 0.02 g/bhp-hr, respective for the 6.7L and 8.9L LNG YTs, except some of the cold start cycles. NOx emissions for the LNG YTs were predominantly produced during the very initial portions of the cycles, with very limited emissions emitted throughout most of the rest of the cycles.

Figure ES-1: Average NO_x Emissions for 6.7L LNG, 8.9L LNG and Diesel Yard Tractors in g/bhp-hr units

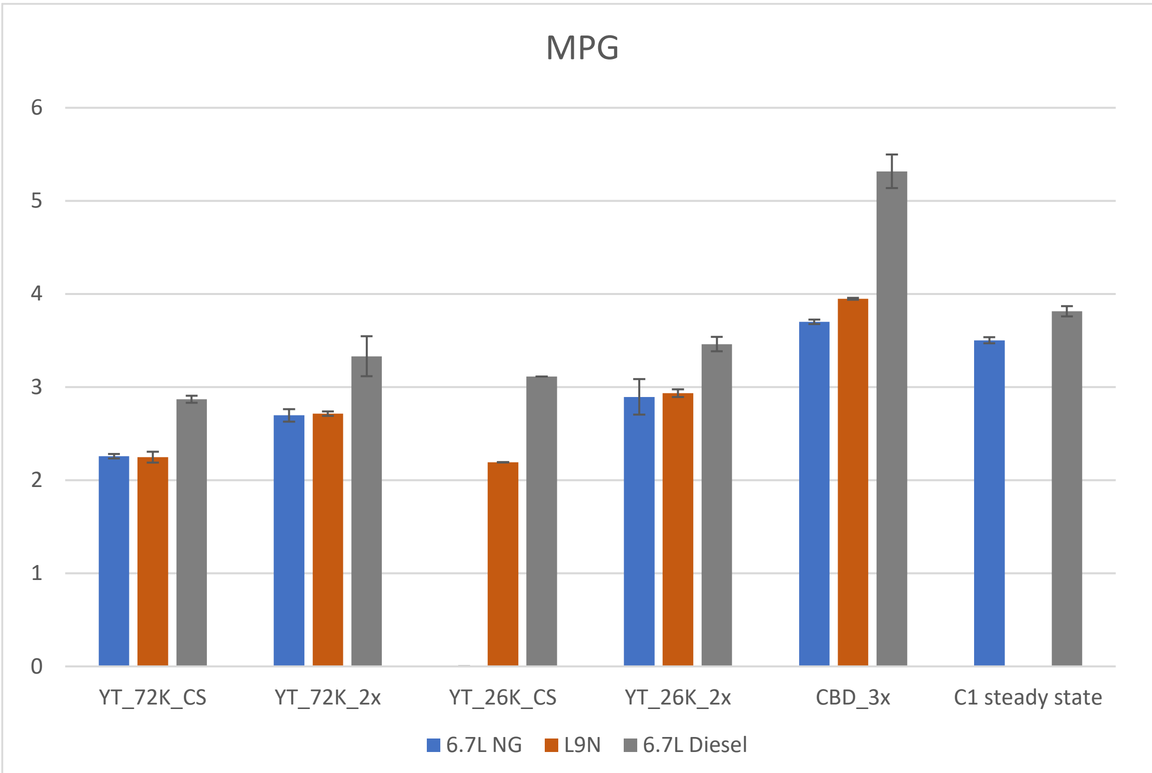


Source: University of California, Riverside

The LNG YTs showed lower fuel economies than the diesel YT for all the cycles, as shown in Figure ES-2, which is consistent with the generally higher efficiencies for diesel engines as compared to stoichiometric natural gas engines. Fuel economy did not show significant differences between the 6.7L and 8.9L LNG YTs, on the other hand. CO_2 emissions were more comparable between the LNG and diesel YTs because the greater efficiency of the diesel engine is somewhat offset by the higher carbon intensity of diesel fuel compared to NG, and did not show significant differences between the 6.7L and 8.9L LNG YTs.

THC, CO and NH_3 emissions were all higher for the 6.7L and 8.9L LNG YTs compared to the diesel YT. The higher THC emissions for the LNG YTs can be attributed to the fact that LNG is primarily composed of methane. The higher CO emissions for the LNG YTs can be attributed to the LNG engine running stoichiometrically, which is richer than the lean conditions that the diesel engine operate under. The higher NH_3 emissions for the LNG YTs can be attributed to the chemical reactions on the three-way catalyst (TWC), which has been seen in other studies.

Figure ES-2: Average Fuel Economy Rates for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors in mi/gal units



Source: University of California, Riverside

Particulate mass (PM), total particle number, and solid particle number emissions were the lowest for the 8.9L LNG YT. The diesel and 6.7L LNG YTs showed considerably higher emissions than the 8.9L LNG YT for PM, total particle number, and solid particle number emissions, with the diesel YT generally showing slightly higher emissions than the 6.7L LNG YT. The PM emissions for the 8.9L LNG YT were from 0.9 to 1.4 on a mg/bhp-hr basis, which is about 10 times lower than the emissions standard, but comparable to what has been seen in other studies with low PM emitting NG and DPF-diesel vehicles. The 6.7L LNG and diesel YT showed higher emissions, but these were also comparable to or below the 10 mg/bhp-hr certification level for all the non-cold start tests.

Comparisons Between Different Liquefied Natural Gas Fuel Blends

The emissions testing results showed differences between fuels for some pollutants, but not for others. For NOx, PM, total particle number, or solid particle number emissions, the test fuels did not show consistent trends over the different cycles. Fuel differences were seen for CO and NH_3 emissions, with the lower MI in Extreme Pipeline, Extreme MI, and In Tank fuels showing higher emissions compared to the higher MI RNG blends. This suggests that the engine is running slightly richer for the lower MI fuels. There was also a trend of higher THC emissions for the In Tank and Extreme Pipeline fuels for the YT_26K_2x cycle, but there were no consistent THC emissions for the different fuels over the other cycles. In comparing fuels, the Extreme Pipeline fuel showed higher CO_2 emissions than the other fuels for all cycles, whereas the other fuels showed similar CO_2 emissions for all cycles. The higher CO_2 emissions for the Extreme Pipeline fuel can be attributed to the higher carbon weight fraction of this fuel due to the lower fractions of methane compared to higher hydrocarbons.

Methane Index Sensor Benefit

The tests used to evaluate the benefit of a sensor did not show significant emissions differences between fuels without expected engine knock and with expected engine knock. Additionally, there were no recorded signs of engine knock for the 6.7L engine tested, despite the use of out-of-specification low MI fuels. These results suggest a MI sensor may not provide an immediate benefit in terms of emissions in this YT application. There was some indication, however, of the potential for richer operation for the lower MI fuels. Additionally, it is possible that other engines, such as the 8.9L and 12L natural gas engines with tighter calibrations and less knock margin, could be more susceptible to engine knock.

Reflashed from 0.1 to 0.02

The 6.7L demonstration vehicle certified to 0.1 was reflashed from 0.1 to 0.02 g/hp-hr NOx after the emissions testing was completed. A subset of emissions tests was run to compare the 0.1 and 0.02 certified calibrations, but no significant changes in emissions were found with the YT application, suggesting that the results of the 6.7L are representative of a NZE vehicle.

Overall Conclusions and Implications

The results showed potential for LNG YTs to provide important reductions in NOx in port operations compared to diesel YTs, with almost no NOx emissions emitted after the YT after the first 50-seconds of operation from engine start. The LNG YTs showed slightly lower CO_2 emissions and the potential for lower PM and particle number emissions compared to the diesel YT, although their fuel economy was slightly worse compared to the diesel YTs. The LNG YTs also showed higher CO, NH_3, and THC emissions compared to the diesel YT, although this is probably a more minor consideration.

Fuel properties did not have a significant impact on impact on NOx or PM-related emissions, although higher emissions of CO and NH_3 with the low MI fuels suggested the engine was running richer for those fuels. The absence of significant fuel effects for NOx, PM, or engine knock may suggest that a fuel quality sensor may not provide significant near-term emissions improvements in this application, although there was some indications of the engine running richer on the lower MI fuels. . Overall, the results suggest that NZE NG engines could play an important role in reducing the emissions contributions of cargo handling equipment in port applications in the near- and intermediate-term.

As the range of applications and potential markets for NG engines continues to expand going into the future, the issue of fuel quality for NG engines will likely remain important. Throughout the U.S., pipeline NG in many areas has higher levels of ethane and MIs near 75. The 8.9L and 12L NG engines are also more tightly calibrated compared to the 6.7L engine, and have less margin of error for knock. As such, fuel quality could have more significant impacts in these engines, and should be investigated further. In terms of applying a fuel quality sensor to a commercial on-highway engine, it would also still require additional development to achieve better accuracy (±2 percent) and to be producible at a viable cost point. Other applications that might benefit from a fuel quality sensor could include non-road NG engines or engines stationed in remote locations. Such engines could run on NG that is not as highly processed as typical pipeline quality NG or biogas generated and used on site with minimal processing. In this application, a fuel quality sensor could make the use of NG generated on site in localized engines more viable, if appropriate adjustments could be made in the engine operation as the fuel quality changes. The potential for a fuel quality sensor in this application would have to further evaluated.

APPENDIX A: Chassis Dynamometer Emissions Test Report

Background and Test Program Purpose

Natural gas composition can vary which has been shown to have negative impacts on both the emissions and performance of heavy-duty natural gas engines. This has and remains a key factor in the development of NG engines. In California, one concern at the time this project was first proposed in 2016 was that renewable natural gas (RNG) composition could vary widely. As the market for RNG has developed in California, the quality of RNG has been fairly well controlled. Currently, almost all heavy-duty engines that use RNG in California are fueled from CNG or LNG made from pipeline quality natural gas. The lack of consistent fuel quality in other areas of the United States (U.S.) and in other parts of the world, however, remains an issue in terms of expanding the marketplace and lowering the capital costs for NG engines. Even in California, where fuel quality is more stringently controlled, there is the potential for increasing on-site production of RNG for HDVs that are domiciled nearby, or off-road vehicles (such as yard tractors).

To understand the impact of variable-quality natural gas (whether fossil or RNG) on the latest-technology near-zero emission (NZE) natural gas engines, two tasks were designed for this program. These tasks include a bench-top laboratory analysis of a fuel quality sensor partially developed as part of this project, and the evaluation of various natural gas blends on the NZE demonstration yard tractor (YT) as well as comparison to other YTs operating at the port. This report describes the emissions results for the comparison between different YTs operating at the Everport Terminal at the Port of Los Angeles (POLA). This includes comparisons of the emissions impacts for different NG blends on an optional low NOx standard (OLNS)-certified 6.7L LNG YT, a comparison of the emissions between different types of YTs operating at POLA, with a OLNS 6.7L LNG YT, a NZE 8.9L LNG YT and a diesel YT. This testing provided a better understanding of the potential impacts of variable-quality NG, the response time for a current technology NG engine to adapt and learn to operate on different qualities of NG, and the basis for the continuing development of sensors and control systems for commercial NG engines. By better quantifying the potential impacts of variable-quality NG and how NG engines might adapt to those changes, the development of future NG engines can be optimized and expanded to a broader range of markets.

Experimental Procedures

This section provides a detailed description of the procedures for emissions testing, the measurement systems and the data collection, and data analysis. This includes the methods utilized for the collection of in-use emissions, loaded weight, test cycles, vehicle selection, and fuel blends that were tested.

Test Elements

The test elements described in this subsection include the test cycles, test vehicle and test fuels. The laboratories are described in greater detail below.

Yard Tractors (YTs)

The original chassis dyno testing plan included four different YTs to be tested as part of this project. However, one YT (the BYD battery electric) was not made available to GNA-UCR for testing. Thus, a total of three YTs were tested, two of which were LNG YTs (6.7L and 8.9L engines), and one of which was a baseline diesel YT (also a 6.7L engine).

The main demonstration YT was a 2019 Capacity TJ900 powered by a B6.7N Cummins Westport Inc. (CWI) 6.7L natural gas OLNS-certified engine installed in a YT (NG1 in Table A-1). The engine was developed as a low NOx engine with a NOx standard of 0.1 NOx g/bhp-hr (50 percent below the 2010 NOx emissions standard), see Table A-1. The other two test YTs were an LNG unit powered by CWI's 8.9L NG L9N 250 engine (NZE certified) and a 2010 compliant model year (MY) 2014 diesel YT. It should be noted that the 6.7L LNG YT was also recalibrated to a 0.02 NOx g/bhp-hr certification level for a small subset of tests designed to evaluate the performance of the YT on an low MI fuel, as discussed below.

Table A-1: Summary of Vehicles to be Tested at UCR Chassis Dynamometer

ID	Engine Mfg	Chassis Mfg	Fuel	Model	Year	Disp.	Engine Hours	Cert Level (NOx)	Cert Level (PM)
6.7L NG	CWI [1]	Capacity	Varies	B6.7N 240	2019	6.7	969	0.1	0.01
L9N	CWI	Capacity	As-Received LNG from Clean Energy	L9N 250	2018	8.9	315.2	0.02	0.01
6.7L Diesel	CWI	Capacity	As-Received Diesel from Everport	QSB6.7 225	2014	6.7	1976	0.2	0.01

[1] **The B6.7 N 240 is the demonstration engine installed in a YT chassis and also the engine utilized for the demonstration of the MI sensor. CWI = Cummins Westport Inc.**

Source: University of California, Riverside

Cycles

The YTs were tested over several different cycles designed to represent different operations at a typical port terminal as well as in other applications. A summary of the basic characteristics of the cycles is provided in Table A-2, with more detailed information about the cycles provided in Appendix B (CALSTART, 2011; McKain et al., 2009). Two different YT duty cycles were used. These cycles were developed specifically for YT type operation during container movement at a cargo handling marine facility. The Central Business Cycle (CBD) is a bus cycle represents a bus application for the 6.7L engine. This cycle was included to provide a broader evaluation of the engines under a broader range of conditions that they might be used in. The steady state test was included because it represents one of the cycles used in the certification of non-road engines, (ISO 8178 test cycle listed in Table B-4, Appendix B). The steady state cycle was run at two different speeds, 15 mph and 25 mph, to represent the intermediate and rated speeds, respectively, utilized for this test when it is run on an engine dynamometer. The load points were then developed for each of the torque percentages for the test points at these two speeds. Note that the steady state testing on the 8.9L LNG YT could not be completed due to technical problems with the as-received YT at the time of testing, which delayed the start of testing by approximately two days. The steady state cycle was also only run at the 22-mph speed and associated load points for the 6.7L LNG YT due to limitations on the amount of test fuel available. All the transient cycles and the 8-mode test have also been used in previous tests of YTs, including for various conventional diesel yard tractors, a ISL G 2010 certified yard tractor, various hybrid natural gas yard tractors, and a battery electric yard tractor.

The two YT transient cycles are representative YT operation at heavy loads (YT_72K) and light loads (YT_26K), respectively. The YT_72K cycle was performed at 100 percent of the vehicle gross vehicle weight (GVW), which was selected to be 72,000 lbs. for this study, with the exception of the 6.7L LNG YT, which was tested at 69,000 lbs. where it operated better. The light cycle YT_26K_2x cycle was performed at a weight representative of a low weight, which was selected to be 26,000 lbs. for this study. The CBD bus cycle was performed at 35,000 lbs., which is a typical load for a bus in the SCAQMD air basin. The steady state mode test was performed at eight different steady state loads from 100 percent load to 10 percent load at two RPMs (2200 and 1450 rpm), see Appendix B for details. The YT_72K cycle was performed as a cold start and hot start test, see Table A-2, and represented a distance of 2.37 miles with an average speed of 7.1 mph. The YT_26k_2x was performed as a cold start and hot start test, except that no cold start YT_26K cycle was done on the 6.7 L LNG YT. The YT_26K cycle represented a distance of 1.76 miles with an average speed of 5.27 mph. These cycles are short (less than 30 minutes), so double or triple (2x or 3x) cycles were used in order capture enough PM mass to quantify emissions at less than 10 mg/bhp-hr. The cold start test was performed as a single cycle, but the YT transient cycles were repeated twice (x2) and the CBD was performed in triplicate (x3). The average speed of the cycles varies from 7.12 mph (YT_H) to 12.6 mph (CBD), with an overall top speed of just under 30 mph, see Table A-2 and Appendix B for details. The cold start cycles were all run after an overnight soak. The transient cycles were all run as hot start tests, with a 20-minute soak between each test cycle, consistent with the soak time utilize for the Federal Test Procedure (FTP) certification cycle.

Table A-2: Summary of Statistics for Various Proposed Driving Cycles

Day	Test Weight (lb.)	Distance (mi)	Average Speed (mph)	Duration (sec)
YT_72K_CS	72,000	2.37	7.12	1200
YT_72K_2x	72,000	2.37 x 2	7.12	2400
YT_26K_CS	26,000	1.76	5.27	1200
YT_26K_2x	26,000	1.76 x 2	5.27	2400
CBD_3x	35,000	6.0	12.6	1680
SS_Modes	72,000	8.7	18.5	1695

[1] Hot yard tractor (YT) cycles were performed as a double cycle (2x) and a single (1x) for the cold tests. The YT_72K cycles were performed at 69,000 lbs. for the 6.7L LNG YT. The YT_26K_CS test was not performed on the 6.7L LNG YT. The SS-Modes test was not conducted on the 8.9L LNG YT, and the SS_Mode was only run at the 22-mph speed for the 6.7L LNG YT on the Extreme MI fuel. The CBD was performed as a triple (3x) test, see Appendix B for details.

Source: University of California, Riverside

Test Fuels and Fuel Analysis

The 6.7L LNG, 8.9L LNG, and diesel YTs were all tested with the fuel in the tank at the time it was provided to CE-CERT. In addition to the baseline fuel, 4 additional fuels were used to characterize the impact fuel quality has on emissions for a 6.7L yard tractor. The characteristics of these fuels are shown in Table A-3, where the In Tank – LNG Pipeline fuel was based on the analysis of a fuel sample collected from 6.7L LNG YT. Three of these fuels were used in direct comparison to the baseline fuel and one fuel was utilized over selected cycles to evaluate the potential benefits of an integrated natural gas sensor. The three fuels used for the fuel comparison included a blend representing a more extreme low MI pipeline fuel, and two blends that represent typical RNG fuels (Kleeman et al., 2018). The last blend, with a low MI, represented a fuel that would be more susceptible to engine knock, thus providing critical information on the benefit of an integrated fuel quality sensor. The MIs for the fuels ranged from ~65 to over 101. The selection of the blends was done in conjunction with recommendations provided by Cummins Inc, who was part of the project technology advisor committee. The blends included CH_4, C_2H_6, C_3H_8, $C4H_{10}$, N_2, O_2, and CO_2. C_2H_6 and C_3H_8 are particularly important constituents to include, as they can contribute to knock at higher levels. It should be noted that the Extreme MI fuel was only tested over the YT_72K_2x cycle and a 22 mph steady state driving cycle. The Extreme MI fuel was also test after the engine for the 6.7L LNG YT was recalibrated from a 0.1 to a 0.02 g/bhp-hr NOx certification calibration. This was done to better understand the potential impacts of engine knock at the lower NZE calibration.

Table A-3: Natural Gas Fuel Blends Simulating Pipeline and Renewable Natural Gas Fuels (vol percent)

Fuel	MI	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	O_2	CO_2
In tank - LNG Pipeline	83.2	93.0	6.72	0.03	-	0.17	<0.1	<0.1
RNG 1	92.6	93.6	-	-	-	3.7	0.5	2.2
RNG 2	101.2	91	-	-	-	1.9	-	7
Extreme Pipeline	70.7	77	12	5	1	-	-	5
Extreme MI (ExMI)	67.5	89.5	-	10.5	-	-	-	-

MI = Methane Index as determined from https://www.cumminswestport.com/fuel-quality-calculator

Source: University of California, Riverside

Chassis Dynamometer

UCR's chassis dynamometer is an electric AC type design that can simulate inertia loads from 10,000 lb to 80,000 lb which covers a broad range of in-use medium and heavy-duty vehicles, see Figure A-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 dynamometer 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 perform various on-road operation which includes the Port of Los Angeles and Long Beach drayage cycles, California Air Resources Board (CARB) 4-Mode cycle, and the urban dynamometer driving schedule (UDDS). The chassis dynamometer provides the load to the vehicle and engine in real time. The load measurement is accurate to 0.05 percent of full scale and has a response time of less than 100 milliseconds, which is necessary for repeatable and accurate transient testing. The speed accuracy of the rolls is ±0.01 mph and has an acceleration accuracy of ±0.02 mph/sec, which are both measured digitally such that their accuracy can be maintained. These data are collected at 1 Hz. The torque transducer is calibrated as per Code of Federal Regulations (CFR) 1065, which provides standard methods for determining accurate and reliable wheel loads. Data collected in conjunction with the chassis dynamometer include load, speed, and distance that are utilized in the final calculation of emission factors.

The chassis dynamometer is designed to simulate the different forces that a vehicle would experience while driving on a typical roadway. The factors used to simulate on-road conditions are called road load coefficients, which can be calculated based on parameters, such as the frontal area of the vehicle and a factor accounting for is general shape, as described in Appendix C. The road load coefficients are verified by performing a coast down procedures on the chassis dynamometer prior to testing. For the coast down procedures, the vehicle is coasted down from a speed near the upper end of the vehicles speed range to a speed near 10 mph. This procedure allows a comparison between the actual coast times on the dynamometer and theoretical coast down times that would be expected. The road load coefficients can then be adjusted to compensate for the system loses in the dynamometer.

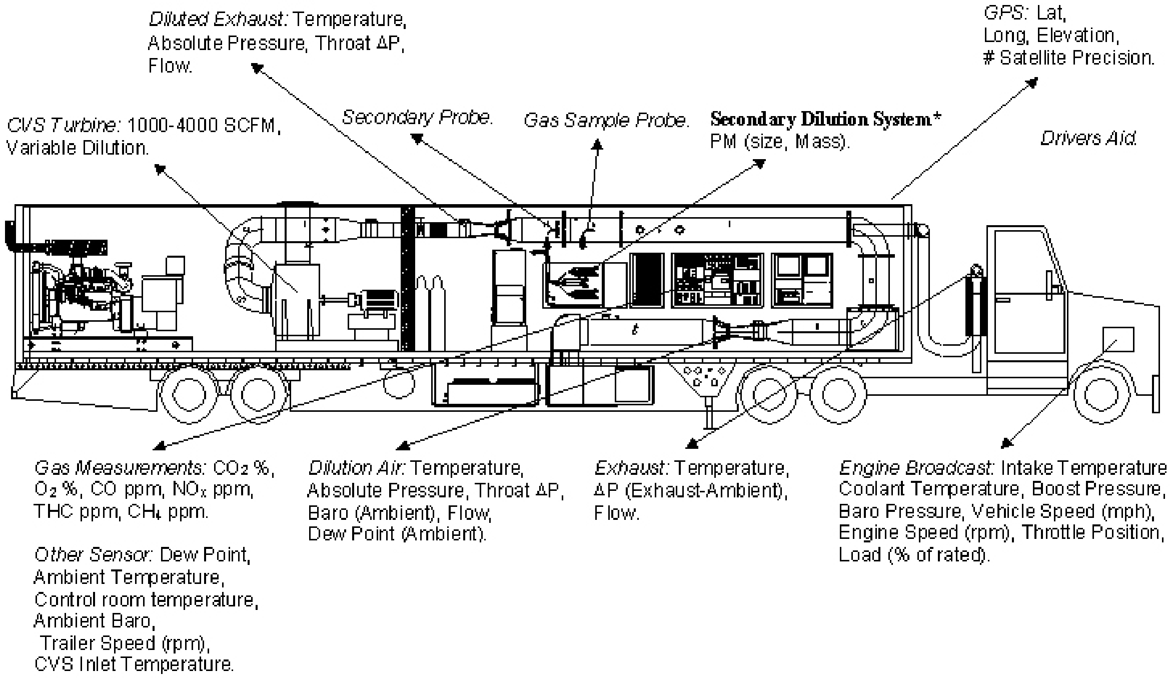
Figure A-1: University of California, Riverside Heavy-Duty Chassis Eddy Current Transient Dynamometer

Source: University of California, Riverside

Emissions Testing

The emissions measurements were performed with UCR's heavy-duty mobile emission lab (MEL), which was connected to the exhaust tailpipe of the YT. The details for sampling and measurement methods of mass emission rates from heavy-duty engines are specified in CFR, Section 40, Part 1065. UCR's unique heavy-duty diesel mobile emissions laboratory (MEL) is designed and operated to meet those stringent specifications. A schematic of the major operating subsystems for the MEL are shown in Figure A-2. The accuracy of the MEL's measurements have been checked/verified against ARB's (Cocker et al, 2004a) and Southwest Research Institute's (Johnson et al., 2009; Johnson et al., 2011) heavy-duty diesel laboratories. The MEL measures Total Hydrocarbons (THC), Methane (CH_4), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x), and fine Particulate Matter with a diameter less than 2.5 nm ($PM_{2.5}$) emissions from diesel engines. Design capabilities and details of MEL are described in Cocker et al, (2004a, 2004b). Samples can also be collected for more detailed analyses such as hydrocarbon speciation, carbonyl emissions, polynuclear aromatic hydrocarbons, etc.

Figure A-2: Major Systems within Mobile Emission Lab



Source: University of California, Riverside

The emission measurements for this testing included THC, CH_4, NO_x, CO, CO_2, $PM_{2.5}$ and fuel economy. In addition, ammonia (NH_3), nitrous oxide (N_2O), total particle number, solid particle number, and particle size distributions were measured. The pollutants measured and methods utilized for each measurement are listed in Table A-4.

Due to the very low NOx measurements expected in this project, improved NOx measurements have been integrated into UCR testing capabilities. These additional measurements were designed, integrated, and evaluated during previous Low NOx NG engine testing at UCR. The raw measurement upgrades included the addition of a raw NOx chemiluminescent analyzer with direct exhaust flow measurement into the MEL. Previous studies have shown improved accuracy for the raw NOx chemiluminescent measurements over the dilute measurement method.[1] These methods are expected to provide a measurement accuracy at 0.02 g/bhp-hr of ±10 percent or better.

