CRC Report No. E-109

EFFECT OF FUEL COMPOSITION ON THE EMISSIONS AND PERFORMANCE OF MODERN, LIGHT-DUTY NATURAL GAS VEHICLES

May 2015

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CRC Project No. E-109

Effect of Fuel Composition on the Emissions and Performance of Modern, Light-Duty Natural Gas Vehicles

April 28, 2015

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Orion Registrar, Inc. Certificate Number A0000602-7.
American Association for Laboratory Accreditation Certificate Number 1975-01

1975-01

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Effect of Fuel Composition on the Emissions and Performance of Modern, Light-Duty Natural Gas Vehicles – CRC Project No. E-109

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Abbreviations and Acronyms

A/C	Air Conditioning
ARB	California Air Resources Board
Bag	Pertaining to post-catalyst emissions from the vehicle, calculated from bag analysis
CAN	Controller Area Network
CARB	California Air Resources Board
CFR	EPA Code of Federal Regulations
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COA	Certificate of Analysis
CRC	Coordinating Research Council
CREE	Carbon-Related Exhaust Emissions calculated per Title 40 CFR Part 600
CVS	Constant Volume Sampling
CWF	Carbon Weight Fraction of fuel
DFCO	Deceleration Fuel Cut-Off
DOE	U.S. Department of Energy
DTC	Diagnostic Trouble Code
ECM	Engine Electronic Control Module
EER	Energy Economy Rating
EGT	Exhaust Gas Temperature
EO	Engine-out
EPA	U.S. Environmental Protection Agency
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
ETW	Equivalent Test Weight, for vehicle inertial simulation on the dynamometer
FE	Fuel Economy
FTP75	Federal Test Procedure consisting of a 3 Phase drive cycle
FWD	Front Wheel Drive
GGE	Gasoline Gallon Equivalent
HC	Total Hydrocarbons, also THC
IMEP	Indicated Mean Effective Pressure
INCA	Commercial software from ETAS used to record and analyze sensor data broadcast on CAN
LA4	2 Phase drive cycle also known as the FTP72 or Urban Dynamometer Driving Schedule
LA92	Drive cycle also known as the California Unified Cycle
MIL	Malfunction Indicator Lamp
MN	Methane Number
MPGe	Miles per Gasoline Gallon Equivalent
MPRR	Maximum Pressure Rise Rate
mg	Milligrams
N-CH4	Non-Methane Hydrocarbons, also NMHC
NGV	Natural Gas Vehicle
NMHC	Non-Methane Hydrocarbons, also N-CH4
NPT	National Pipe Thread
NOx	Oxides of nitrogen
OBD	On Board Diagnostics
OEM	Original Equipment Manufacturer

ppm	Parts per million, single carbon equivalent basis for hydrocarbons (ppmC1)
RPM	Engine speed Rotations per Minute
PRD	Pressure Relief Device
RWD	Rear Wheel Drive
SCF	Standard Cubic Feet
SGS	SGS Environmental Testing Corporation
TDC	Top Dead Center
THC	Total Hydrocarbons, also HC
TP	Tailpipe
VW	Volkswagen
WI	Wobbe Index
WOT	Wide Open Throttle (i.e.: Maximum Engine Load)

Acknowledgements

The authors would like to thank the following companies and individuals for their contributions to this project: Kris Kielty of Ward Energy for his expertise and assistance with bypassing the vehicle's fuel systems and supplying external CNG components; Craig Etherton of AirGas for his efforts supplying and expediting the CNG fuels; Burl McEndree from Empact Analytical for providing excellent and timely analysis of CNG fuel samples; Robert Michael, Timothy Hurst, and Daniel Manzanares from the SGS Automotive vehicle testing staff for running tests and providing extended support to condense the testing schedule.

The authors also acknowledge the contributions and support from the E-109 technical committee members:

Chris Tennant	Coordinating Research Council
Jeff Jetter	Honda, panel chairman
Jenny Sigelko	Volkswagen
Dan Bowerson	Fiat Chrysler Automobiles

1.0 Executive Summary

To help automakers and other stakeholders understand the implications of pipeline CNG fuel quality on light-duty vehicle performance and emissions, SGS has conducted a study to test seven synthetically blended fuels on three different vehicles. The vehicles included a naturally aspirated CNG-only 2012 Honda Civic GX, a turbocharged bi-fuel 2014 European Volkswagen Golf TGI, and a naturally aspirated bi-fuel Dodge Ram 2500 CNG. Replicate LA92 3-bag emissions tests were performed on the chassis dynamometer. Exhaust gas emissions were bagged, and modal emissions sampled at the pre-catalyst and tailpipe locations for catalyst efficiency determination.

Seven test fuels were chosen by the CRC panel to represent a wide range of fuels available to consumers in the United States. Fuel selection was based on fuel samples collected and analyzed in the CRC Performance Committee Project PC-2-12. Methane number ranged from 60 to 105.7, and Wobbe Index ranged from 1228 to 1428 BTU/ft^3. The study included a test fuel to represent the average CNG composition of 97 Methane Number and 1344 BTU/ ft^3 Wobbe Index. Each vehicle was tested twice on all seven of the CNG fuels.

Conclusions from the investigation are as follows:

1. The bag-weighted fuel economy, in miles per gasoline gallon equivalent (MPGe), varied in direct proportion to the Wobbe Index for all vehicles in the study. This effect was expected due to different energy content of the test fuels.
2. NOx and CO bag-weighted emissions from Vehicle A and Vehicle B were unaffected by the fuel type.
3. NOx engine-out-weighted emissions increased with higher Wobbe Index fuels for all three vehicles tested.
4. THC and CH_4 bag emissions increased with lower Wobbe Index fuels for all three vehicles tested.
5. Of the three vehicles in the study, Vehicle C was most affected by fuel type.
    a. When run on the fuel with lowest Wobbe Index (CNG01), bag-weighted NOx emissions increased by over 300% compared to the average CNG fuel (CNG07). The lowest Wobbe Index fuel produced highest NOx emissions during the Phase 2 stabilized portion of the LA92 cycle.
    b. CO bag-weighted emissions decreased for the lowest Wobbe Index fuel.
    c. Methane emissions increased by over 50% for the lowest Wobbe Index fuel.
    d. The effects appeared to be catalyst-conversion related as the trends were less apparent from engine-out emissions data.
6. A statistical analysis for all vehicles pooled together revealed:
    a. The effect of fuel type on mean bag-weighted fuel economy was significant with 95% confidence
    b. The effect of fuel type on mean bag-weighted NOx and CO was not statistically significant
    c. The effect of fuel type on mean bag-weighted CH_4 and total THC emissions was significant with 95% confidence.

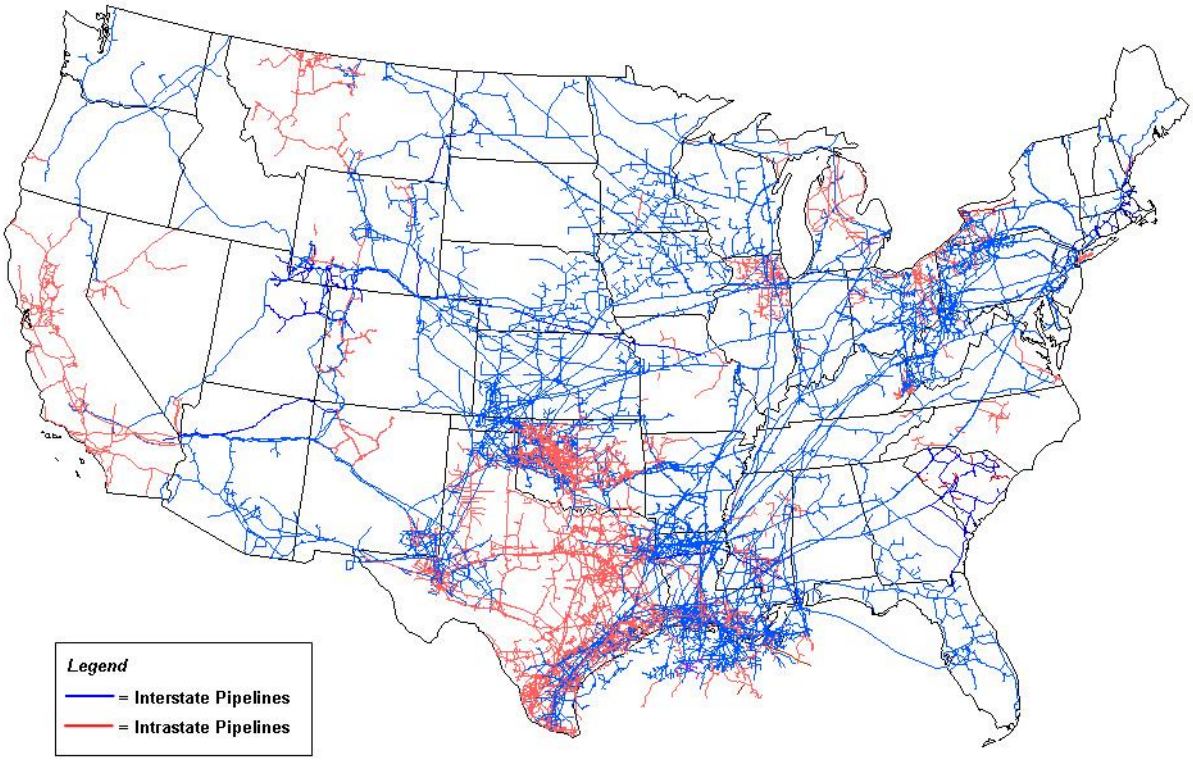
7. Engine knock was not observed for either Knock Investigation #1 or #2, indicating that the combination of compression ratio, EGR, ignition timing, and valve timing employed on these vehicles can accommodate the lowest methane number fuel under the conditions tested.

2.0 Introduction

The demand for natural gas fueled vehicles has increased as domestically-produced natural gas has grown dramatically in the U.S. with the implementation of new gas extraction technologies. CNG has become a cost effective and clean burning alternative to gasoline and diesel. Formulation of liquid fuels has been tightly regulated allowing manufacturers of light duty vehicles to design their engines and calibrations to operate within the regulated fuel specifications. Gaseous fuels, like CNG, have much broader specifications which can generate fuels available for public refueling to vary greatly. Two of the most important characteristics of a fuel for base engine design and calibration are its resistance to engine knock which is closely tied to methane number (MN), and its stoichiometric air fuel ratio which has a nearly linear relationship to Wobbe Index (WI).

The fueling infrastructure for natural gas is based on a pipeline infrastructure serviced by multiple wellheads across North America as shown in Figure 1. As the wellheads are not connected to one another, the products pumped out of the ground are different from site to site. Pipes from wellheads gather at a central processing plant where oil, condensate, water, liquids, sulfur (normally less than 17ppm), and carbon dioxide are removed. Most of the more valuable gaseous hydrocarbon constituents (ethane, propane, butane, etc.) can be recovered by different methods, but are not all 100% efficient. Since the final product is normally sold based on energy content for residential and business use there is little concern for further refining the fuel for transportation use. This leaves heavier hydrocarbon components that can reduce the fuels knock resistance. In some higher altitude environments oxygen is injected into the pipeline to better combust the gas in burner applications like stoves and water heaters.

The objective of this study was to compare the performance and emissions of three CNG vehicles operating on a wide range of CNG fuels available in the United States.



Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System

Figure 1. U.S. Natural Gas Pipeline Network, 2009

3.0 Approach and Test Procedures

SGS Environmental Testing Corporation (SGS) collaborated with CRC to develop the project approach and test procedures. Vehicle lab testing was performed at SGS's Aurora, Colorado laboratory. SGS is an accredited laboratory in compliance with ISO 17025-2005 quality management, and performs emissions certification tests per EPA's 40CFR86 standards.

3.1 Vehicle Models and Recruitment

This study was designed to discern the effects of extreme CNG fuel composition on vehicle exhaust emissions and fuel economy. Base engine architecture and control strategies vary within natural gas powered light-duty vehicles offered from each manufacturer. Of all available options, one common feature is that light-duty NGVs are all operating with stoichiometric combustion and spark ignition. This also implies that three way catalytic converters are used to meet exhaust emissions regulations. Three different vehicle models were chosen for this study which capture bi-fuel, natural aspiration, and turbocharging. The vehicle model years ranged from 2012 to 2014 with two models currently available in the US and one selected from Europe.

The three vehicles participating in the study are summarized in Table 1. The vehicles were production models supplied by participating manufacturers.

Table 1. Vehicles Participating in CRC E-109 Study

Model Year	Make	Model	Engine Size (L)	# of Cylinders	Configuration	Gasoline Fuel Tank Size (Gal)	CNG Fuel Tank Size (GGE)	CNG Fuel Tank Material	Engine Family	Exap Family	Exhaust Emissions Standard
2014	RAM	2500 CNG	5.7	8	Normally Aspirated, Bi-Fuel	8.0	18.2	Steel	ECRXD05.75VY	ECRXR0272TCY	HDV / ULEV II MDV
2012	Honda	Civic GX	1.8	4	Normally Aspirated, CNG Only	n/a	8.0	Composite	CHNXV01.88DT	n/a	T2B2 / LEV II SULEV
2014	Volkswagen	Golf TGI	1.4	4	Turbocharged, Bi-Fuel	13.2	7.3	Steel	n/a	n/a	EURO 6

The 2014 Ram 2500 CNG is shown in Figure 2. The Dodge Ram was received on 9/25/2014 with 3364 miles on the odometer and in good overall condition. The mileage at the beginning of the first as-received emissions test was 3409 miles. The engine configuration was a naturally aspirated 5.7L 8-cylinder operating on both CNG and gasoline shown in Figure 3. The fuel system had two composite CNG tanks capable of 3600psig storage with a total capacity of 18.2 GGE. Exhaust aftertreatment consisted of a two close coupled three-way-catalysts with engine-out narrowband oxygen sensors and post-catalyst narrow band oxygen sensors. Cylinder specific port fuel injectors delivered CNG to the intake ports. An additional gasoline fuel system was also installed with port injection. An 8-speed automatic transmission drives the rear wheels.

Figure 2. 2014 Dodge Ram 2500 CNG

Figure 3. 2014 Dodge Ram 2500 CNG Engine Bay

The 2012 Honda Civic GX is shown in Figure 4. The Honda Civic was received on 5/8/2014 with 4690 miles on the odometer and in good overall condition. The engine configuration was a naturally aspirated 1.8L 4-cylinder operating on CNG only shown in Figure 5. The fuel system had one composite CNG tank capable of 3600psig storage with a total capacity of 8.0 GGE. Exhaust aftertreatment consisted of a close coupled three-way-catalyst with engine-out and post-catalyst narrow band oxygen sensors and close coupled secondary catalyst. Cylinder specific port fuel injectors delivered CNG to the intake manifold. A 5-speed automatic transmission drives the front wheels.

Figure 4. 2012 Honda Civic GX

Figure 5. 2012 Honda Civic GX Engine Bay

The 2014 Volkswagen Golf TGI is shown in Figure 6. This vehicle was a European model transported to the United States for testing purposes. The VW Golf was received on 8/8/2014 with 6059 miles on the odometer and in overall good condition. The engine configuration was a turbocharged 1.4L 4-cylinder operating independently on both CNG and gasoline depending on the available CNG tank pressure and is shown in Figure 7. The system operates on CNG until the tank is depleted, then switches to gasoline until the CNG tank pressure is restored. The fuel system had two steel CNG tanks capable of 3000psig storage with a total capacity of 7.3 GGE. The gasoline tank had a capacity of 13.2 gallons. Exhaust aftertreatment consisted of a three-way-catalyst downstream of the turbocharger with an engine-out wideband oxygen sensor and a post-catalyst narrow band oxygen sensor. Cylinder specific port fuel injectors deliver CNG to the intake manifold. The gasoline fuel system was direct injection. A 6-speed manual transmission drives the front wheels.

Figure 6. 2014 Volkswagen Golf TGI

Figure 7. 2014 Volkswagen Golf TGI Engine Bay

3.2 Preparation and As-Received Emissions

The test vehicles completed an inspection and screening test to confirm proper vehicle operation and collect baseline emissions:

- No active or pending MILs/DTCs
- Serviceable and safe tires, but not new tires
- VIN, ECM calibration, and emissions certification family check
- Check for exhaust leaks and readiness for testing
- Refuel with locally available CNG
- Road Load Derivation
- LA4 Preparation Cycle
- Soak 12-36 hours
- Evaporative Canisters were preconditioned for the bi-fueled vehicles at 40g/hr with a 2 gram break through method
- FTP-75 Bag Only
- LA-92 preparation cycle
- Soak 12-36 hours
- LA-92 3-bag test

SAE J2264 road load derivations were performed for the vehicles using vehicle target coefficients listed in Table 2 below. Target coefficients for the Honda Civic were chosen from the EPA certification 2012 database. The target coefficients for the VW Golf were chosen after consultation with the manufacturer since there are no data available in the United States. The target coefficients for the Dodge Ram were chosen from the EPA certification database for the 2014 model year. The road load comparison for each vehicle is shown in Figure 8. The Volkswagen Golf TGI had the lightest road load of the three vehicles and the Ram 2500 CNG had the highest road load.

Table 2. Vehicle Target Road Load Coefficients

Manufacturer	Ram 2500 CNG	Honda Civic GX	Volkswagen Golf TGI
ETW (lbs)	8500	3125	3250
A (lb_f)	65.88	23.0700	17.3100
B (lb_f/mph)	1.7806	0.1703	0.1339
C (lb_f/mph^2)	0.02642	0.0166	0.01729
Tire Pressure (psig)	80	30	35
Tire Size	275/70/18	195/65/R15	205/55/R16
Tire Manufaturer	Firestone	Firestone	Continental
Tire Model	Transforce HT	Affinity Touring S4	ContiEcoContact

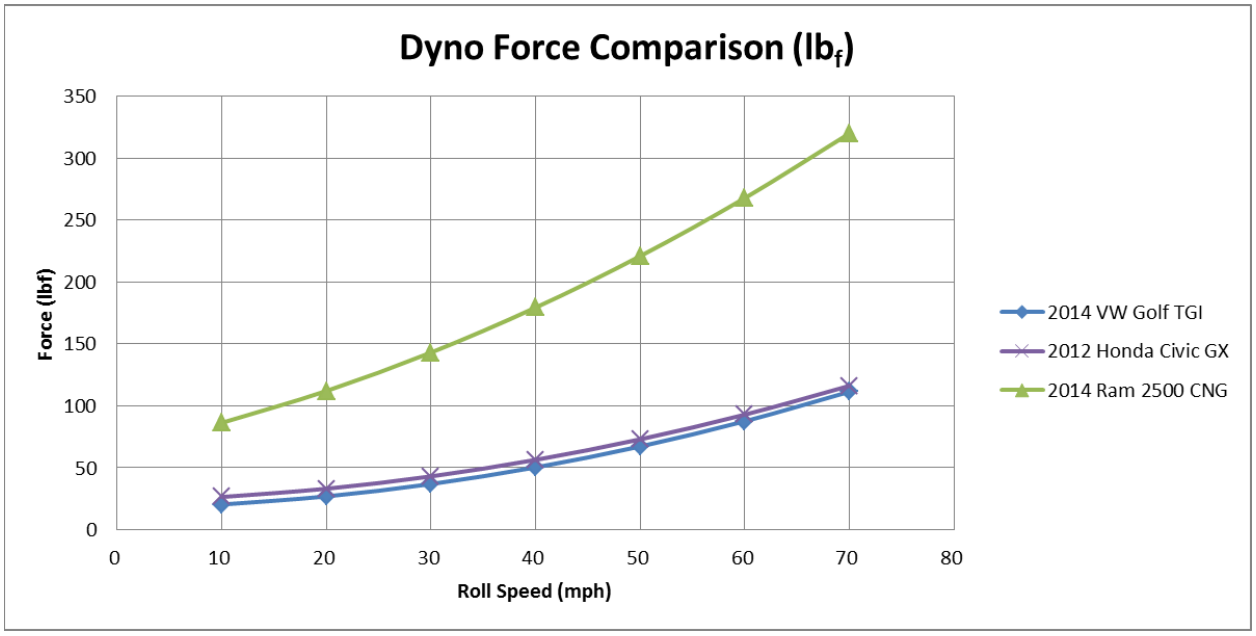


Figure 8. Dyno Force Comparison

Following the derivations, each vehicle received a LA4 prep cycle, canister loading for the bi-fuel vehicles, and a 12-36 hour soak in a temperature and humidity controlled environment prior to the FTP75 emissions test. For all testing, the manual transmission Volkswagen Golf TGI followed the EPA recommended shift schedule as shown in Table 3.

Table 3. EPA Standard Shift Schedule for 6-Speed Manual

Gear	Standard Shift Speeds
1-2	≥ 15mph
2-3	≥ 25mph
3-4	≥ 40mph
4-5	≥ 45mph
5-6	≥ 50mph

Gasoline drain and fills were performed on the two bi-fuel vehicles prior to performing the as-received emissions tests. EPA Federal Tier 2 High Altitude Certification fuel was used and remained in the gasoline tanks of the bi-fuel vehicles for the duration of the program testing with COA documentation provided in Appendix 12.2. The CNG fuel used for the as-received test was market fuel sourced from a local Denver CNG station with reported constituents as shown below in Table 4. The fuel had an average Wobbe Index of 1267.05 BTU/ft^3 and a MN of 81.

Table 4. Denver BTU Zone – 2014 Average Gas Quality

MONTHLY AVERAGE GAS QUALITY [1] DENVER BTU ZONE - 2014			
	July mol %	August mol %	Average mol %
CARBON DIOXIDE	1.153	1.22	1.1865
OXYGEN	1.215	1.126	1.1705
NITROGEN	5.027	4.986	5.0065
METHANE	84.08	84.324	84.202
ETHANE	7.386	7.213	7.2995
PROPANE	0.952	0.948	0.95
I-BUTANE	0.056	0.055	0.0555
N-BUTANE	0.101	0.099	0.1
I-PENTANE	0.013	0.013	0.013
N-PENTANE	0.011	0.011	0.011
HEXANE-PLUS	0.006	0.005	0.0055
TOTAL	100	100	
Gas Properties (14.73 psia, 60°F, dry)			
NET HEATING VALUE [2] (Btu/scf)	916.3	915.5	915.9
GROSS HEATING VALUE [2] (Btu/scf)	1014.9	1014.1	1014.5
SPECIFIC GRAVITY [2]	0.6415	0.6406	0.64105
WOBBE	1267.1	1267	1267.05
KG CO_2/MMBtu[3]	53.9	53.9	53.9

[1] Values shown are volume weighted averages for all supplies into zone and may not represent deliveries to a specific location at a given time
[2] ASTM D3588 Standard Practice for Calculating Heat Value, Compressibility Factor and Relative Density (Specific Gravity) of Gaseous Fuels and GPA 2145 Table of Physical Constants of Paraffin Hydrocarbons and Other Components of Natural Gas
[3] Carbon dioxide factor based only on combustion of gas with given composition. Multiply by Gross Heating Value/1,000,000) for MT/Mscf

Source: http://www1.xcelenergy.com/webebb/html/GasQualityZone.asp

As-received 3-bag LA92 tests were also performed on all three vehicles with results shown in Table 5. Emissions certification standards for the Honda Civic GX and Ram 2500 CNG were available

from the public EPA database for the FTP75 emission test and shown for comparison, while values for the Volkswagen Golf TGI were unavailable as it is a European market vehicle.