The data for the regulated measurements were collected in bags and in real-time at 1 Hz. The unregulated emissions were measured in real-time at a sampling rate of 1 Hz. PM emissions were sampled on a Teflon filter and the mass was determined gravimetrically with a microbalance in a temperature and humidity-controlled weighing chamber.

1 Various reports and presentations by the Emissions Measurement and Testing Committee (EMTC) for NOx measurements at and below 0.02 g/bhp-hr and personal discussions with Cummins Inc. emissions team.

Table A-4: Emissions Measurements Proposed and Optional

Proposed	Method	Proposed	Method
NO_x [1]	Chemiluminescence (CLD)	**N_20**	Quantum Cascade Laser (QCL)
CO	Non-dispersive Infra-Red (NDIR)	**PM Fines (if available)**	Particle counting, and particle size distribution (APC)
CO_2	NDIR	**PM Real-time (if available)**	PM mass concentration mobility and aerodynamic (EEPS)
THC	Heated flame ionization detection (FID)	**Black Carbon (if available)**	Photo acoustic soot measurement (MSS 483)
CH_4	Heated FID methane cutter	NH_3	QCL
O_2	Paramagnetic Oxygen	$PM_{2.5}$	Gravimetric Filter

Source: University of California, Riverside

Engine Operating Parameters

The engine control unit (ECU) was monitored for specific information such as load, operating conditions, exhaust and aftertreatment temperatures, and other details. For the NG engine operated on different quality fuels, additional measurements were made with a Cummins Insite to better evaluate the potential for engine knock and equivalence ratio. These data are collected at 1 Hz with the chassis and emissions data.

Results

The emissions results for the testing of the 6.7K LNG, the 8.9L LNG and diesel YTs are discussed in this section. All the emissions data are reported on a g/bhp-hr units, as this is the basis of the emissions standards, as well as g/mi units for the NOx and CO_2 emissions, as these were especially critical pollutants. The individual test results are provided in Appendix D for all tests in g/bhp-hr, g/mi, and g/gal-fuel units. Fuel economy was determined via the carbon balance method. Work was calculated using ECM signals, as is typically done for in-use testing. It should be noted that a regeneration occurred during one of the tests on the diesel YT. The results for the regeneration test were not included in the results below because regenerations occur only sporadically in actual in-use conditions, and the frequency of such regenerations was not known for this YT.

NOx Emissions

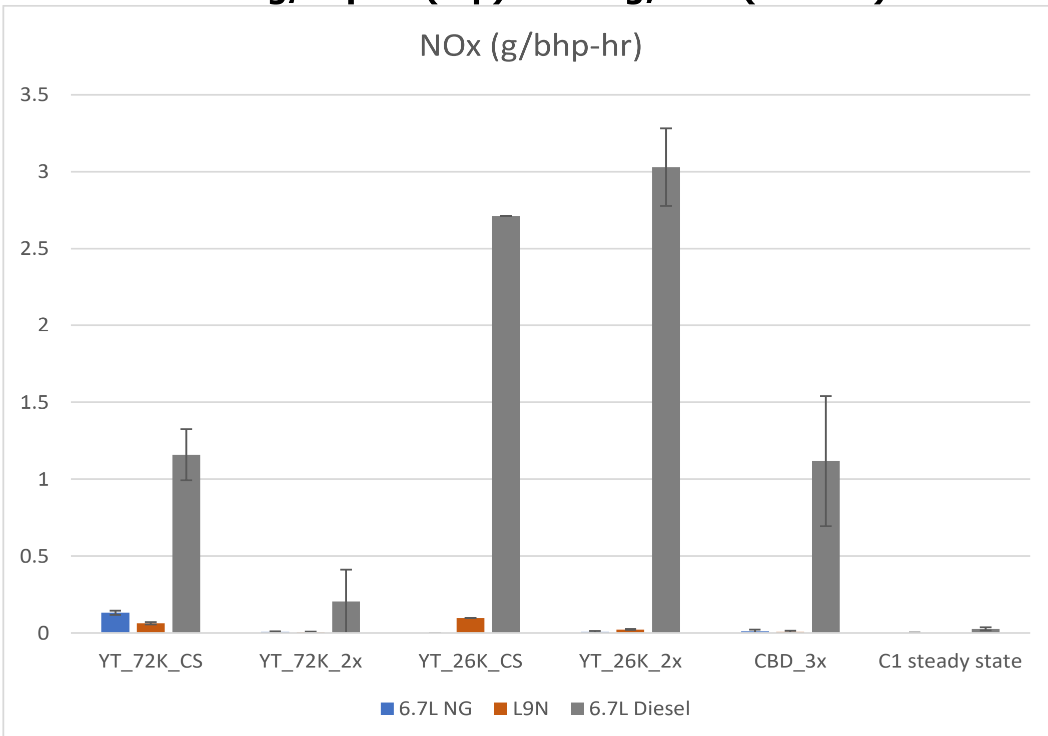
NOx emissions for the 6.7L LNG, 8.9L LNG and diesel yard tractors are shown on a g/bhp-hr and a g/mi basis in Figure A-3 (top) and (bottom), respectively. The results from Figure A-3 show that the emissions for the diesel yard tractor were considerably higher than those for both LNG yard tractors for all cycles. Average NOx emissions ranged from 0.002 to 0.13 g/bhp-hr and from 0.014 to 0.730 g/mi for the 6.7L LNG yard tractor, from 0.005 to 0.098

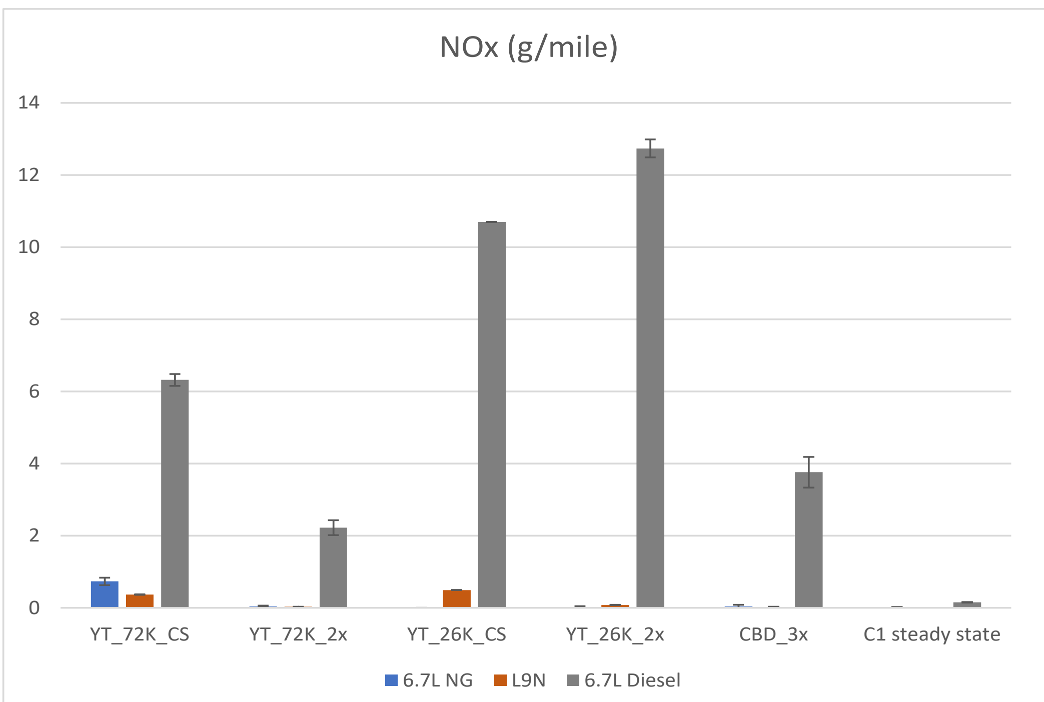
g/bhp-hr and from 0.025 to 0.491 g/mi for the 8.9L LNG yard tractor, and from 0.027 to 3.029 g/bhp-hr and from 0.150 to 12.739 g/mi for the diesel yard tractor.

The LNG vehicles showed some difference between the cycles. For the 6.7L LNG yard tractor, the highest emissions were found for the cold start cycles, with the emissions of 0.13 g/bhp-hr and 0.73 g/mi. Emissions from YT_72K_2x, YT_26K_2x and CBD_3x ranged from 0.007 to 0.01 g/bhp-h and 0.022 to 0.038 g/mi, which were considerably lower than the certification standard of 0.1 g/bhp-hr. For the 8.9 L LNG yard tractor, the highest emissions were found for the cold start cycles, where emissions were above the certification levels from 0.06 to 0.09 g/bhp-hr and from 0.36 to 0.49 g/mi, with the highest emissions for the YT_26K_CS cycle. These values are higher than those found in other studies of cold start emissions from OLNS/NZE CNG vehicles, which have been closer to 0.02 to 0.12 g/bhp-hr (Zhu et al., 2020; Li et al., 2020). The emissions for the 8.9L LNG YT, the hot start YT_72K_2x, YT_26K_2x, and CBD_3x, on the other hand, were all at or below the 0.02 g/bhp-hr and below 0.08 g/mi, with the lowest emissions were found for the YT_72K_2x cycle. Emissions levels below 0.02 g/bhp-hr has also been seen in other studies of OLNS/NZE CNG vehicles over transient cycles (Zhu et al., 2020; Li et al., 2020).

For the diesel yard tractors, the highest emissions were found for the YT_26K_2x and YT_26K_CS cycles, with emissions ranging from 2.7 to 3.0 g/bhp-hr and 10.69 to 12.74 g/mi. The YT_72K_CS, CBD_3x cycles showed the next highest emissions, with emissions slightly higher than 1 g/bhp-hr and 6.32 g/mi. The lowest diesel emissions were for the C1 Steady state cycle test, which had emissions of 0.027 g/bhp-hr and 0.15 g/mi. This is very similar to values found from the heavy-duty in-use testing compliance program, where average NOx emissions for non-credit heavy-duty vehicles averaged 0.37 g/bhp-hr (Spears, 2018).

Figure A-3: Average NO_x Emissions for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors in g/bhp-hr (top) and in g/mile (bottom) units

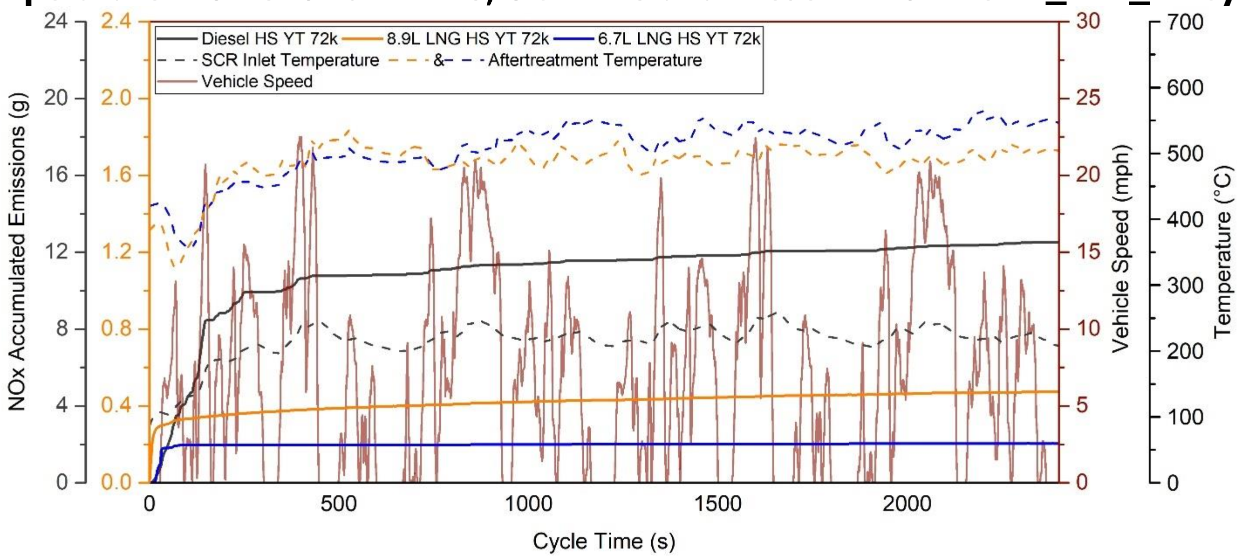




Source: University of California, Riverside

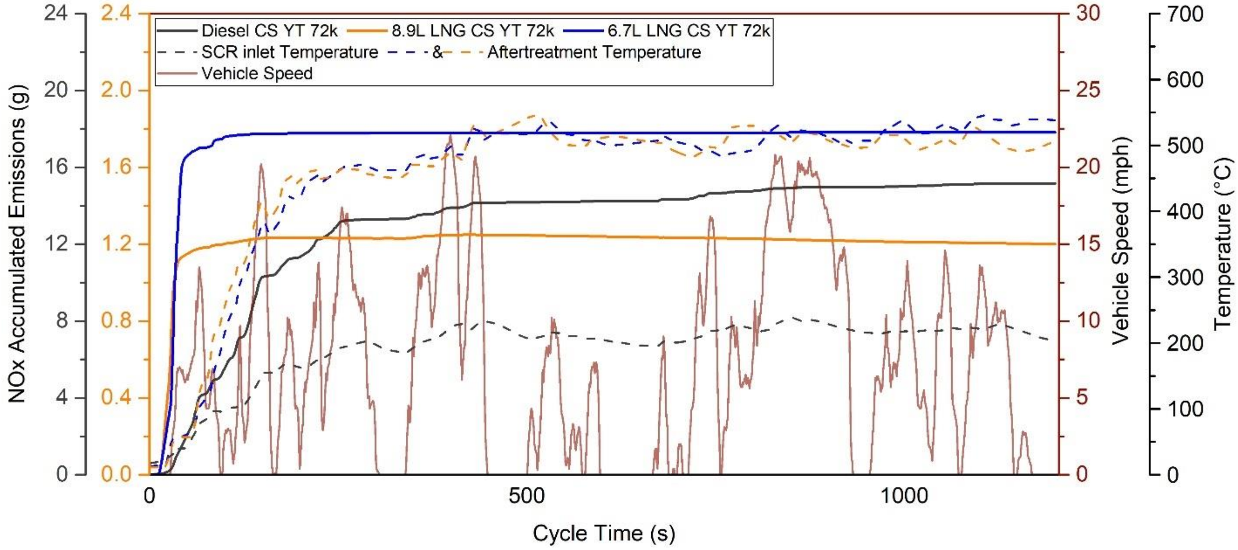
The emissions profiles for the different cycles can be more readily understood by a closer examination of the real-time data. Plots of time-based cumulative NOx emissions are provided in Figure A-4 and Figure A-5, respectively, for one YT_72K_2x test and for one YT_72K_CS for each of the YTs. Note that the LNG and diesel YT NOx emissions are plotted using different scales to allow their emissions to all be shown on the same graph. Figure A-4 and Figure A-5 show that for the LNG YTs, the emissions are primarily formed during the first portion of the test cycle. Once the catalyst lights off, the emissions maintain very low levels till the end of the cycle, as indicated by the accumulation lines being essentially flat. The largest fraction of NOx emissions also occurs in the first portion of the cycle for the diesel YT as well, particularly when the exhaust temperature stays below 200°C. Additional NOx does still accumulate for the diesel YT over the course of the rest of the cycle as well, in contrast the near zero emissions after catalyst light off for the LNG YTs. For the YT_72K_CS cycle, the NOx emissions show much higher levels during the initial portion of the cycle, and also have higher emissions as the cycle extends out and as the aftertreatment takes longer to get to its typical operating temperature. The real-time results also show that the differences in the tests on the different NG blends are also primarily during the initial portion of the testing, which is shown in Figure A-6 for the YT_72K_2x cycle. This is consistent with the differences in the tests being primarily attributed to how sensitive the engine is operating during the initial portions of the cycles, rather than to consistent and systematic fuel effects. Additional real-time plots for the YT_26K_2x and YT_26K_CS cycles are provided in Appendix E.

Figure A-4: Real-time Hot Start NOx Emissions, Cycle Trace and aftertreatment Temperature Profile for 6.7L LNG, 8.9L LNG and Diesel YT for the YT_72K_2x Cycle



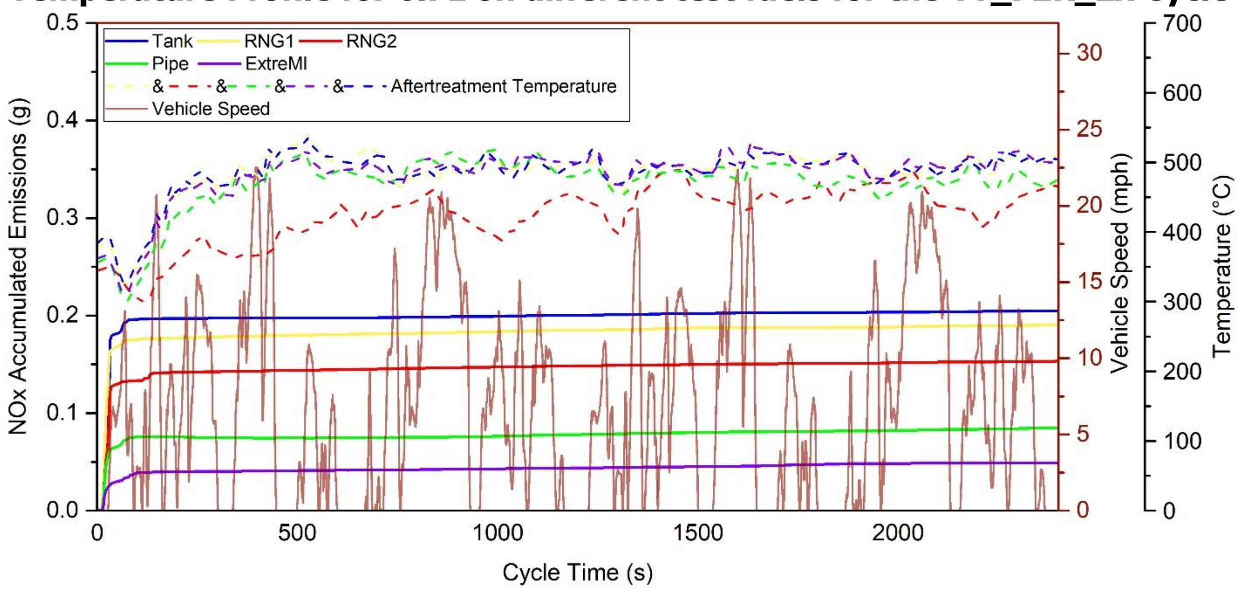
Source: University of California, Riverside

Figure A-5: Real-time Cold Start NOx Emissions, Cycle Trace and aftertreatment Temperature Profile for 6.7L LNG, 8.9L LNG and Diesel YT for the YT_72K_CS Cycle



Source: University of California, Riverside

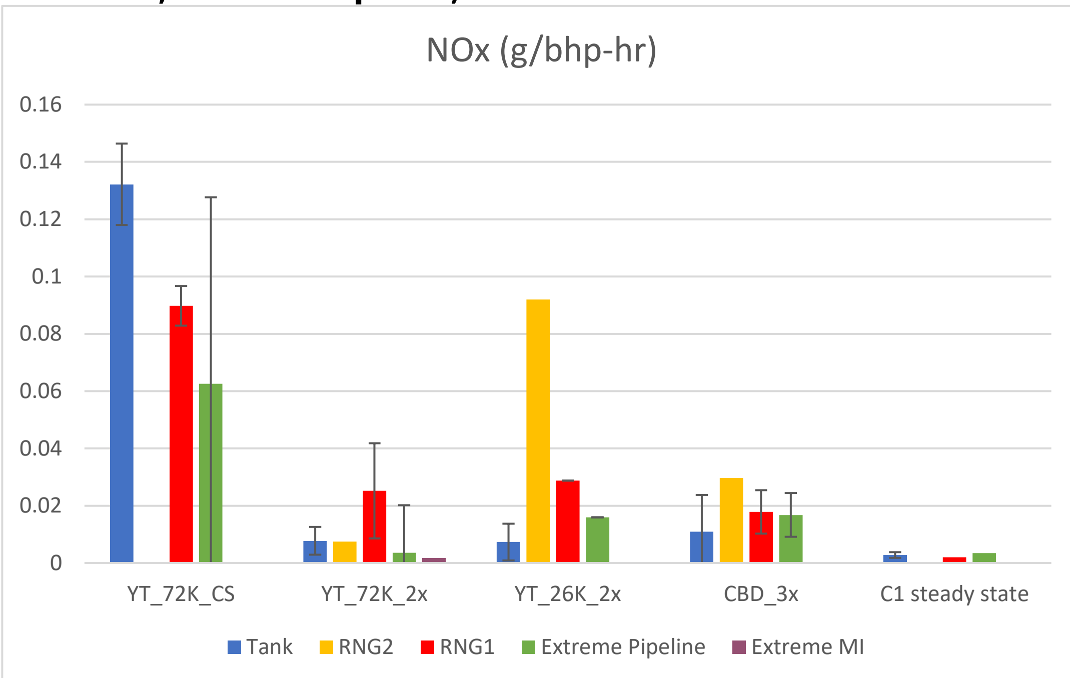
Figure A-6: Real-time Hot Start NOx Emissions, Cycle Trace and aftertreatment Temperature Profile for 6.7L on different test fuels for the YT_72K_2x Cycle



Source: University of California, Riverside

NOx emissions for the 6.7L LNG with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels are shown on a g/bhp-hr in Figure A-7. While the results show some differences between tests done on different fuels, the differences are not consistent enough to suggest that fuel properties are systematically impacting NOx emissions. RNG2 showed the highest emissions for YT_26K_2x and CBD_3x cycles, but not for the YT_72K_2x cycle, while RN1 showed higher emissions for the YT_72K_2x, and the tank fuel showed the highest emissions for the YT_72K_CS. The variation between the different test fuels could instead indicate subtle differences in the operation of the engine over the different test cycles on different days that could be attributed to factors other than fuel properties. The high sensitivity of the emissions to the first 100 second of operation, as shown above, suggests that the specific start conditions between different tests is probably more critical in the differences between tests than the fuel properties.

Figure A-7: Average NO_x Emissions for 6.7L LNG Yard Tractor with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme Methane Index fuels

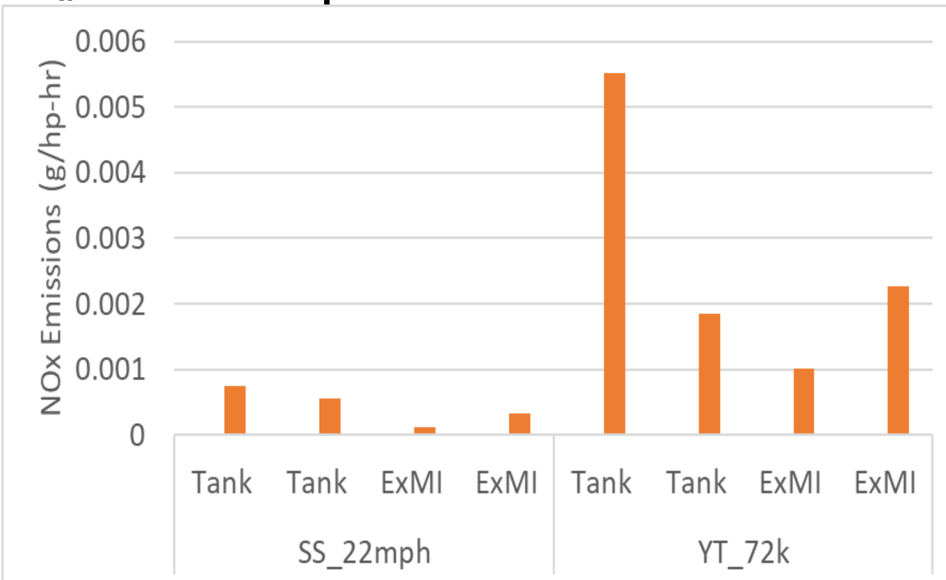


Source: University of California, Riverside

Note that in all cases, with the exception of the cold start test, the NOx emissions were below the applicable standard. In comparison with other results, studies have shown that in older lean burn CNG/LNG engines, lower MI fuels can produce higher NOx emissions in comparison with higher MI fuels (Karavalakis et al., 2013; Hajbabaei et al., 2013; Karavalakis et al., 2016a). This could be attributed to the fact that lower MI fuels tend to create higher flame temperatures, and hence higher NOx levels during combustion. Previous tests for stoichiometric CNG/LNG engines more minimal fuel effects, with some vehicle showing fuel effects (Karavalakis et al., 2016a & b), while others have not (Hajbabaei et al., 2013). This can be attributed to the effectiveness of the TWC in eliminating NOx emissions, such that the tailpipe emissions show levels that are much lower than the engine out emissions levels. To the extent that fuel effects have been identified, the trends were generally for lower NOx emissions for lower MI fuels, which could be attributed to richer operation with these fuels.

A more specific comparison between the In Tank and Extreme MI fuels is provided in Figure A-8. This figure shows the results for the individual tests that were run on both fuels. Note that the 6.7L LNG YT was recalibrated from a 0.1 to a 0.02 NOx standard for the testing on the Extreme MI fuel. Although the tests with the Extreme MI fuel on the 0.02 calibration did show somewhat lower emissions compared to the 0.1 calibration, the results were still comparable, with most of the emissions differences coming at the start of the cycle. Comparisons of available ECU parameters also suggested that the vehicle did not suffer from engine knock during this testing, suggesting the engine can still operate on lower MI fuels without suffering significant short-term emissions or operational impacts. Changes in the emission level for other pollutants (as shown below), on the other hand, suggest that the engine was operating richer on the Extreme MI fuel.

Figure A-8: NO_x Emissions Comparison for Tank and Extreme Methane Index fuels



Source: University of California, Riverside

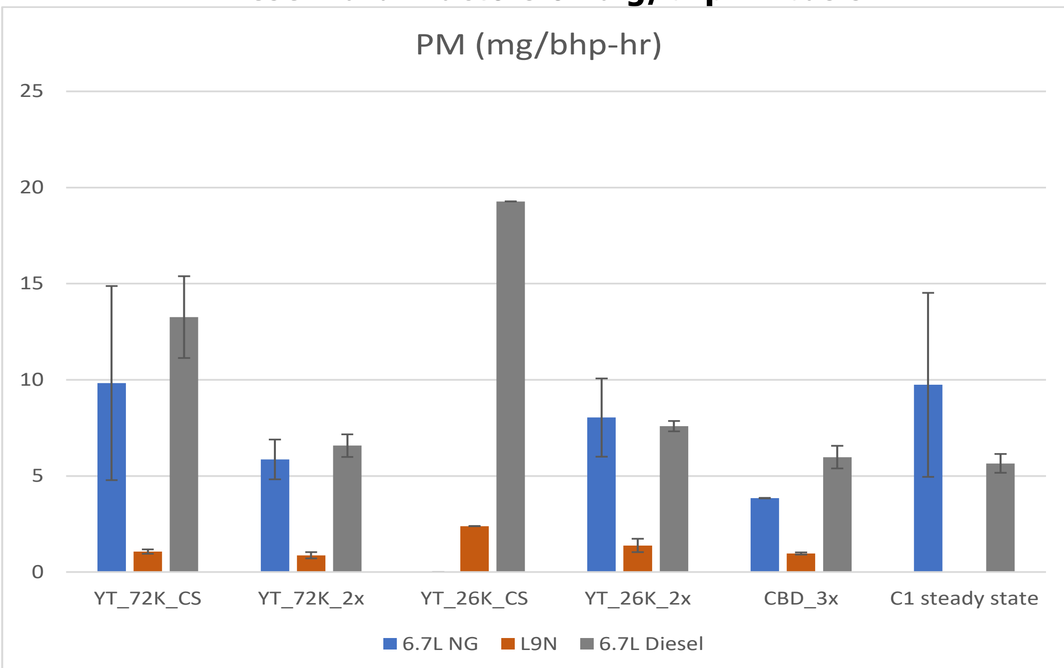
Particulate Matter Emissions

PM emissions for the 6.7L LNG, 8.9L LNG and diesel yard tractors are shown on a mg/bhp-hr basis in Figure A-9. The diesel yard tractor had higher PM emissions than those for both 6.7L and 8.9L LNG yard tractor for all test cycles except for the YT_26k_2x cycle from 6.7L LNG. For the 6.7L LNG and 8.9L LNG yard tractor, the average PM emissions ranged from 5.8 to 9.8 and 0.9 to 1.4 on a mg/bhp-hr basis. Overall, the PM emissions for both the 6.7L and 8.9L LNG yard tractor are all at or below the 10 mg/bhp-hr standard. The PM results for the 8.9L LNG tractor are comparable to the low levels seen in other studies of OLNS/NZE CNG vehicles (Li et al., 2019; Zhu et al., 2020) and comparable to the low levels that would be expected for a DPF equipped vehicle. The PM emissions for the 6.7L LNG YT were somewhat higher than typical levels seen in other studies of NG vehicles or for typical operating DPF-equipped DPFs.

For the diesel yard tractor, the average PM emissions ranged from 6.0 to 19.3 on a g/bhp-hr basis. For the diesel yard tractor, the highest emissions were found for the YT_26K_CS and YT_76k_ CS cycles, with levels ranging from 13.3 to 19.3 mg/bhp-hr. The PM emissions for the hot start tests were lower, and all in a similar range of approximate 5 to 10 mg/bhp-hr. Although the PM emissions levels for the diesel yard tractor were at or below 10 mg/bhp-hr certification level for all the non-cold start tests, they were higher than the levels typically seen for the DPF equipped heavy-duty diesel vehicles, which are generally closer to 1 mg/bhp-hr, or about 1/10 of the standard.

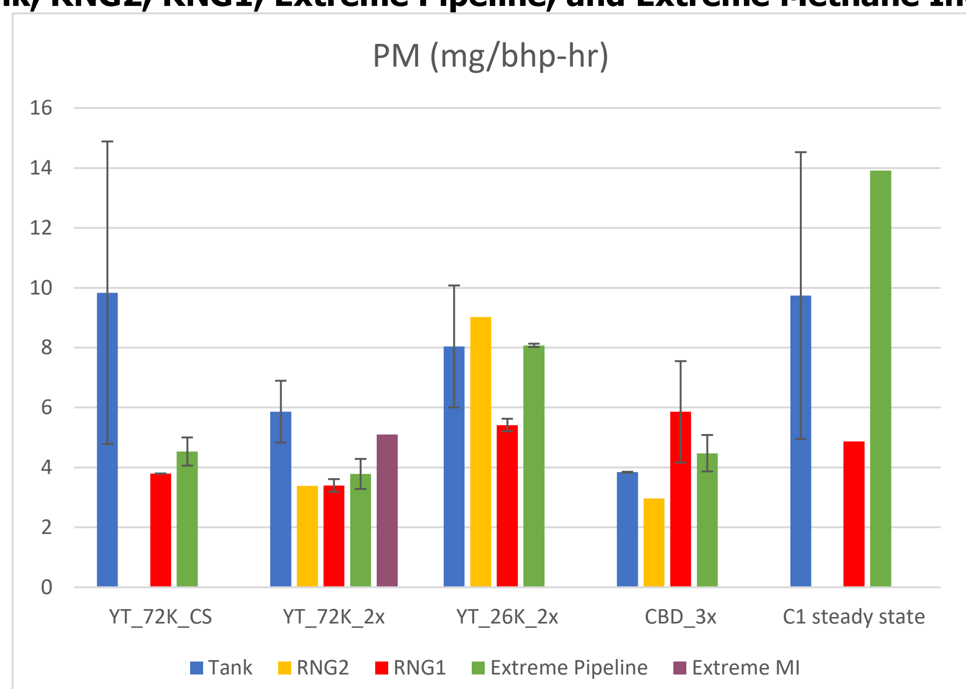
PM emissions for the 6.7L LNG with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels are shown on a mg/bhp-hr basis in Figure A-10. Average PM emissions for RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels were all at or below the 10 mg/bhp-hr standard, with the exception of the Extreme Pipeline fuel over the C1 cycle. Although the fuels showed differences for different test cycles, there were no consistent fuel trends for PM emissions. The differences are also relatively small in terms of absolute PM emissions. These findings are consistent with results from other studies of stoichiometric TWC NG engine-equipped heavy-duty vehicles (Hajbabaei et al., 2013; Karavalakis et al., 2016a & b).

Figure A-9: Average Particulate Matter Emissions for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors on a g/bhp-hr basis



Source: University of California, Riverside

Figure A-10: Average Particulate Matter Emissions for the 6.7L LNG Yard Tractor with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme Methane Index fuels



Source: University of California, Riverside

Total Hydrocarbon Emissions

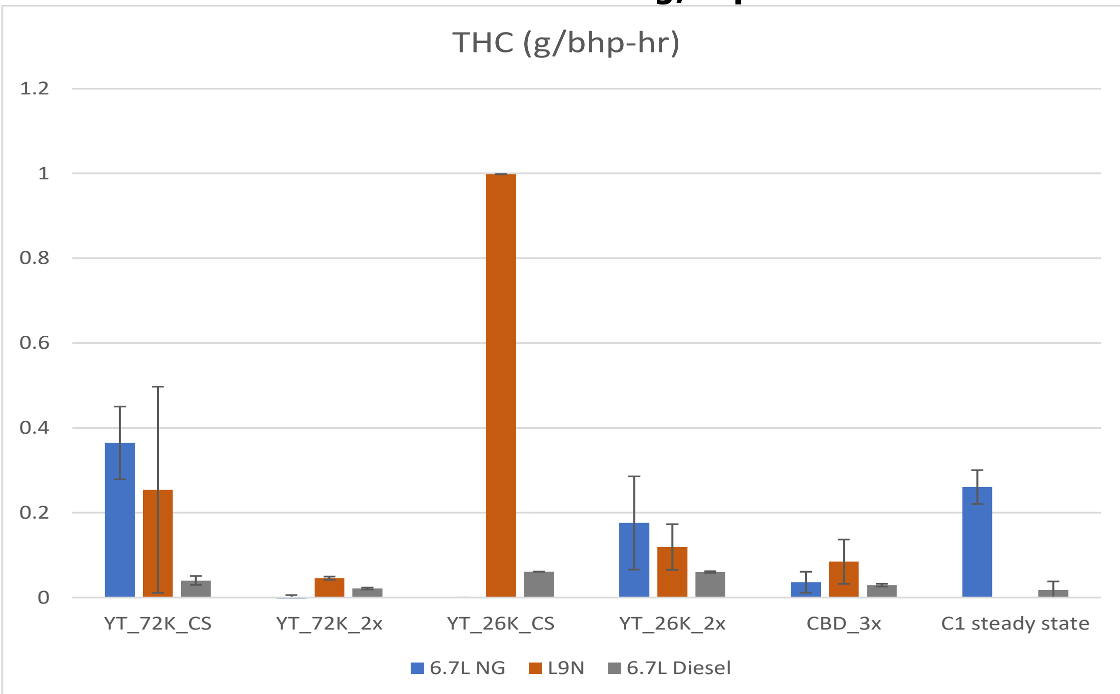
THC emissions for the 6.7L, 8.9L LNG and diesel yard tractors are shown on a g/bhp-hr in Figure A-11. It should be noted that NMHC emissions for the diesel YT were very low, and NMHC emissions for the LNG YTs were essentially below the instrument detection levels, as shown in Appendix D. THC emissions for the 6.7L and 8.9L LNG YTs were higher compared to the diesel YT, especially for the cold start test cycles. For the 6.7L and 8.9L LNG yard tractor, the average THC emissions ranged from 0.037 to 0.365 and 0.046 to 0.999 on a g/bhp-hr basis, respectively. For the 6.7L LNG yard tractors, the highest emissions were found for the YT_72K_CS cycle at around 0.364 g/bhp-hr. For the 8.9L LNG yard tractors, the highest emissions were found for the YT_26K_CS cycle at around 1.0 g/bhp-hr, followed by the YT_72K_CS at slightly less than 0.2 g/bhp-hr. These values are comparable to those found in previous studies of cold start tests, which have shown THC emissions on the order of 0.4 g/bhp-hr (Li et al., 2019; Zhu et al., 2020). For both the 6.7L and 8.9L LNG YTs, the hot start cycles all showed relatively low emissions.

For the diesel yard tractors, the emissions were all relatively low. For the diesel yard tractors, the average THC emissions ranged from 0.017 to 0.060 on a g/bhp-hr basis. For comparison, THC emissions of five 2010+ diesel trucks with DOC/DPF/SCR systems were below 0.034 g/mile over the UDDS (Jiang et al., 2018).

Real-time THC emissions are shown in Appendix E, Figures E-3 and E-4, respectively, for the YT_72K_CS cycle and the YT_72K_2x cycle. Similar to the NOx emissions, THC emissions for the cold start are predominantly from the initial portion of the cycle where the catalyst is below its light off temperature, and once the catalyst lights off, the emissions maintain very low levels till the end of the cycle. THC emissions for the hot start cycles were lower than those for cold start, with emissions from 6.7L LNG YT being predominantly in the first 100s of the cycle. Emissions from 8.9L LNG and Diesel YTs show initially lower levels, and then gradually increase through the cycle.

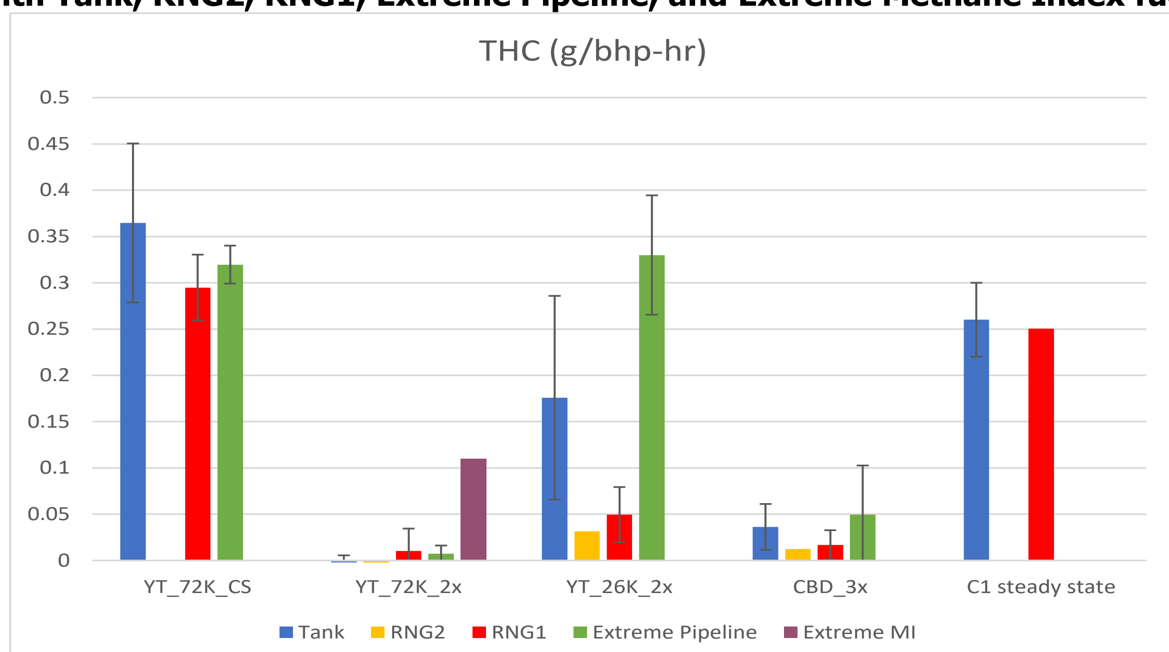
THC emissions for the 6.7L LNG with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels are shown on a g/bhp-hr basis in Figure A-12. There was a trend of higher emissions for the tank and Extreme Pipeline fuels for some of the cycles, particularly for the YT_26k_2x cycle. The trend was not consistent over the other cycles, where the THC emissions for the different fuels were similar within the experimental variability. Interestingly, the Extreme MI fuel did show considerably higher THC emissions over the YT_72K_2x fuel. Previous studies of 0.2 g/bhp-hr NOx certified, stoichiometric TWC NG engine-equipped heavy-duty vehicles have not shown consistent effects for THC emissions (Hajbabaei et al., 2013; Karavalakis et al., 2016a & b).

Figure A-11: Average Total Hydrocarbon Emissions for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors on a g/bhp-hr basis



Source: University of California, Riverside

Figure A-12: Average Total Hydrocarbon Emissions for the 6.7L LNG Yard Tractor with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme Methane Index fuels

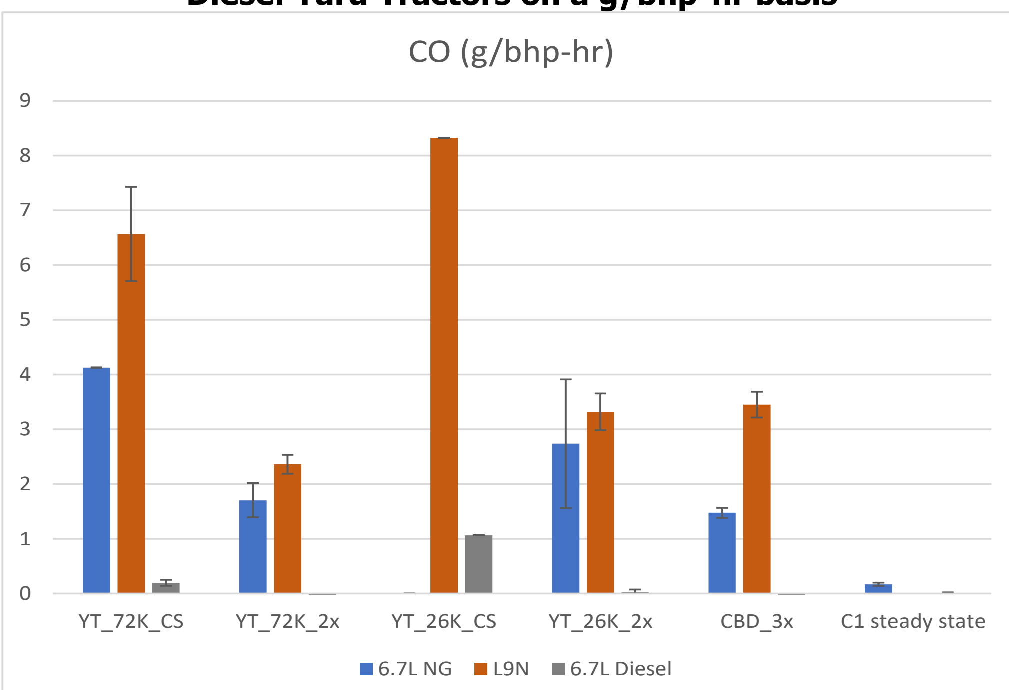


Source: University of California, Riverside

Carbon Monoxide Emissions

CO emissions for the 6.7L LNG, 8.9L LNG and diesel yard tractors are shown on a g/bhp-hr basis in Figure A-13. For the 6.7L and 8.9L LNG yard tractor, the average CO emissions ranged from 0.16 to 4.13 and 2.36 to 6.56 on a g/bhp-hr basis. The CO emissions levels are comparable to those found in previous studies of ultralow NOx CNG vehicles, which have ranged from 0.75 to 5 g/bhp-hr. For the diesel yard tractor, the average CO emissions ranged from 0.001 to 1.06 on a g/bhp-hr basis. Previous studies of diesel vehicles have also shown lower CO emissions, on the order of 0.2 g/mi or less (Jiang et al., 2018). For both the 6.7L and 8.9L LNG yard tractors, CO emissions from cold-start cycles showed higher emissions than the hot start cycles. For the 6.7L LNG YT, the highest emissions were found for the YT_72K_CS cycle, while the lowest emissions were found for a hot start YT_72K_2x cycle. For the 8.9L LNG yard tractors, the highest emissions were also found for a cold start cycle, the YT_26K_CS cycle, while the lowest emissions were found for the hot start YT_72K_CS cycle. For the diesel yard tractors, the highest emissions were found for the YT_26K_CS cycle, while the hot start cycles all showed very low emissions. Real-time CO emissions plots for the YT_72K_CS and YT_72K_2x cycles, as provided in Appendix E, show that while the predominant portion of CO emissions for the LNG YTs is produced in the initial parts of the cycle for the cold start cycle, that CO emissions are produced throughout the full duration of both cycles, in contrast to NOx emissions.

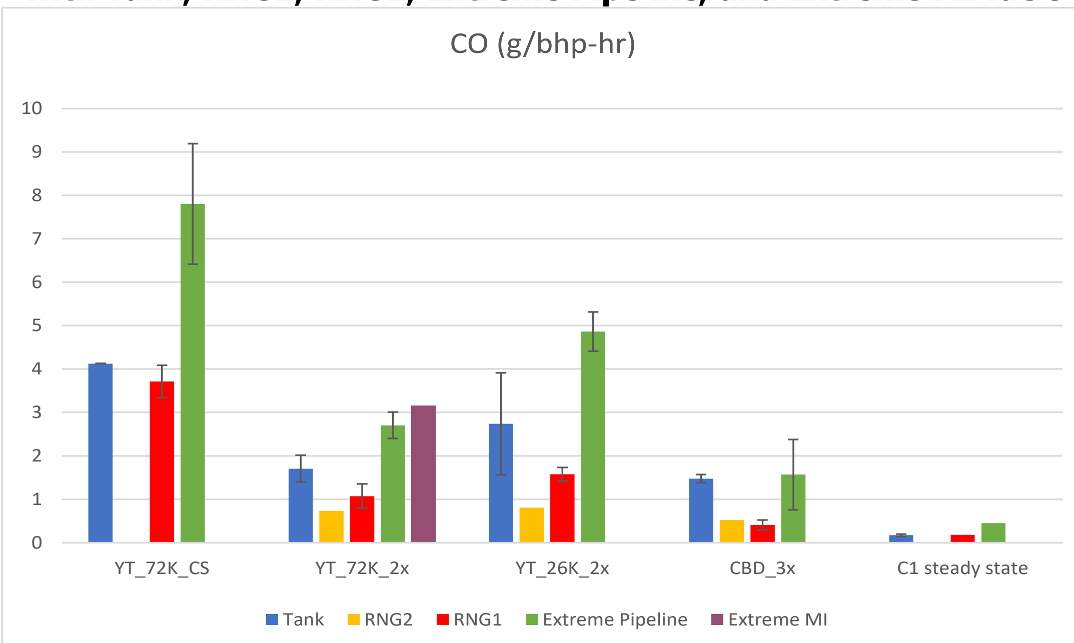
Figure A-13: Average Carbon Monoxide Emissions for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors on a g/bhp-hr basis



Source: University of California, Riverside

CO emissions for the 6.7L LNG with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels are shown on a g/bhp-hr basis in Figure A-14. The results from Figure A-14 showed that the emissions from the 6.7L LNG with Extreme Pipeline fuel were higher than the other RNGs for all five test cycles. The Extreme MI fuel CO emissions were also the highest for YT_72K_2x cycles. The In Tank fuel CO emissions generally lower than those for the Extreme Pipeline, but were higher than those for RNG2 and RNG1 for three of the five cycles. Taken together, the results suggest that the engine is running richer on the lower MI fuels in comparison with the higher MI RNG fuels, which could be a consideration for long term durability. Previous studies of 0.2 g/bhp-hr NOx certified, stoichiometric TWC NG engine-equipped heavy-duty vehicles have shown increases in CO emissions for lower MI fuels in some cases, but not others (Hajbabaei et al., 2013; Karavalakis et al., 2016a & b).

Figure A-14: Average Carbon Monoxide Emissions for the 6.7L LNG Yard Tractor with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels

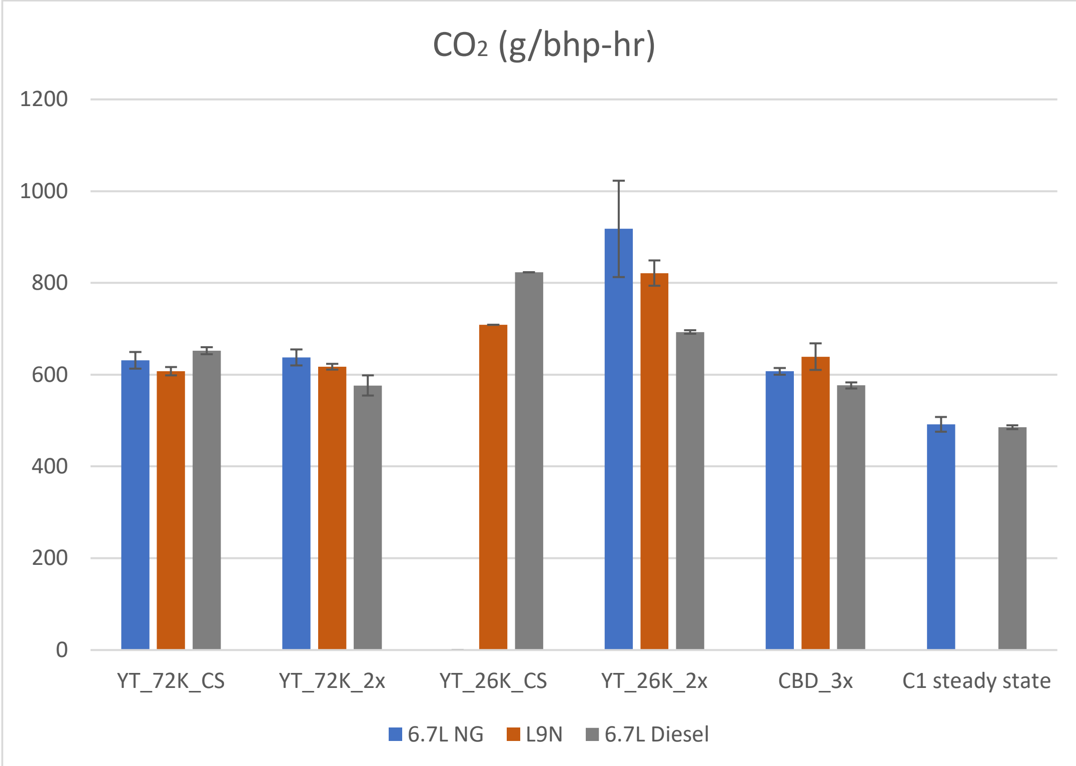


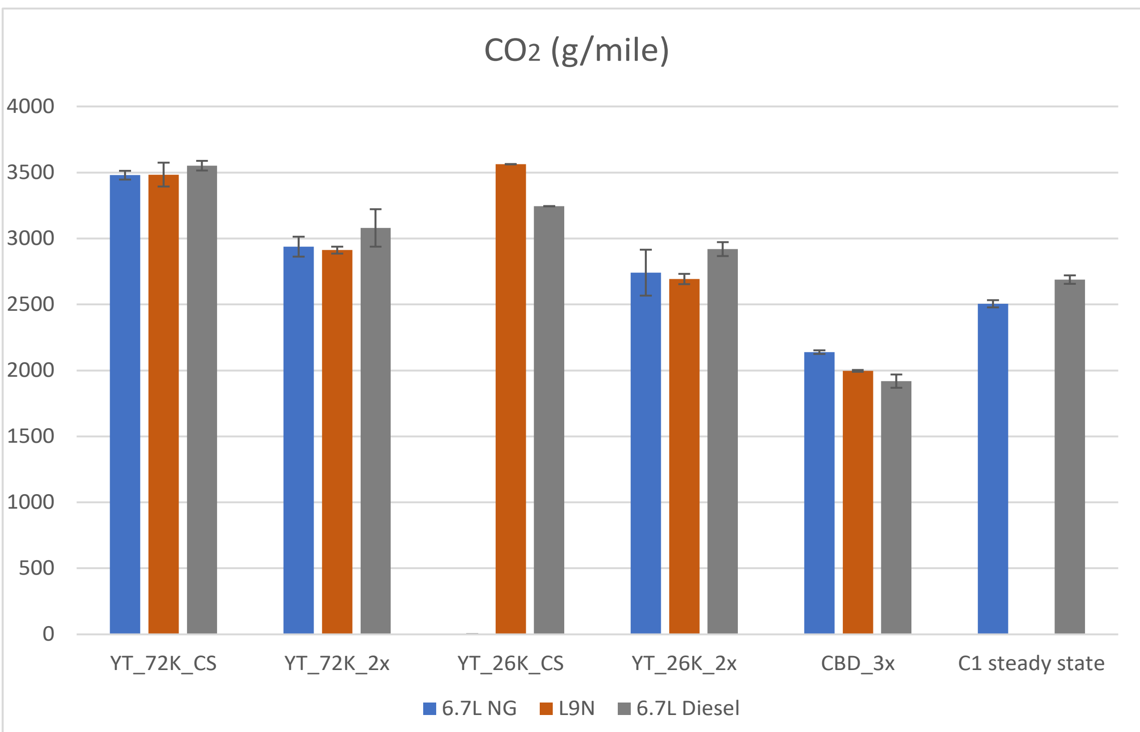
Source: University of California, Riverside

Carbon Dioxide Emissions

CO_2 emissions for the 6.7L LNG, 8.9L LNG and diesel yard tractors are shown on a g/bhp-hr and a g/mi basis in Figure A-15 (top) and (bottom), respectively. CO_2 emissions were more comparable between the different YTs. For the 6.7L LNG yard tractor, the average CO_2 emissions ranged from 607.3 to 918.1 on a g/bhp-hr basis and from 2139.7 to 3480.3 on a g/mi basis. For the 8.9L LNG yard tractor, the average CO_2 emissions ranged from 607.5 to 821.2 on a g/bhp-hr basis and from 1997.0 to 3563.3 on a g/mi basis. For the diesel yard tractor, the average CO_2 emissions ranged from 576.4 to 823.0 on a g/bhp-hr basis and from 1918.7 to 3551.4 on a g/mi basis. Overall, these levels below the range seen in previous studies of ultralow NOx CNG vehicles and 2010+ diesel vehicles (Jiang et al., 2018; Li et al., 2019; Zhu et al., 2020). For both 6.7L and the 8.9L LNG yard tractor, the highest emissions found for the YT_26K_2x cycles on a g/bhp-hr basis, while the YT_72K_CS, YT_72K_CS, and CBD_3x cycle showed lower emissions that were roughly comparable on a g/bhp-hr basis. For the diesel yard tractor, the highest emissions were found for the YT_26K_CS cycle, while the lowest emissions were found for the YT_72K_2x and CBD_3x cycles. On a g/mi basis, the YT_72K_CS and YT_26K_CS showed the highest emissions, while the CDB_3x showed the lowest emissions for each of the YTs.