Table 5. FTP75 and LA92 As-Received Vehicle Emissions

FTP75 and LA92 As-Received Results	CO (g/mi)	NOx (g/mi)	CH4 (g/mi)	CREE (g/mi)	NMOG (g/mi)	N-CH4 (g/mi)	HCHO (g/mi)	HC (g/mi)	CO2 (g/mi)	FE (mpg)
Honda Civic GX										
FTP75 Emission Standard T2B2	2.1	0.02	0.03	n/a	0.01	n/a	n/a	n/a	n/a	n/a
FTP75 SGS 2116985 As-Received	0.1061	0.004	0.0108	208.2963	n/a	0.0008	n/a	0.011	208.1	31.09
LA92 SGS 3118990 As-Received	0.2716	0.0016	0.0079	225.9284	n/a	0.0029	n/a	0.0102	225.48	28.66
Volkswagen Golf TGI										
FTP75 Emission Standard	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
FTP75 SGS 3119188 As-Received	0.0725	0.0551	0.0424	200.2202	n/a	0.0052	n/a	0.0448	199.99	32.34
LA92 SGS 3119162 As-Received	0.1041	0.0613	0.0278	209.7798	n/a	0.0044	n/a	0.0304	209.54	30.87
Ram 2500 CNG										
FTP75 Emission Standard HDV1	7.3	0.2	0.267	n/a	0.195	n/a	0.032	n/a	n/a	n/a
FTP75 SGS 3119377 As-Received	0.2853	0.0242	0.1344	621.6669	n/a	0.0129	n/a	0.1384	620.85	10.42
LA92 SGS 3119435 As-Received	0.343	0.1282	0.1996	693.6864	n/a	0.0215	n/a	0.2079	692.6	9.34

All three vehicles exhibited higher composite CO_2 and lower fuel economy for the LA92 test versus the FTP75 test. Both of the US market vehicles tested within the applicable federal emissions standard. Results were deemed acceptable to proceed with vehicle preparation for further testing.

3.3 Vehicle Preparation

Each vehicle was modified for test instrumentation, including:

- Temporary defeat of traction control for testing on the chassis dynamometer.
- Installation of a K-type thermocouple upstream of the first catalyst, for exhaust temperature measurement, as required by the EPEFE/WOT catalyst conditioning procedure.
- Installation of a gaseous emissions sample port upstream of the first catalyst for air-fuel ratio determination with a lambda sensor, as required by the EPEFE/WOT catalyst conditioning procedure and for engine-out emissions sampling.
- Installation of signal breakout connected to the engine's 60-2 crank angle sensor signal wires.
- Isolation of the bi-fuel vehicle's evaporative emissions system by means of completely purging the charcoal canister prior to the emissions test. This minimized possible commanded purge events of the gasoline fuel system from influencing emissions results.
- Isolation of the vehicle's fuel tank by means of closing tank shut-off valve(s) specific to each vehicle.

3.3.1 Pre Catalyst Instrumentation

An emissions sample probe and exhaust gas thermocouple were instrumented at the engine-out location upstream of the first three-way catalyst by welding NPT bungs to the factory exhaust systems. Locations are illustrated in Figure 9, Figure 10, and Figure 11 below.

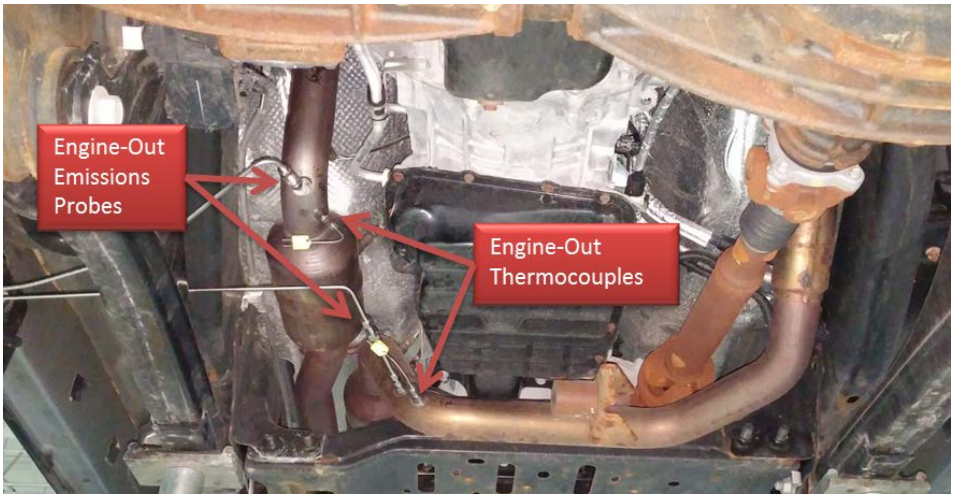


Figure 9. Dodge Ram 2500 CNG Pre Catalyst Instrumentation

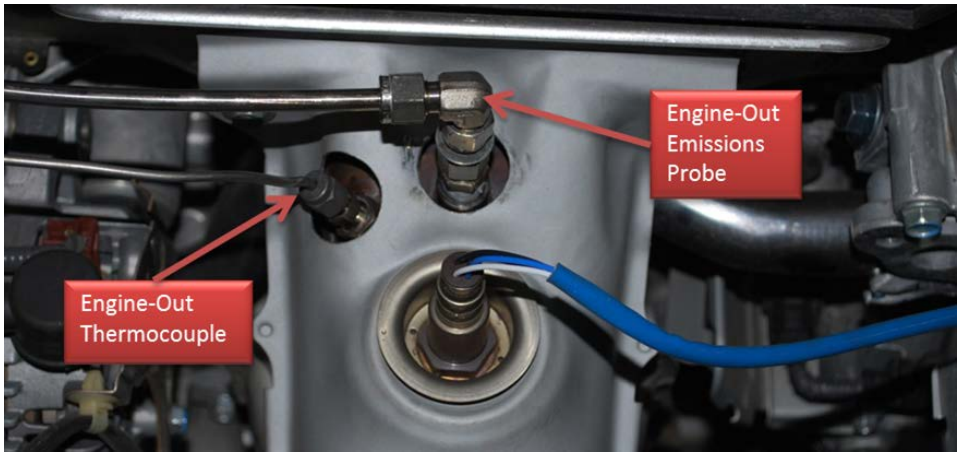


Figure 10. Honda Civic GX Pre Catalyst Instrumentation

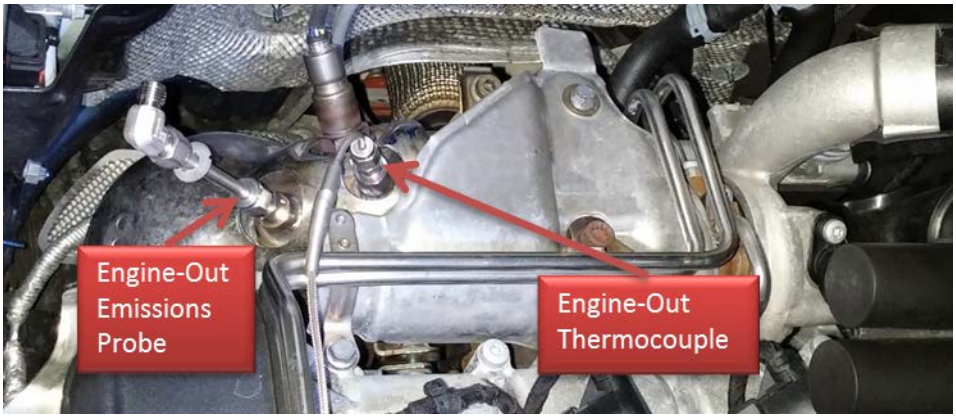


Figure 11. VW Golf TGI Pre Catalyst Instrumentation

The refueling ports on all three vehicles were NGV1 type as shown in Figure 12, Figure 13, and Figure 14 below. The European market Volkswagen Golf TGI had a slightly larger outer diameter which allowed only 3000 psig filling receptacles to attach. This design ensured a higher pressure 3600 psig receptacle cannot attach to the 3000 psig filling port. Both the Honda Civic GX and Ram 2500 CNG had a smaller outer diameter NGV1 port allowing use of both 3000 and 3600 psig filling receptacles.

Figure 12. NGV1 3600psig Fill Port (Dodge Ram 2500 CNG)

Figure 13. NGV1 3600psig Fill Port (Honda Civic GX)

Figure 14. NGV1 3000psig Fill Port (VW Golf TGI)

The Type 3 tank design for the Honda Civic GX was composed of a metal liner reinforced with a composite wrap as shown in Figure 16 below. Both the Volkswagen Golf TGI and Dodge Ram 2500 CNG utilized a Type 1 tank design of all steel construction shown in Figure 15 and Figure 17.

Figure 15. Dodge Ram 2500 CNG Fuel Tanks (Steel Type 1)

Figure 16. Honda Civic GX Fuel Tank (Composite Type 3)

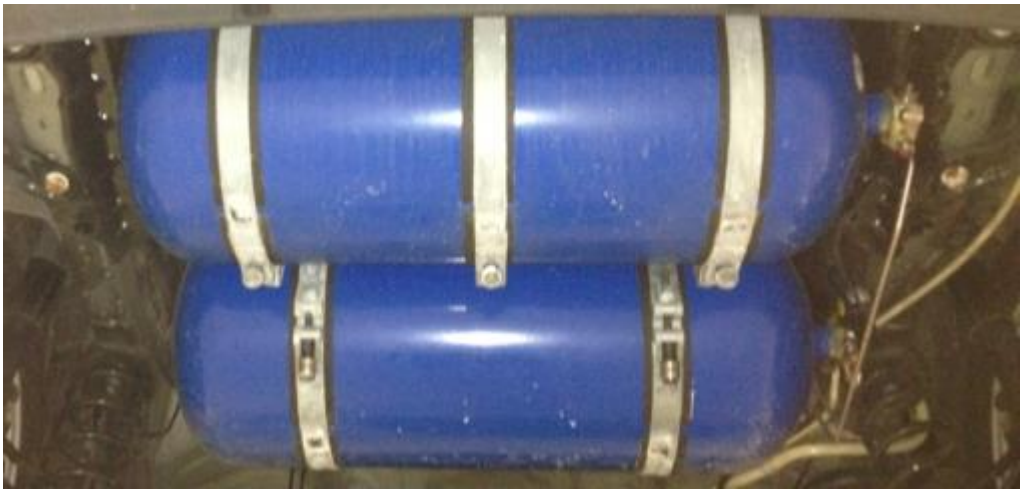


Figure 17. VW Golf TGI Fuel Tanks (Steel Type 1)

3.3.2 CNG Tank Bypass

Each vehicle was equipped with a tank shut-off valve that allowed service to the natural gas fuel system. When the shut-off valve was in the closed position, it allowed the fuel fill port to remain connected to the engine supply line to the regulator and bypassed the vehicle's CNG fuel tank.

In order to supply an external fuel source of six-pack bottled gases to the each vehicle a method was selected that was analogous to the control system. Each CNG tank system had an electronic shutoff valve at the inlet/outlet of the tank which may be opened by energizing the valve coil. Typically the valve is only energized when the ignition is in the on or run position. To prevent any diagnostic trouble codes from setting, the electrical harness was left connected to the electronic shutoff valve.

Each setup had a jack screw or manual shutoff valve on the end of the tank for serviceability. To isolate the flow of gas from the onboard tanks the manual shutoff valves were closed. On both the Volkswagen Golf TGI, shown in Figure 18, and the Dodge Ram 2500 CNG, shown in Figure 19, the NGV1 fill port was connected to the fuel system between the fuel tank and the engine supply line. When the

fuel tank manual shutoff valves are in the closed position it leaves the NGV1 fill port connected to the engine supply line.

Figure 18. VW CNG Tank Shut-Off Valve (One per Tank)

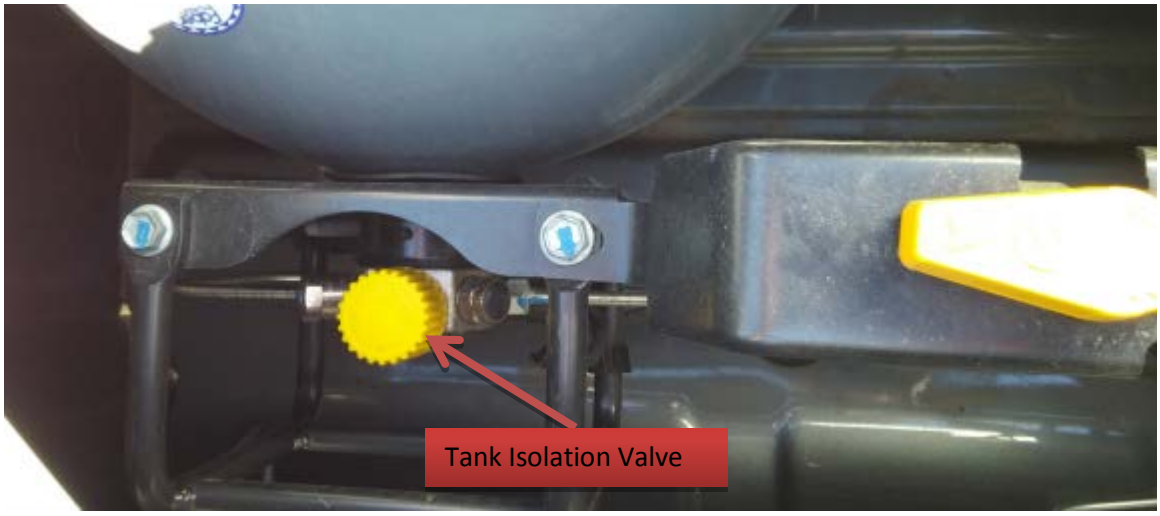


Figure 19. Ram 2500 CNG Fuel Tank Shut-Off Valve (One per Tank)

Figure 20 below shows an internal cutaway view of the Faber tank valve common to both the Volkswagen Golf TGI and the Ram 2500 CNG. With the mechanical shut-off valve in the closed position, CNG is not allowed to flow into or out of the tank under normal conditions. If the temperature of the thermally activated pressure relief device, or PRD, exceeds 110°C the fusible plug will melt allowing gas to escape from the tank at a controlled rate into the atmosphere.

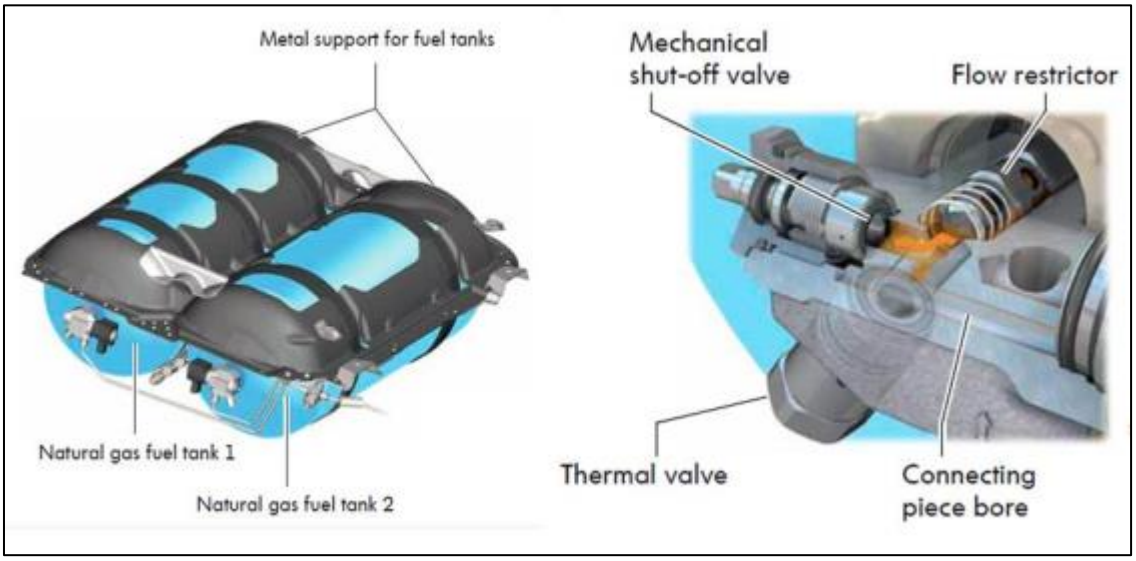


Figure 20. VW Golf TGI Fuel Tank Shut-Off Valve
From Volkswagen Service Training Self-Study Programme 528, "The Natural Gas Drive in the Golf/Golf Estate TGI BlueMotion"

The Honda Civic GX had a unique tank valve where one jack screw is available to close off the inlet to the tank, and a second jack screw is available to close off the outlet of the tank. The separate flow paths allow for a controlled fill rate taking advantage of the cooling effect produced by pressure drop of fuel entering the tank. The separate outlet then allows for less restricted CNG flow to the engine. The plumbing of the system does not allow easy isolation of the tank since the NGV1 fill port is connected directly to the tank valve at the inlet jack screw location. The method used to bypass the Honda's tank was to close both jack screws, disconnect the engine supply line, and adapt a NGV1 fill port direct to the engine supply line as shown in Figure 21 below.

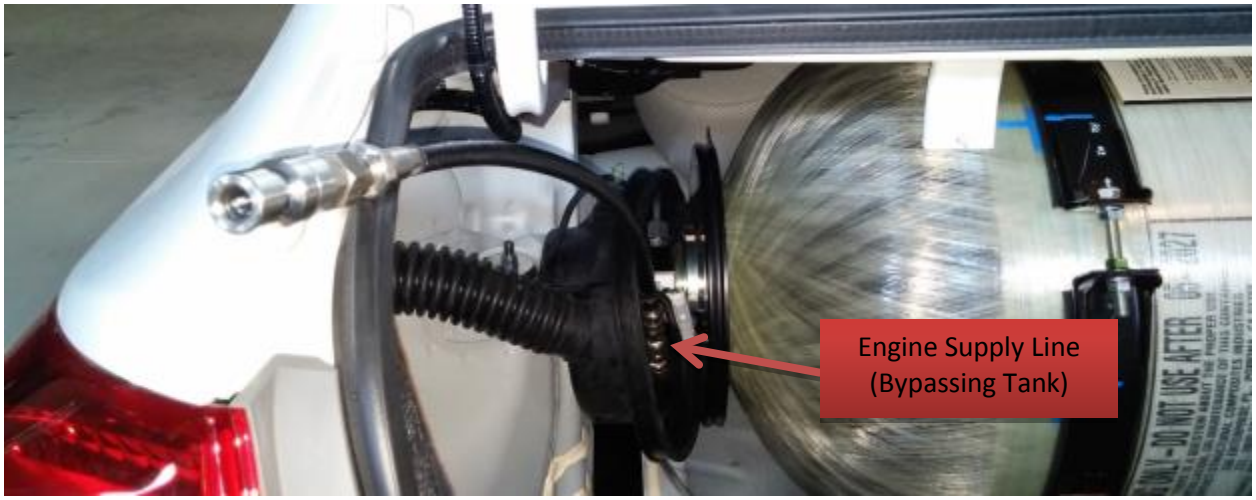


Figure 21. Honda Civic GX Tank Bypass Setup

3.4 Overall Test Plan and Test Sequence

The test plan was designed to compare the emissions and fuel economy from varying natural gas fuel blends. In order to control the fuel supply to the vehicle's engine, fuels were synthetically blended into 300 series DOT cylinders. Six cylinders of the same fuel were grouped together and connected by a single outlet manifold to provide approximately 13.3 GGE at 1800 psig. This allowed for one round of testing for three vehicles with the same six-pack of cylinders consuming 8.7 GGE.

Connection to each vehicle's NGV1 fill port was done by a CNG certified fuel supply hose with a NGV1 dry break filling receptacle that keeps the fuel line free of atmospheric air. The two US market vehicles used a 3600 psi NGV1 fill port. The European Volkswagen Golf used a 3000-3600 psig NGM1 adapter fitting as the system is designed for lower maximum fill pressure.

The test sequence and fuel used for each test procedure is summarized in Table 6. An attempt was made to randomize the fuel and vehicle test order within practical constraints.

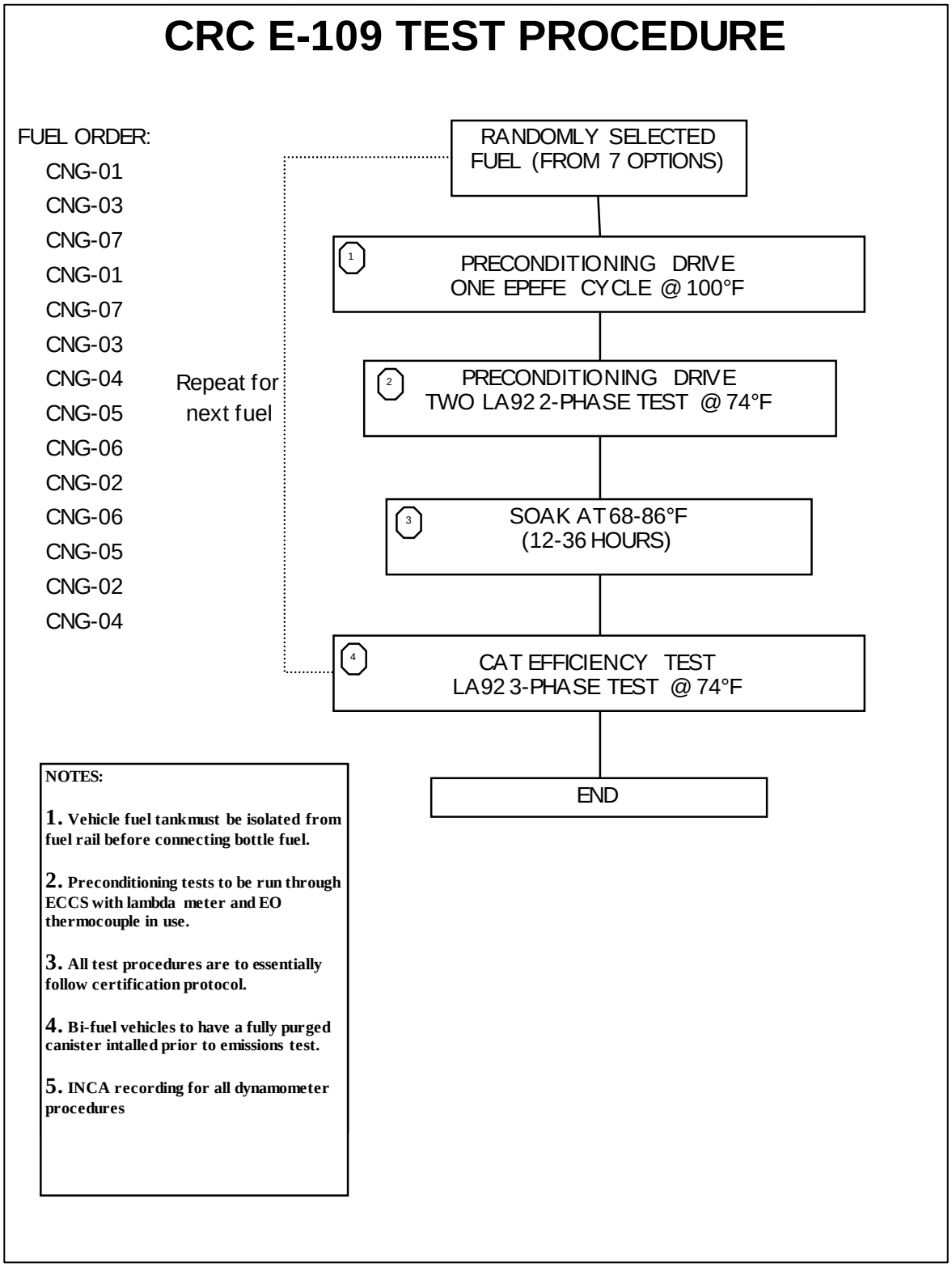
The most efficient way to test each vehicle was to use one fuel blend each day. The Ram was tested first in sequence for each fuel change to allow the lower horsepower vehicles to deplete the fuel cylinders at a slower rate when there was less pressure. The Ram 2500 CNG has the highest horsepower rating and therefore it required the highest fuel flow rate during the EPEFE test. The fuels used in the study are described in Section 4.0.