Figure A-15: Average Carbon Dioxide Emissions for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors in g/bhp-hr (top) and in g/mile (bottom) units

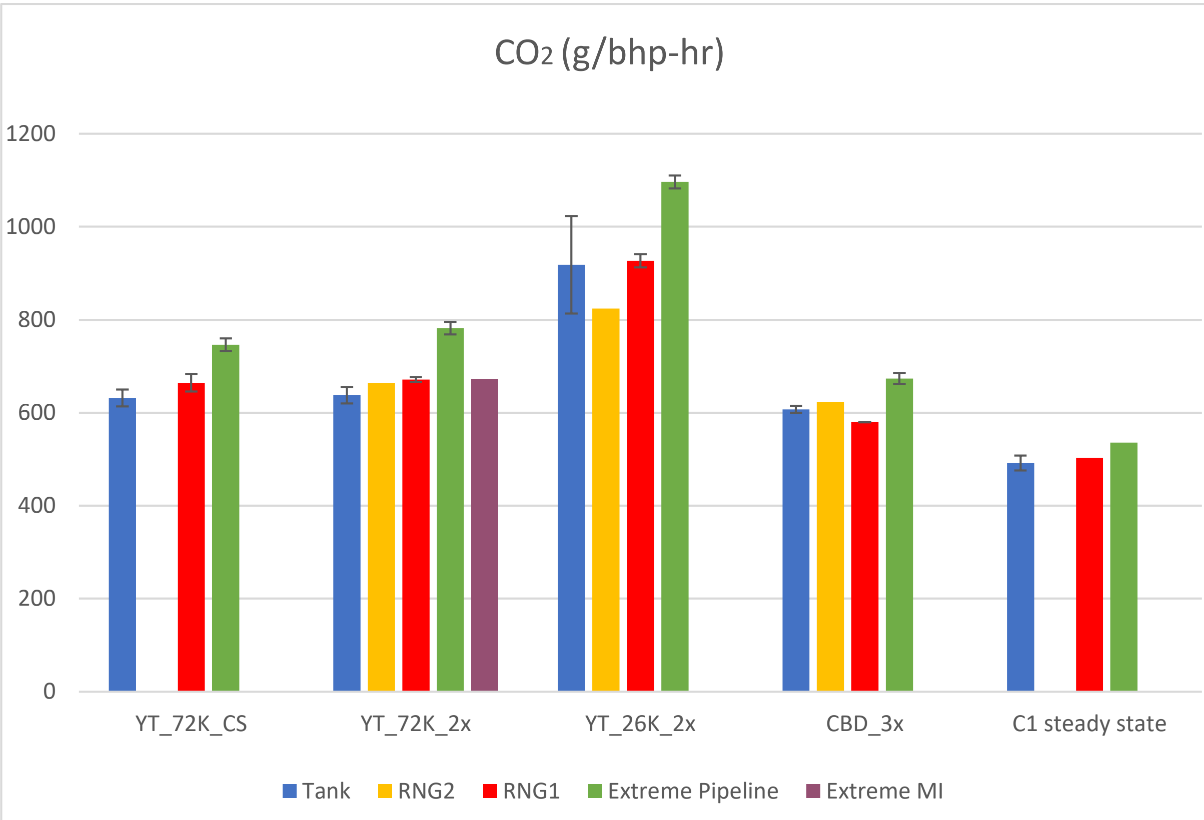




Source: University of California, Riverside

CO_2 emissions for the 6.7L LNG with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels are shown on a g/bhp-hr basis in Figure A-16. The results from Figure A-16 showed that the emissions from 6.7L LNG with Pipeline fuel were higher than the other RNGs for all cycles, whereas the other 3 blends and the Extreme MI fuel showed similar CO_2 emissions for all the cycles. The higher CO_2 emissions for the Extreme Pipeline fuel can be attributed to the higher carbon weight fraction of this fuel due to the lower fractions of methane compared to higher hydrocarbons. Although this difference was not seen for the Extreme MI fuel, this could be attributed to differences in the system calibration to the 0.02 g/bhp-hr NOx level. Previous studies of 0.2 g/bhp-hr NOx certified, stoichiometric TWC NG engine-equipped heavy-duty vehicles have not shown strong fuel effects for CO_2 emission (Hajbabaei et al., 2013; Karavalakis et al., 2016a & b).

Figure A-16: Average Carbon Dioxide Emissions for the 6.7L LNG Yard Tractor with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels



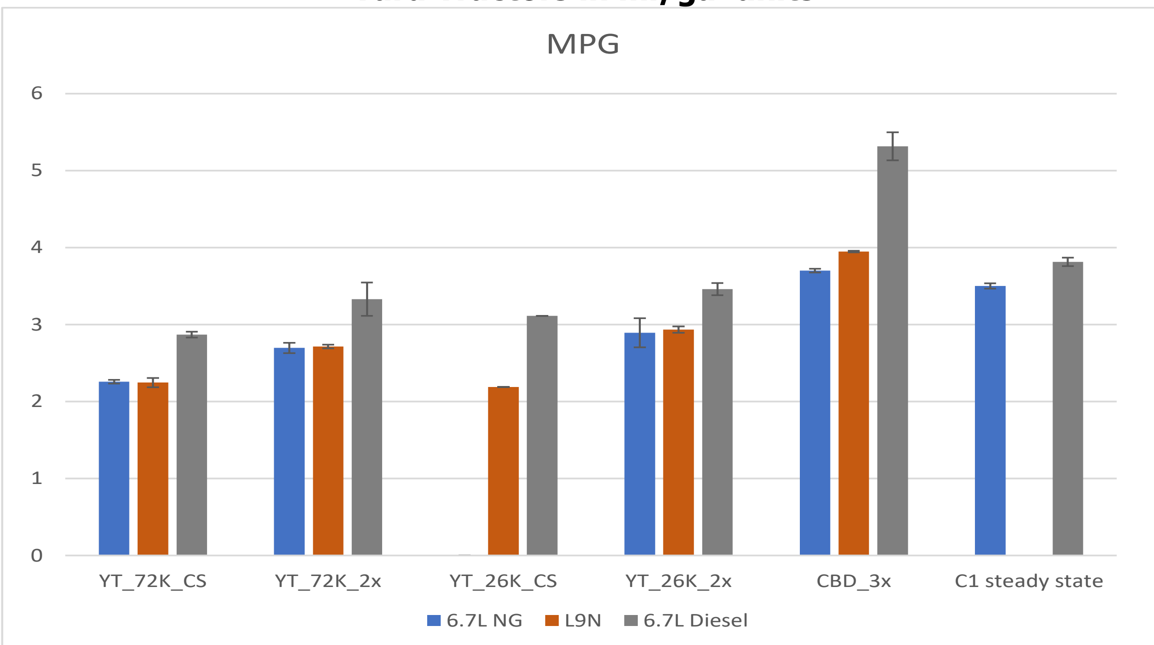
Source: University of California, Riverside

Fuel Economy

Fuel economy measurements for the 6.7L LNG, 8.9L LNG and diesel YTs are shown on a mi/diesel gallon equivalent basis in Figure A-17. The diesel YT showed consistently higher fuel economies than either of the LNG yard tractors. The 6.7L and 8.9L YT showed similar fuel economies for all of the cycles. The average fuel economy ranged from 2.25 to 3.70 mpg for the 6.7L LNG YT, ranged from 2.19 to 3.95 mpg for the 8.9L LNG YT, and from 2.87 to 5.32 mpg for the diesel yard tractor. The highest fuel economies were found for the CBD_3x for each of the YTs. Fuel economies for the other cycles were relatively comparable, although the hot start tests show slightly higher fuel economies compared to the cold start tests.

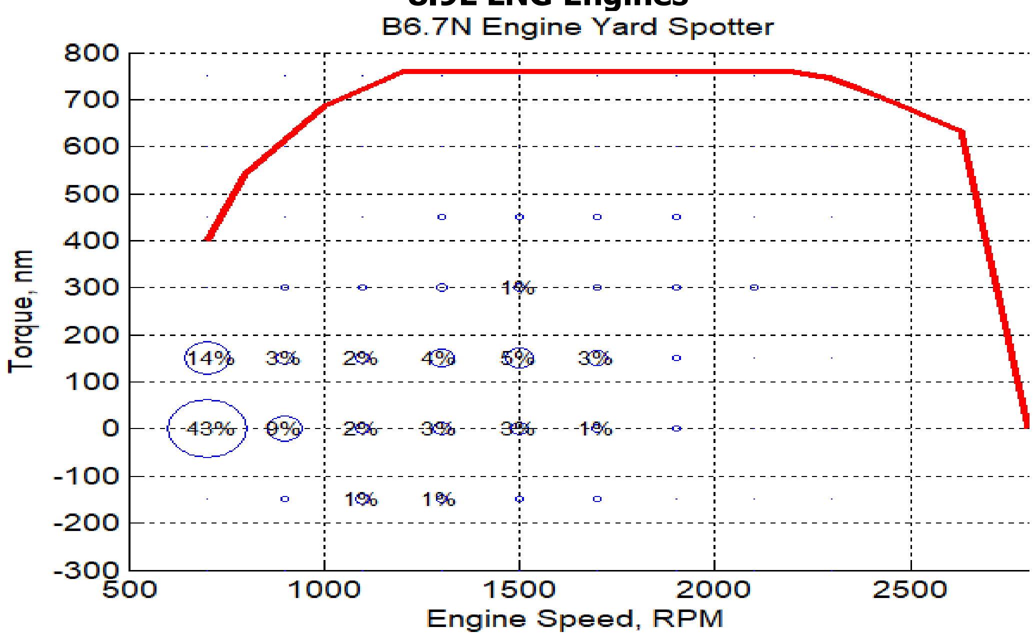
The fuel economy values for the 6.7L and 8.9L LNG YTs can be compared with theoretical values based on engine laboratory testing results. Engine testing results suggest that some benefits in fuel efficiency could be achieved with the 6.7L engines compared to the 8.9L engine, as shown in Figure A-18, but that these improvements are primarily in the lower load/idle ranges. The cycles utilized for the chassis dynamometer testing, however, did not contain a significant amount of time in this area of operation, as shown in Figure A-19. So, additional fuel economy benefits could be found under in-use conditions with high percentages of idle that were not incorporated into the chassis dynamometer test cycles used for the present study.

Figure A-17: Average Fuel Economy Rates for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors in mi/gal units



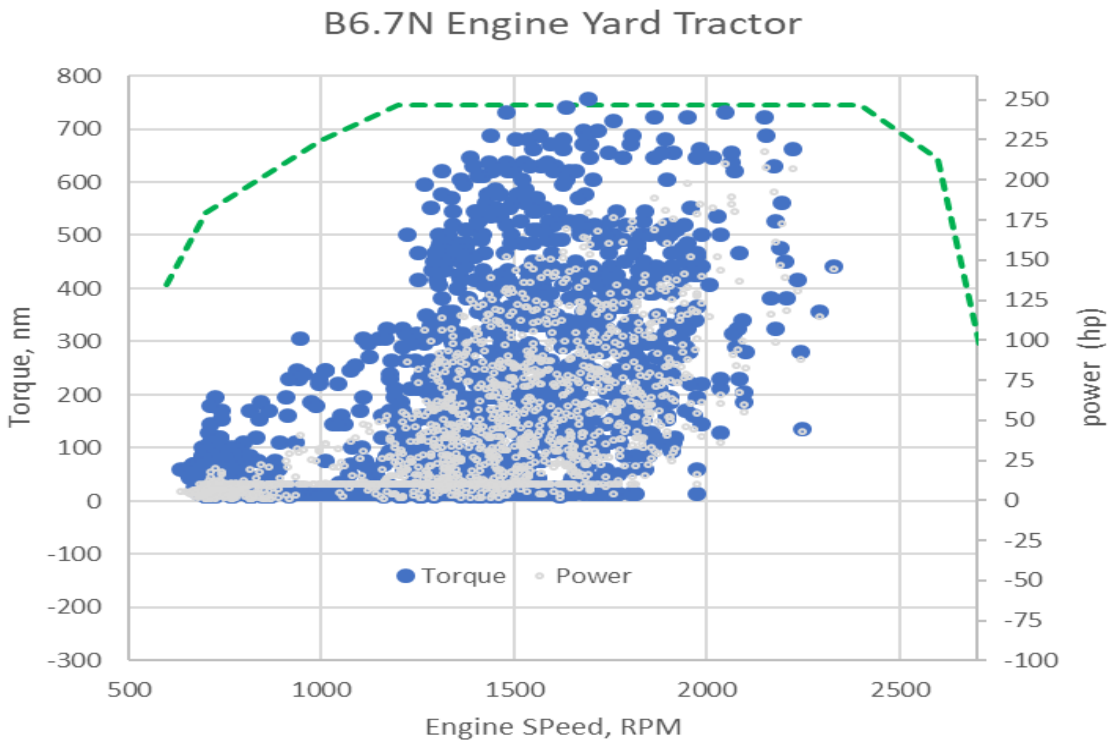
Source: University of California, Riverside

Figure A-18: Original Equipment Manufacturer Fuel Rate Percent Difference 6.7L to 8.9L LNG Engines



Source: Cummins Inc.

Figure A-19: Torque and Power Map for the 72,000 lb. Transient Test Cycle 6.7L LNG Engine



Source: University of California, Riverside

Unregulated Emissions

Ammonia Emissions

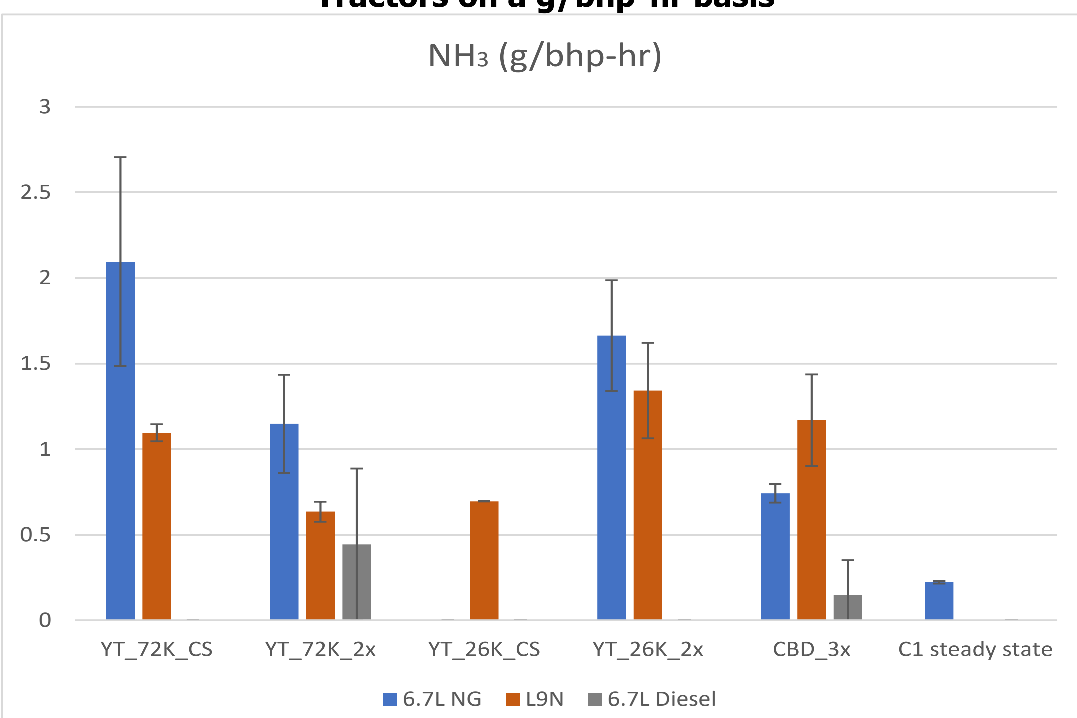
Ammonia (NH_3) emissions can be formed over TWCs and has been seen in previous studies of vehicles equipped with stoichiometric NG engines with TWCs, so measurements of NH_3 emissions were included as part the testing (Hajbabaei et al., 2013; Karavalakis et al., 2016a & b, Li et al., 2019; Zhu et al., 2020). NH_3 emissions can be attributed to byproduct reactions on the TWC between N from NO and hydrogen from water gas shift reactions (involving CO and H_2O) or steam reforming reactions (involving CH_4 and H_2O) (Durbin et al., 2003; Neeb et al., 2006 a & b; Shelef and Gandhi, 1974). NH_3 emissions for the 6.7L LNG, 8.9L LNG and diesel yard tractors are shown on a g/bhp-hr basis in Figure A-20. NH_3 emissions were higher for the LNG yard tractors than the diesel yard tractor for all the test cycles, with the section of the YT_72K_2x for the 8.9L LNG and diesel YTs. For the 6.7L and 8.9L LNG yard tractor, the average NH_3 emissions ranged from 0.742 to 2.094 and 0.635 to 1.342, respectively, on a g/bhp-hr basis, with the 6.7L LNG YT showing higher emissions for each of the cycles compared to the 8.9L LNG YT. High NH_3 emissions for NG vehicles with TWCs have been seen previously in other studies, with emissions levels in a similar range to those seen in the current study (Li et al., 2019; Zhu et al., 2020). For the diesel yard tractor, average NH_3 emissions ranged from 0.00025 to 0.444 on a g/bhp-hr basis.

For the 6.7L LNG yard tractor, the highest emissions were found for the YT_72K_CS cycle, with the lowest emissions for the C1 Steady-state cycle. For the 8.9L LNG yard tractor, the highest emissions were found for the YT_72K_CS cycle, while the NH_3 emissions for other cycles were comparable, with the lowest emissions for the YT_72K_2x cycle. For the diesel yard tractor, the highest emissions were found for the YT_72K_2x cycle followed by the YT_72K_CS cycle, with NH_3 emissions for the other cycles being near the measurement limits.

Real-time NH_3 emissions plots for the YT_72K_CS and YT_72K_2x cycles, as provided in Appendix E, show that the formation of NH_3 does not begin until approximately 100 seconds into the cycle, once the TWC is sufficiently warm to begin catalytic reaction. This trend is the opposite of what is seen for other pollutants because, unlike other pollutants, NH_3 is formed on the surface of the TWC, as opposed to in the combustion as for other pollutants. As such, NH_3 emissions only form after the catalyst is sufficiently warm to allow the nitrogen and hydrogen byproducts to recombine on the TWC surface to form NH_3. The formation of NH_3 after catalyst light-off has also been seen in other studies of vehicles with TWCs (Durbin et al., 2003).

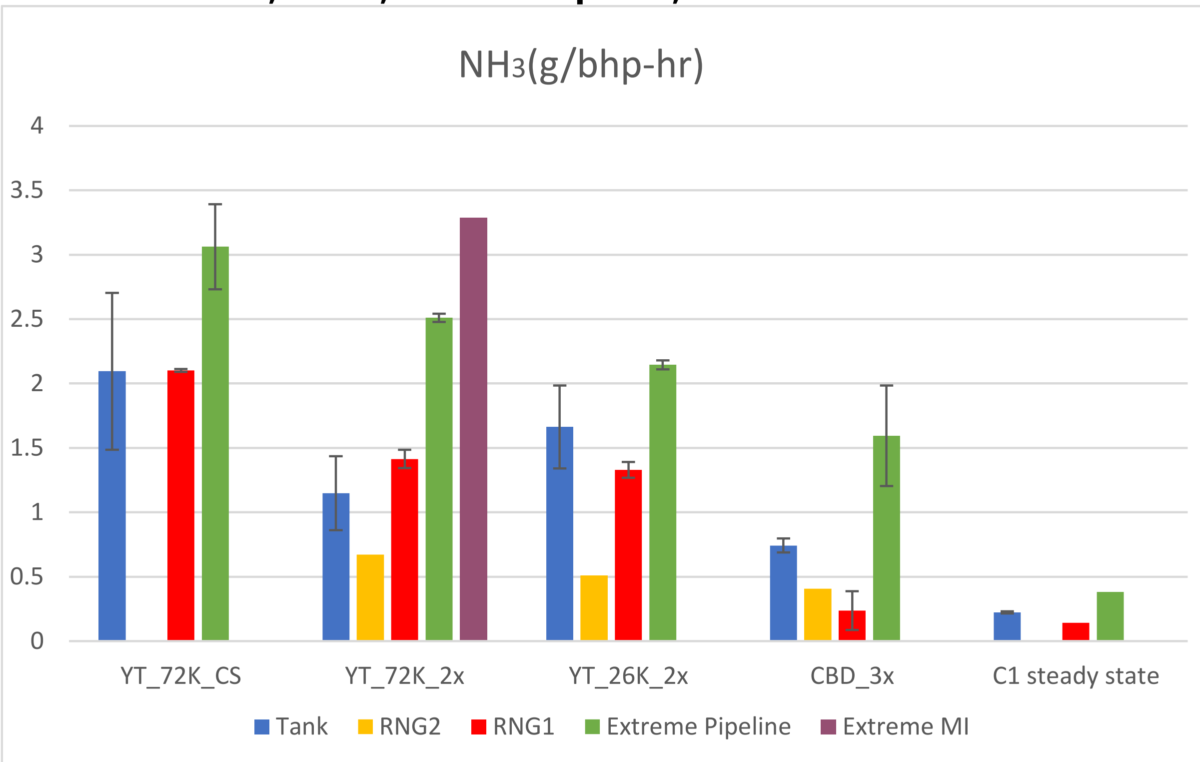
NH_3 emissions for the 6.7L LNG with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels are shown on a g/bhp-hr basis in Figure A-21. The results from Figure A-21 showed that the emissions from 6.7L LNG with the Extreme MI and Extreme Pipeline fuels were higher than the other RNGs and the tank fuel for all cycles. This is consistent with previous studies that have shown higher NH_3 emissions over a TWC are richer operating conditions (Huai et al., 2003; Neeb et al., 2006a), and with the CO fuel blend results, which suggested richer operation for the Extreme Pipeline and Extreme MI fuels. The tank fuel was higher than the RNG1 and RNG2 fuels for the YT_26K_2x and CBD cycles, but not consistently for the YT_72K_CS and YT_72K_2x cycles. Previous studies of 0.2 g/bhp-hr NOx certified, stoichiometric TWC NG engine-equipped heavy-duty vehicles have also shown some increases in NH_3 emissions for lower MI fuels (Hajbabaei et al., 2013; Karavalakis et al., 2016a & b).

Figure A-20: Average NH_3 Emissions for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors on a g/bhp-hr basis



Source: University of California, Riverside

Figure A-21: Average NH_3 Emissions for the 6.7L LNG Yard Tractor with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels



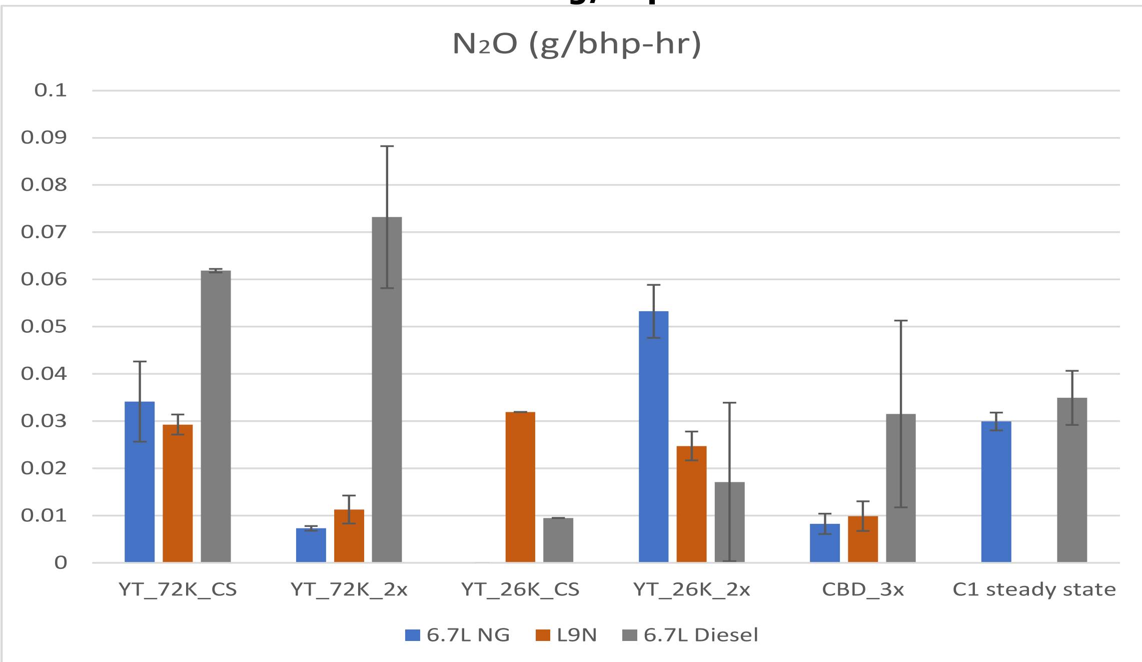
Source: University of California, Riverside

Nitrous Oxide Emissions

N_2O is an important greenhouse gas with a global warming potential 298 times greater than that of CO_2. N_2O emissions for the 6.7L LNG, 8.9L LNG and diesel yard tractors are shown on a g/bhp-hr basis in Figure A-22. N_2O emissions were relatively low for all YTs and all test cycles. Average N_2O emissions for the 6.7L LNG yard tractor, the 8.9L LNG yard tractor and the diesel yard tractor ranged 0.007 to 0.053, 0.001 to 0.034, and 0.017 to 0.073 on a g/bhp-hr basis, respectively. The N_2O emissions did not show consistent trends between the different YTs, with the diesel YT have the highest emissions for the YT_72K_CS, YT_72K_2x and CBD_3x cycles, the 6.7L LNG showing the highest emissions for the YT_26K_2x cycles, and the 8.9L LNG showing the highest emissions for the YT_26K_2x cycle.

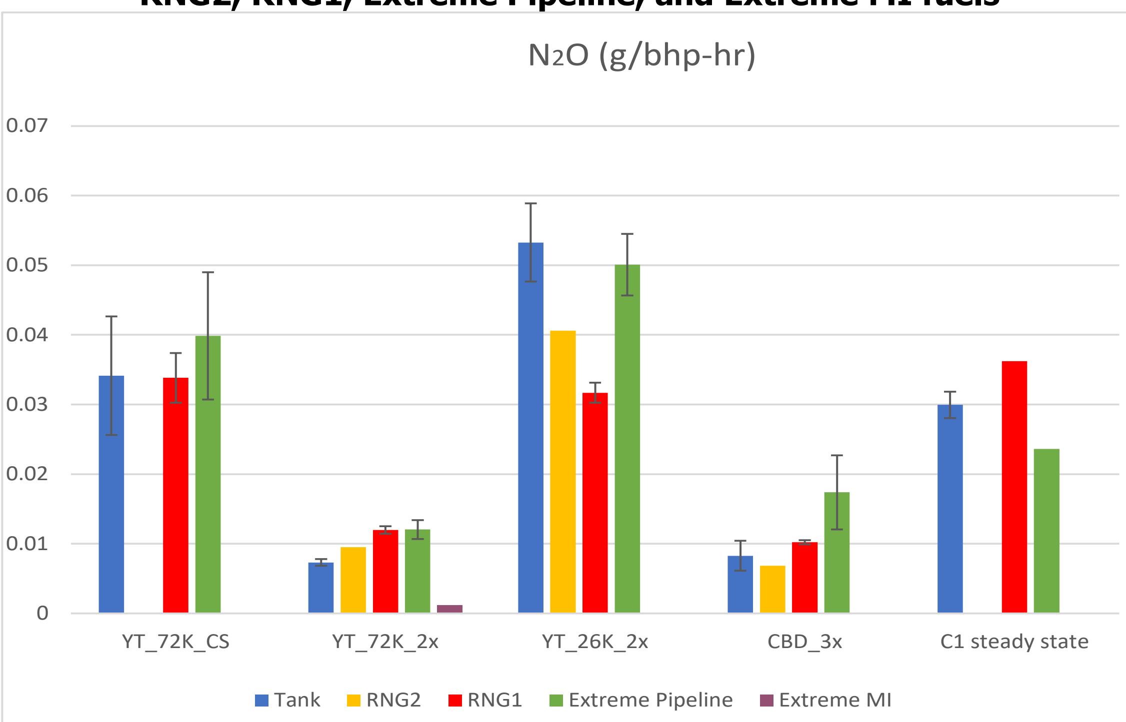
N_2O emissions for the 6.7L LNG with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels are shown on a g/bhp-hr basis in Figure A-23. The tank and pipeline fuels showed highest emissions for the YT_26K_2x cycle, and the Extreme Pipeline fuel showed the highest emissions for the CBD_3x cycle. N_2O emissions showed more comparable emissions between fuels for the YT_72K_CS and YT_72K_2x cycles. So, the fuels did not show consistent trends over the range of cycles evaluated. N_2O emissions for the Extreme MI fuel showed considerably lower emissions than the other fuels for the YT_72K_2x cycle, while could be due to the 0.02 g/bhp-hr NOx calibration rather than any specific fuel differences. Previous studies of 0.2 g/bhp-hr NOx certified, stoichiometric TWC NG engine-equipped heavy-duty vehicles have shown increases in N_2O emissions for lower MI fuels (Karavalakis et al., 2016b), but not for others (Karavalakis et al., 2016a).

Figure A-22: Average N_2O Emissions for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors on a g/bhp-hr basis



Source: University of California, Riverside

Figure A-23: Average N_2O Emissions for the 6.7L LNG Yard Tractor with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels

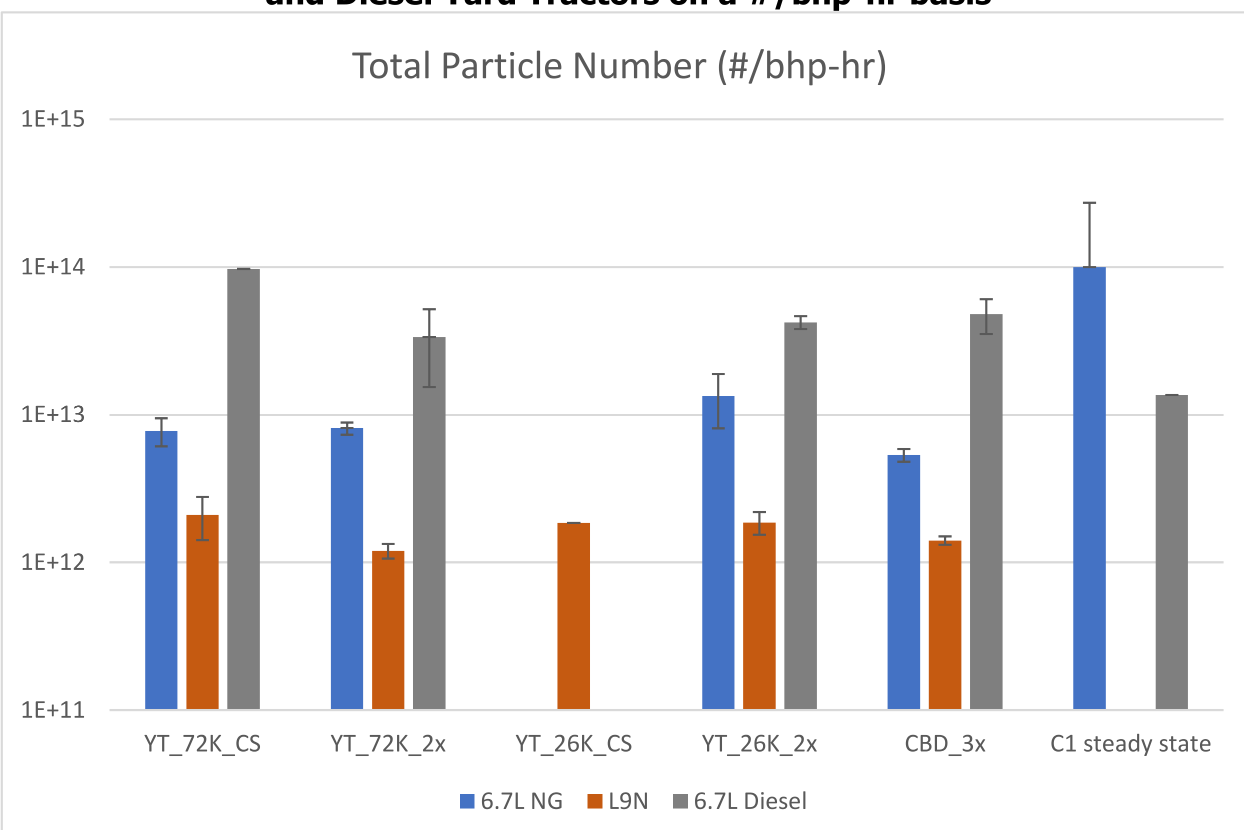


Source: University of California, Riverside

Total Particle Number Emissions

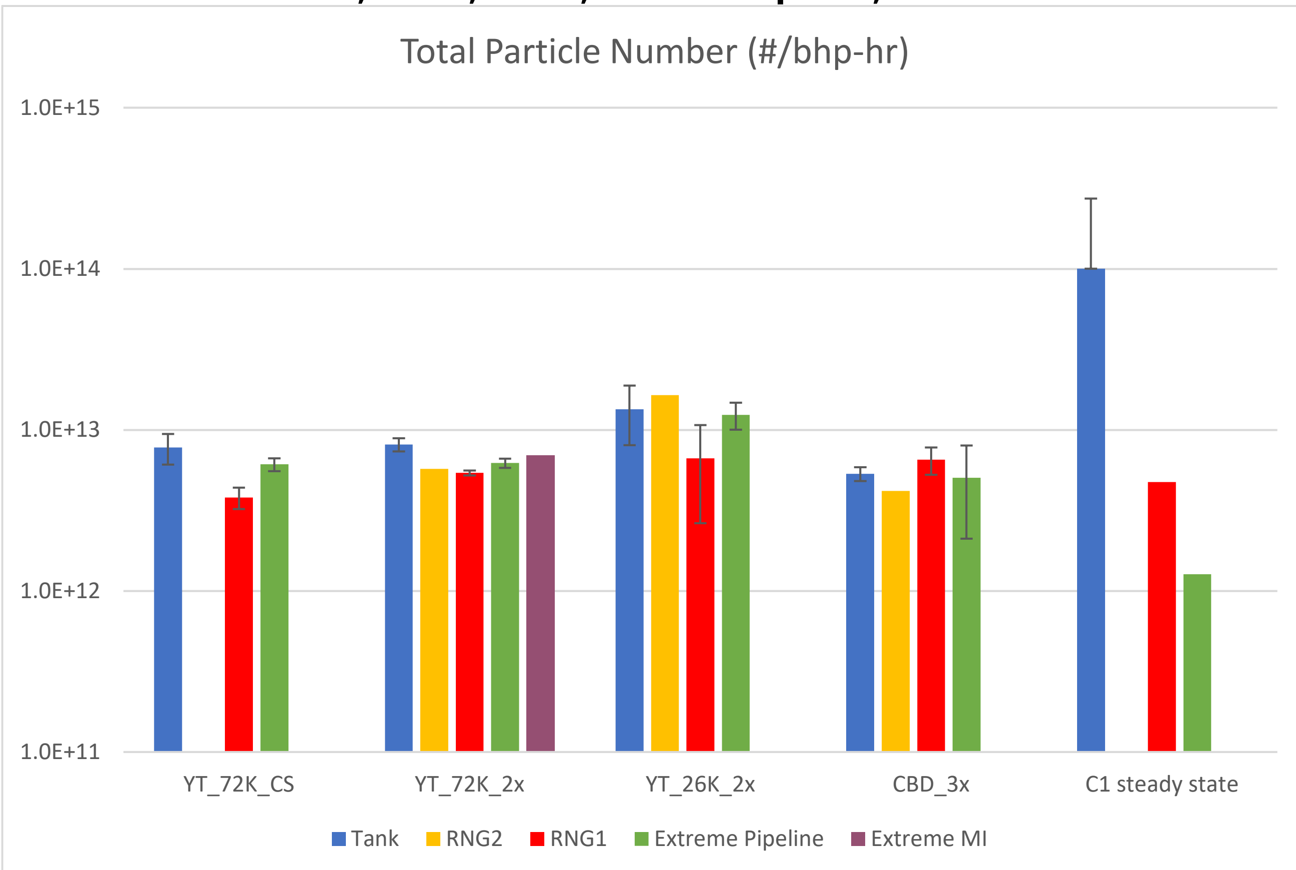
Total particle number emissions for the 6.7L LNG, 8.9L LNG and diesel yard tractors are shown on a #/bhp-hr basis in Figure A-24. Total particle number emissions were higher for the diesel yard tractor than the 6.7L and 8.9L LNG YTs for all test cycles. Average total particle emissions for the 6.7L LNG yard tractor, the 8.9L LNG yard tractor and the diesel yard tractor ranged from 5.34E+12 to 1E+14, from 1.20E+12 to 2.09E+12, and from 3.35E+13 to 9.72E+13 on a #/bhp-hr basis, respectively. Total particle number emissions were relatively comparable between the different cycles for the 6.7L and 8.9L LNG YTs, with the YT_26k_2x showing slightly higher emissions for the 6.7L LNG YT. The diesel YT also showed relatively similar emissions between cycles, with slightly higher emissions for the YT_72K_CS cycle. Total particle number emissions for the 6.7L LNG with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels are shown on a #/bhp-hr basis in Figure A-25. In general, the total particle emissions were comparable between the different fuels for the different test cycles, with no significant fuel trends. Previous studies of 0.2 g/bhp-hr NOx stoichiometric TWC NG engine-equipped heavy-duty vehicles have also not shown strong fuel effects for PN (Hajbabaei et al., 2013; Karavalakis et al., 2016a & b).

Figure A-24: Average Total Particle Number Emissions for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors on a #/bhp-hr basis



Source: University of California, Riverside

Figure A-25: Average Total Particle Number Emissions for the 6.7L LNG Yard Tractor with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels

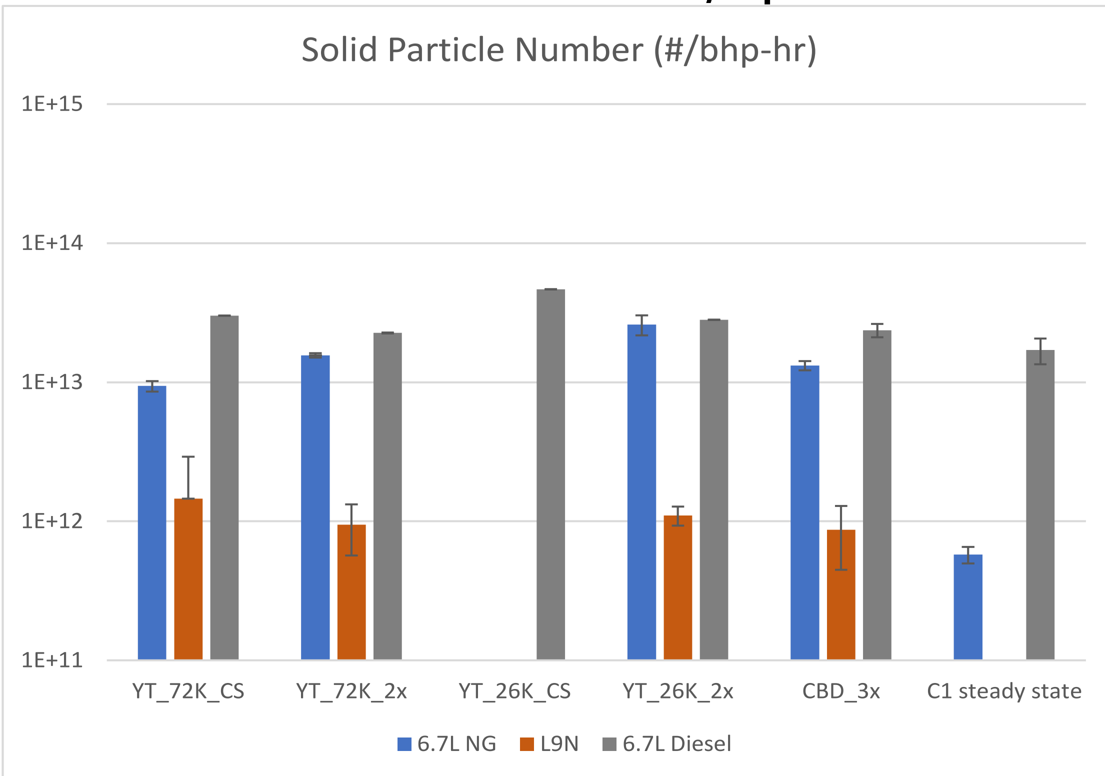


Source: University of California, Riverside

Solid Particle Number Emissions

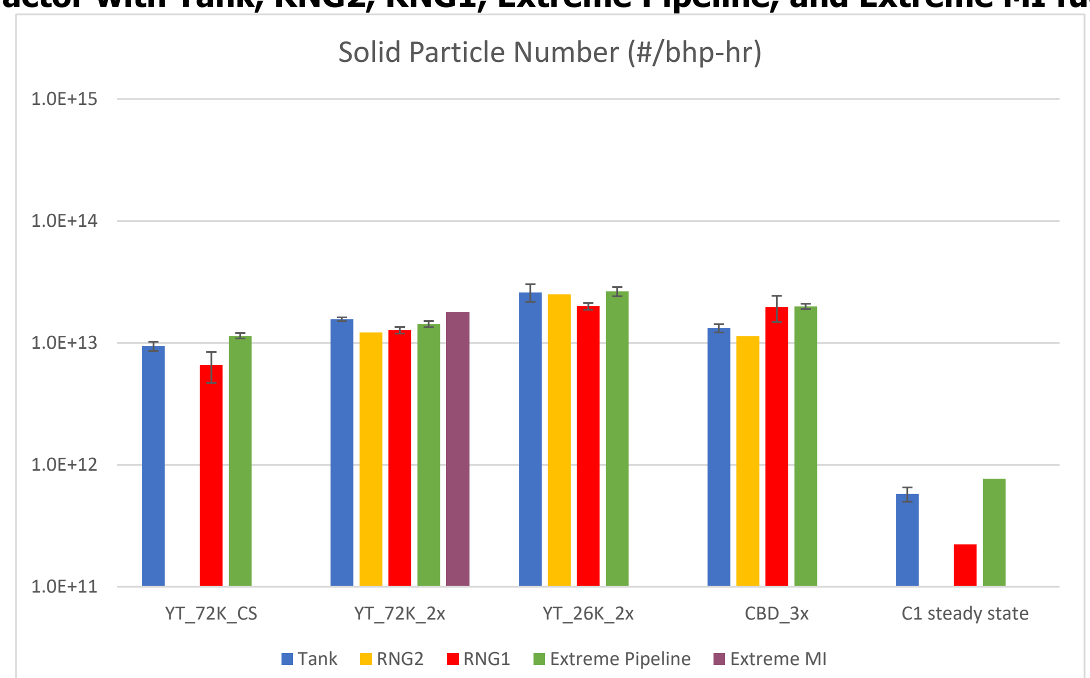
Solid particle number emissions for the 6.7L LNG, 8.9L LNG and diesel yard tractors are shown on a #/bhp-hr basis in Figure A-26. Solid particle number emissions were similar for the 6.7L LNG and diesel YTs with the diesel YT showing slightly higher emissions for some cycles, while the 8.9L LNG YT showed considerably lower emissions for all test cycles. Average solid particle emissions for the 6.7L LNG yard tractor, the 8.9L LNG yard tractor and the diesel yard tractor ranged from 5.77E+11 to 2.60E+13, 8.69E+11 to 1.45E+12, and 2.26E+13 to 4.65E+13 on a #/bhp-hr basis, respectively. Solid particle number emissions showed some differences between different cycles for different YTs, but overall the solid particle numbers were relatively similar between the different cycles. Real-time solid particle emissions plots for the YT_72K_CS and YT_72K_2x cycles, as provided in Appendix E, show that form throughout the course of the cycles, in contrast to other pollutants that show sharp decreases in emissions once the TWC has reached its light-off temperature. Total particle number emissions for the 6.7L LNG with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels are shown on a #/bhp-hr basis in Figure A-27. Overall, the solid particle number emissions did not show significant differences between different fuels over the different test cycles. Previous studies of 0.2 g/bhp-hr NOx stoichiometric TWC NG engine-equipped heavy-duty vehicles have not shown strong fuel effects for PN (Karavalakis et al., 2016b).

Figure A-26: Average Solid Particle Number Emissions for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractors on a #/bhp-hr basis



Source: University of California, Riverside

Figure A-27: Average Solid Particle Number Emissions for the 6.7L LNG Yard Tractor with Tank, RNG2, RNG1, Extreme Pipeline, and Extreme MI fuels



Source: University of California, Riverside

Conclusions

This study was conducted to evaluate the potential impact of different natural gas compositions on both the emissions and performance of heavy-duty natural gas engines and to provide a comparison between different YTs operating at the Everport Terminal at the Port of Los Angeles (POLA). Chassis dynamometer emissions tests were conducted on a OLNS 6.7L LNG YT, a NZE 8.9L LNG YT and a diesel YT, with addition testing conducted on the 6.7L LNG YT to evaluate the emissions impacts for different NG blends (tank, RNG2, RNG1, and pipeline). This testing provided a better understanding of the potential impacts of variable-quality NG, the response time for a current technology NG engine to adapt and learn to operate on different qualities of NG, and the basis for the continuing development of sensors and control systems for commercial NG engines.

A summary of the results of this study follows.

NOx emissions for the 6.7L and 8.9L LNG YTs were considerably lower than those for the diesel YT. The emissions for the LNG YTs were comparable to the emissions that they were certified to or less for most of the cycles, i.e., 0.1 g/bhp-hr and 0.02 g/bhp-hr, respective for the 6.7L and 8.9L LNG YTs, except some of the cold start cycles. NOx emissions for the LNG YTs were predominantly produced during the very initial portions of the cycles, with very limited emissions emitted throughout most of the rest of the cycles. For the testing on the fuel blends, the results showed some differences between fuels for the different cycles, but there were no consistent fuel trends.

Some additional tests were run to specifically look at the potential benefit for mitigating emissions increases that could occur during periods when engine knock is observed. Some additional tests were also conducted to evaluate the recalibration of the 0.1 certified LNG YT to 0.02 NOx g/bhp-hr. These additional tests were done on the 6.7L LNG YT on the Extreme MI fuel blend. For these tests, overall, the engine did not show significant differences between the 0.1 and 0.02 calibrations for NOx, with the exception of some lower emissions during the start for the 0.02 calibration. Additionally, there were not recorded signs of engine knock for the 6.7L engine tested.

Particulate mass (PM), total particle number, and solid particle number emissions were the lowest for the 8.9L LNG YT. The diesel and 6.7L LNG YTs showed considerably higher emissions than the 8.9L LNG YT for PM, total particle number, and solid particle number emissions, with the diesel YT generally showing slightly higher emissions than the 6.7L LNG YT. The PM emissions for the 8.9L LNG YT were from 0.9 to 1.4 on a mg/bhp-hr basis, which is about 10 times lower than the emissions standard, but comparable to what has been seen in other studies with low PM emitting NG and DPF-equipped diesel vehicles. The 6.7L LNG and diesel YT showed higher emissions, but these were also comparable to or below the 10 mg/bhp-hr certification level for all the non-cold start tests. The test fuels did not show consistent trends over the different cycles for PM, total particle number, or solid particle number emissions.

THC, CO and NH_3 emissions were all higher for the 6.7L and 8.9L LNG YTs compared to the diesel YT. The higher THC emissions for the LNG YTs can be attributed to the fact that LNG is primarily composed of methane. The higher CO emissions for the LNG YTs can be attributed to the LNG engine running stoichiometrically, which is richer than the lean conditions that the diesel engine operate under. The higher NH_3 emissions for the LNG YTs can be attributed to the chemical reactions on the TWC, which has been seen in other studies. Fuel differences were seen for CO and NH_3 emissions, with the lower MI in Extreme Pipeline, Extreme MI, and In Tank fuels showing higher emissions compared to the higher MI RNG blends. This suggests that the engine is running slightly richer for the lower MI fuels. There was also a trend of higher THC emissions for the in tank and Extreme Pipeline fuels for the YT_26k_2x cycle, but there were not consistent THC emissions for the different fuels over the other cycles.

The LNG YTs showed lower fuel economies than the diesel YT for all of the cycles, which is consistent with the generally higher efficiencies for diesel engines as compared to typical stoichiometric engines. CO_2 emissions were more comparable between the LNG and diesel YTs because the greater efficiency of the diesel engine is somewhat offset by the higher carbon intensity of diesel fuel compared to NG. Fuel economy and CO_2 emissions did not show significant differences between the 6.7L and 8.9L YTs, on the other hand. In comparing fuels, the Extreme Pipeline fuel showed higher CO_2 emissions than the other fuels for all cycles, whereas the other fuels showed similar CO_2 emissions for all the cycles. The higher CO_2 emissions for the Extreme Pipeline fuel can be attributed to the higher carbon weight fraction of this fuel due to the lower fractions of methane compared to higher hydrocarbons.