To mitigate and chance of fuel carryover and to allow the vehicle's control system to fully adapt to the test fuel, a total of 43.9 miles were driven over preparation cycles.

The EPEFE cycle consisted of ten WOT events. The EPEFE cycle was run at 100°F ambient temperature, as it was also used for the purpose of performing Knock Investigation #1.

The preparation cycle used prior to the emissions test was two consecutive LA92 2-Phase cycles driven back to back as shown in Figure 22 below. Vehicles were then soaked for 12-36 hours in a temperature and humidity controlled environment. The two bi-fuel vehicles' canisters were purged for one hour during every soak period prior to the emissions test.

Table 6. Emissions Test Sequence for CRC E-109



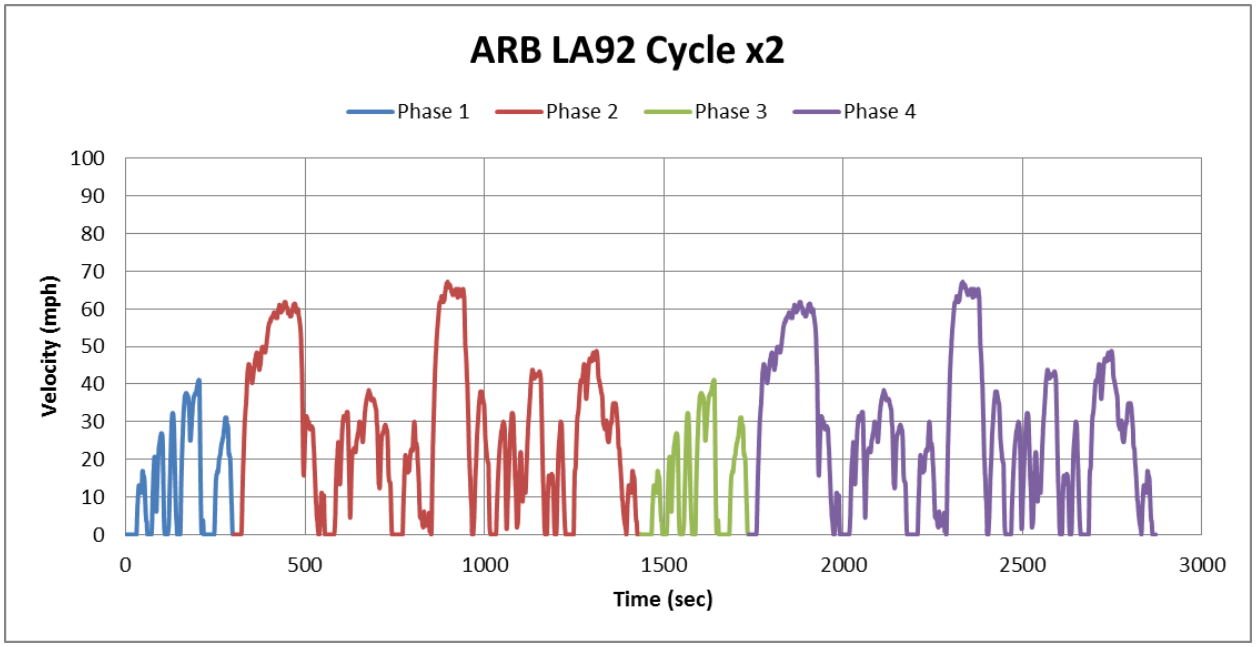


Figure 22. Preconditioning Cycle, LA92 x2

A LA-92 emissions test procedure was then performed following the soak period in a certification-compliant chassis dynamometer laboratory. The LA92 test procedure was a 3-Phase transient drive cycle further described in Figure 23. The first and third phases were 300 seconds and had an average speed of 14.18 mph. The second phase was 1135 seconds and had an average speed of 27.37 mph. A ten-minute hot soak period was included between phases 2 and 3. The LA92 had higher speeds and more aggressive accelerations than the FTP75, and was used to explore relativistic effects of each fuel.

All emissions tests were driven by the same technician to control test-to-test driver variability.

Vehicle exhaust emissions were measured for each LA-92 3-Phase drive cycle performed as part of the test sequence. Emissions were measured by collecting bag samples for each phase from the constant volume sampling system as well as engine-out and tailpipe raw modal emissions.

Engine-out emissions were sampled upstream of the aftertreatment system, to compare lambda and modal emissions. Raw-tailpipe emissions and dilute bag emissions were sampled downstream of all after treatment components in order to compare and correlate the sampling methods. Using two sampling methods downstream of the aftertreatment system adds an extra quality check to ensure the operation of each analyzer.

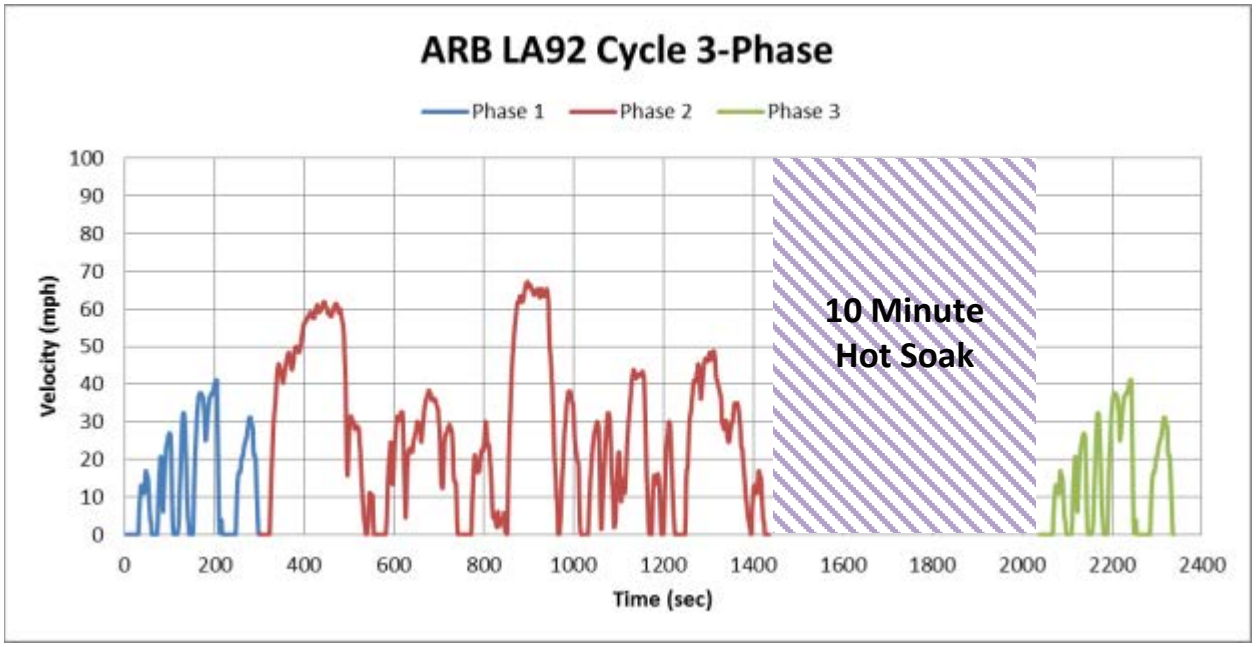


Figure 23. Emissions Cycle, LA92 3-Phase Test

3.5 Test Cell Equipment and Layout

Emissions tests were performed in an emissions certification-compliant chassis dynamometer laboratory at SGS Environmental Testing Corporation in Aurora, Colorado. All emissions tests were run on Site 3, featuring a Burke Porter 48" roll dynamometer in a temperature and humidity controlled environment. The laboratory has a constant volume sampling system (CVS), raw modal and dilute bag gas sampling and analysis. Bag samples were simultaneously collected from the diluted vehicle exhaust and from the ambient, to ensure quantification of the background and accurate calculation of phase-averaged exhaust mass emissions. The bag analysis included measurement of CO, CO_2, NOx, THC, and CH_4 gases. Emissions laboratory equipment was compliant with EPA 40CFR Part 86 subpart B standards.

The six-pack cylinders were positioned behind the vehicle in the test cell as shown in Figure 244 for both the FWD and RWD vehicle configurations. When changing from RWD to FWD, the position of the cylinders remained the same. The 20' fuel supply hose was able to reach the filling port on all vehicles, regardless of the vehicle driveline. Safety ventilation was plumbed into the fuel supply line that would evacuate any gaseous fuel pressure in the NGV1 fill port adaptor or fuel line from the six-pack to the vehicle.

When changing vehicles using the same fuel, the dry break NGV1 fill port allowed minimal gas pressure to escape from the fuel supply. The EPEFE and 2xLA92 preparation cycles ensured the vehicle supply line was purged of any carry over residual fuel. At the end of the preparation cycles the vehicle's fuel system remained pressurized when the supply line was disconnected for the soak period, and then reconnected to the same fuel prior to the emissions test.

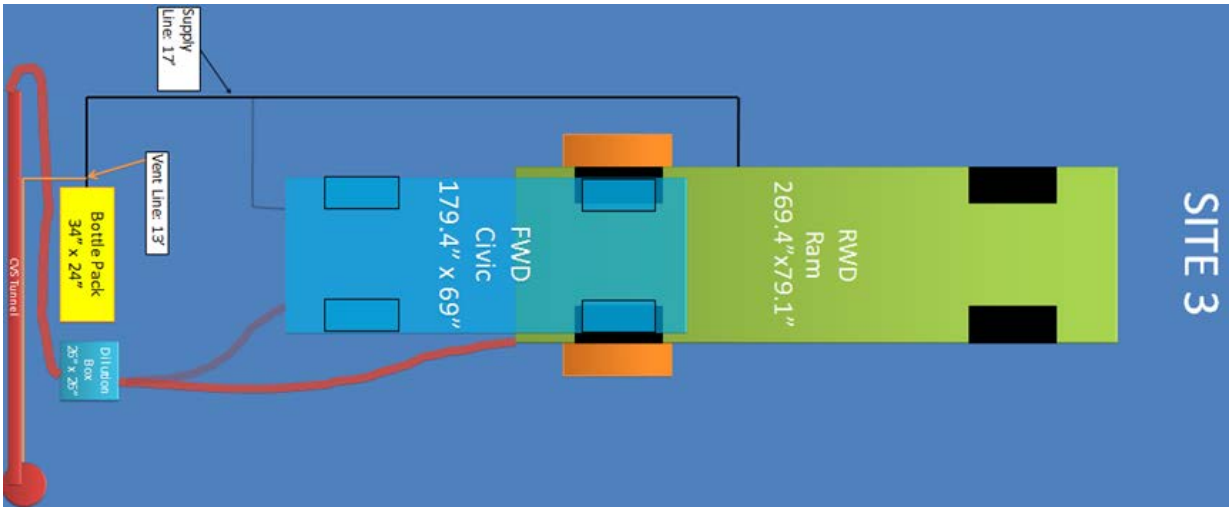


Figure 24. SGS Site 3 Test Cell Layout for RWD and FWD Vehicles

Figure 255, Figure 26, and Figure 27 below illustrate the test cell setup for all three vehicles with the six-pack bottle cart behind the vehicle, Coriolis flow meter in-line with the supply line, and the supply line connected to the NGV1 fill port. The cart holding the Coriolis flow meter was secured to the floor which created a stationary mounting point for the dry-break quick disconnect fittings in the supply line in the unlikely event the vehicle were to move off the dynamometer.

Figure 25. Dodge Ram 2500 CNG Installed on SGS Site 3

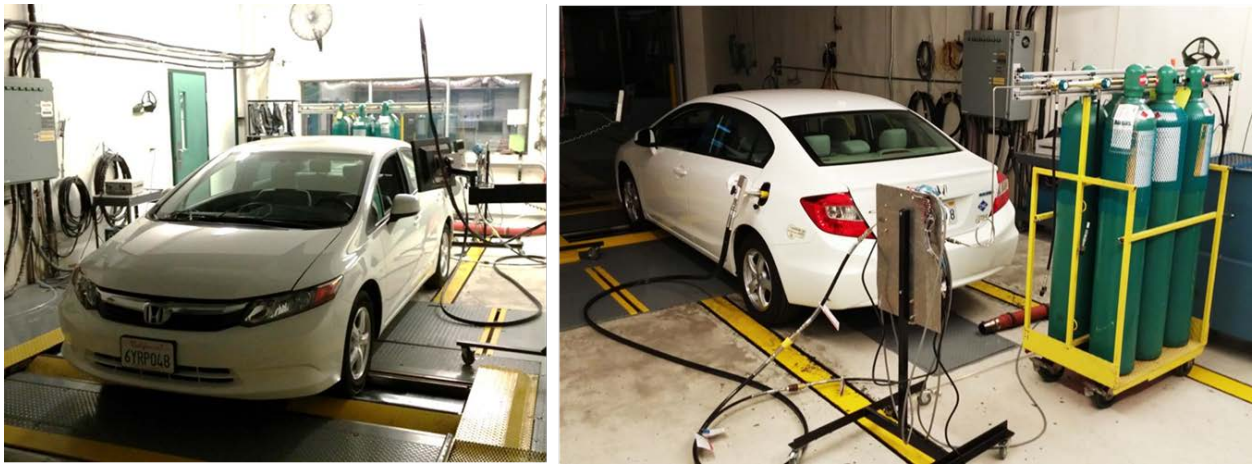


Figure 26. Honda Civic GX Installed on SGS Site 3

Figure 27. Volkswagen Golf TGI Installed on SGS Site 3

4.0 Fuels

Originally six target fuel blends were selected based on results from the CRC PC-2-12 program encompassing high and low methane number and Wobbe Index. A seventh fuel was added to capture the average of the fuels found in the field. The table below illustrates the CRC targets and the SGS proposed target fuels. Differences between the values were because of gravimetric blending limits as directed by the fuel supplier. The maximum pressure was targeted at 1800 psig which excluded hexane from the blends and limited pentane to 0.5%, and butane to a maximum of 2% per supplier guidance. To create fuel with a high methane number, the majority of the blend must contain mostly methane. Adding heavier molecular weight hydrocarbons had an impact of both lowering the methane number and increasing the Wobbe Index as the heavier hydrocarbons have greater energy density.

Table 7 below shows the SGS proposed target percent volume of each constituent for each fuel. Methane number was calculated using the California Air Resource Board (CARB) hydrogen-to-carbon atomic ratio method (H/C method), where the motor octane number (MON) was used to determine

methane number (MN). The H/C ratio is 4 for pure methane. The correlation (1) for MON is not valid for H/C < 2.5 and for inert gas concentrations in fuel greater than 5%. The correlation shown in (2) typically predicts MNs 8.6% higher than the actual test values[1].

$$MON = -406.14 + 508.04(H/C) - 173.55(H/C)^2 + 20.17(H/C)^3 \quad (1)$$

$$MN = 1.624(MON) - 119.1 \quad (2)$$

Wobbe Index was calculated using the fuel's higher heating value and specific gravity as shown below in (3).

$$Wobbe\ Index(BTU/ft^3) = \frac{HHV\ (BTU/ft^3)}{\sqrt{SG}} \quad (3)$$

Table 7. CNG Target Fuel Blends

Fuel #		1	2	3	4	5	6	7
CRC Proposed Targets	Methane Number	85	105	85	60	85	60	97
	Wobbe Index (BTU/ft^3)	1225	1330	1330	1330	1425	1425	1345
SGS Proposed Blends	Methane Number	85.13	105.59	85.28	60.02	84.95	60.07	96.95
	Wobbe Index (BTU/ft3)	1227	1334	1334	1327	1404	1427	1342
		(% Vol)	(% Vol)	(% Vol)	(% Vol)	(% Vol)	(% Vol)	(% Vol)
Methane	CH4	94.300%	98.780%	92.500%	75.000%	94.700%	77.800%	96.700%
Ethane	C2H6	0.000%	0.000%	0.000%	10.500%	0.000%	13.900%	2.200%
Propane	C3H8	0.000%	0.000%	4.300%	4.000%	5.300%	4.000%	0.000%
Butane	C4H10	0.000%	0.000%	0.000%	2.000%	0.000%	1.500%	0.000%
Pentane	C5H12	0.000%	0.000%	0.000%	0.500%	0.000%	0.500%	0.000%
Hexane	C6+	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
Oxygen	O2	1.000%	0.000%	0.500%	1.000%	0.000%	0.000%	0.000%
Nitrogen	N2	0.000%	0.720%	2.000%	4.700%	0.000%	0.000%	0.000%
Carbon Dioxide	CO2	4.700%	0.500%	0.700%	2.300%	0.000%	2.300%	1.100%
H/C Ratio		3.810	3.980	3.811	3.485	3.808	3.486	3.914
O/C Ratio		0.115	0.010	0.023	0.055	0.000	0.036	0.022
Stoich A/F Ratio		14.737	16.710	15.957	14.509	16.948	15.844	16.611
HHV (BTU/ft^3)		954.0	1000.0	1045.0	1133.0	1092.0	1205.0	1018.0
Specific Gravity		0.605	0.562	0.613	0.729	0.605	0.714	0.575

[1] "Paper Study on the Effect of Varying Fuel Composition on Fuel Supplied to Detroit Diesel Gas Engines", Report prepared for Southern California Gas Company, May 2005.

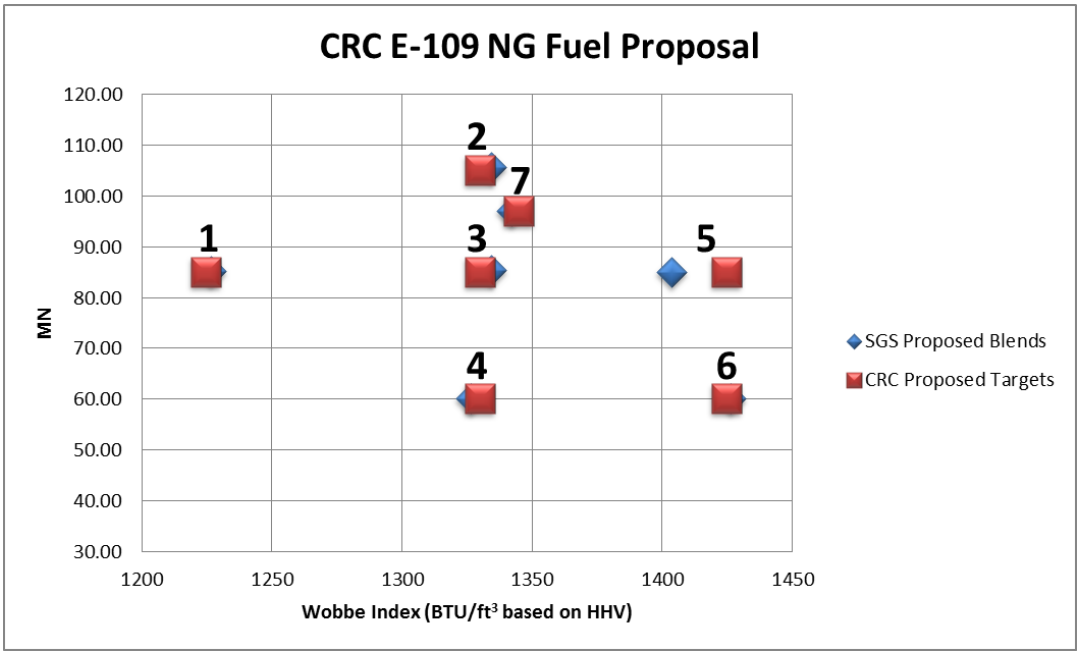


Figure 28. CNG Fuel Blends Chart

Blends were prepared by the fuel supplier gravimetrically by dispensing the raw constituents into DOT 300 series bottles using calibrated flow meters. Twenty cylinders of each fuel were procured totaling 140 300-series cylinders. The bottles were delivered and stored inside SGS's facility in a temperature controlled environment with methane detection and an explosion proof fan. Handling of the cylinders was conducted according to an internal safety plan for flammable gases. The fuel did not need conditioning prior to the emissions testing as the bottle storage was at the same environmental conditions as the emissions test cell. Six cylinders of each test fuel were staged on six-pack carts with a common outlet manifold for easy transportation and change out as shown in Figure 29 below.

Figure 29. SGS CNG Bottle Storage Room

Fuel speciation was cataloged by gas chromatography to determine molar % of methane, ethane, propane, isobutane, N-butane, isopentane, N-pentane, hexane+, helium, hydrogen, oxygen, nitrogen, and carbon dioxide. Heating value was determined by ASTM D3588-98. From these data, methane number was calculated by the ARB measured H/C ratio method, Wobbe Index by higher heating value, specific gravity, and stoichiometric air/fuel ratio were also calculated. Table 8 below shows a summary of the AirGas fuel analysis.

Table 8. AirGas Certification Analysis

Fuel #		1	2	3	4	5	6	7
Air Gas Report #		126-400413793-1	126-400411188-1	126-400414939-1A	126-400410049-1	126-400412626-1	126-400410051-1	126-400416507-1
CRC Proposed Targets	Methane Number	85	105	85	60	85	60	97
	Wobbe Index (BTU/ft^3)	1225	1330	1330	1330	1425	1425	1345
Based on AirGas Certification	Methane Number	85.06	105.66	85.23	60.02	84.96	60.06	96.89
	Wobbe Index (BTU/ft3)	1228	1337	1338	1328	1406	1428	1344
		(% Vol)	(% Vol)	(% Vol)	(% Vol)	(% Vol)	(% Vol)	(% Vol)
Methane	CH4	94.270%	98.810%	92.510%	75.000%	94.710%	77.790%	96.680%
Ethane	C2H6	0.000%	0.000%	0.000%	10.500%	0.000%	13.900%	2.218%
Propane	C3H8	0.000%	0.000%	4.352%	4.000%	5.295%	4.001%	0.000%
Butane	C4H10	0.000%	0.000%	0.000%	1.999%	0.000%	1.500%	0.000%
Pentane	C5H12	0.000%	0.000%	0.000%	0.501%	0.000%	0.503%	0.000%
Hexane	C6+	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
Oxygen	O2	1.016%	0.000%	0.485%	1.000%	0.000%	0.000%	0.000%
Nitrogen	N2	0.000%	0.702%	1.987%	4.700%	0.000%	0.000%	0.000%
Carbon Dioxide	CO2	4.716%	0.489%	0.666%	2.300%	0.000%	2.303%	1.103%
H/C Ratio		3.809	3.980	3.811	3.485	3.808	3.486	3.913
O/C Ratio		0.116	0.010	0.022	0.055	0.000	0.036	0.022
Stoich A/F Ratio		14.725	16.720	15.979	14.509	16.948	15.843	16.609
HHV (BTU/ft^3)		956.3	1002.3	1048.7	1135.4	1094.9	1208.3	1020.2
Specific Gravity		0.606	0.562	0.615	0.731	0.606	0.716	0.576

Independent verification of the supplier's measured gas constituents was performed by Empact Analytical using gas chromatography per ASTM D1945-10. The sample preparation method was done by connecting a vacuum evacuated 300cc cylinder to the gas bottle, drawing a vacuum on the connection, then charging the 300cc cylinder to full bottle pressure of approximately 1800 PSIG. The sample collection method minimized contamination from atmospheric air and if there was contamination it would be a much smaller percent of the total mass. Results from Empact Analytical closely matched the target fuel blends as shown in Table 9 below. In addition they are nearly identical to the certifications provided by the gas supplier.

Table 9. Empact Analytical Certification Analysis vs. Target CNG Blends

Fuel #		1	2	3	4	5	6	7
Empact Analystical Report #		20141022-04	20141022-06	20141022-05	20141022-02	20141022-01	20141022-03	20141022-07
CRC Proposed Targets	Methane Number	85	105	85	60	85	60	97
	Wobbe Index (BTU/ft^3)	1225	1330	1330	1330	1425	1425	1345
Based on Empact Certification	Methane Number	84.96	105.48	85.37	60.32	85.05	60.07	96.83
	Wobbe Index (BTU/ft3)	1228	1335	1338	1324	1405	1427	1343
		(% Vol)	(% Vol)	(% Vol)	(% Vol)	(% Vol)	(% Vol)	(% Vol)
Methane	CH4	94.230%	98.760%	92.610%	75.120%	94.710%	77.830%	96.650%
Ethane	C2H6	0.000%	0.000%	0.000%	10.420%	0.000%	13.820%	2.210%
Propane	C3H8	0.000%	0.000%	4.290%	3.980%	5.270%	4.010%	0.000%
Butane	C4H10	0.000%	0.000%	0.000%	1.950%	0.000%	1.510%	0.000%
Pentane	C5H12	0.000%	0.000%	0.000%	0.450%	0.000%	0.500%	0.000%
Hexane	C6+	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
Oxygen	O2	1.010%	0.000%	0.470%	1.010%	0.010%	0.000%	0.000%
Nitrogen	N2	0.020%	0.720%	1.930%	4.760%	0.010%	0.010%	0.020%
Carbon Dioxide	CO2	4.740%	0.520%	0.690%	2.300%	0.000%	2.310%	1.120%
H/C Ratio		3.808	3.979	3.812	3.491	3.809	3.486	3.913
O/C Ratio		0.116	0.010	0.022	0.055	0.000	0.036	0.022
Stoich A/F Ratio		14.713	16.701	15.991	14.493	16.942	15.839	16.596
HHV (BTU/ft^3)		955.9	1001.8	1048.1	1131.0	1094.3	1207.7	1019.8
Specific Gravity		0.606	0.563	0.614	0.729	0.606	0.716	0.576

The AirGas chromatography targets and measured results were within 4.8% for hydrocarbon based constituents, and within 1.6% for non-hydrocarbon based constituents. The Empact Analytical results fell within 10% of the target values for the hydrocarbon constituents and within 6% for the non-hydrocarbon constituents. Fuel properties for emissions calculations were based on EPA 40CFR600.113 to determine the carbon weight fraction for the total natural gas blend, hydrocarbon specific carbon weight fraction, CO_2 weight fraction, and non-methane hydrocarbon weight fraction based on the AirGas certification values. This report's emissions calculations were also based on the AirGas certification reports.

5.0 Test Results Organization

Over 42 LA-92 exhaust emissions tests were performed for the study. The test results reside in a master dataset in Microsoft Excel® format. This master dataset is also illustrated in Appendices 5-20 of this report showing weighted and per-phase bag, engine-out, and tailpipe emissions in bar charts. To aid in visualization and understanding of data scatterplots, series sets have different symbols per fuel type as shown in Figure 30.

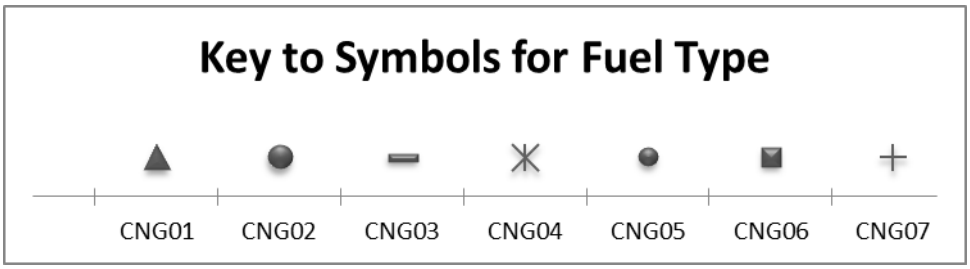


Figure 30. Key to Symbols for Fuel Type

6.0 LA-92 Exhaust Emissions Test Results, Plots, and Data Summaries

In this report, "Bag" emissions refers to the diluted exhaust emissions captured in bags and corrected for ambient background. The ambient sample was also simultaneously collected in bags from the test cell room. Bag emissions are therefore the post-catalyst emissions from the vehicle. Bag results are most accurate for mass emissions determination, and were used for the statistical analysis and to draw most conclusions.

"Engine" or "Engine-Out" designates modal emissions exhausted directly from the engine, with the sample being drawn continuously and upstream of the catalysts. "Tailpipe" modal results pertain to emissions downstream of all catalysts but prior to exhaust dilution. Unlike discrete batch-analyzed "Bag" emissions, both "Engine-Out" and "Tailpipe" modal emissions were sampled continuously and provided information about the time to catalyst light-off and catalyst conversion efficiency.

"Weighted" emissions were determined using results from the three phases of the LA92 cycle. The formula for weighting was the same as the FTP75, taking actual mileage from each phase of the LA92 cycle into account.

In the figures presented, "THC" and "HC" designations are used interchangeably and represent the total hydrocarbons measured using a flame ionization detector.

Natural gas fuel economy was calculated as MPGe (miles per gasoline gallon equivalent) based on EPA 40CFR600.113-12(k)(1) per the equation (4) below using the fuel properties shown in Section 4.0.

$$MPGe = \frac{CWF_{HC/NG} \times D_{NG} \times 121.5}{(0.749 \times CH_4) + (CWF_{NMHC} \times NMHC) + (0.429 \times CO) + \left(0.273 \times (CO_2 - CO_{2NG})\right)} \quad (4)$$

Where:

MPGe = miles per gasoline gallon equivalent of natural gas.

$CWF_{HC/NG}$ = carbon weight fraction based on the hydrocarbon constituents in the natural gas fuel.

D_{NG} = density of the natural gas fuel [grams/ft^3 at 20 °C and 760 mmHg].

CH_4, NMHC, CO, and CO_2 = weighted mass exhaust emissions [grams/mile] for methane, non-methane hydrocarbons, carbon monoxide, and carbon dioxide.

CWF_{NMHC} = carbon weight fraction of the non-methane hydrocarbon constituents in the fuel as determined from the speciated fuel composition.

CO_{2NG} = grams of carbon dioxide in the natural gas fuel consumed per mile of travel.

6.1 Vehicle A Results

Vehicle A was the only dedicated NGV of the test group and did not have an evaporative emissions system. Therefore there were no special considerations needed for canister preconditioning during the soak period prior to the emissions test. Fourteen LA92 3-bag emissions tests were performed with bag-weighted (post-catalyst) results shown below in Table 10. Tests performed on the same fuel show good repeatability for all emissions measurements. Fuel economy changed significantly between fuels with the lowest value of 25.94 MPGe on CNG01 and the highest of 34.39 MPGe on CNG06. Fuel economy was found to be proportional to the Wobbe Index, as expected. Bag-weighted THC were below 0.0180 g/mi for all tests and bag-weighted NOx was nearly zero. CO fell between 0.255 g/mi and 0.354 g/mi.

Table 10. Vehicle A LA92 Post-Catalyst Bag-Weighted Emissions Results

Date	Test Number	Fuel	Weighted Summary						
			BAG_HC	BAG_CO	BAG_CO2	BAG_NOx	BAG_CH4	BAG_N-CH4	BAG_FE
Vehicle A			(g/mi)	(g/mi)	(g/mi)	(g/mi)	(g/mi)	(g/mi)	(MPGe)
10/24/2014	3119919	CRC_CNG01	0.018	0.295	230.900	0.004	0.017	0.002	26.030
10/29/2014	3120008	CRC_CNG01	0.011	0.314	231.630	0.001	0.010	0.001	25.940
11/6/2014	3120196	CRC_CNG02	0.012	0.264	220.780	0.002	0.011	0.002	28.200
11/11/2014	3120305	CRC_CNG02	0.011	0.339	220.860	0.003	0.011	0.001	28.180
10/27/2014	3119966	CRC_CNG03	0.015	0.309	221.750	0.002	0.014	0.002	30.010
10/31/2014	3120066	CRC_CNG03	0.010	0.285	224.790	0.002	0.009	0.002	29.610
11/3/2014	3120102	CRC_CNG04	0.009	0.277	236.170	0.002	0.007	0.002	31.780
11/12/2014	3120347	CRC_CNG04	0.011	0.324	236.180	0.000	0.008	0.003	31.770
11/4/2014	3120122	CRC_CNG05	0.010	0.255	223.460	0.002	0.009	0.002	31.160
11/10/2014	3120272	CRC_CNG05	0.012	0.307	226.640	0.003	0.010	0.002	30.710
11/5/2014	3120155	CRC_CNG06	0.009	0.310	232.230	0.002	0.007	0.003	34.390
11/7/2014	3120216	CRC_CNG06	0.009	0.354	234.720	0.002	0.007	0.003	34.010
10/28/2014	3119987	CRC_CNG07	0.011	0.347	229.390	0.002	0.010	0.002	27.810
10/30/2014	3120045	CRC_CNG07	0.011	0.302	221.670	0.002	0.011	0.001	28.790

Post-catalyst bag NOx emissions were at very low levels, varying between zero (below detection limit) and 4 mg/mile. The engine-out NOx varied between fuels. The catalyst NOx conversion efficiency fell between 99.9% and 100% indicating accurate fueling and a well-developed control strategy. An increasing trend was seen in engine-out NOx when compared to the fuel's total NMHC concentration as shown in Figure 31.

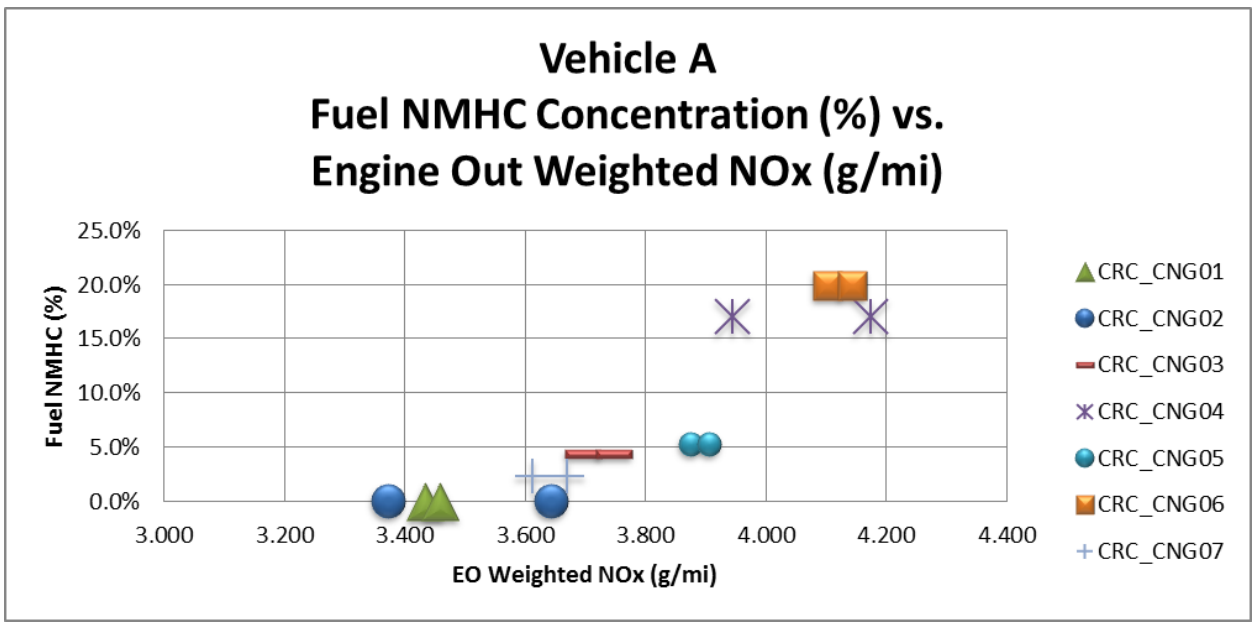


Figure 31. Vehicle A Fuel NMHC % Concentration vs. Engine-Out-Weighted NOx

Differences were seen in NMHC emissions during Phase 1 which encompassed the cold start. CNG01 and CNG02 fuels did not contain any NMHC and showed near zero NMHC emissions. Fuel CNG04 and CNG06 had the highest concentration of NMHC (17.0% and 19.9% respectively) and had correspondingly higher NMHC emissions during Phase 1. Figure 32 below shows a linear trend with increasing fuel NMHC percentage as there was an increase in Phase 1 NMHC emissions.

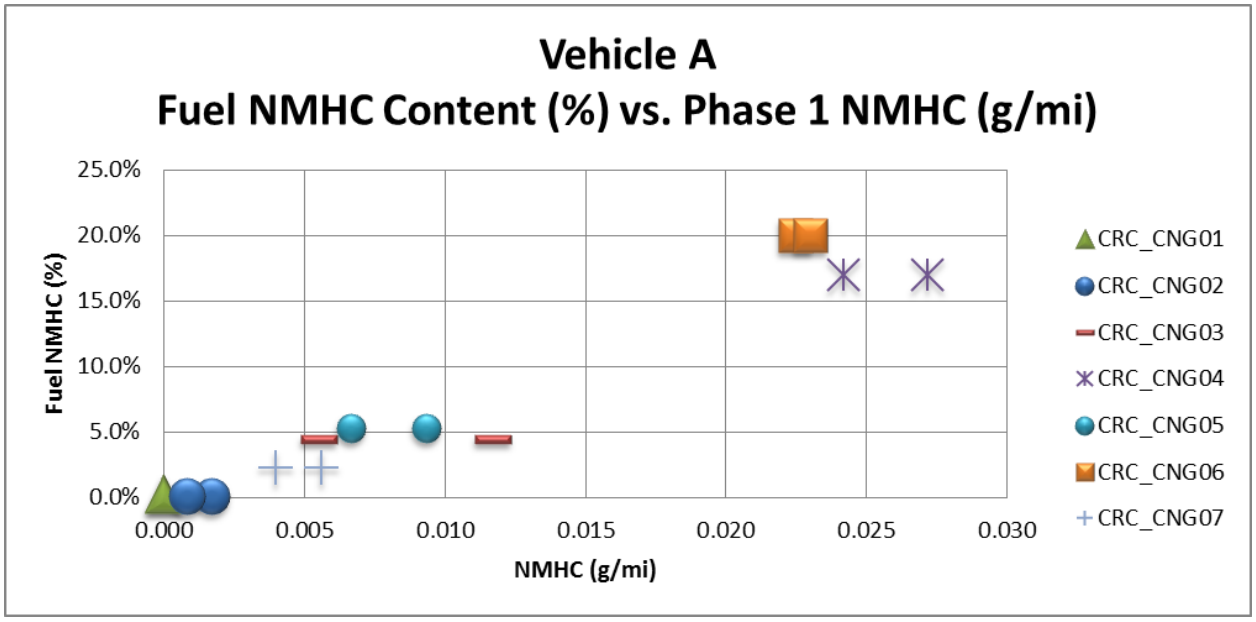


Figure 32. Vehicle A Fuel NMHC Content vs. Phase 1 Bag NMHC

6.2 Vehicle B Results

Vehicle B had a bi-fuel system with dedicated CNG and gasoline fuel systems. An evaporative emissions charcoal canister was fitted to the vehicle which was purged prior to every emissions test to mitigate any influence in emissions due to canister purge events. Purge flow rate was recorded to identify when the system was commanding the canister purge valve to open. The purge volume recorded for all tests with Vehicle B were below 1.0 ft^3.

Fourteen LA92 3-bag emissions tests were performed with bag-weighted results shown below in Table 11. Tests performed on the same fuel showed good repeatability for all emissions measurements. Fuel economy changed between fuels with the lowest value of 28.39 MPGe on CNG01 and the highest of 38.24 MPGe on CNG06. Bag-weighted THC were below 0.047 g/mi for all tests and bag-weighted NOx was had a maximum of 0.060 g/mi. CO fell between 0.255 g/mi and 0.354 g/mi.

Table 11. Vehicle B LA92 Post-Catalyst Bag-Weighted Emissions Results

Date	Test Number	Fuel	Weighted Summary						
			BAG_HC	BAG_CO	BAG_CO2	BAG_NOx	BAG_CH4	BAG_N-CH4	BAG_FE
Vehicle B			(g/mi)	(g/mi)	(g/mi)	(g/mi)	(g/mi)	(g/mi)	(MPGe)
10/24/2014	3119916*	CRC_CNG01	0.047	0.182	211.740	0.051	0.032	0.017	28.390
10/29/2014	3120018	CRC_CNG01	0.039	0.093	207.340	0.033	0.040	0.002	29.010
11/6/2014	3120187	CRC_CNG02	0.039	0.087	199.820	0.030	0.040	0.002	31.190
11/11/2014	3120303	CRC_CNG02	0.040	0.072	198.800	0.040	0.042	0.001	31.350
10/27/2014	3119964*	CRC_CNG03	0.043	0.163	205.020	0.060	0.027	0.018	32.480
10/31/2014	3120071	CRC_CNG03	0.041	0.083	199.580	0.042	0.041	0.002	33.380
11/4/2014	3120114	CRC_CNG04	0.026	0.091	209.730	0.027	0.025	0.003	35.820
11/12/2014	3120343	CRC_CNG04	0.027	0.112	213.990	0.022	0.025	0.004	35.100
11/10/2014	3120270	CRC_CNG05	0.035	0.084	199.470	0.032	0.034	0.004	34.940
11/13/2014	3120367*	CRC_CNG05	0.038	0.132	208.540	0.027	0.022	0.017	33.410
11/5/2014	3120158	CRC_CNG06	0.028	0.097	209.930	0.036	0.025	0.005	38.080
11/7/2014	3120221	CRC_CNG06	0.027	0.103	209.060	0.036	0.024	0.005	38.240
10/28/2014	3119985*	CRC_CNG07	0.044	0.169	205.870	0.033	0.028	0.018	31.020
11/14/2014	3120391*	CRC_CNG07	0.040	0.151	207.030	0.032	0.025	0.017	30.850

*Tests with cold start operation on gasoline for first 160 seconds during Phase 1

Figure 33 below shows Phase 1 NMHC for Vehicle B. Five out of the fourteen tests had NMHC emissions above 0.05 g/mi during Phase 1. Correspondingly the instantaneous CNG flow measurement using the Coriolis meter was zero for the first 160 seconds of these tests. An example for Test #31120391 is shown in Figure 34 and indicates gasoline operation for the first 160 seconds of this test.