Overall, the results showed a good potential for LNG YTs to provide important reductions in NOx in port operations compared to diesel YTs, with almost no NOx emissions emitted after the YT was started for more than 50 seconds. The LNG YTs showed slightly lower CO_2 emissions and the potential for lower PM and particle number emissions compared to the diesel YT, although their fuel economy was slightly worse compared to the diesel YTs. Fuel properties did not have a significant impact on impact on NOx or PM-related emissions, suggesting that a fuel quality sensor may not provide significant near-term NOx benefits in this application. However, the higher emissions of CO and NH_3 with the lower MI fuels suggested the engine was running richer for those fuels.

As the range of applications and potential markets for NG engines continues to expand in the future, the issue of fuel quality for NG engines will likely remain important. Throughout the U.S., pipeline NG in many areas has higher levels of ethane and MIs near 75. The larger 8.9L and 12L NG engines are also more tightly calibrated compared to the 6.7L engine, and have less margin of error for knock. As such, fuel quality could have more significant impacts in these engines, and should be investigated further. In terms of applying a fuel quality sensor to a commercial on-highway engine, it would also still require additional development to achieve better accuracy ($\pm$2 percent) and to be producible at a viable cost point. NG engines for off-road applications or use in remote locations might benefit from a fuel quality sensor. Such engines could run on NG that is not as highly processed as typical pipeline quality NG or that could even be generated and used on site without any processing. In this application, a fuel quality sensor could make the use of NG generated on site in localized engines more viable, if appropriate adjustments could be made in the engine operation as the fuel quality changes. The potential for a fuel quality sensor in this application would have to further evaluated.

APPENDIX B: Test Cycle Descriptions

Yard Tractor Cycle

A yard tractor duty cycle was developed as part of a Hybrid Yard Tractor Demonstration and Commercialization Project funded by the Port of Long Beach (POLB), the Port of Los Angeles (POLA), and the U.S. Environmental Protection Agency (EPA) (CALSTART, 2011; McKain et al., 2009). The purpose of developing a yard tractor duty cycle is to be able to compare the relative emissions and fuel economy of hybrid yard tractors vs. diesel yard tractors at the chassis level. Note that there is currently no standard, chassis-level duty cycle specifically for yard tractors.

This duty cycle was developed based on yard tractor operation in a marine terminal environment. The Long Beach Container Terminal (LBCT) at POLB was selected as the site for the cycle development data logging, because it was considered to be representative of a typical small container handling marine terminal. It may also prove useful in representing other yard tractor applications, such as intermodal yards and/or distribution centers, however, these applications have not been investigated sufficiently to make such a determination yet. Additionally, it may be found that the distribution of loaded vs unloaded cycles may vary by distribution areas such as IKEA, thus these results represent best available assessment of emissions, GHG and cost benefits using the YT test cycles.

Technical Considerations

Yard tractors are heavy-duty vehicles used for moving cargo containers within port container terminals and other off-road areas. At any given time during the operation of a particular yard tractor, the physical load being pulled by the yard tractor can vary dramatically depending on the weights of the trailer and container connected to the tractor. In extreme cases, this weight difference can easily exceed 80,000 lb. Therefore it is necessary to know both the vehicle speed and the physical load (weight) of the trailer and container being pulled by the yard tractor at any given time as both have a significant effect on how hard the engine has to work, (which in turn directly affects emissions and fuel consumption). While the use of data loggers to collect vehicle speed vs. time data is common, determination of the vehicle physical load vs. time added significant complexity to the real-time data collection procedures.

Another technical issue associated with the yard tractor application is that yard tractors spend a significant portion of their operation in "creep" mode. "Creep" mode is informally defined as forward movement at speeds below 4 mph. (Note that 4 mph is approximately the lowest speed where the transmission can directly couple the engine speed to the drive train speed.) This frequently occurs while yard tractors are waiting in a queue to have a cargo container loaded or unloaded. Since GPS-based data loggers typically do not have the resolution to distinguish "creep" operation vs. a stopped or idling vehicle, additional vehicle instrumentation was necessary to identify real-time "creep" operation to ensure that it would be adequately represented in the final yard tractor duty cycle. Note that the loads on the vehicle's propulsion and auxiliary systems can be significantly different during "creep" vs. idle operation, which may in turn affect emissions and fuel consumption.

Yard Tractor Duty Cycle Statistics

There are three main categories of work that yard tractors perform: ship work, rail work and dock work (sometimes called yard work). Ship work and rail work involve a high degree of repetitive activities while dock work tends to involve more non-repetitive activities. Ship and rail work constituted the vast majority of all yard tractor activities at the terminal that was originally evaluated for the yard tractor cycles (about 95 percent). For these reasons, in-use data collection at the terminal focused on ship and rail activities, purposely excluding dock work activities. A summary of the key statistics associated with the yard tractor in-use data collected at terminal is given below:

Table B-1: Summary of Yard Tractor Activities

Parameter	All Activities	Rail Only	Ship Only
Avg. Speed	7.5 mph	8.9 mph	7.0 mph
Std. Dev. Speed	3.4 mph	4.2 mph	3.2 mph
Creep	21.4%	15.1%	23.3%
Idle	40.1%	31.7%	41.8%
Creep + Idle	61.5%	46.8%	65.1%

Source: University of California, Riverside

Yard Tractor Weight Categories

As a result of the significant variability in physical load (weight) of the yard tractor during operation and the constraints of typical heavy-duty chassis dynamometers, the yard tractor duty cycle was split into two (2) sub-cycles. Each sub-cycle corresponds to that portion of the yard tractor duty cycle associated with yard tractor operation in one of two (2) weight categories: medium-heavy duty and heavy-heavy duty. The "dividing line" between the medium-heavy duty and heavy-heavy duty weight categories was chosen as a Gross Combined Vehicle Weight (GCVW) of 20,040 kg. (44,181 lb.). The choice of this "dividing line" was based on an analysis of the combined vehicle, trailer and container weights of all potential tractor/trailer combinations. Average weights for each category were then calculated based on actual data as the number of pound-trips in each category divided by the total number of trips in each category. The results are as follows:

- Average weight for medium-heavy duty category: 11,888 kg. (26,209 lb.)
- Average weight for heavy-heavy duty category: 32,837 kg. (72,393 lb.)
- From the yard tractor in-use data collection, the actual percentage of time spent in each weight category was as follows:
- Percentage of time in medium-heavy duty category: 64.1%
- Percentage of time in heavy-heavy duty category: 35.9%

During previous testing of heavy-duty yard tractors, the weights and ABC coefficients in Table B-2 were used for yard tractors. These tractors were designed for GVWs of up to 80,000 lb. Other tractors may be rated at different capacities. When this occurs, it is recommended to test at both loads of full capacity (100 percent GVW) and 50 percent capacity (50 percent GVW).

Table B-2 Chassis dyno setup, cycles, and test weights utilized

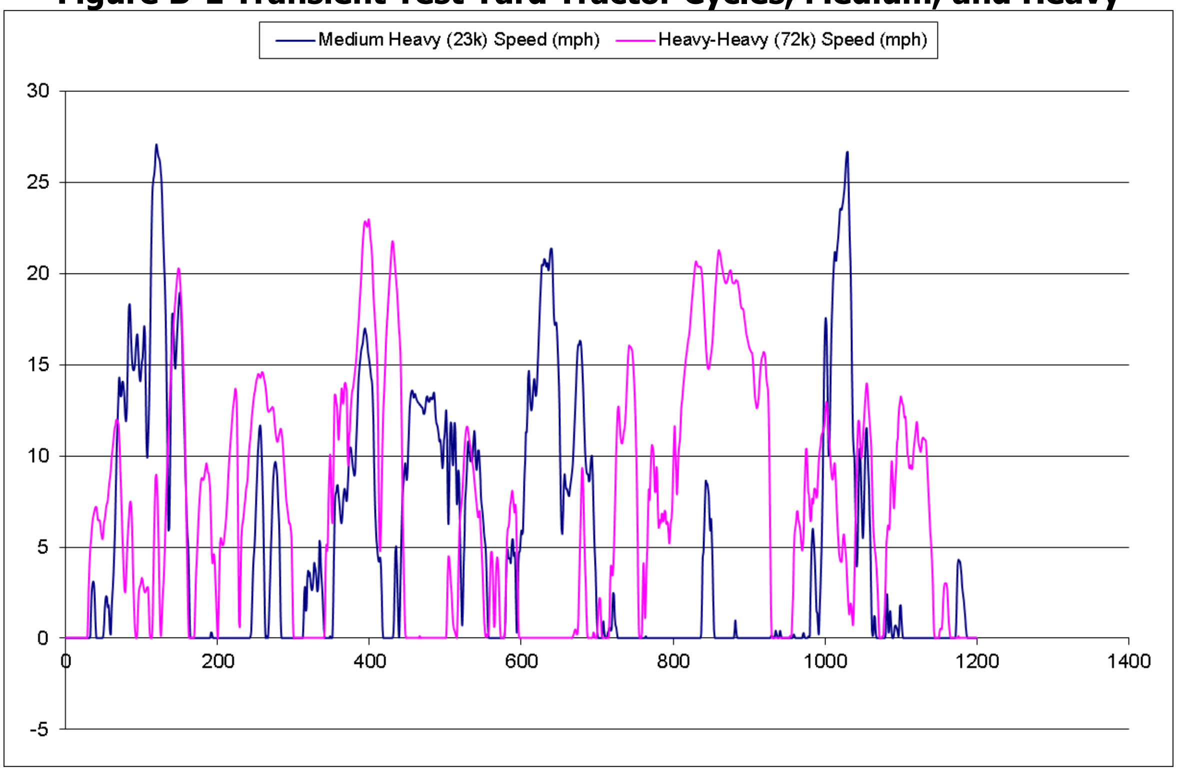
Test Cycle [1]	Abbreviated Test Name	HP @ 50	Test Weight [2]	A	B	C
Medium YT Transient (Modified)	YT6k_M	97.3	30000	213.07	-3E-13	0.2068
Heavy YT Transient (Modified)	YT72k_M	140.9	76000	539.79	1E-13	0.2068
Medium YT Transient	YT_26k	97.3	30000	213.07	-3E-13	0.2068
Heavy YT Transient	YT_72k	140.9	76000	539.79	1E-13	0.2068

[1] Test cycles are the standard and modified medium and heavy YT transient cycles. The modified were based on the maximum speed of 18 mph for legacy hybrid YT tested in 2010.

[2] Test weight of 26,000 lb and 72,000 lb are the baseline loads for the medium and heavy load cycle. The electric vehicle was ~4,000 lb heavier than the conventional so the utilized test weight was 26,000 lb+ 4,000 lb = 30,000 lb and 72,000 + 4,000 lb or 76,000lb.

Source: University of California, Riverside

Figure B-1 Transient Test Yard Tractor Cycles, Medium, and Heavy



Source: University of California, Riverside

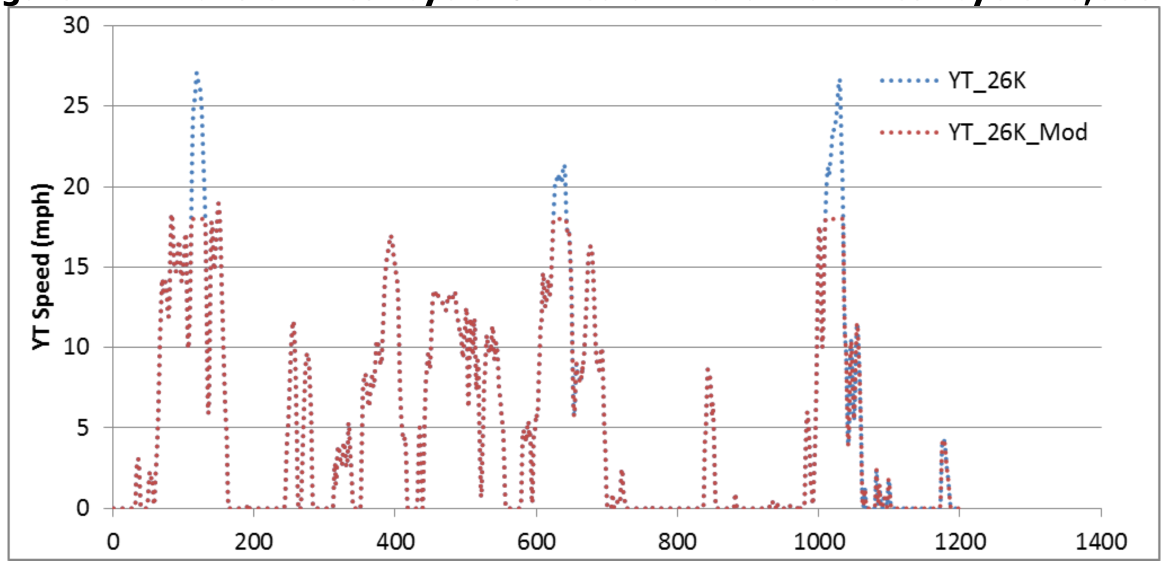
Table B-3: Summary of Cycle Statistics

Name	Fig Name	Total Time (Sec)	Total Time (hour)	Average Speed	Std. Dev. Speed	Distance	Max Acceleration	Max Speed
YT_Trans_76K	YT1_H	1200	0.333	7.12	6.46	2.37	3.14	23.01
YT_Trans_23k	YT2_L	1200	0.333	5.27	6.80	1.76	3.87	27.10

Source: University of California, Riverside

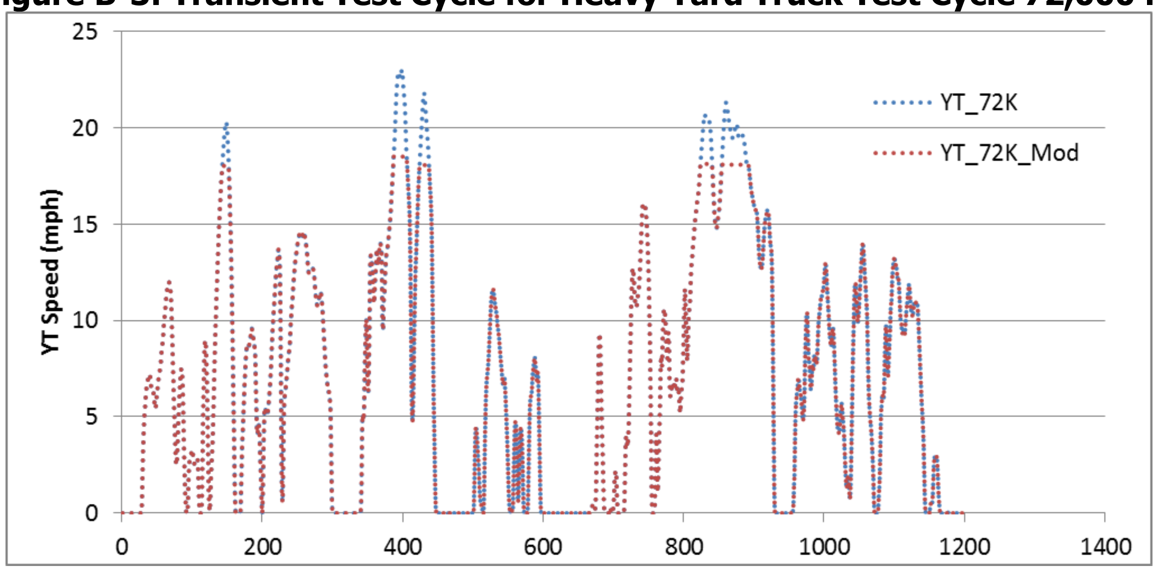
In some applications, YT that were speed governed not able to perform the YT cycle due to limited speeds below 18 mph. The next two figures (Figure B-2 and B-3) show how the original cycles were modified to reduce the maximum speed to 18 mph.

Figure B-2: Transient Test Cycle for Medium Yard Truck Test Cycle 26,000 lb



Source: University of California, Riverside

Figure B-3: Transient Test Cycle for Heavy Yard Truck Test Cycle 72,000 lb



Source: University of California, Riverside

Central Business District Cycle

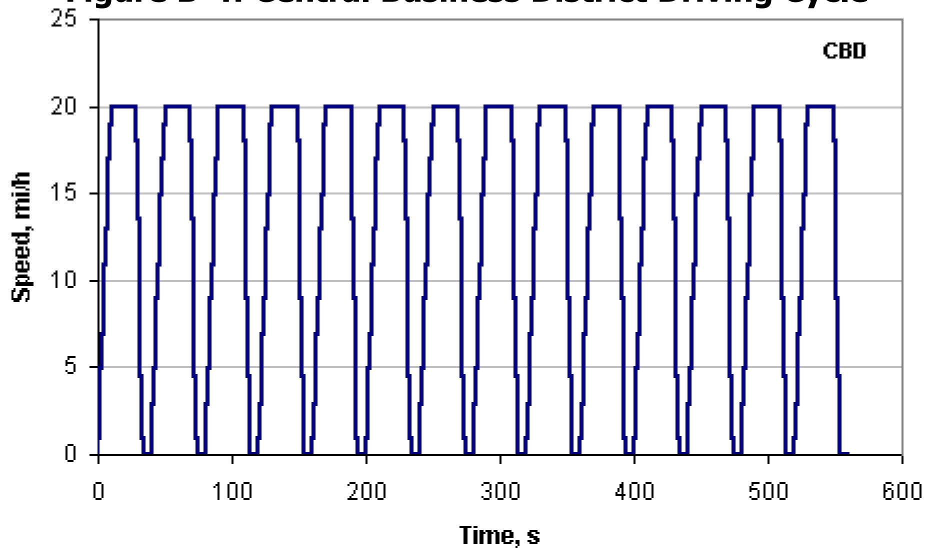
The Central Business District (CBD) Cycle is a chassis dynamometer testing procedure for heavy-duty vehicles (*SAE J1376*). The CBD cycle represents a "sawtooth" driving pattern, which includes 14 repetitions of a basic cycle composed of idle, acceleration, cruise, and deceleration modes. The following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

- Duration: 560 s
- Average speed: 20.23 km/h (12.6 mph)
- Maximum speed: 32.18 km/h (20 mph)

- Driving distance: 3.22 km (2.0 mi)
- Average acceleration: 0.89 m/s^2
- Maximum acceleration: 1.79 m/s^2

Vehicle speed over the duration of the CBD cycle is shown in Figure below.

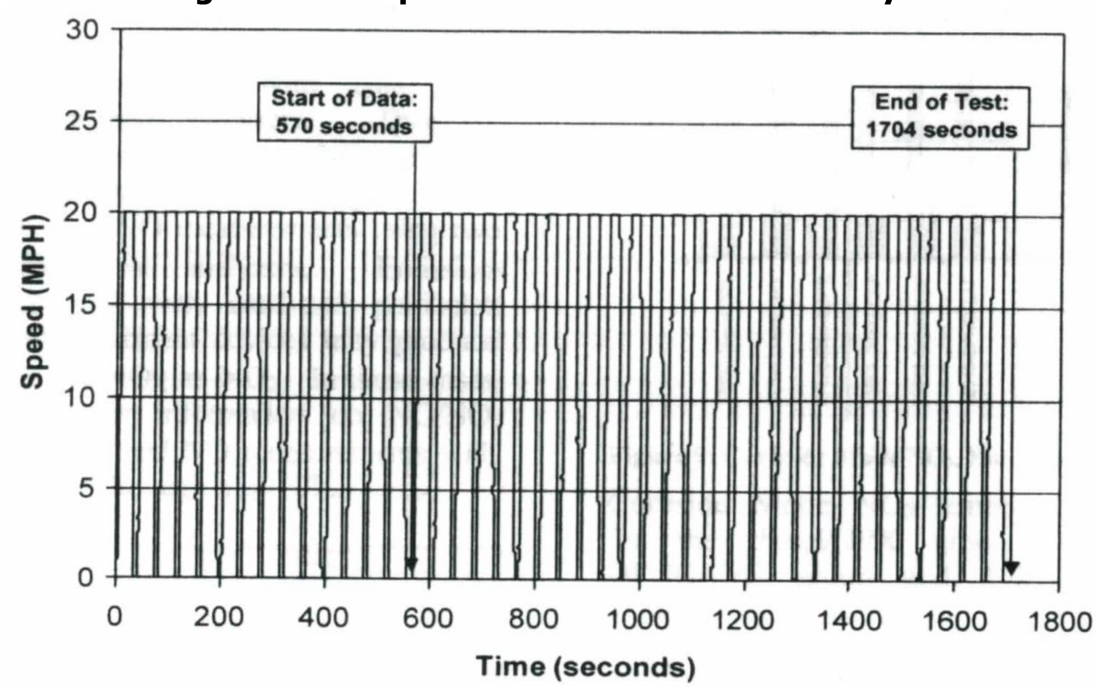
Figure B-4: Central Business District Driving Cycle



Source: Dieselnet.com

The standard CBD test cycle is used for bus testing where three cycles are combined for a triple CBD for a total sample time of 30 minutes. Performing the CBD cycle three times in one test allows for additional sample volumes to be collected for all batched type analysis (filters, DNPH, BETEX and N_2O). The test also involves preconditioning, which is defined as performing a previous triple CBD and a 20-minute soak to improve repeatability between hot repeats. Emissions analyses for gaseous emissions were also collected over the triple CBD cycles. This cycle is shown in Figure B-5.

Figure B-5: Triple Central Business District Cycle



Source: West Virginia University

Steady State 8-Mode Off-Road Cycle

The ARB 8–Mode Cycle for certifying off-road vehicles and diesel-powered off-road industrial equipment is the same as ISO-8178-C1[2] shown in Table B-4. According to Reference 6, specific examples are: industrial drilling rigs, compressors, construction equipment including wheel loaders, bulldozers, crawler tractors, crawler loaders, truck-type loaders, off-highway trucks, hydraulic excavators, agricultural equipment, rotary tillers, forestry equipment, self-propelled agricultural vehicles (including tractors), material handling equipment, fork-lift trucks, road maintenance equipment (motor graders, road rollers, asphalt finishers), snow-plough equipment, airport supporting equipment, aerial lifts, and mobile cranes. An example of an 8-mode test performed on a yard tractor is shown in Figure B-7.

Table B-4: Test Modes, Torque and Weighting Factors for the ISO-8178-C1 Cycle

Mode number (cycle B)	1	2	3	4	5	6	7	8	9	10	11
Mode number (cycle C1)	**1**	**2**	**3**		**4**	**5**	**6**	**7**			**8**
Speed 1)	Rated speed					Intermediate speed					Low-idle speed
Torque 1), %	100	75	50		10	100	75	50			0
Weighting factor	0,15	0,15	0,15		0,1	0,1	0,1	0,1			0,15

Source: International Standard Organization

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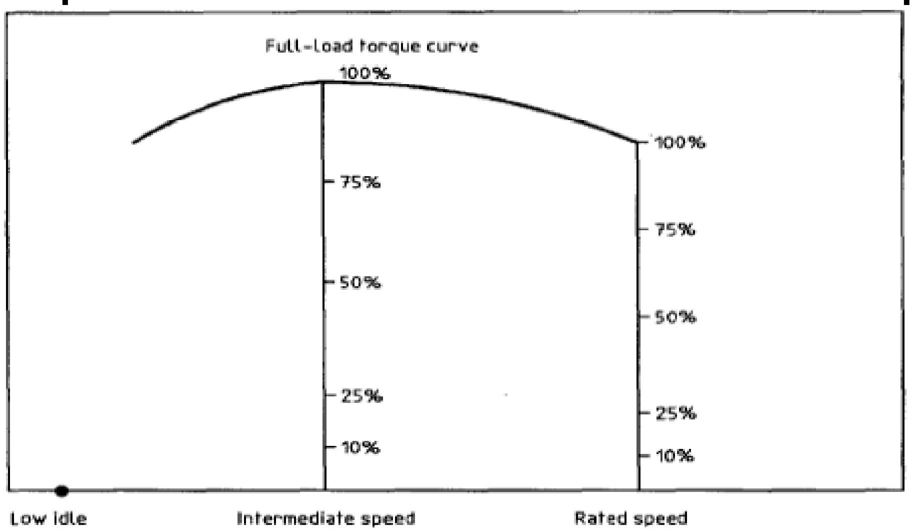
[2] International Standard Organization ISO 8178-4 *Reciprocating internal combustion engines - Exhaust emission measurement -Part 4:Test cycles for different engine applications*, First edition 1996-08-l 5

A more complete understanding of the definition of rated and intermediate speed is provided in the ISO reference[2] and captured in Figure B-6 below. While rated speed is the governed speed, intermediate speed is less obvious and defined as:

- For engines designed to operate over a speed range on a full-load torque curve, the intermediate speed is the declared maximum torque speed if it occurs between 60 percent and 75 percent of rated speed.
- If the declared maximum torque speed is less than 60 percent of rated speed, then the intermediate speed shall be 60 percent of the rated speed.
- If the declared maximum torque speed is greater than 75 percent of the rated speed then the intermediate speed shall be 75 percent of rated speed.

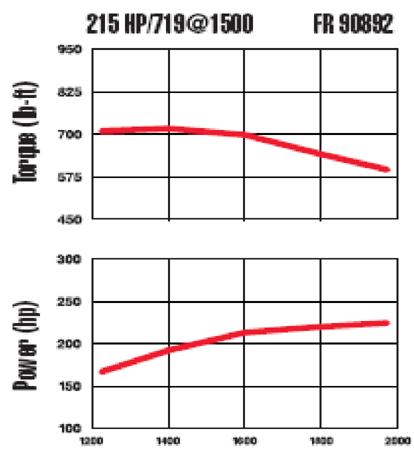
Figure B-6: Torque Scales and Location of Intermediate and Rated Speed Points.