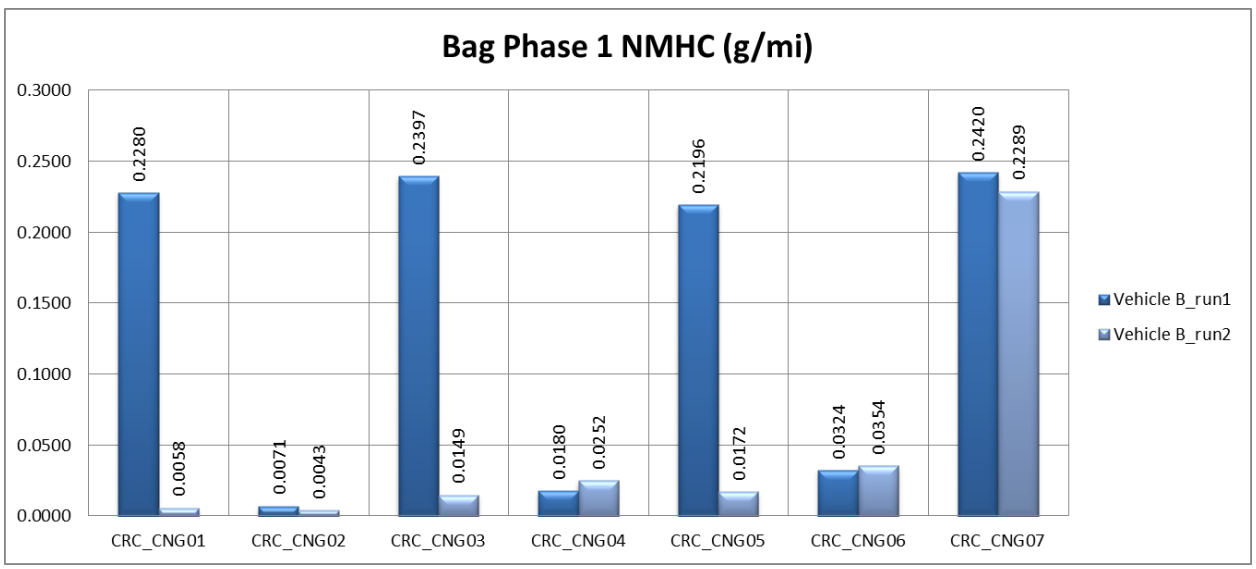


Figure 33. Vehicle B Phase 1 Bag NMHC (g/mi)

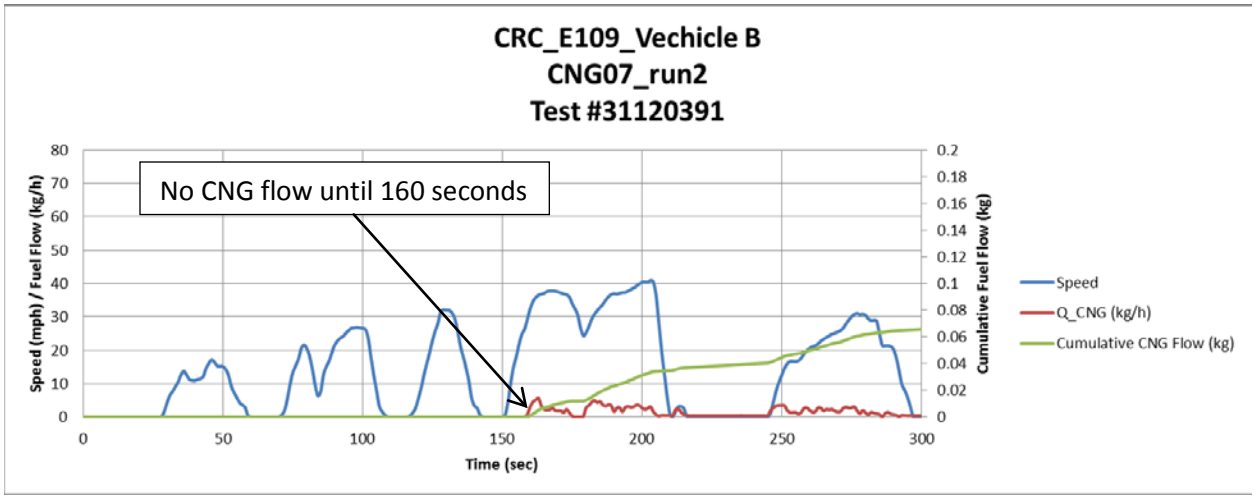


Figure 34. Vehicle B CNG07_run2 (Gasoline Cold Start)

Documentation provided for Vehicle B indicated that the control system uses gasoline if the ambient temperature is below -10°C for cold start operation. It is undetermined what parameter(s) are used for gasoline operation during cold starts at 74°F ambient temperature used for these tests, but it is apparent the control system used gasoline under certain operating conditions. The gasoline fuel use on start-up was part of the vehicle's control strategy, and could not be readily defeated by SGS during the testing program. The gasoline fuel use is therefore a confounding factor for some tests for this vehicle. Statistical analysis of the results presented later in this report excluded the tests with gasoline operation during the cold start for Vehicle B.

6.3 Vehicle C Results

Vehicle C had a bi-fuel system with dedicated CNG and gasoline fuel systems. An evaporative emissions charcoal canister was fitted to the vehicle which was purged prior to every emissions test to mitigate any influence in emissions due to canister purge events. Purge flow rate was recorded to identify when the system was commanding the canister purge valve to open. The purge volume recorded for all tests with Vehicle C varied between a total of 6.2-16.98 ft^3.

The injection control strategy for Vehicle C consisted of gasoline operation while on CNG to help purge the gasoline injectors at predetermined intervals during a drive cycle to keep the fuel fresh. The manufacturer of Vehicle C provided a modified calibration to disable the periodic gasoline injection to eliminate influence on LA92 emissions test results with OBD scans provided in Appendix 12.3 showing the calibration identification numbers.

Fourteen LA92 3-bag emissions tests were performed with bag-weighted results shown below in Table 12. Tests performed on the same fuel showed good repeatability for all emissions measurements. Fuel economy changed between fuels with the lowest value of 8.79 MPGe on CNG01 and the highest of 11.53 MPGe on CNG06. Bag-weighted THC were below 0.146 g/mi for all tests and bag-weighted NOx had a maximum of 0.259 g/mi. CO fell between 0.369 g/mi and 0.871 g/mi.

Table 12. Vehicle C LA92 Post-Catalyst Bag-Weighted Emissions Results

Date	Test Number	Fuel	Weighted Summary						
			BAG_HC	BAG_CO	BAG_CO2	BAG_NOx	BAG_CH4	BAG_N-CH4	BAG_FE
Vehicle C			(g/mi)	(g/mi)	(g/mi)	(g/mi)	(g/mi)	(g/mi)	(MPGe)
11/14/2014	3120386	CRC_CNG01	0.146	0.369	684.500	0.259	0.152	0.003	8.790
10/29/2014	3120013	CRC_CNG01	0.133	0.388	678.810	0.157	0.138	0.004	8.860
11/6/2014	3120191	CRC_CNG02	0.121	0.392	653.380	0.051	0.125	0.004	9.540
11/25/2014	3120572	CRC_CNG02	0.127	0.550	649.520	0.049	0.131	0.006	9.590
10/27/2014	3119960	CRC_CNG03	0.130	0.871	663.430	0.068	0.128	0.010	10.030
10/31/2014	3120069	CRC_CNG03	0.110	0.425	663.140	0.050	0.110	0.007	10.040
11/3/2014	3120096	CRC_CNG04	0.086	0.410	683.860	0.084	0.076	0.015	10.980
11/21/2014	3120529	CRC_CNG04	0.092	0.458	688.300	0.138	0.079	0.018	10.910
11/4/2014	3120121	CRC_CNG05	0.119	0.839	651.890	0.062	0.119	0.009	10.680
11/11/2014	3120295	CRC_CNG05	0.111	0.466	658.910	0.071	0.110	0.008	10.570
11/5/2014	3120148	CRC_CNG06	0.086	0.866	692.770	0.041	0.072	0.019	11.530
11/7/2014	3120218	CRC_CNG06	0.081	0.464	694.750	0.046	0.068	0.017	11.500
10/28/2014	3119982	CRC_CNG07	0.126	0.681	660.090	0.051	0.128	0.006	9.670
10/30/2014	3120044	CRC_CNG07	0.125	0.839	656.140	0.045	0.128	0.005	9.720

Overall the mass emissions from Vehicle C were higher than the other vehicles as expected for this heavier class vehicle. Differences were seen in NMHC emissions during Phase 1 which encompassed the cold start. Fuels CNG01 and CNG02 did not contain any NMHC and had near zero NMHC emissions in the exhaust. Fuels CNG04 and CNG06 had the highest concentration of NMHC (17.0% and 19.9% respectively) and had correspondingly higher NMHC during Phase 1. Figure 35 below shows a linear trend with increasing fuel NMHC percentage and Phase 1 NMHC emissions.

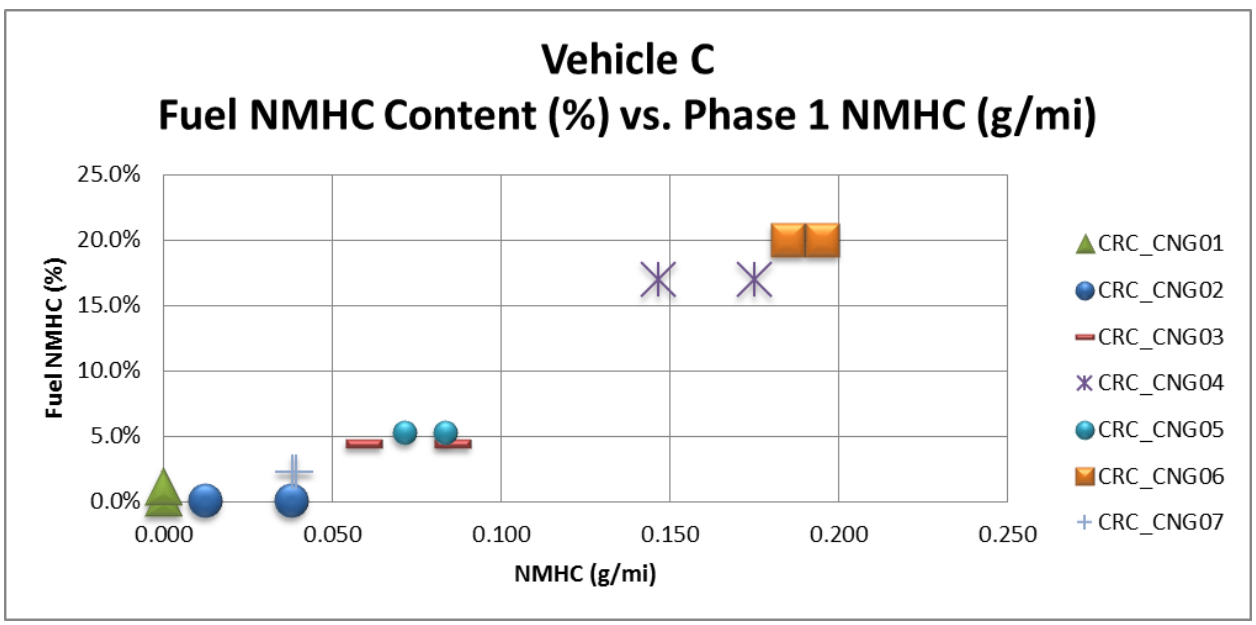


Figure 35. Vehicle C Fuel NMHC Content vs. Phase 1 Bag NMHC

6.4 Vehicle Comparison

To gain a better understanding of the fuel effects, the vehicles are further compared by using modal data, bag data, and other measurements in this section. The data can be used to determine the degree the fuel affected the engine-out emissions and catalyst conversion efficiency.

The stoichiometric air/fuel ratio (volume based) was calculated by taking the mass based Stoich A/F ratio and multiplying it by the fuel's specific gravity. The volume based Stoich A/F ratio versus the bag-weighted fuel economy is shown in Figure 36. The 42 data points for all emissions tests exhibited a strong increasing trend in MPGe with higher volume based Stoich A/F. As less fuel volume was required to achieve stoichiometric combustion, higher fuel economy was achieved.

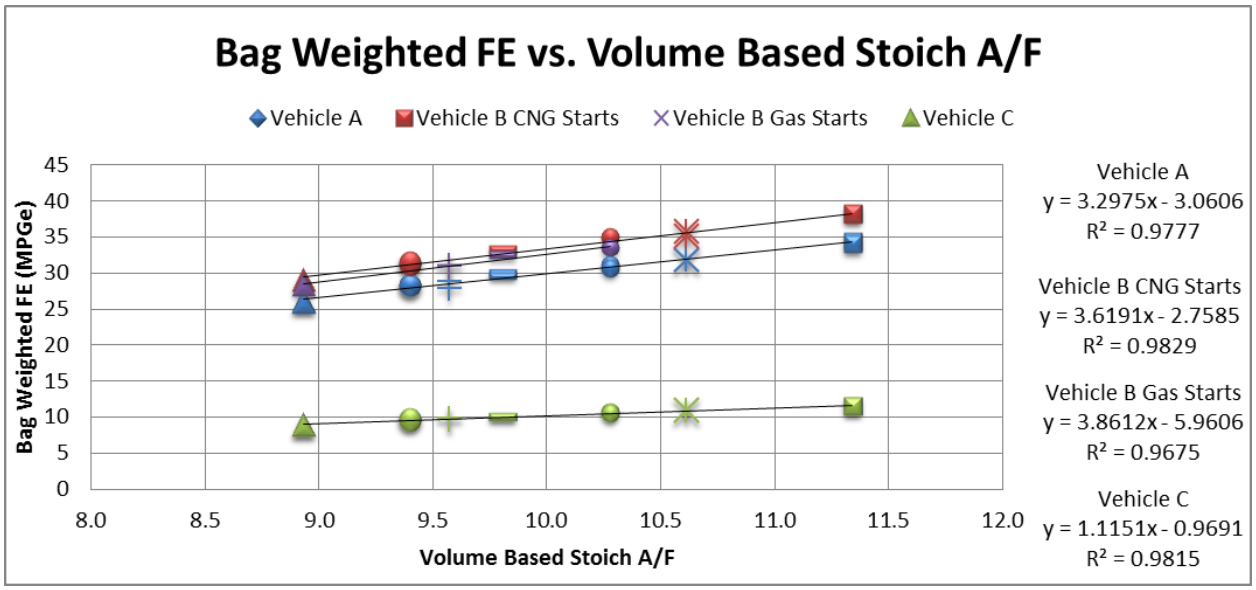


Figure 36. Bag-Weighted FE vs. Volume Based Stoichiometric A/F

With decreasing fuel energy density there was an increase in average mass fuel flow required as shown in Figure 37. As energy content decreased, more fuel mass was required to maintain the same power level to drive the LA92 cycle. The five tests on Vehicle B showed the lowest average CNG mass fuel flow since the first 160 seconds of the test replace CNG flow with gasoline fuel flow.

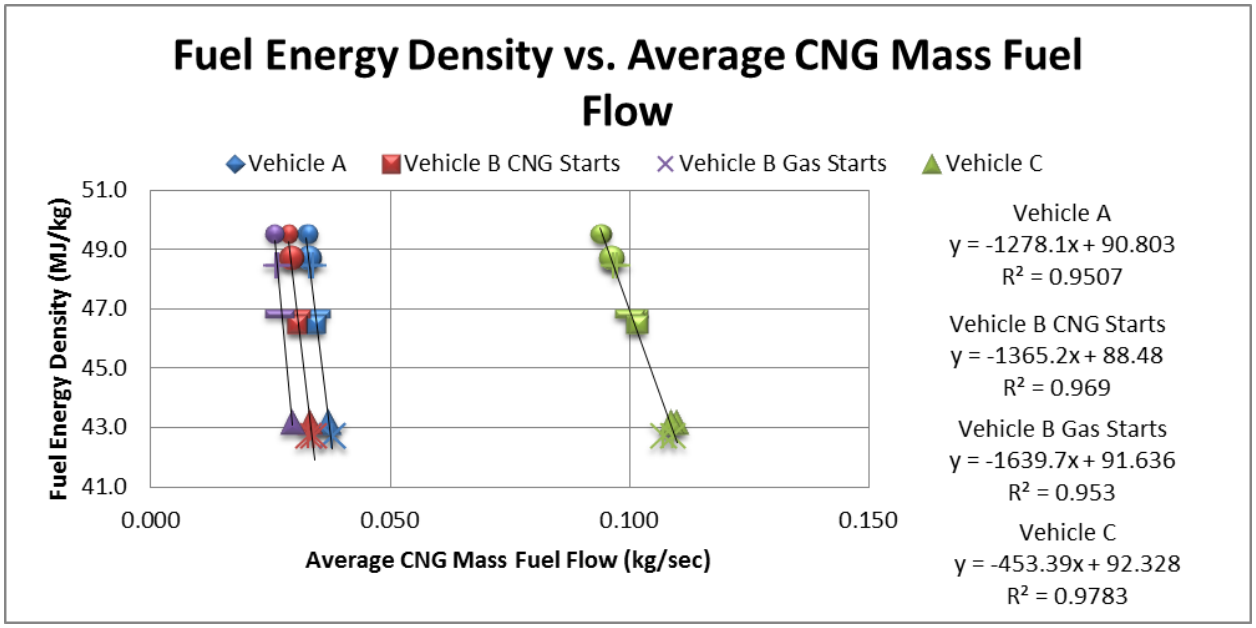


Figure 37. Fuel Energy Density vs. Average CNG Mass Fuel Flow

A data quality check comparing the Coriolis flow meter integrated volume fuel flow to the bag-weighted fuel economy is shown below in Figure 38. A linear trend was observed in this comparison and also highlighted the five Vehicle B tests (purple series) which operated on gasoline during the first 160 seconds of the cold start of Phase 1.

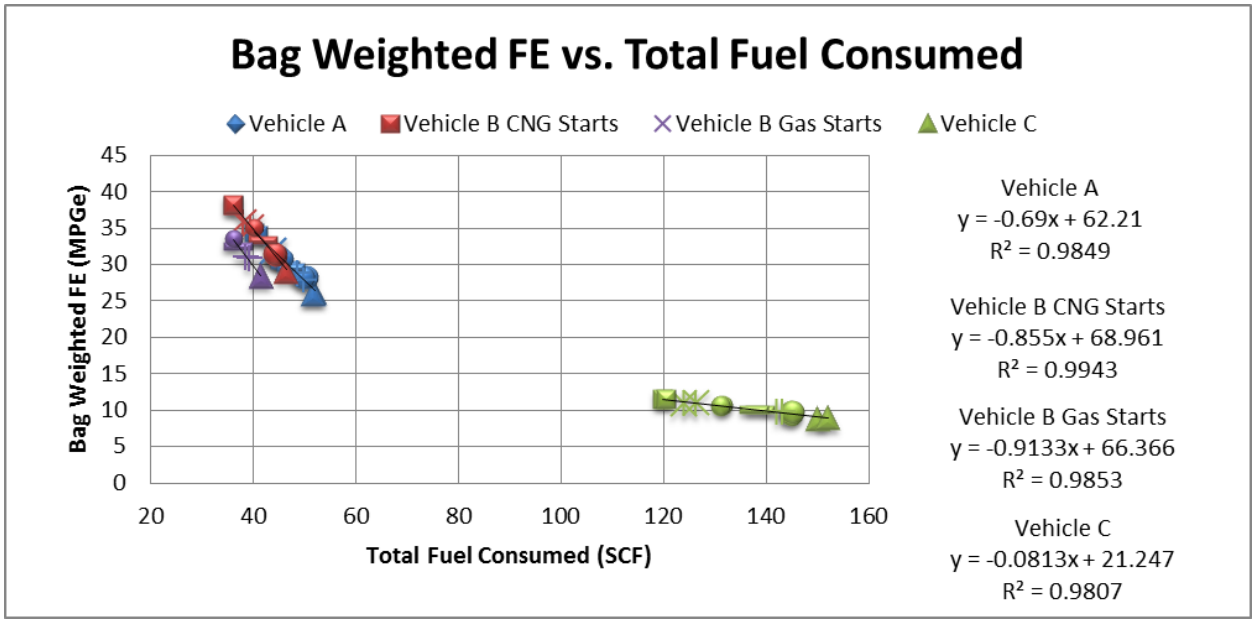


Figure 38. Bag-Weighted MPGe vs. Total Fuel Consumed (SCF)

Figure 39 illustrates that all vehicles had linear trends in Phase 1 NMHC emissions versus the total NMHC content percentage in the fuel. Vehicle B had five tests with NMHC greater than 0.02 g/mi corresponding to the first 160 seconds of Phase 1 operation on gasoline, circled in red.

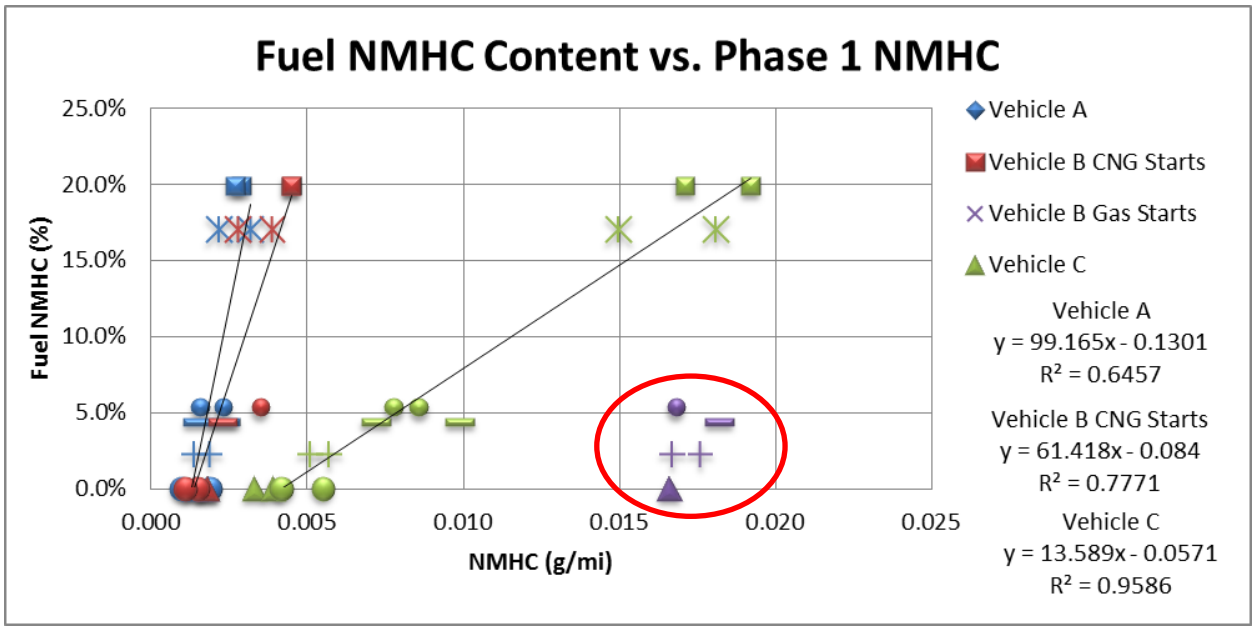


Figure 39. Fuel NMHC Content (%) vs. Phase 1 Bag NMHC (g/mi) for all vehicles

Total canister purge volume for the two bi-fuel vehicles is shown below in Figure 40. The canisters were fully purged prior to emissions testing and the purge volume shown accounts for additional fresh air entering the engine. Purging the canister eliminated any emissions influence of gasoline vapors entering the engine while testing on CNG. Vehicle B had very low purge volume commanded over the LA92 drive cycle. Vehicle C commanded purge events were much more frequent with total volume between 6.2 ft^3 and 16.98 ft^3.

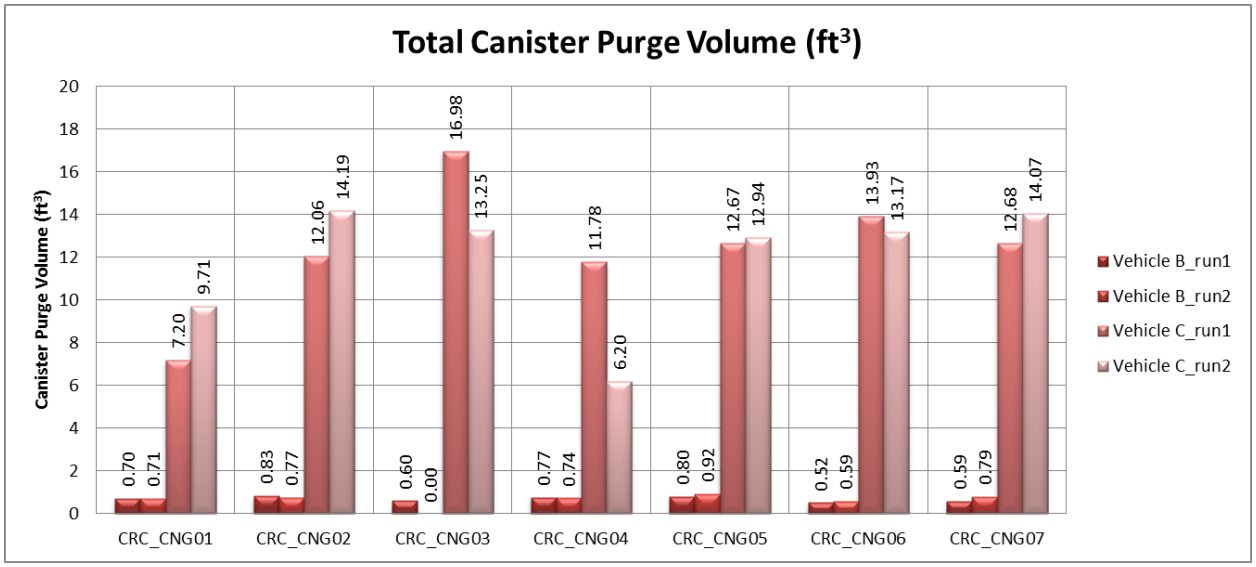


Figure 40. Bi-Fuel Vehicle Total Canister Purge Volume

A comparison of the NOx conversion efficiency is shown below in Figure 41 including engine-out NOx and bag-weighted NOx in grams per mile. Vehicle A demonstrated very good NOx conversion efficiency performance with the lowest value of 99.89% on CNG01. Both Vehicle B and Vehicle C exhibited lower NOx conversion efficiency on CNG01 compared to the other fuels.

Overall Vehicle A had the highest NOx conversion efficiency out of the group even though the engine-out NOx emissions were higher than Vehicle B's. The highest engine-out NOx was produced with fuel CNG06 for all vehicles which has the lowest methane number (60.07) and highest Wobbe Index (1427.46 BTU/ft^3). Although cylinder pressure data was not captured for the emissions tests, it follows that the higher the Wobbe Index fuels should result in higher combustion temperatures that are a key contributor to in-cylinder NOx formation.

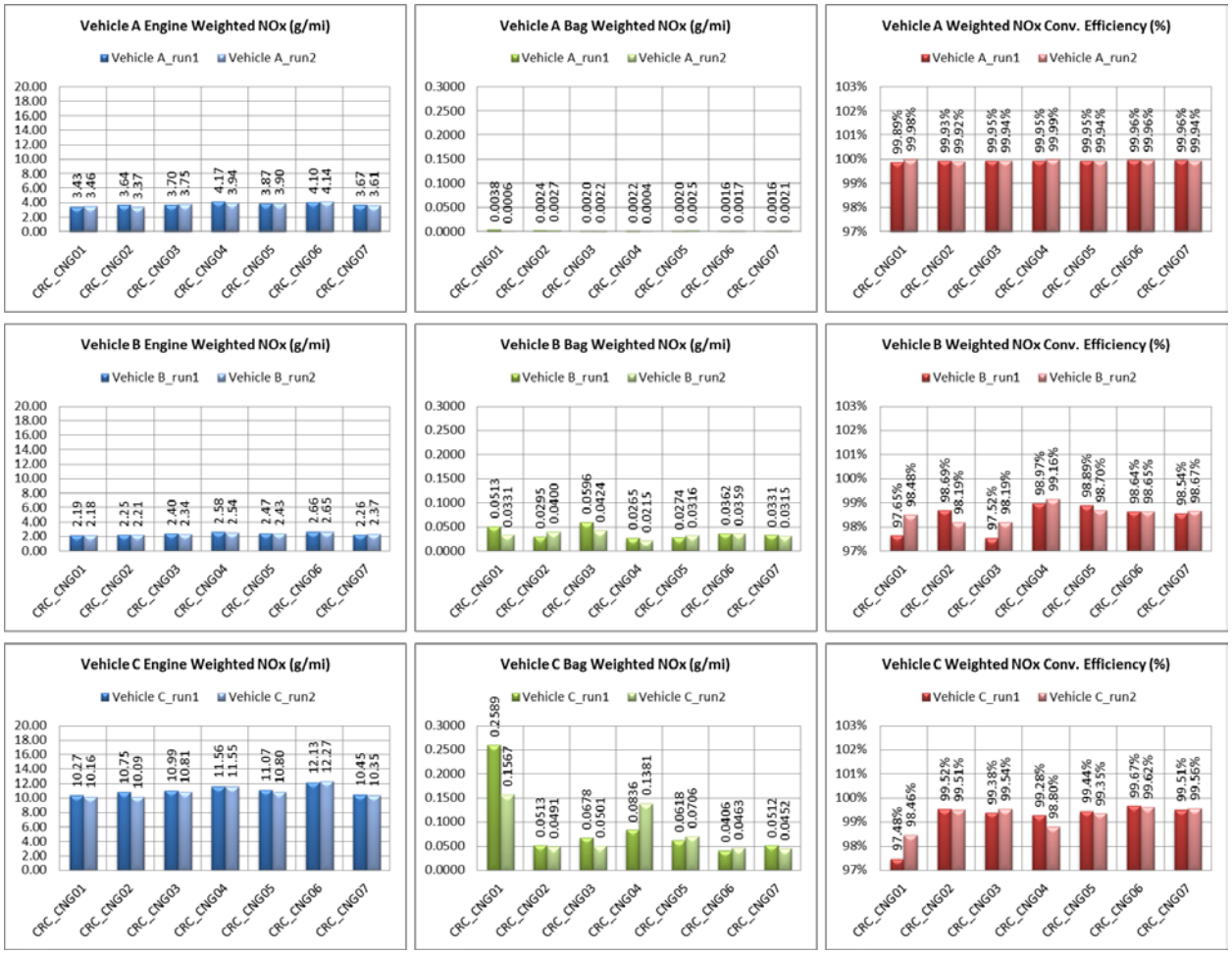


Figure 41. NOx Conversion Efficiency for All Vehicles

Vehicle B produced the lowest weighted composite engine-out CO and best overall CO conversion efficiency out of the group as shown below in Figure 42. The five tests where Vehicle B ran the first 160 seconds of Phase 1 on gasoline produced slightly lower composite CO conversion efficiency below 98.6% (CNG01_run1, CNG03_run1, CNG05_run1, CNG07_run1, and CNG07_run2) compared to the other tests. Vehicle A's CO conversion efficiency consistently fell between 96.87 to 97.54%. Vehicle C's tests show consistency with lower engine-out CO on fuels CNG01 and CNG02 which did not have any NMHC constituents in the fuel.

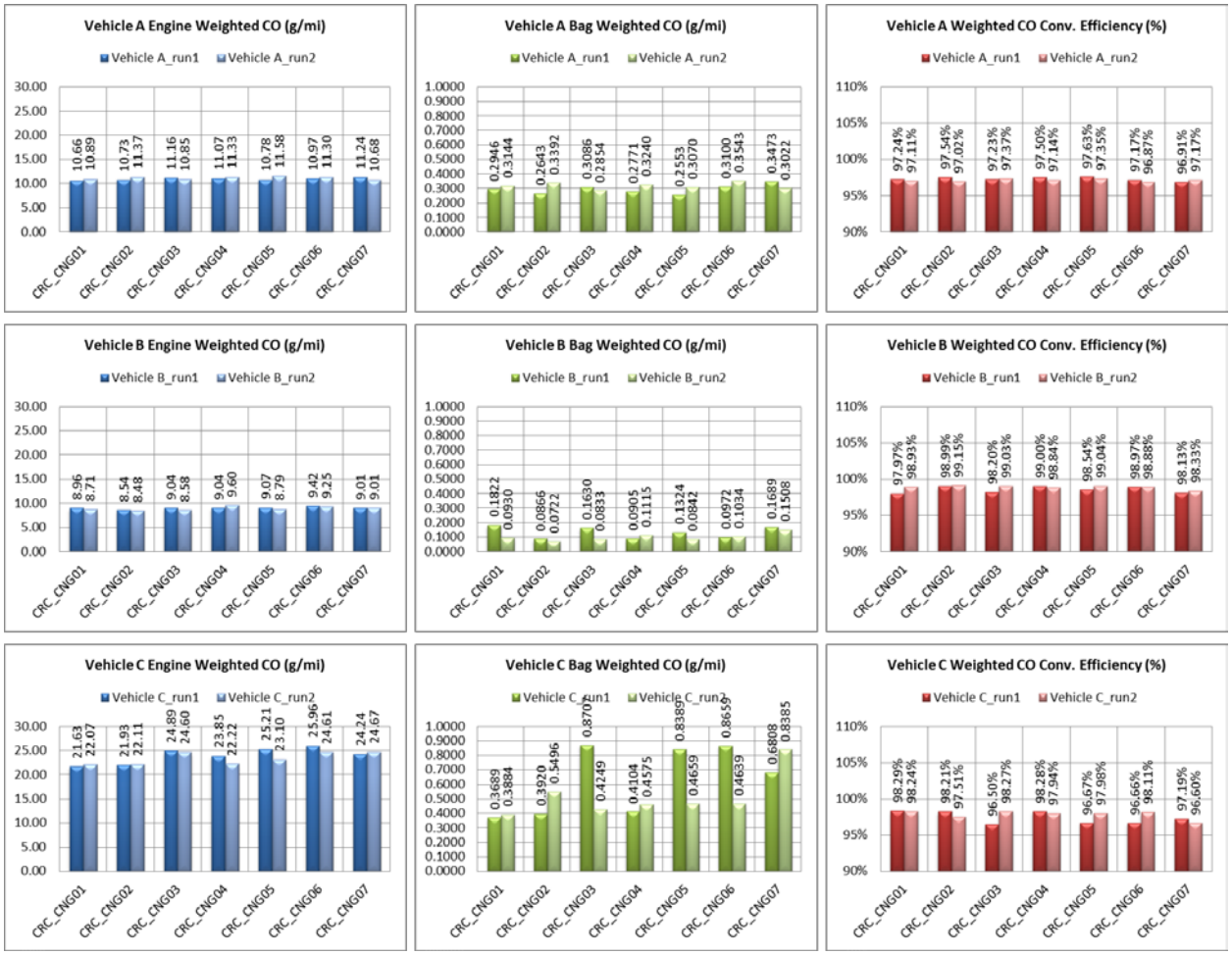


Figure 42. CO Conversion Efficiency for All Vehicles

Vehicle A did not have less than 98.43% weighted THC conversion efficiency as shown in Figure 43, whereas the overall average for Vehicle B and Vehicle C were as low as 95.7% and 93.59% respectively. The five tests where Vehicle B ran the first 160 seconds of Phase 1 on gasoline show on average 17% higher weighted THC emissions than the tests ran only with CNG. All vehicles had the lowest engine-out THC emissions on fuels CNG04 and CNG06 which are the two lowest MN fuels and have the highest NMHC concentrations (17% and 20%).

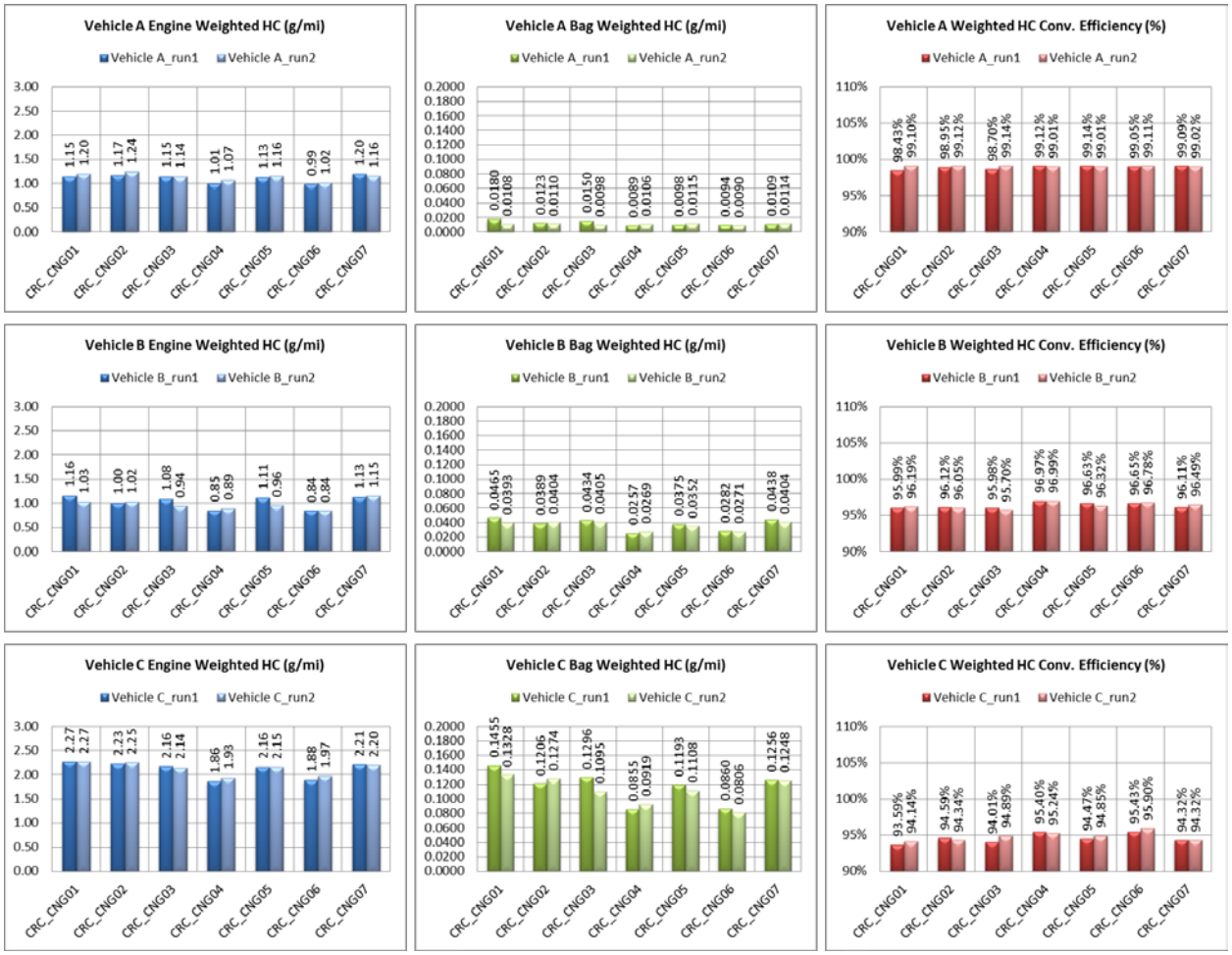


Figure 43. THC Conversion Efficiency for All Vehicles

All hydrocarbon related emissions had increasing relationships to MN and decreasing relationships to Wobbe Index as shown in Figure 44. The exceptions were the five tests ran on Vehicle B which operated on gasoline for the first 160 seconds of the test and are isolated as a separate series on the charts. For all vehicles an increasing trend was observed in bag-weighted THC as MN increased, and a decreasing relationship with Wobbe Index. All vehicles indicate NMHC decreased with higher MN. The methane emissions increased with higher MN and decreased with higher Wobbe Index.

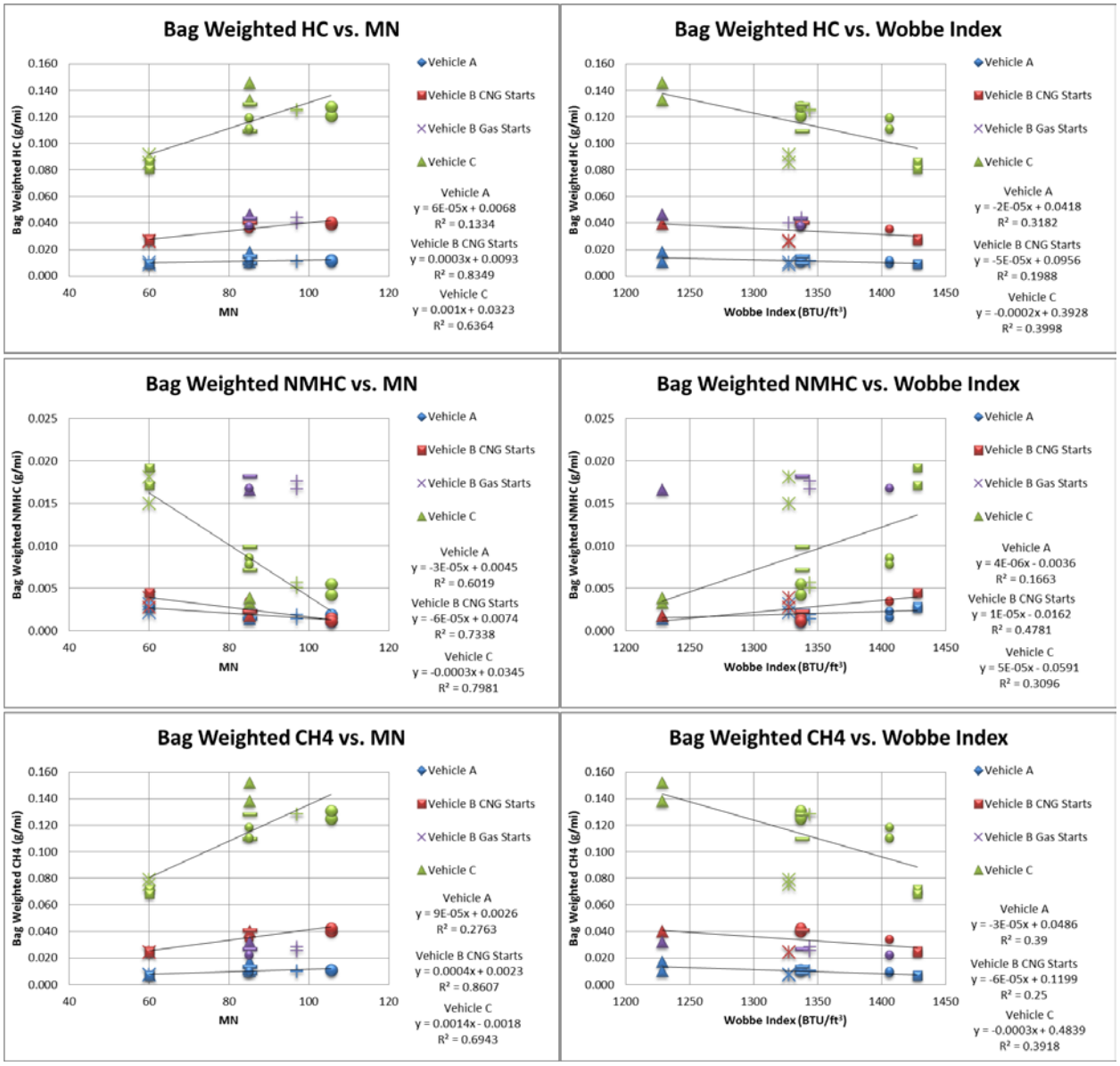


Figure 44. THC, NMHC, and CH_4 Emissions vs. MN and Wobbe Index

Bag-weighted NOx, CO, CO_2, and FE are shown below in Figure 45. Both Vehicle A and Vehicle B were nearly insensitive to MN and Wobbe Index related to NOx and CO post-catalyst. Vehicle C exhibited a strong decreasing trend in NOx as Wobbe Index increased. Engine-out NOx from Vehicle C increased with increasing Wobbe Index, which indicated the catalyst conversion efficiency was a key contributor to the higher bag NOx with lower Wobbe Index. CO_2 and FE trended with MN and Wobbe Index expected, since higher Wobbe Index fuels have higher energy density and require less fuel to achieve the same power level.

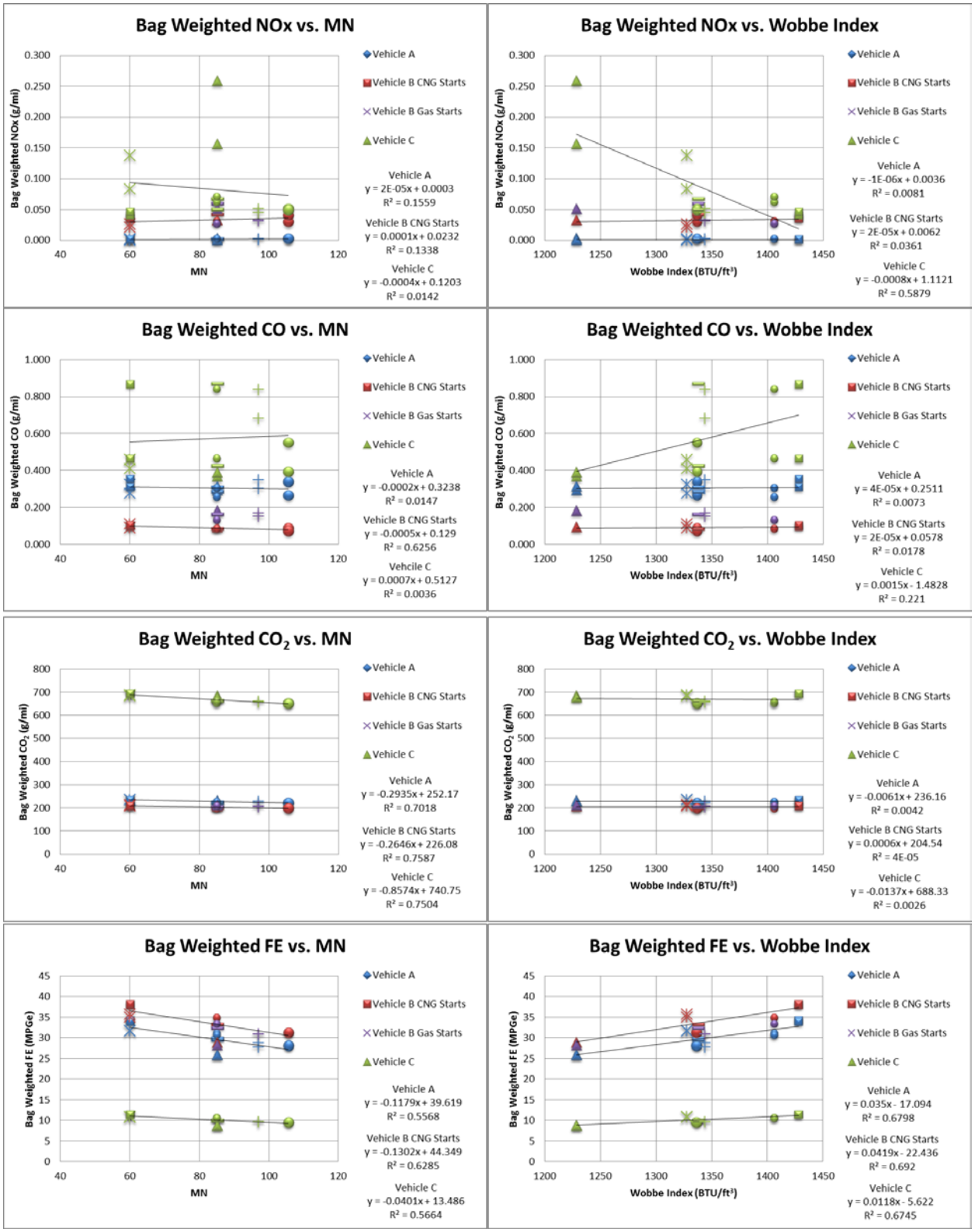


Figure 45. NOx, CO, CO_2, and FE vs. MN and Wobbe Index

Below in Figure 46 are bag-weighted THC, NOx, and CO trends for each vehicle including the conversion efficiency for each constituent. For all vehicles, bag and engine-out-weighted THC decreased with higher Wobbe Index with corresponding increases in THC conversion efficiency with higher Wobbe Index. NOx had a decreasing trend with Wobbe Index for Vehicle C, whereas Vehicle A and Vehicle B were insensitive. Increasing trends in weighted engine-out NOx are seen as Wobbe Index increased for all vehicles. Vehicle C showed sensitivity to NOx conversion efficiency with varying Wobbe Index fuels. As Wobbe Index increased, Vehicle C showed sensitivity to bag-weighted CO. For all vehicles engine-out-weighted CO had increasing trends with increasing Wobbe Index. CO conversion efficiency appeared insensitive for Vehicles A and B, with some differences seen for Vehicle C.