Source: University of California, Riverside

Figure B-7: Example of the 8-Mode Test Performed on a Yard Tractor

Transmission mk/md/sn		Allison Automatic/MT643/2410500876			
Tire Circumference	130	80psi all tires			
Driver Name	John	Mode	RPM	HP	Duration
Date	12/14/2006	1	2200	107	5
Location	Johnson Powe	2	2200	80	5
YT Number	Ottawa #118	3	2200	54	5
Serial Number	46079183	4	2200	11	5 filt chng
Rated Speed/Load	215/2200	5	1800	83	5
Engine Model/Yr	Cum/C/2001	6	1800	62	5
Peak Torque,ft-lbs	719/1500	7	1800	42	5
Fuel	ULSD	8	1400	59	5 filt chng
Milage/hrs	10,333hr	9	700	0	8



Source: University of California, Riverside

APPENDIX C: Road Load Determination

Road load coefficients are important where at 65 mph the aerodynamic term accounts for 53 percent of the resisting force, rolling resistance 32 percent, driveline losses 6 percent and auxiliary loads at 9 percent. 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.[3] 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:

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

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 C-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 C-1 below. However, experience performing in-use coastdowns is complex and requires grades of less than 0.5 percent over miles of distance, average wind speeds < 10 mph ± 2.3 mph gusts and < 5 mph cross wind[4]. As such, performing in-use coastdowns in California where grade and wind are unpredictable can be unreliable, where a calculated approach is more consistent and appropriate. Additionally, vehicles equipped with automatic transmissions have shown that on-

3 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

4 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

road loading is also affected by the characteristics of the vehicle transmission, especially when reverse pumping losses at low speed begin to dominate.

UCR uses 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 C-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 (i.e., a certified SmartWay design) then a lower drag coefficient can be selected. Table C-1 lists the coefficients to use based on different ZET/NZET configurations. Once the coefficients are selected then they can be used in the above equation to calculate coastdown times to be used for calculating the A, B, C coefficients in Equation 2 for the dynamometer operation parameters. From these equations calculate the coastdown times from based on the coefficients in Table C-1 as shown in Table C-2 (65,000 lb, ustd, Cdstd and Table C-1). From Table C-2 one can plot the force (lb) vs average speed bin to get the ABC coefficients for the chassis dynamometer (see Figure C-2). These are the coefficients to enter into the chassis dynamometer to validate that the theoretical and actual coast down times are sufficiently well matched. This process is repeated until validation criteria is met. Typically, one or two iterations is needed to meet the validation criteria.

Table C-1 Constants and parameters for Class 8 HDTs

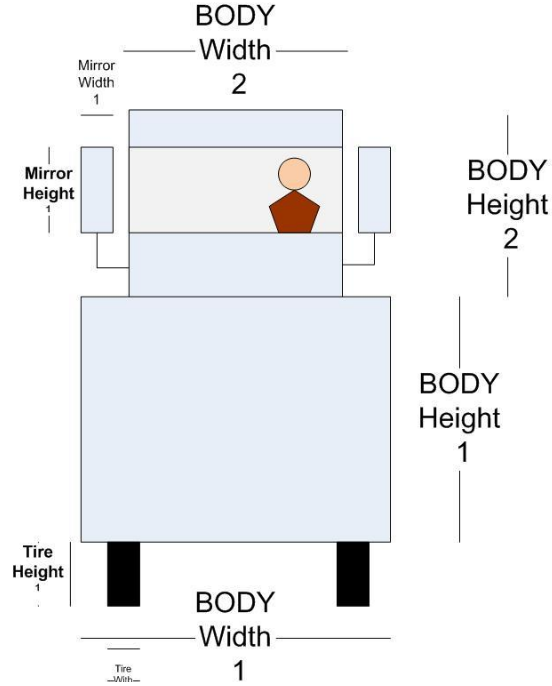
Variable	Value	Description
Θ	0	no grade in these tests
P	1.202	standard air density kg/m^3
μ_{std}	0.00710	standard tires
μ_{adv}	0.00696	low rolling resistant tires
C_{D_std}	0.750	for non-SmartWay tractor
C_{D_adv}	0.712	for SmartWay tractor
g	9.806	nominal value m/sec^2
M	Varies	mass: final test weight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

[1] The tire rolling resistance, μ, for low rolling resistant tires shows a 1-2% savings (ref SmartWay). As such, a μ of 0.00696 is utilized for low rolling resistant tires. Tractors may vary, but in this document the trailers are assumed to be similar. As such, if the tractor utilizes the certified SmartWay tractor type then the 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

Source: University of California, Riverside

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

Figure C-1: Vehicle Frontal Area Dimensions Method



Source: University of California, Riverside

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 C-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 C-2. The simulated force (lb) can be plotted on the y-axis vs truck speed (mph) on the x-axis. Using a best fit polynomial of order two, the polynomial coefficients A (0^{th} order term), B (1^{st} order term), and C (2^{nd} order term) can be calculated, see Figure C-2. These coefficients are entered into the chassis dynamometer and the coast down times are verified to match desired coast down times to within 5 percent. This is repeated as needed until the final coefficients are reported.

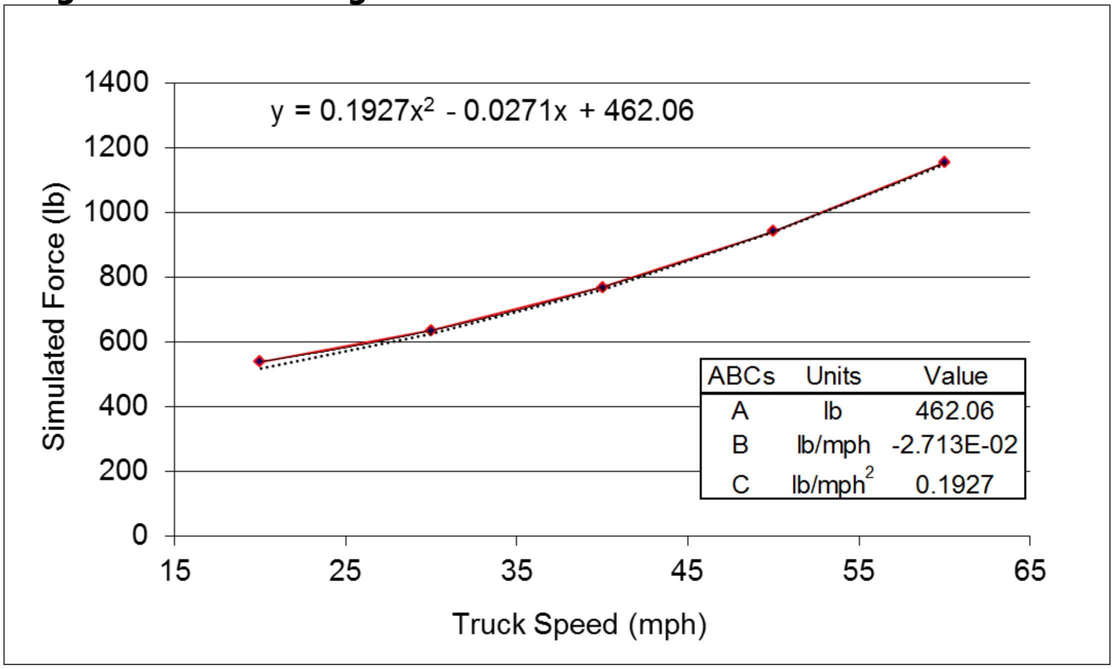
The calculation approach is consistent and has proven very reliable for chassis testing HDT and has been used for years by UCR and others.

Table C-2: Desired Coastdown Times for Class 8 Truck with Standard Components

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

Source: University of California, Riverside

Figure C-2: Resulting ABC Coefficients Based on Table C-2 Results



Source: University of California, Riverside

APPENDIX D: Detailed Test Results

Table D-1: Average and Standard Deviation Emission Factors of 6.7L LNG with Tank Fuel

6.7L CNG																		
Avg g/bhp-hr										CPC	APC	APC_CPC	MSS	Teflon	Ave g/mile		
Cycle Name	MPG	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_mg	PM_mg	Nox	CO2	gal/bhp-hr
YT_72K_CS	2.26	0.365	4.13	631.5	0.132	0.364	0.001	0.034	2.09	7.78E+12	9.4E+12	1.56E+13	2.81	9.83	0.730	3480.3	0.080
YT_72K_2x	2.70	-0.002	1.70	637.4	0.008	0.054	-0.057	0.007	1.15	8.11E+12	1.56E+13	1.86E+13	8.50	5.86	0.035	2937.2	0.081
YT_26K_2x	2.89	0.176	2.74	918.1	0.007	0.280	-0.105	0.053	1.66	1.34E+13	2.6E+13	3.34E+13	6.99	8.04	0.023	2740.9	0.116
CBD_3x	3.70	0.036	1.48	607.3	0.011	0.076	-0.040	0.008	0.74	5.34E+12	1.32E+13	1.47E+13	6.87	3.84	0.038	2139.7	0.077
C1 steady state	3.50	0.260	0.17	491.8	0.003	0.261	0.000	0.030	0.22	1E+14	5.77E+11	7.63E+11	0.26	9.74	0.014	2504.5	0.073

Std g/bhp-hr										CPC	APC	APC_CPC	MSS	Teflon	Std g/mile		
Cycle Name	MPG	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_g	PM_mg	Nox	CO2	gal/bhp-hr
YT_72K_CS	0.02	0.086	0.00	18.2	0.014	0.070	0.016	0.009	0.61	1.68E+12	8.2E+11	3.36E+12	0.92	5.05	0.106	33.5	0.002
YT_72K_2x	0.07	0.008	0.31	17.4	0.005	0.010	0.004	0.000	0.29	7.59E+11	5.85E+11	6.2E+11	0.30	1.04	0.021	75.6	0.002
YT_26K_2x	0.19	0.110	1.18	105.0	0.006	0.112	0.002	0.006	0.32	5.38E+12	4.29E+12	9.1E+12	2.05	2.04	0.021	174.0	0.013
CBD_3x	0.02	0.025	0.09	7.3	0.013	0.025	0.003	0.002	0.05	5.26E+11	1.02E+12	1.23E+12	0.72	0.01	0.046	13.6	0.001
C1 steady state	0.03	0.040	0.03	16.1	0.001	0.054	0.000	0.002	0.01	1.73E+14	7.77E+10	7.34E+10	0.02	4.79	0.005	27.9	0.002

Table D-2: Average and Standard Deviation Emission Factors of 8.9L LNG

L9N																	
Avg g/bhp-hr										CPC	APC	APC_CPC	MSS	Teflon	Ave g/mile		
Cycle Name	MPG	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_mg	PM_mg	Nox	CO2	gal/bhp-hr
YT_72K_CS	2.25	0.254	6.57	607.5	0.063	0.476	-0.235	0.029	1.09	2.09E+12	1.45E+12	2.13E+13	0.30	1.07	0.364	3484.1	0.078
YT_72K_2x	2.71	0.046	2.36	617.4	0.006	0.099	-0.056	0.011	0.64	1.2E+12	9.47E+11	1.09E+13	0.00	0.87	0.027	2911.8	0.078
YT_26K_CS	2.19	0.999	8.33	708.5	0.098	1.126	-0.152	0.032	0.70	1.85E+12			0.17	2.38	0.491	3563.3	0.091
YT_26K_2x	2.93	0.119	3.32	821.2	0.023	0.208	-0.094	0.025	1.34	1.86E+12	1.1E+12	3.62E+12	0.26	1.38	0.077	2693.7	0.104
CBD_3x	3.95	0.085	3.45	639.3	0.008	0.119	-0.037	0.010	1.17	1.41E+12	8.69E+11	3.06E+12	0.28	0.97	0.025	1997.0	0.081

Std g/bhp-hr										CPC	APC	APC_CPC		Teflon	Std g/mile		
Cycle Name	MPG	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3		PM	Nox	CO2	gal/bhp-hr
YT_72K_CS	0.06	0.243	0.86	9.3	0.008	0.031	0.279	0.002	0.05	6.81E+11	1.46E+12	6.04E+12	0.14	0.11	0.041	90.1	0.001
YT_72K_2x	0.02	0.004	0.17	6.0	0.005	0.047	0.047	0.003	0.06	1.36E+11	3.79E+11	9.14E+12	0.00	0.16	0.023	26.9	0.001
YT_26K_CS													0.00	0.00			
YT_26K_2x	0.04	0.054	0.34	27.5	0.003	0.052	0.006	0.003	0.28	3.23E+11	1.74E+11	8.98E+11	0.19	0.35	0.011	38.5	0.003
CBD_3x	0.01	0.052	0.24	29.2	0.007	0.054	0.003	0.003	0.27	9.02E+10	4.21E+11	1.11E+12	0.03	0.06	0.022	6.5	0.004

Table D-3: Average and Standard Deviation Emission Factors of 6.7L Diesel

Diesel																	
Avg g/bhp-hr										CPC	APC	APC_CPC		Teflon	Ave g/mile		
Cycle Name	MPG	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3		PM	Nox	CO2	gal/bhp-hr
YT_72K_CS	2.87	0.040	0.20	652.0	1.159	0.012	0.030	0.062	0.00	9.72E+13	3.01E+13	6.04E+13	10.44	13.26	6.317	3551.4	0.064
YT_72K_2x	3.33	0.021	-0.10	576.4	0.206	0.006	0.017	0.073	0.44	3.35E+13	2.26E+13	3.09E+13	5.64	6.58	2.219	3080.2	0.056
YT_26K_CS	3.11	0.061	1.06	822.9	2.711	0.015	0.048	0.010	0.00		4.65E+13	1.12E+14	0.00	19.27	10.693	3246.1	0.081
YT_26K_2x	3.46	0.060	0.03	692.9	3.029	0.020	0.043	0.017	0.00	4.22E+13	2.82E+13	3.91E+13	6.83	7.59	12.739	2919.7	0.075
CBD_3x	5.32	0.029	-0.09	576.6	1.117	0.007	0.023	0.032	0.15	4.79E+13	2.37E+13	3.46E+13	4.39	5.98	3.758	1918.7	0.057
C1 steady state	3.81	0.018	0.00	485.5	0.027	0.001	0.017	0.035	0.00	1.36E+13	1.71E+13	2.24E+13	5.04	5.65	0.150	2688.5	0.047

Std g/bhp-hr										CPC	APC	APC_CPC		Teflon	Std g/mile		
Cycle Name	MPG	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3		PM	Nox	CO2	gal/bhp-hr
YT_72K_CS	0.04	0.010	0.06	7.7	0.166	0.003	0.008	0.000	0.00			5.25E+12	2.06	2.13	0.913	36.8	0.001
YT_72K_2x	0.22	0.002	0.06	22.0	0.206	0.001	0.002	0.015	0.44	1.81E+13	1.43E+11	3.24E+09	0.11	0.59	0.000	142.5	0.003
YT_26K_CS																	
YT_26K_2x	0.08	0.002	0.05	3.7	0.251	0.002	0.003	0.017	0.00	4.25E+12		5.34E+12	0.08	0.27	0.764	51.6	0.011
CBD_3x	0.18	0.003	0.03	6.5	0.422	0.001	0.003	0.020	0.20	1.27E+13	2.56E+12	4.42E+12	0.32	0.59	1.511	49.8	0.001
C1 steady state	0.05	0.021	0.02	4.3	0.010	0.000	0.021	0.006	0.00		3.61E+12	4.25E+12	0.84	0.49	0.058	31.2	0.001

Table D-4: Average and Standard Deviation Emission Factors of 6.7L LNG with RNG2

RNG2													
Avg g/bhp-hr									CPC	APC	APC_CPC	MSS	Teflon
Cycle Name	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_mg	PM_mg
YT_72K_CS													
YT_72K_2x	-0.041	0.735	663.8	0.007	0.034	-0.062	0.010	0.671	5.74E+12	1.22E+13		3.26	3.38
YT_26K_2x	0.032	0.805	823.8	0.092	0.214	-0.117	0.041	0.509	1.65E+13	2.51E+13	4.55E+13	7.77	9.02
CBD_3x	0.012	0.523	623.5	0.030	0.062	-0.042	0.007	0.405	4.19E+12	1.13E+13	1.29E+13	2.28	2.96

Std g/bhp-hr									CPC	APC	APC_CPC	MSS	Teflon
Cycle Name	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_mg	PM
YT_72K_CS													
YT_72K_2x													
YT_26K_2x													
CBD_3x													

Table D-5: Average and Standard Deviation Emission Factors of 6.7L LNG with RNG1

RNG1													
Avg g/bhp-hr									CPC	APC	APC_CPC	MSS	Teflon
Cycle Name	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_mg	PM
YT_72K_CS	0.295	3.713	664.4	0.090	0.335	-0.040	0.034	2.102	3.81E+12	6.58E+12	1.01E+13	1.52	3.79
YT_72K_2x	0.010	1.073	671.2	0.025	0.056	-0.046	0.012	1.414	5.41E+12	1.27E+13	1.68E+13	3.42	3.40
YT_26K_2x	0.050	1.576	926.7	0.029	0.145	-0.096	0.032	1.329	6.68E+12	2E+13	2.71E+13	5.76	5.41
CBD_3x	0.017	0.409	579.8	0.018	0.054	-0.037	0.010	0.236	6.53E+12	1.96E+13	2.25E+13	6.02	5.86
C1 steady state	0.250	0.178	503.1	0.002	0.272	0.000	0.036	0.141	4.75E+12	2.23E+11	3.52E+11	0.23	4.87

Std g/bhp-hr									CPC	APC	APC_CPC	MSS	Teflon
Cycle Name	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_mg	PM
YT_72K_CS	0.036	0.372	19.1	0.007	0.028	0.008	0.004	0.012	5.77E+11	1.87E+12	2.66E+12	0.62	
YT_72K_2x	0.024	0.282	4.8	0.017	0.007	0.017	0.001	0.071	1.83E+11	8.1E+11	4.21E+11	0.43	0.21
YT_26K_2x	0.030	0.157	14.3		0.027	0.003	0.001	0.062	4.04E+12	1.31E+12	1.76E+12	0.72	0.21
CBD_3x	0.016	0.114	0.1	0.008	0.016	0.000	0.000	0.150	1.25E+12	4.77E+12	5.14E+12	2.08	1.70

Table D-6: Average and Standard Deviation Emission Factors of 6.7L LNG with Extreme Pipeline

Pipe													
Avg g/bhp-hr									CPC	APC	APC_CPC	MSS	Teflon
Cycle Name	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_mg	PM_mg
YT_72K_CS	0.320	7.803	746.0	0.063	0.299	0.021	0.040	3.062	6.11E+12	1.15E+13	1.61E+13	3.99	4.53
YT_72K_2x	0.007	2.704	781.8	0.004	0.062	-0.055	0.012	2.510	6.23E+12	1.43E+13	1.9E+13	3.84	3.79
YT_26K_2x	0.330	4.866	1096.4	0.016	0.435	-0.106	0.050	2.145	1.24E+13	2.65E+13	3.8E+13	8.03	8.07
CBD_3x	0.050	1.567	673.6	0.017	0.089	-0.040	0.017	1.594	5.06E+12	2E+13	2.43E+13	8.00	4.47
C1 steady state	0.000	0.451	535.9	0.003	0.239	0.237	0.024	0.380	1.27E+12	7.7E+11	1.68E+12	0.41	13.92

Std g/bhp-hr									CPC	APC	APC_CPC	MSS	Teflon
Cycle Name	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_mg	PM
YT_72K_CS	0.020	1.388	13.6	0.065	0.031	0.010	0.009	0.331	5.55E+11	5.8E+11	1.44E+12	1.29	0.47
YT_72K_2x	0.009	0.306	13.7	0.002	0.004	0.005	0.001	0.031	4.04E+11	8.2E+11	1.23E+12	0.23	0.50
YT_26K_2x	0.064	0.451	13.9	0.016	0.064	0.001	0.004	0.035	2.35E+12	2.3E+12	6.23E+12	0.31	0.05
CBD_3x	0.053	0.808	11.8	0.007	0.049	0.004	0.005	0.390	2.94E+12	9.83E+11	9.99E+11	0.03	0.61

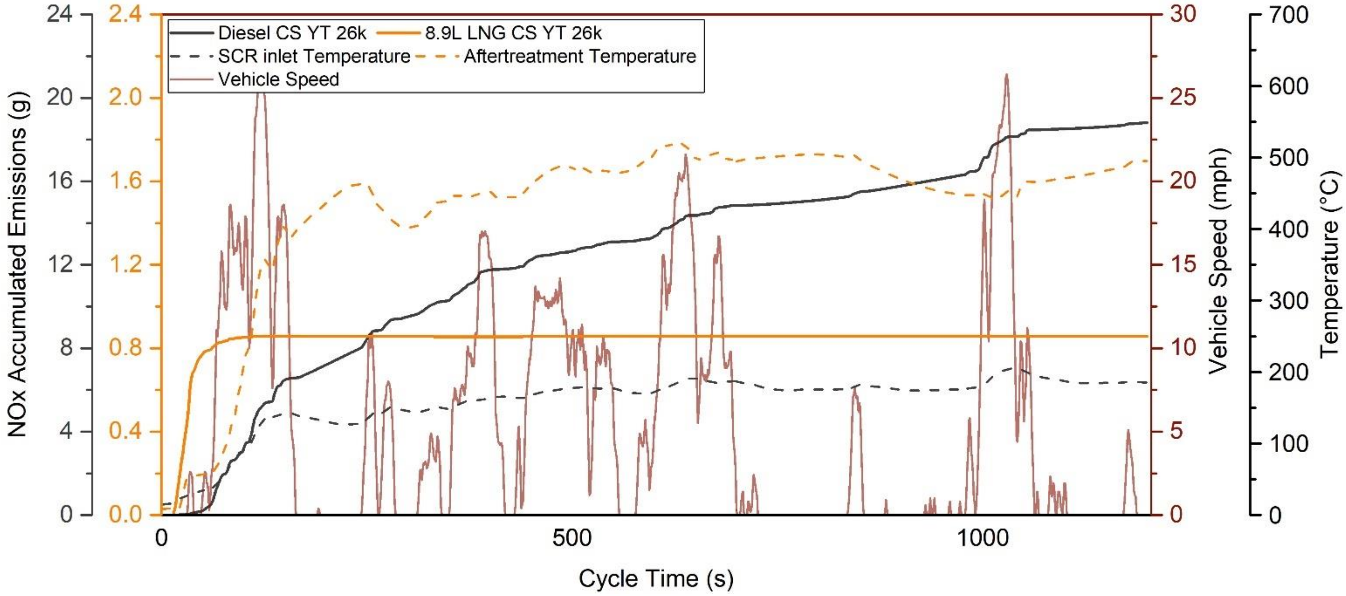
Table D-7: Average and Standard Deviation Emission Factors of 6.7L LNG with Extreme MI

ExtreMI													
Avg g/bhp-hr									CPC	APC	APC_CPC	MSS	Teflon
Cycle Name	THC	CO	CO2	NOx Raw	CH4	NMHC	N2O	NH3	TPN_3	SPN_23	SPN_3	eBC_mg	PM_mg
YT_72K_2x	0.110	3.161	672.9	0.002	0.167	-0.106	0.001	3.286	6.96E+12	1.79E+13	2.24E+13	4.72	5.10

Std g/bhp-hr													
Cycle Name													
YT_72K_2x	0.074	0.853	4.5	0.001	0.066	0.060	0.001	0.100	1.64E+11	1.63E+12	9.55E+11	0.47	0.39

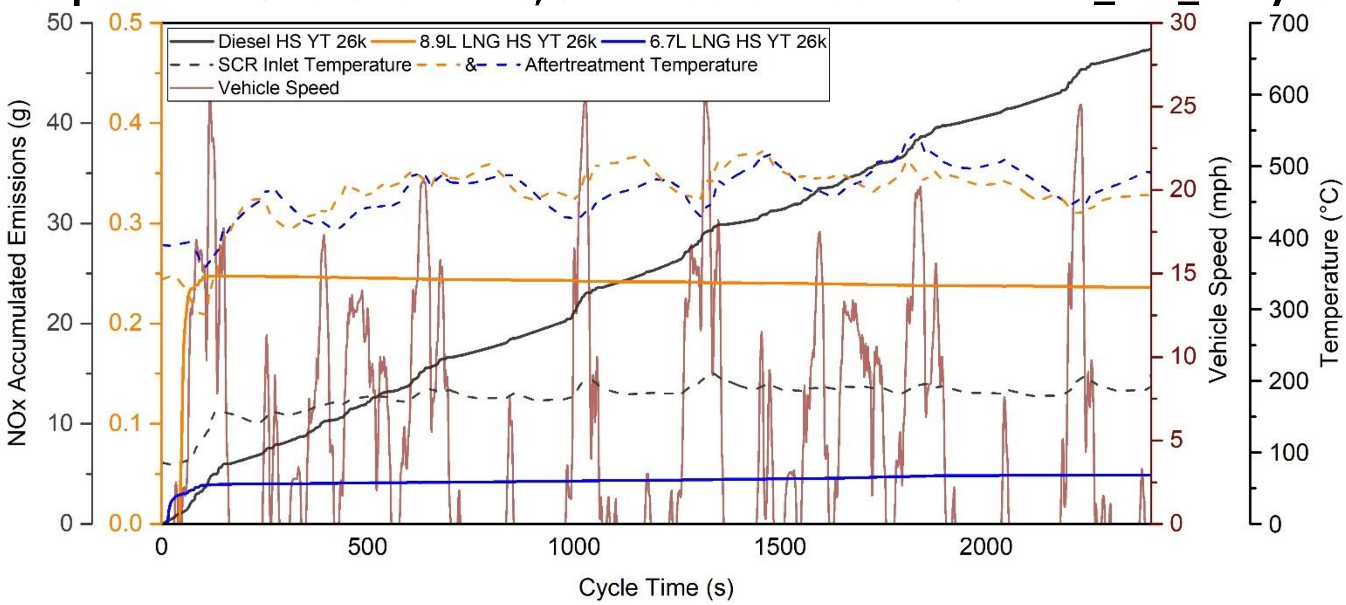
APPENDIX E:
Real-Time Plots

Figure E-1: Real-time Cold Start NOx Emissions, Cycle Trace and Aftertreatment Temperature Profile for 8.9L LNG and Diesel YT for the YT_26K_CS Cycle.