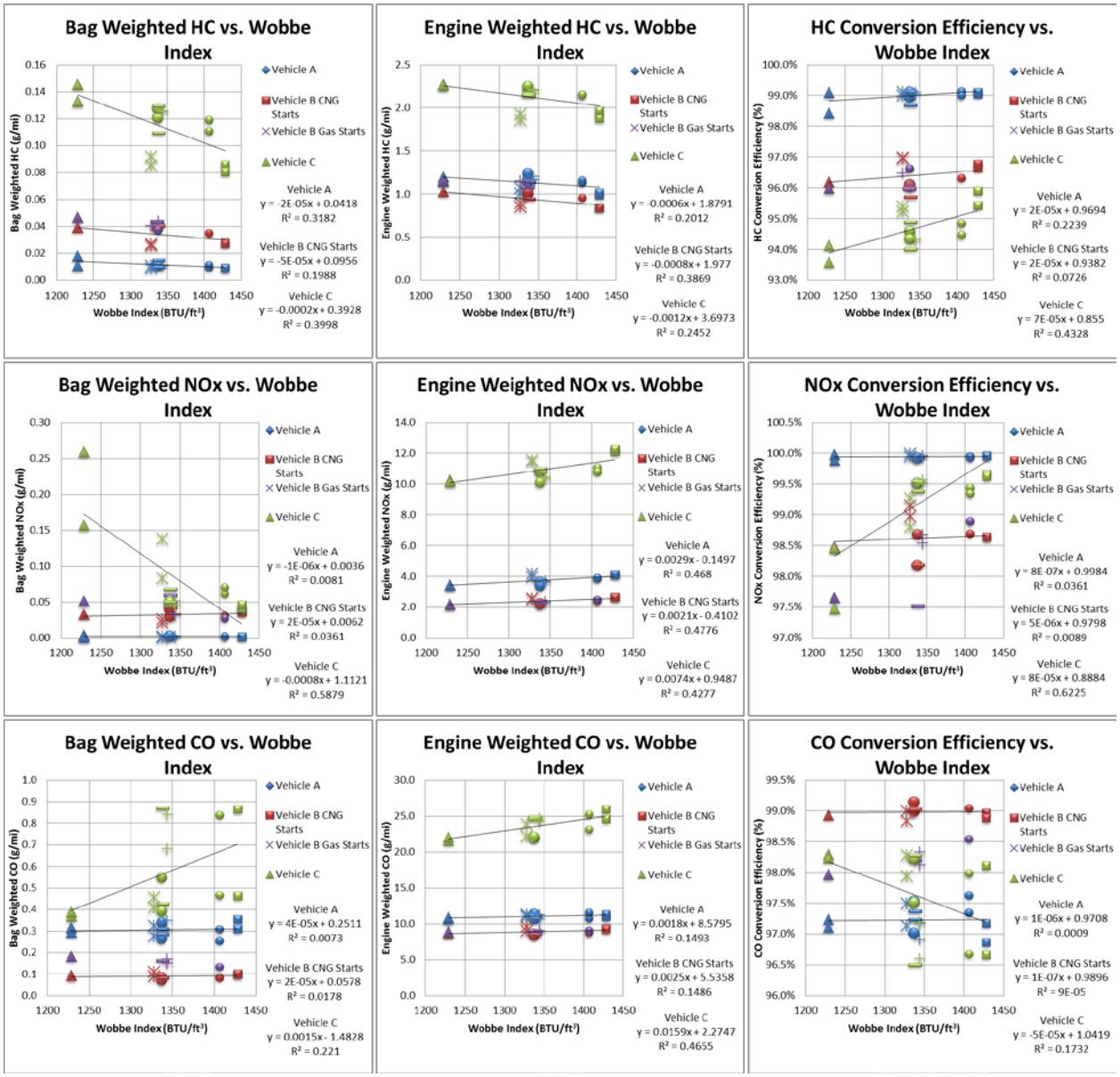


Figure 46. THC, NOx, and CO Conversion Efficiency vs. Wobbe Index

Exhaust gas temperatures at the engine-out location are plotted for the first 100 seconds of the LA92 in Figure 47 below. Vehicle A and Vehicle C had consistent engine-out exhaust gas temperature for all tests whereas Vehicle B has a wider spread between tests. Where Vehicle B performed tests operating on gasoline for the cold start portion of Phase 1, the exhaust gas temperature exceeded 850°F before 40 seconds elapsed. Also, tests on CNG06 with the highest Wobbe Index of 1427.46 BTU/ft^3 show the lowest EGTs from 20 to 100 seconds for Vehicle B.

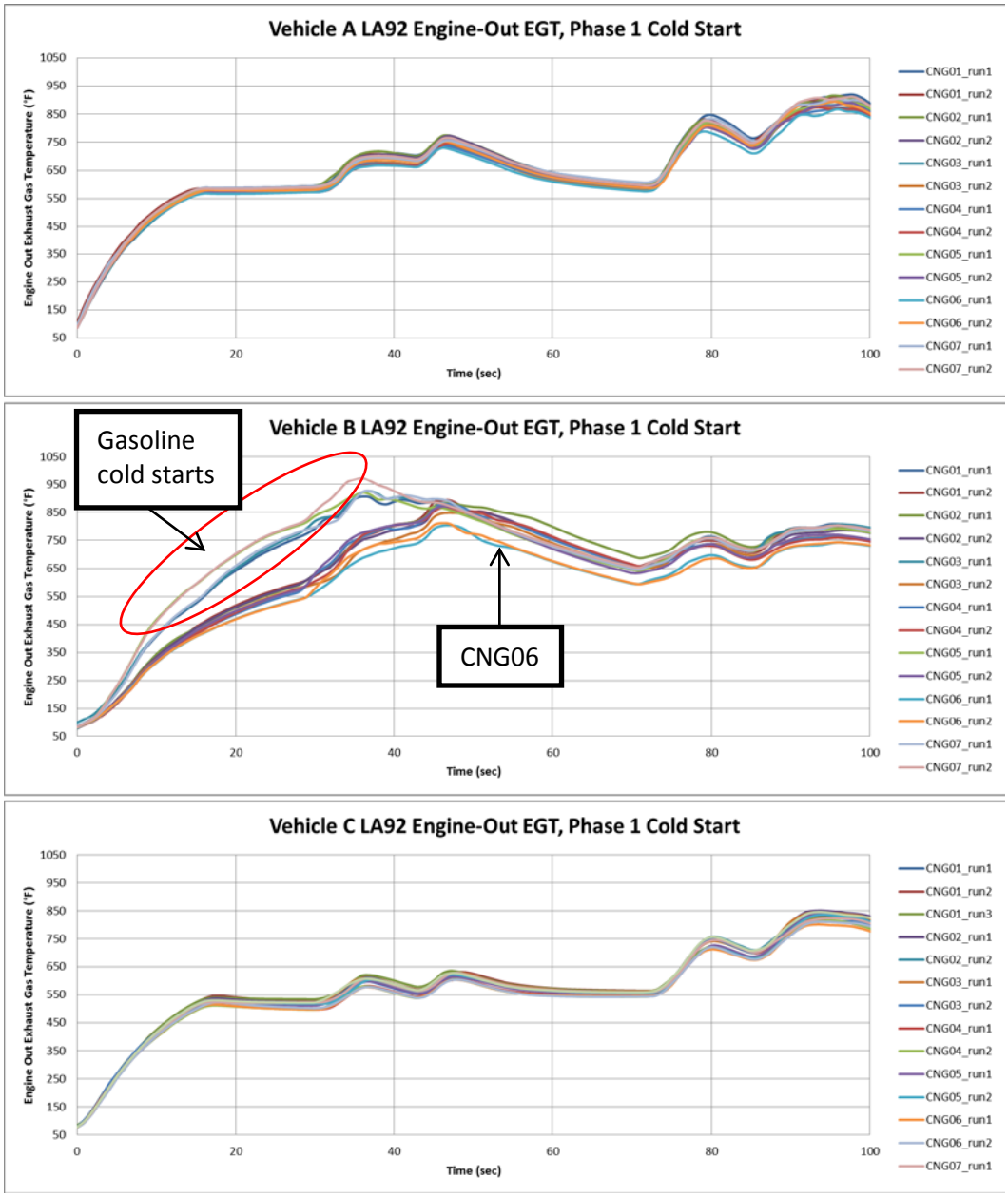


Figure 47. Engine-Out EGT during 1st 100 Seconds of LA92

Figure 48 shows engine-out exhaust gas temperature 40 seconds into the LA92 drive cycle. Linear trends were seen with a decrease in exhaust gas temperature as the fuel NMHC content increased. Since fuels with higher NMHC content generally have higher Wobbe Index, it follows that lower exhaust temperature corresponds to more of the fuel's energy being converted into mechanical energy with better fuel economy.

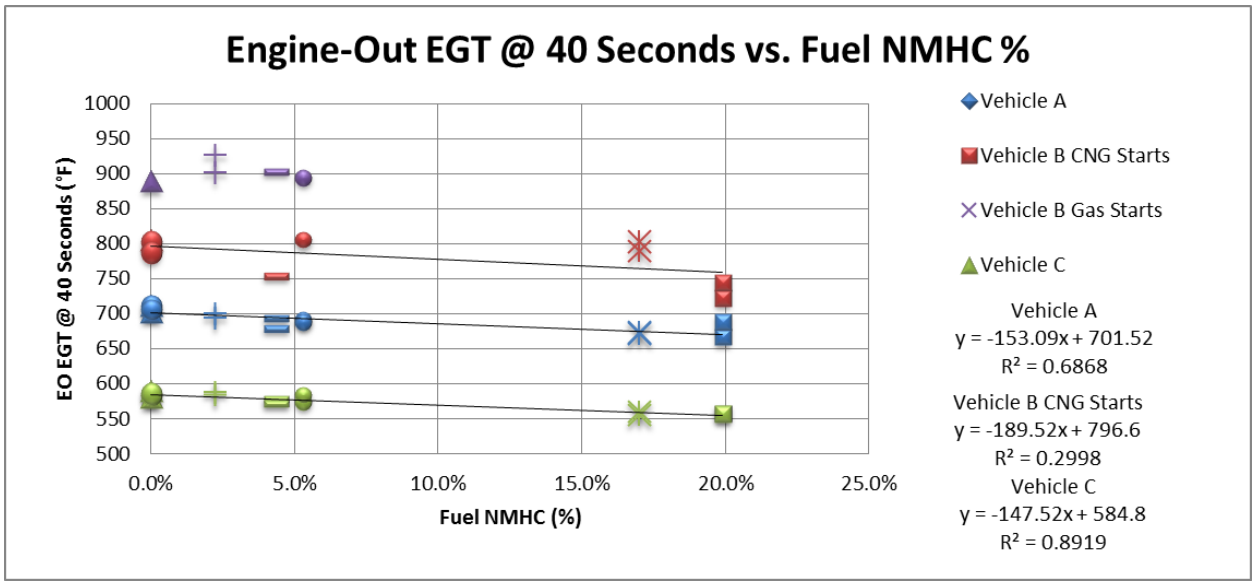


Figure 48. Engine-Out EGT at 40 Seconds vs. Fuel NMHC Percentage

Higher volume fuel flow corresponded to higher exhaust gas temperatures at 40 seconds into the LA92 as shown below in Figure 49. The tests where Vehicle B started on gasoline are grouped together with higher engine-out exhaust gas temperature at 40 seconds into the LA92 (purple series).

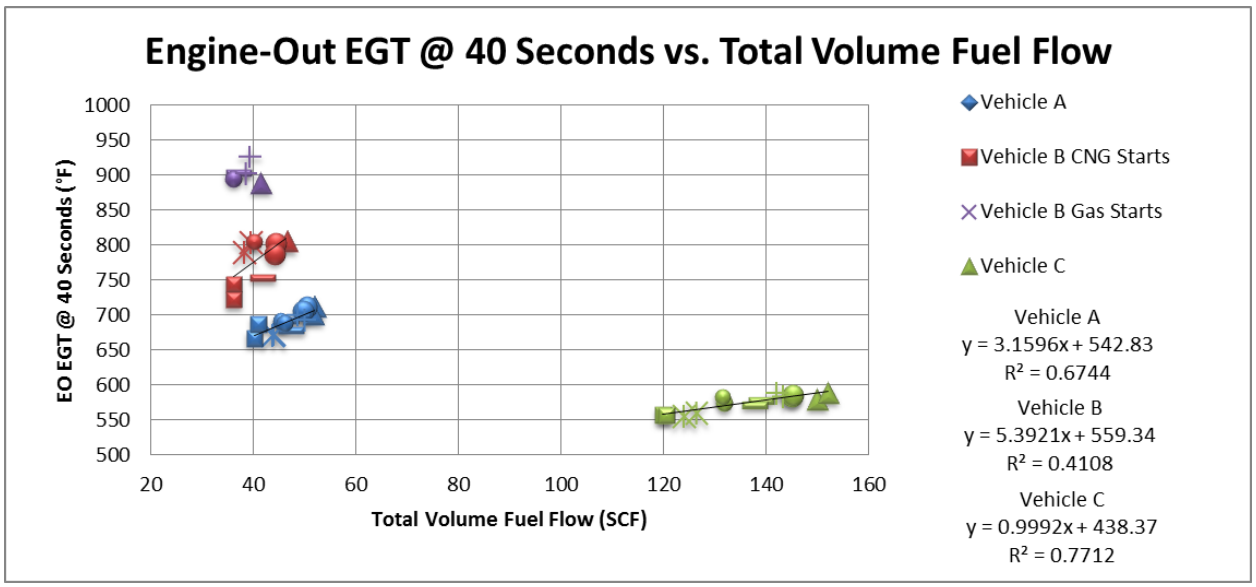


Figure 49. Engine-Out EGT at 40 Seconds vs. Total Volume Fuel Flow

Engine-out-weighted CO, NOx, and THC emissions are displayed below in Figure 50 along with bag-weighted emissions. As engine-out CO increased NOx also increased for all vehicles. Bag-weighted CO results had a strong hook for Vehicle C's data at 0.4 g/mi of CO showing increasing NOx. With increasing engine-out THC there was a decrease in NOx for all vehicles. Post-catalyst there was the opposite trend showing increased THC emissions with increasing NOx emissions. Comparing engine-out THC versus CO, a decreasing trend in NOx was observed with increasing THC. Lastly, the bag-weighted THC and bag-weighted CO only exhibited a strong linear relationship for Vehicle B.

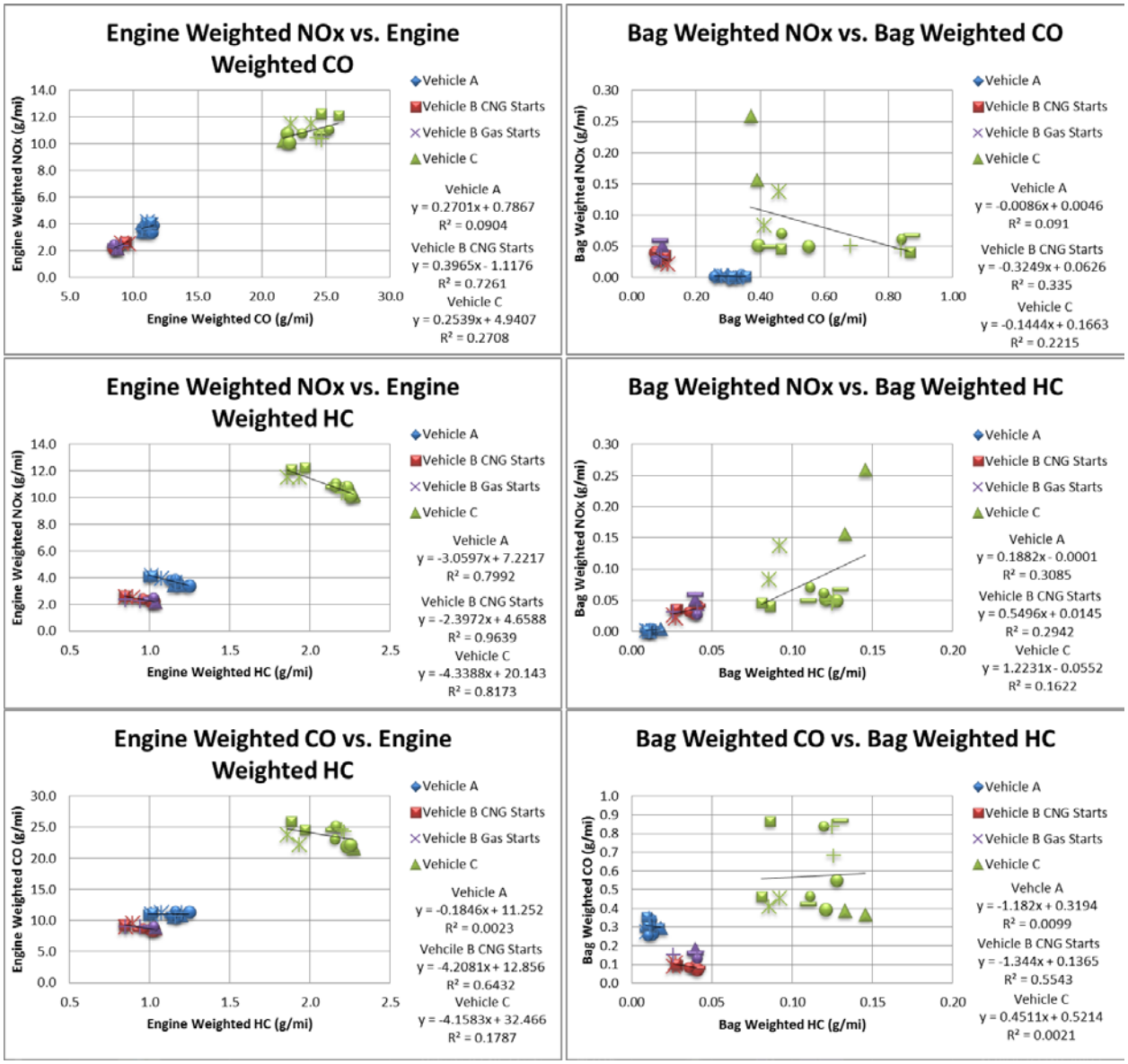


Figure 50. Engine-Out and Bag-Weighted Emissions Comparison

A comparison of engine-out lambda versus time for all three vehicles and all tests is shown in Figure 51. Vehicle A exhibited instances of DFCO (deceleration fuel cut-off) during Phases 2 and 3 of the LA92 drive cycle where lambda was greater than 1.10. At the cold start portion of Phase 1, Vehicle A showed fueling varied between tests from zero to five percent lean (stoich to 5% excess air). Vehicle B showed fueling at the cold start of Phase 1 to be from zero to fifteen percent lean (stoich to 15% excess air), and the only vehicle with instances of DFCO during Phase 1. All of the Phase 3 hot starts for Vehicle B are fueled five to six percent lean for the first fifteen seconds for all tests. This was an indication that Vehicle B has an offset in adaptive learned fuel trims for hot start fueling, and then maintains lean fueling at idle until the lambda sensor becomes active for closed loop operation. Vehicle C showed consistent fueling at the cold start of Phase 1 with minimal lean excursions and had its highest frequency of deceleration fuel cut occurring during Phase 2.

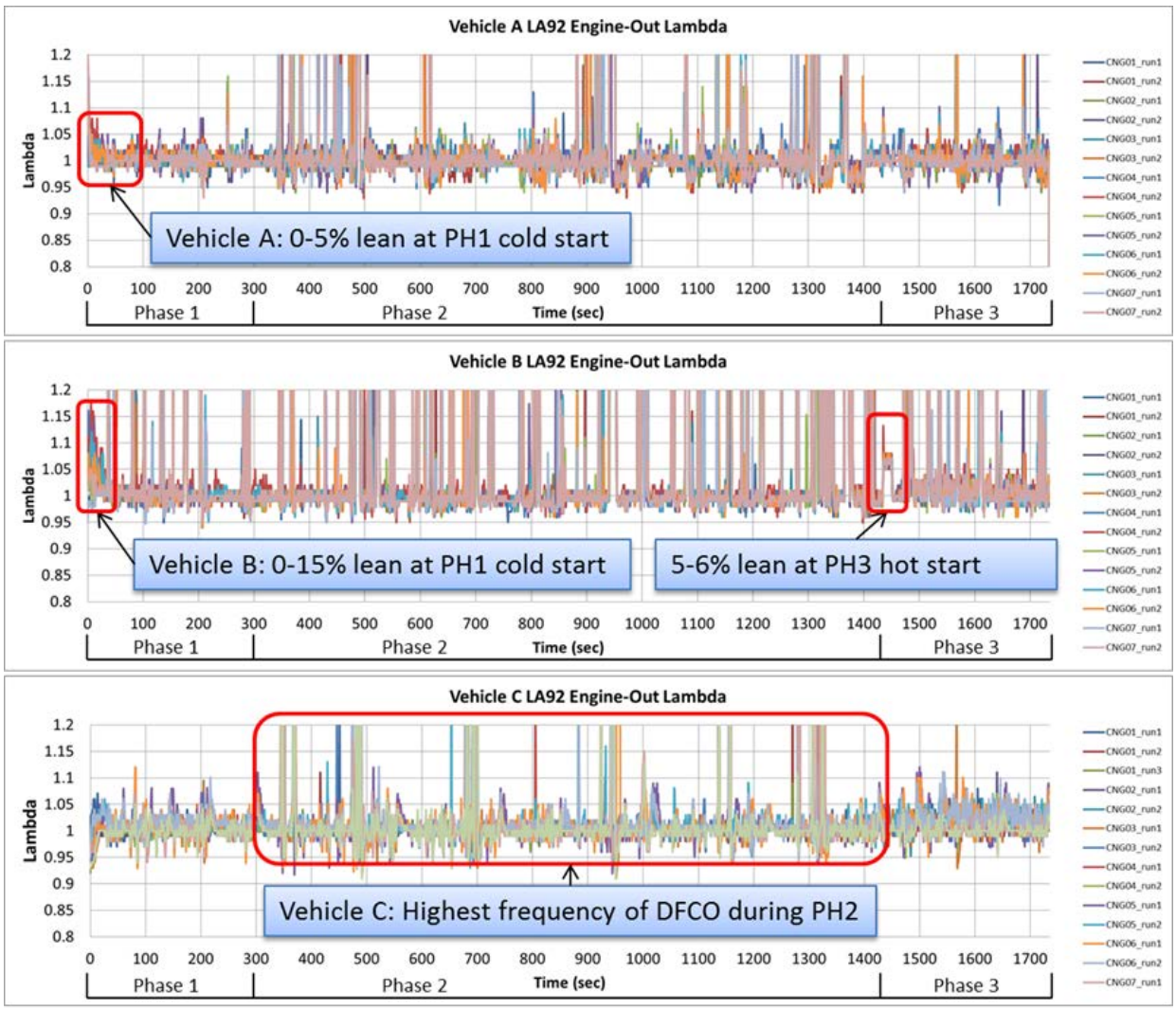


Figure 51. Lambda vs. Time for All Vehicles

Some emissions trends for Vehicle B and Vehicle C were unexpected, because the highest mass emissions (in g/mile) were not produced during the phase 1 cold start, but rather were produced after the initial catalyst light-off. The fueling strategies for both of these vehicles can be closely tied to characteristics of the emissions results. The lean operation of Vehicle B during the Phase 3 hot start corresponds to higher engine-out and tailpipe NOx, in addition to the DFCO events producing tailpipe NOx spikes.