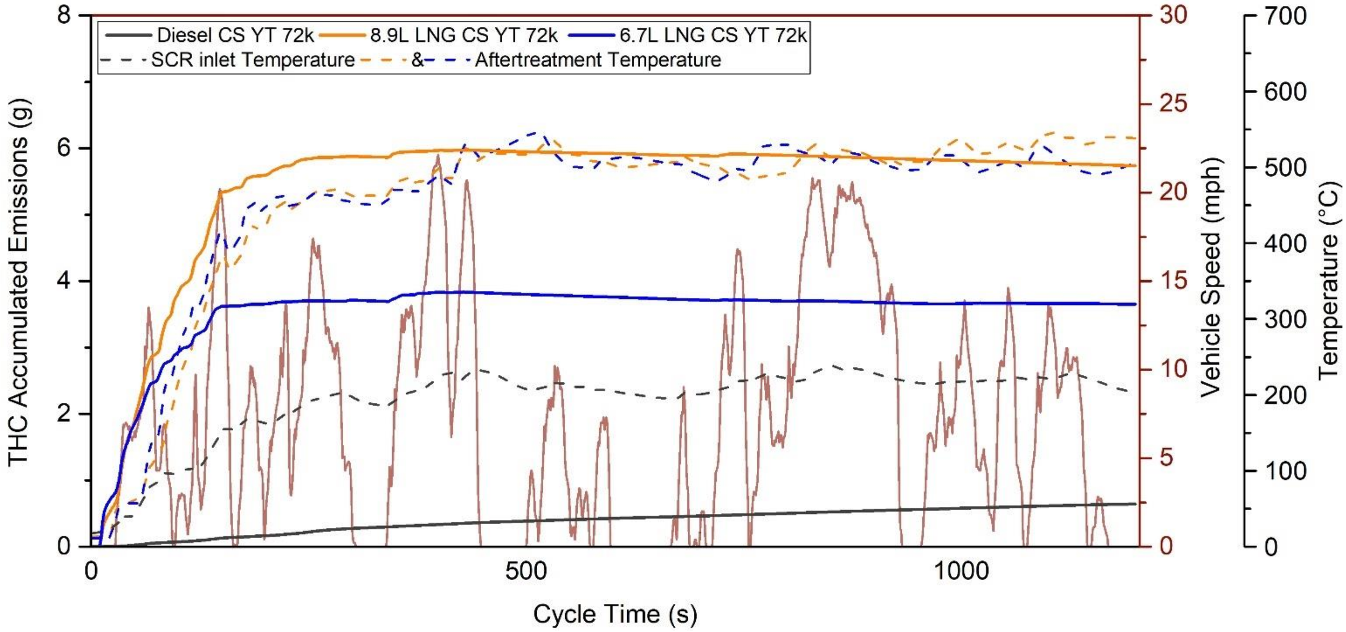
Source: University of California, Riverside

Figure E-2: Real-time Hot Start NOx Emissions, Cycle Trace and Aftertreatment Temperature Profile for 6.7L LNG, 8.9L LNG and Diesel YT for the YT_26K_2x Cycle.



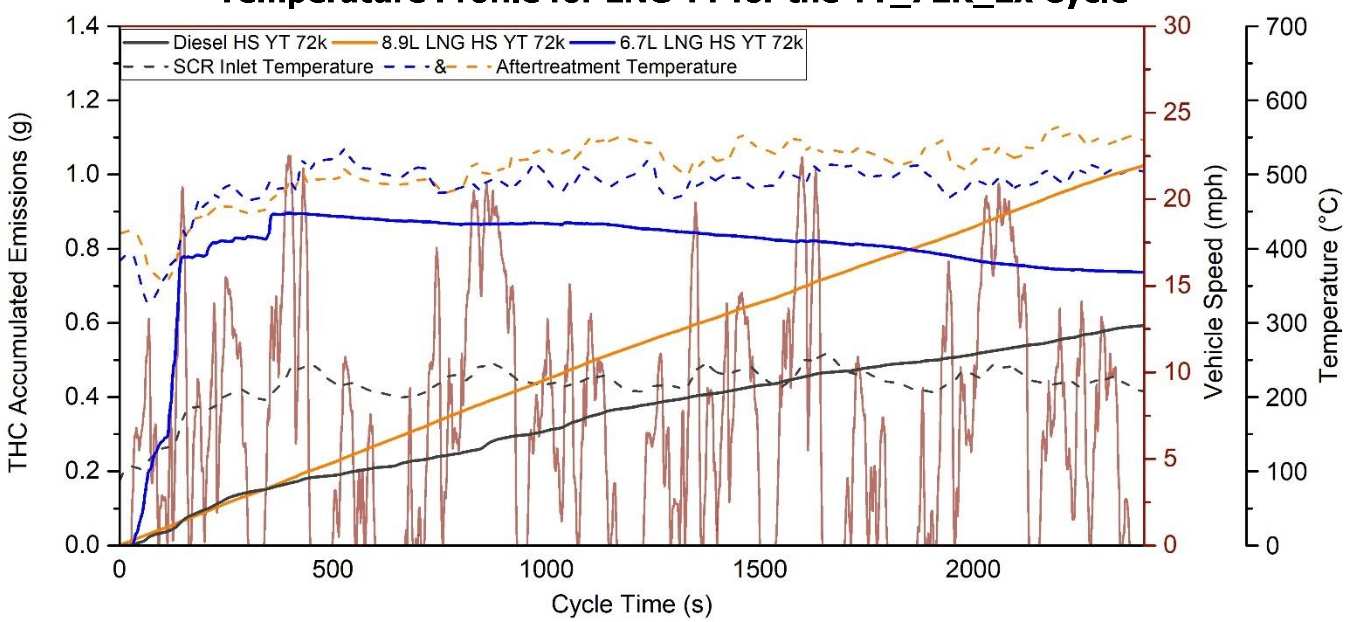
Source: University of California, Riverside

Figure E-3: Real-time Cold Start THC Emissions, Cycle Trace and Exhaust Temperature Profile for LNG YT for the YT_72K_CS Cycle



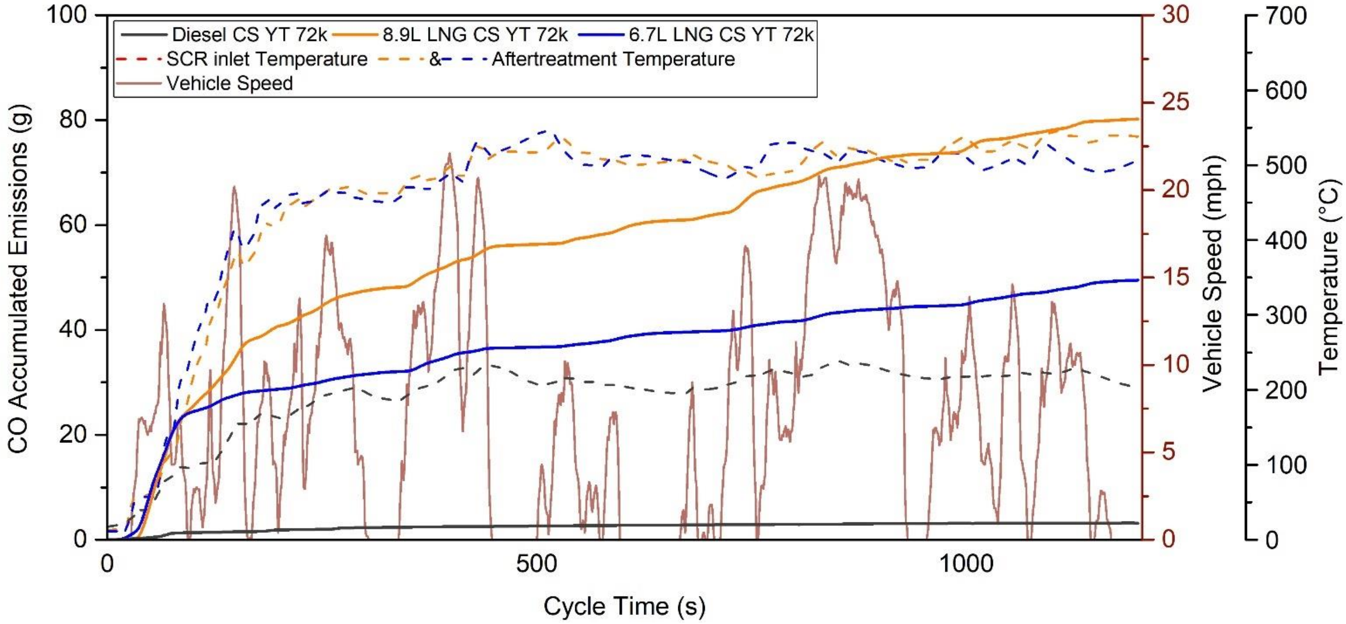
Source: University of California, Riverside

Figure E-4: Real-time Hot Start THC Emissions, Cycle Trace and Exhaust Temperature Profile for LNG YT for the YT_72K_2x Cycle



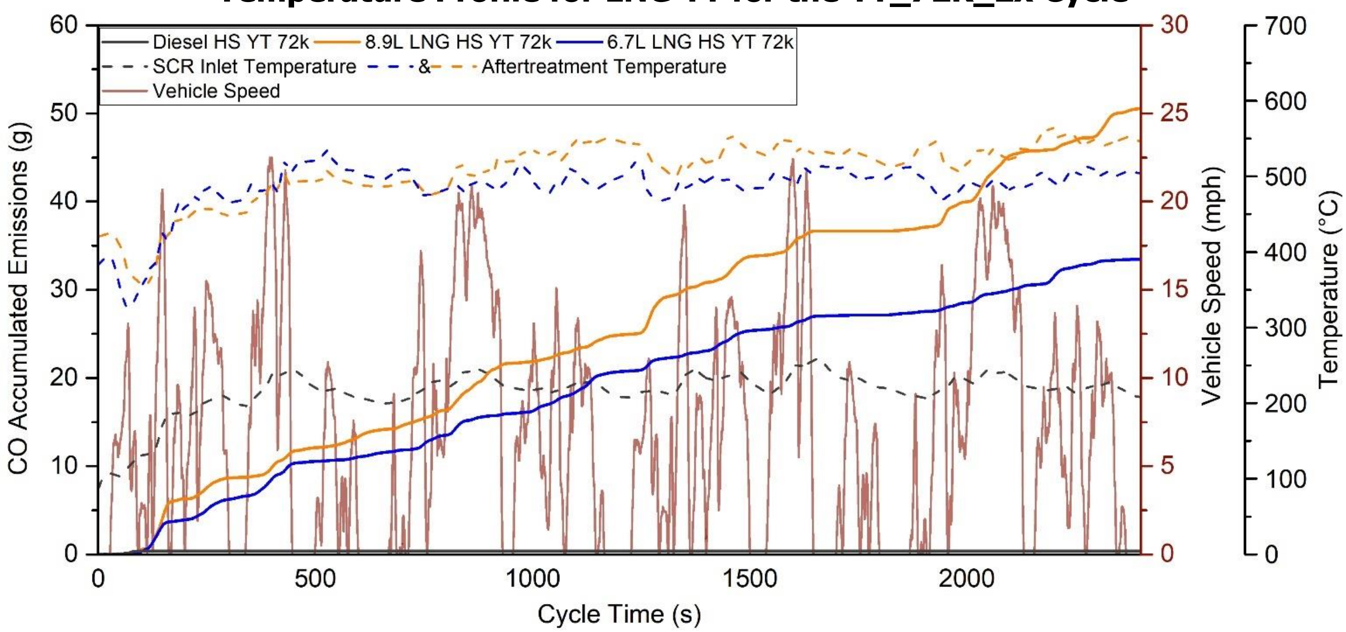
Source: University of California, Riverside

Figure E-5: Real-time Cold Start CO Emissions, Cycle Trace and Exhaust Temperature Profile for LNG YT for the YT_72K_CS Cycle



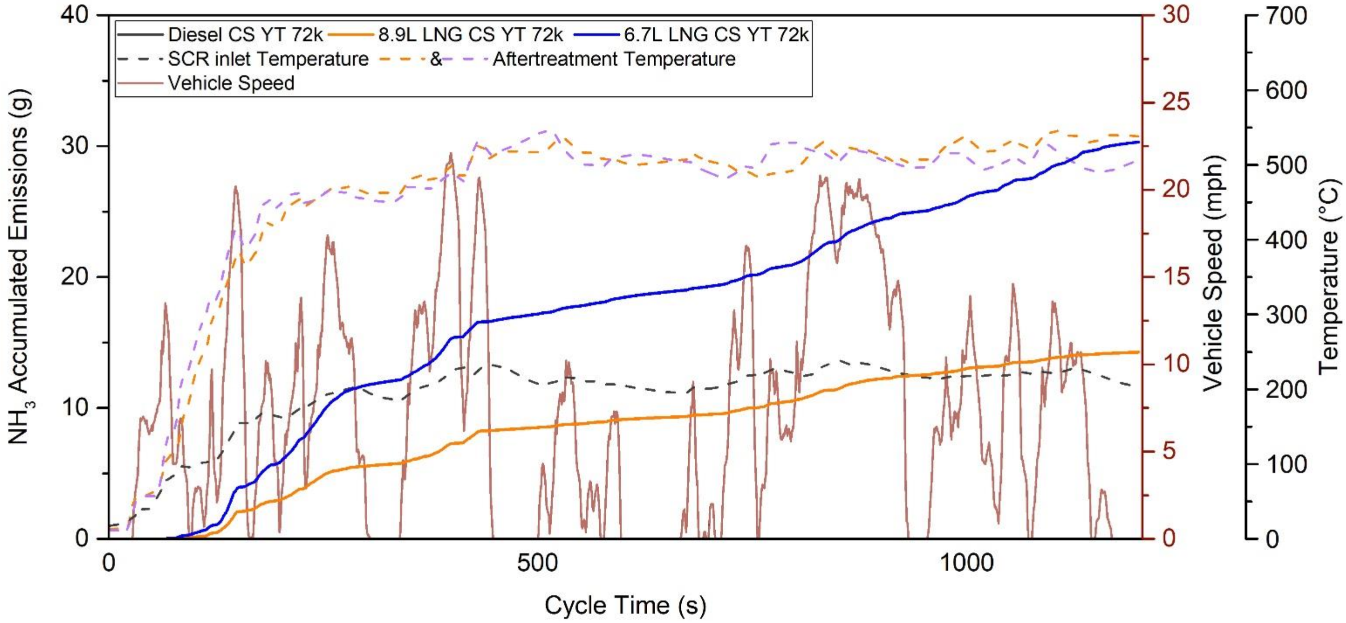
Source: University of California, Riverside

Figure E-6: Real-time Hot Start CO Emissions, Cycle Trace and Exhaust Temperature Profile for LNG YT for the YT_72K_2x Cycle



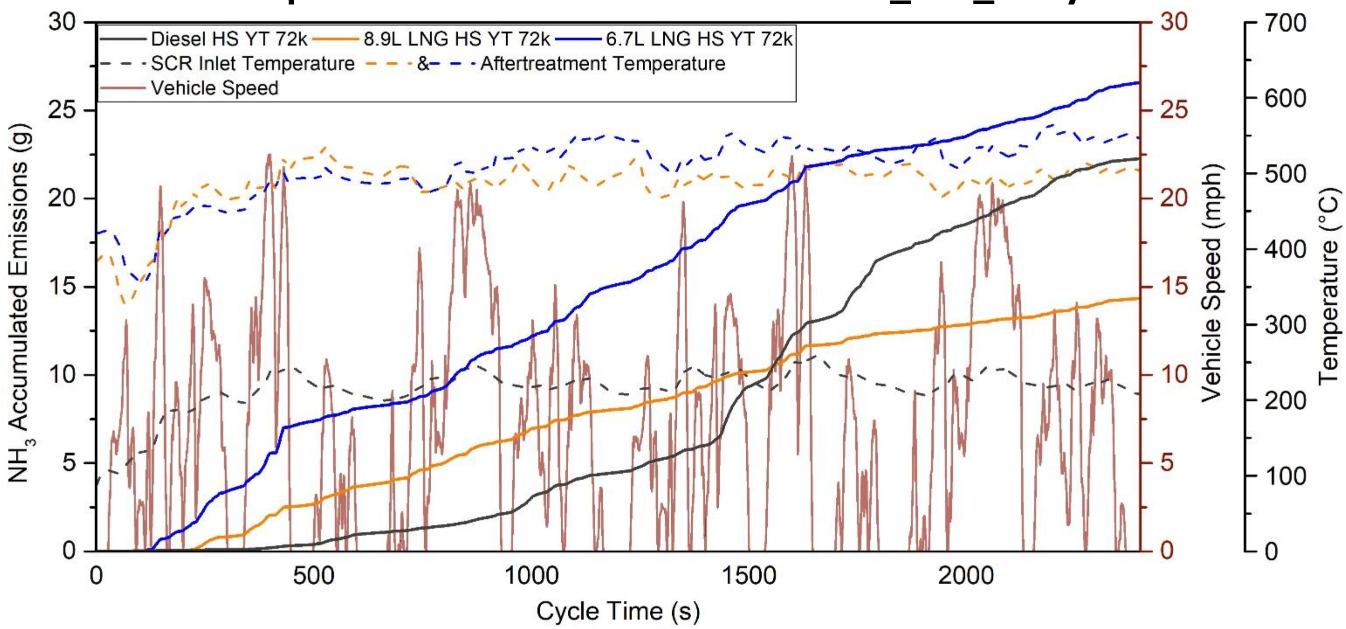
Source: University of California, Riverside

Figure E-7: Real-time Cold Start NH_3 Emissions, Cycle Trace and Exhaust Temperature Profile for LNG YT for the YT_72K_CS Cycle



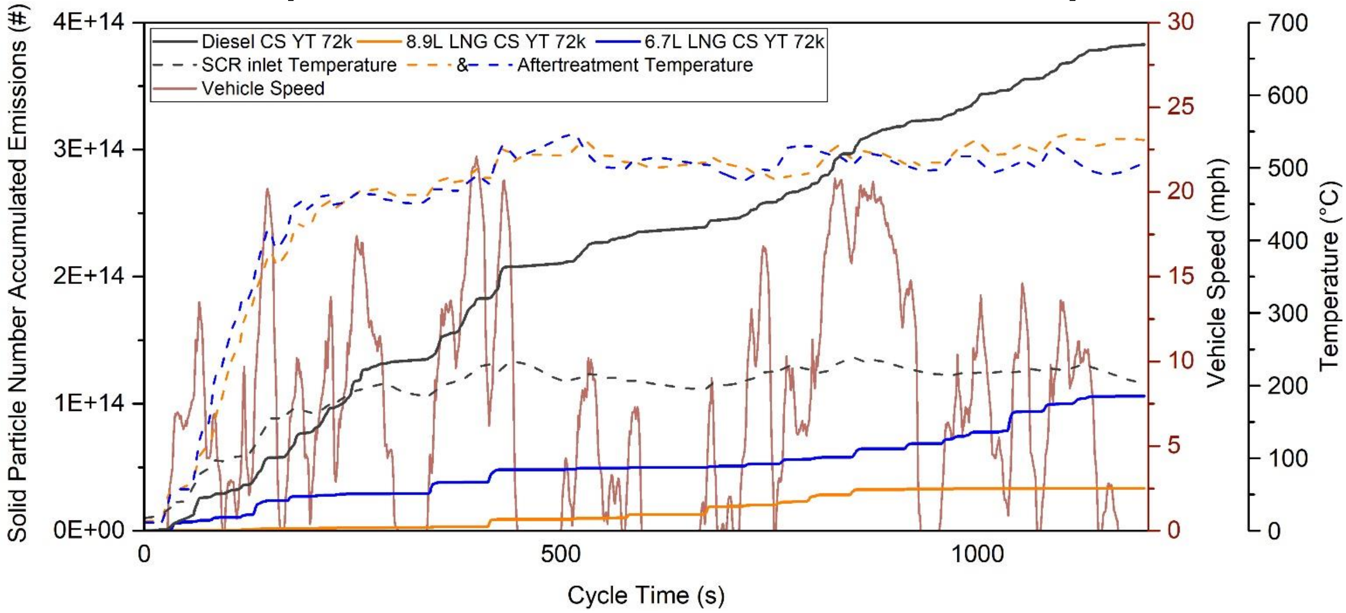
Source: University of California, Riverside

Figure E-8: Real-time Hot Start NH_3 Emissions, Cycle Trace and Exhaust Temperature Profile for LNG YT for the YT_72K_2x Cycle



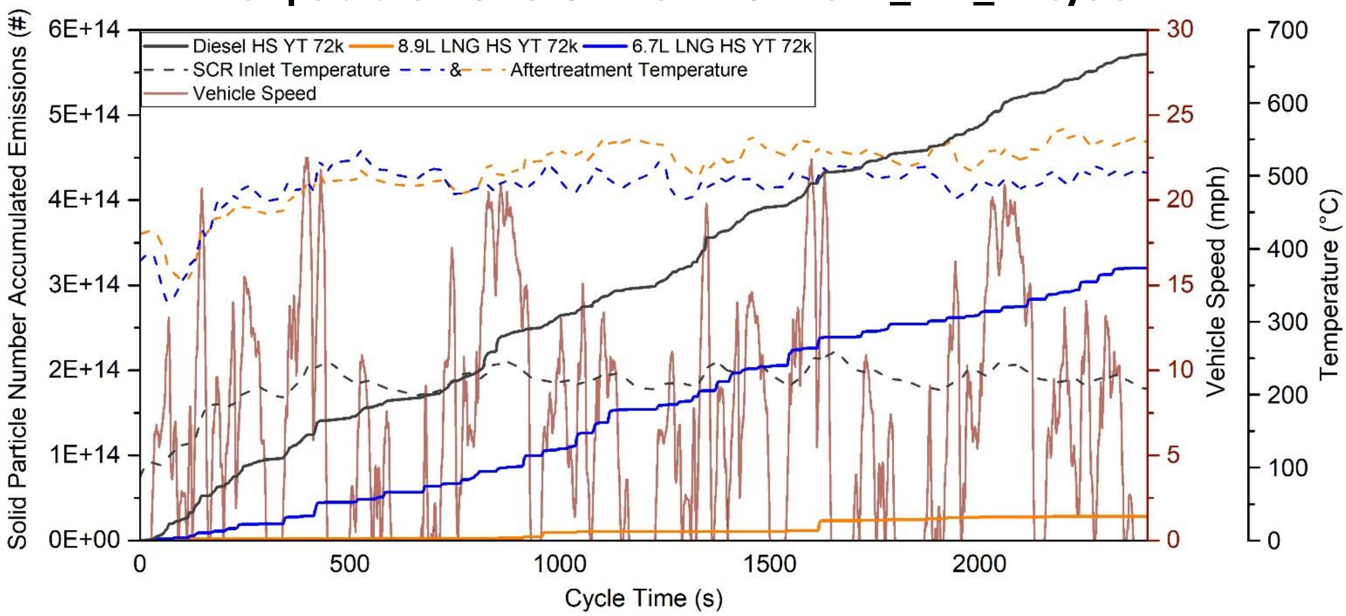
Source: University of California, Riverside

Figure E-9: Real-time Cold Start SPN Emissions, Cycle Trace and Exhaust Temperature Profile for LNG YT for the YT_72K_CS Cycle



Source: University of California, Riverside

Figure E-10: Real-time Hot Start SPN Emissions, Cycle Trace and Exhaust Temperature Profile for LNG YT for the YT_72K_2x Cycle



Source: University of California, Riverside

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LIST OF ACRONYMS

Term	Definition
APC	AVL Particle Counter
CAM	Commission Agreement Manager
CARB	California Air Resources Board
CBD	Central Business District
CE-CERT	College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CEC	California Energy Commission
CFR	Code of Federal Regulations
CH_4	Methane
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Butane
CHE	Cargo handling equipment
CLD	Chemiluminescence
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CWI	Cummins Westport Inc.
d	distance
ECU	Engine control unit
EEPS	Engine Exhaust Particle Sizer
EGR	Exhaust gas recirculation
EXMI	Extreme Methane Index
FID	flame ionization detection
GHG	Greenhouse gas
G/BHP-HR	Grams per Brake Horsepower Hour
GVW	Gross Vehicle Weight
HD	Heavy-duty
HDV	heavy-duty vehicle

Term	Definition
LNG	Liquefied natural gas
MEL	UCR's Mobile Emissions Laboratory
MI	Methane index
MN	Methane number
mpg	Miles per Gallon
mph	Miles per Hour
MY	Model Year
NG	Natural gas
NGV	Natural gas vehicle
nm	nanometer
N_2	Nitrogen
NDIR	Non-dispersive Infra-Red
NH_3	Ammonia
N_2O	Nitrous Oxide
NO_x	Oxides of nitrogen
NZE	Near zero emission – refers to a NOx emission certification level 90 percent below the prevailing heavy-duty engine standard of 0.20 g/bhp-hr
O_2	Oxygen
OLNS	Optional Low-NOx Standard
PM	Particulate matter
$PM_{2.5}$	Particulate Matter with a diameter less than 2.5 nm
POLA	Port of Los Angeles
QA/QC	Quality assurance/quality control
QCL	Quantum Cascade Laser
RNG	Renewable natural gas
rpm	Revolutions per minute
SCAQMD	South Coast Air Quality Management District
SCR	Selective Catalytic Reduction
T	Temperature
TAC	Technical Advisory Committee

Term	Definition
THC	Total Hydrocarbons
TWC	Three way catalyst
UCR	University of California, Riverside
UDDS	Urban Dynamometer Driving Schedule
U.S.	United States
WI	Wobbe Index - higher heating value divided by the square root of the specific gravity with respect to air
YT	Yard tractor
YT_72K	Yard Tractor heavy load transient cycle at 72,000 lbs.
YT_26K	Yard Tractor light load transient cycle at 26,000 lbs.