The continuous engine-out and tailpipe measurements were further investigated for Vehicle B to analyze the differences in bag NOx results. During Phase 3, fueling differences were seen between CNG01_run2 and CNG03_run1 as shown below in Figure 52. When the engine-out lambda measurement steps towards lean operation this is an indication of deceleration fuel cut-off (DFCO). CNG03_run1 showed an instance of DFCO just after 1550 seconds with a corresponding increase in engine-out NOx starting at 1555 seconds followed by a spike in tailpipe NOx. As illustrated in Figure 53 bag NOx results from CNG03_run1 had higher engine-out and bag NOx during Phase 3. A decrease in catalyst conversion efficiency was also observed for this test.

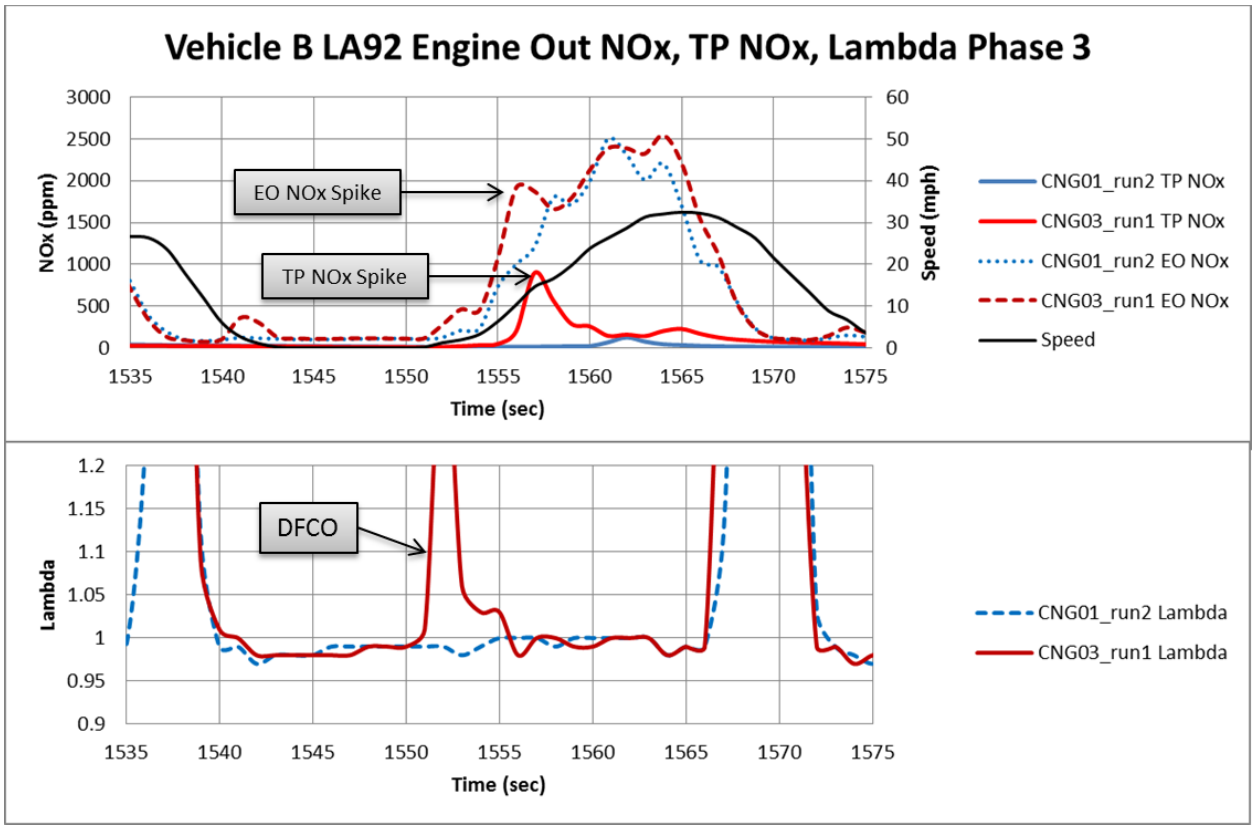


Figure 52. Vehicle B LA92 Engine-Out NOx, Tailpipe NOx, Lambda Phase 3

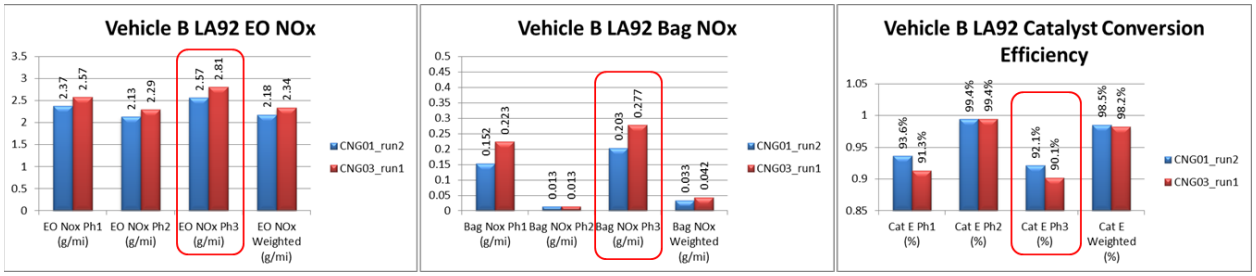


Figure 53. Vehicle B NOx by Phase Comparison for CNG01 and CNG03 Fuels

INCA data from CNG01_run2 and CNG03_run1 is overlaid and shown below in Figure 54 corresponding to the charts shown above. The DFCO event described in Figure 52 is captured in the INCA data shown below. The variable *fuelAirCommandedEquivalenceRatio* goes to a value of 1.99882 when the engine controller turns off fuel injection during CNG03_run1. The event is following a brief rise in engine RPM prior to the acceleration event while the driver was releasing the clutch pedal. With too much throttle application the engine speed was higher than desired for a smooth takeoff. To bring the engine speed down, the driver let off the throttle and the controller cut fuel to decrease engine speed. Although there was the same driver for both tests, slight differences in throttle application resulted in different engine RPM/fuel cut results contributing to measureable differences in emissions.

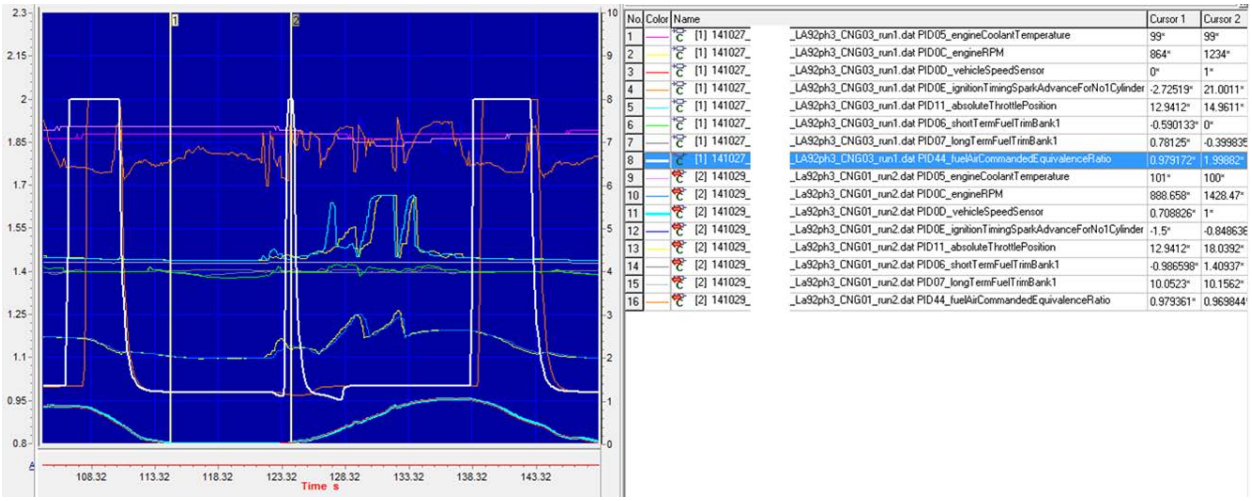


Figure 54. Vehicle B LA92 CNG01_run2 vs. CNG03_run1 INCA Overlay

The continuous engine-out and tailpipe NOx measurements during Phase 2 are shown below for Vehicle C in Figure 55 for tests CNG01_run1 and CNG07_run1. Fueling differences were seen at 450 seconds where CNG01_run1 engine-out lambda indicates a DFCO event. Following the DFCO, a tailpipe NOx spike occurred. Figure 56 shows the bag NOx, engine-out NOx, and NOx catalyst efficiency results with Phase 2 highlighted in red. Whereas the engine-out NOx emissions are comparable for the two fuels, there is clearly poorer catalyst conversion efficiency for the CNG01 fuel.

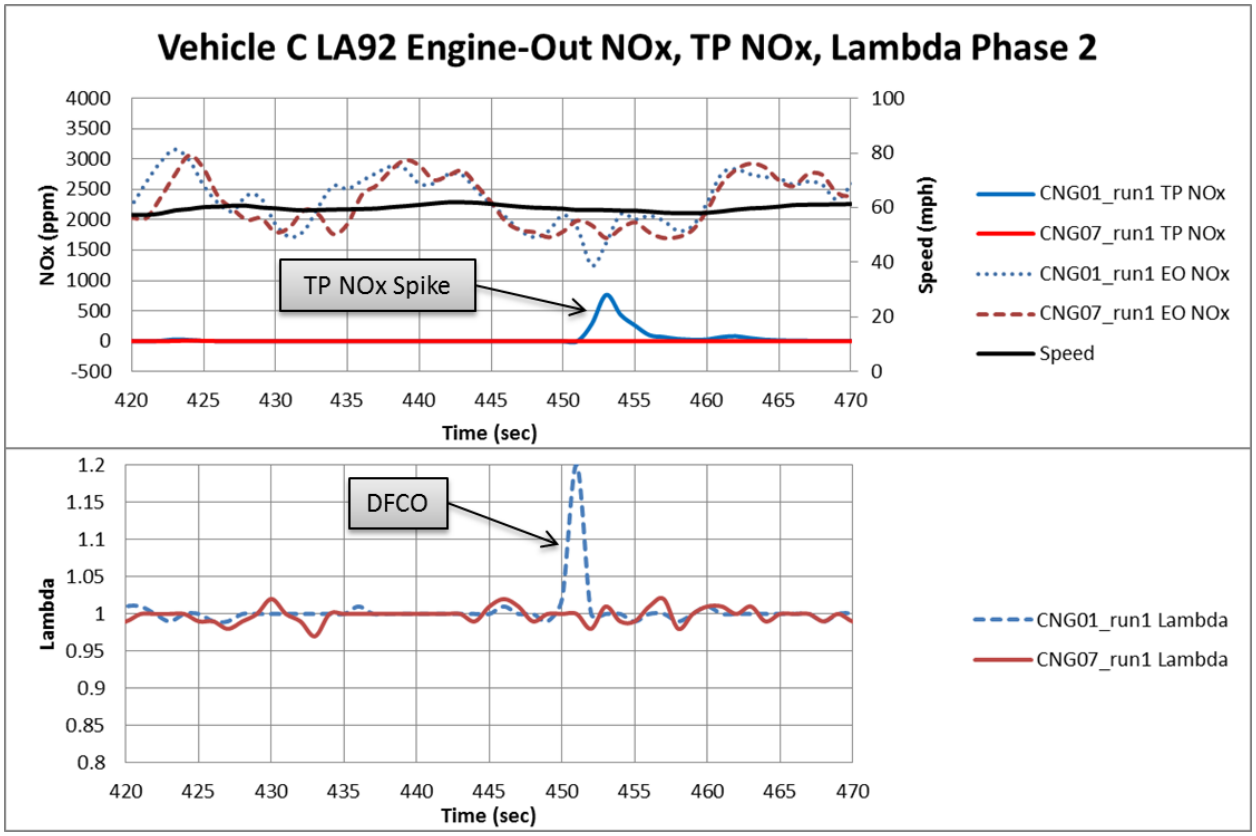


Figure 55. Vehicle C LA92 Engine-Out NOx, Tailpipe NOx, Lambda Phase 3

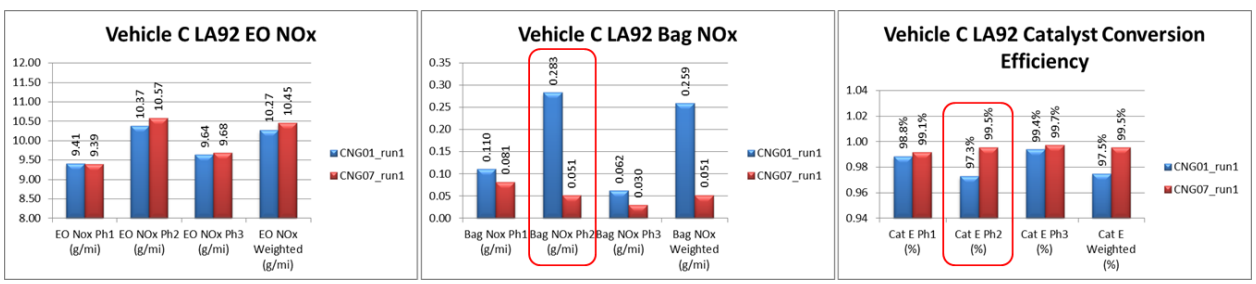


Figure 56. Vehicle C NOx by Phase Comparison for CNG01 and CNG07 Fuels

The continuous engine-out and tailpipe NOx measurements during Phase 1 are shown below for Vehicle A in Figure 57 for tests CNG01_run1 and CNG07_run1. At 365 seconds both tests show a 5 second DFCO event followed by a tailpipe NOx spike. The difference for Vehicle A is that the NOx spike was always less than 100ppm. Slight fueling differences were seen at 387 seconds where CNG07_run1 engine-out lambda indicated an additional DFCO event whereas CNG01_run1 did not. Following the DFCO for both cases, a tailpipe NOx spike did not occur. After the DFCO event the fueling returned to approximately 3-5% rich of stoich. Figure 58 shows the bag NOx, engine-out NOx, and NOx catalyst efficiency results with both tests having near 100% NOx conversion. Engine-out NOx increased over each phase but post-catalyst NOx continued to decrease over each phase.

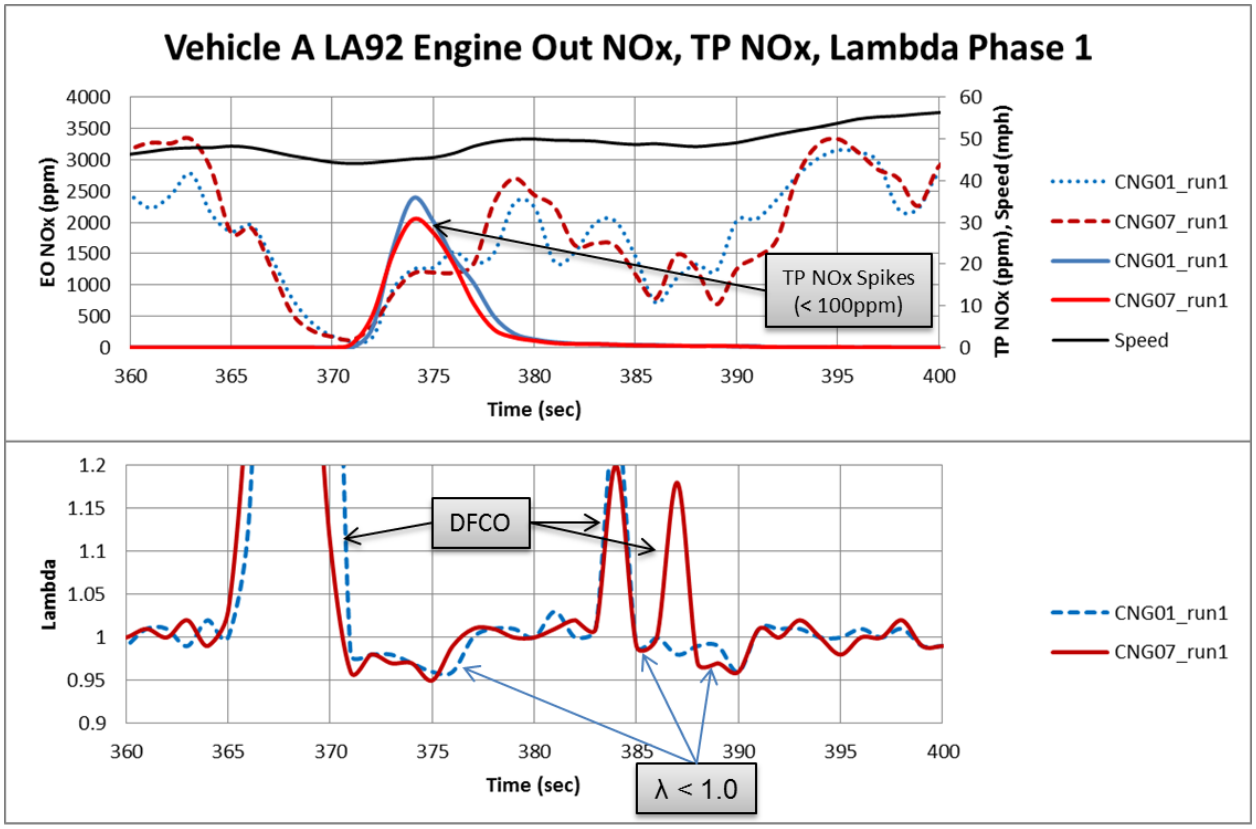


Figure 57. Vehicle A LA92 Engine-Out NOx, Tailpipe NOx, Lambda Phase 1

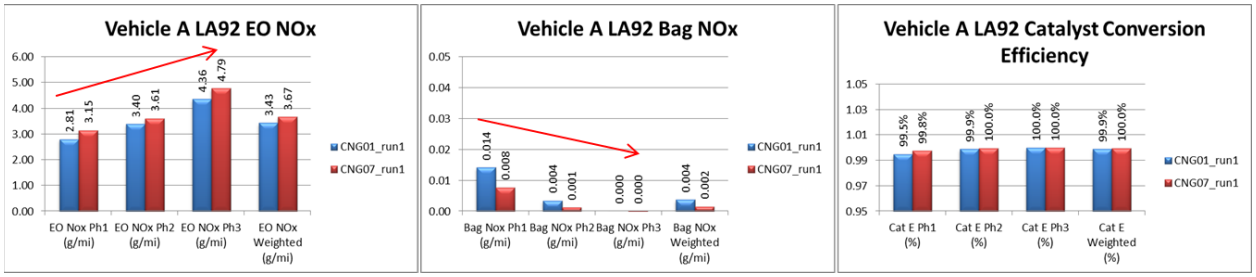


Figure 58. Vehicle A NOx by Phase Comparison

7.0 Statistical Analysis

7.1 Statistical Analysis of Vehicles Pooled Together

A statistical analysis was performed to determine if the fuel effects on emissions results discussed in Section 6.0 were statistically significant. The independent variable, or factor for the analysis, was fuel blend (each having a different methane number and Wobbe Index). The dependent variables, or responses of most interest, were gaseous emissions weighted over the LA92 emissions cycle. Weighted certification-quality bag emissions were the measure of most importance, due to the implication of fuel effects on real world emissions.

The test plan called for testing fuels from 60-105 MN, and Wobbe Index from 1225-1425 BTU/ft^3 in three late model vehicles (Section 3.1). The order for testing each vehicle and fuel combination was randomized per Table 6. For a given vehicle-fuel combination, repeat tests were completed after a preparation cycle on the same fuel to condition the control system prior to the emissions test. Each vehicle and fuel combination was tested twice. The statistical analysis approach did not include hypothesis testing for the fuel blend effects on individual vehicle emissions because there were only two data points for the vehicle-fuel combinations.

The vehicles were pooled together for analysis excluding Vehicle B's tests with gasoline cold starts. Mean values for the responses were calculated for the test vehicle fleet for fuels CNG01, CNG02, CNG03, CNG04, CNG05, CNG06, and CNG07 as shown in Figure 59. A pairwise t-test was used to determine if the difference in the mean values between two fuels were statistically significant. The pairing of samples is a form of blocking where the test article (in this case a specific vehicle) is tested before and after some manipulation (in this case change in fuel blend). By comparing the same vehicle's results before and after the fuel change, each vehicle effectively becomes its own control. The pairwise t-test is statistically powerful because the random between-vehicle variation is eliminated.

The alternative hypothesis was tested for each fuel in matrix format:

H1: Mean of Paired Differences (CNG_A fuel – CNG_B fuel) not equal to Zero

One case to note in each table is CNG07 compared to others fuels, as it represents fuel most abundantly found in North American pipelines per CRC Project No. PC-2-12. The p-values (probability of falsely concluding the alternative hypothesis) from a two sample, 2-tailed paired t-test are shown in Table 13 to Table 19. There is (1-pvalue)*100 percent confidence that the mean of the paired differences is not equal to zero. Values in red text have ≥95% confidence means are not equal and values in blue text have ≥90% confidence that the means are not equal.

From the tables presented below, the percent difference between the mean values are shown with negative values indicating the mean value is higher for the fuel listed in the column versus the row, and positive values indicating the mean value is lower for the fuel in the column versus the row. Again with red values representing ≥95% confidence that the means are not equal and values in blue text with ≥90% confidence that the means are not equal.

Figure 59. Mean Response Values for the Combined Test Vehicle Fleet

Compared to CNG04, THC emissions were 28.8% higher using CNG02 with greater than 95% confidence. The NMHC emissions mean values were lower for fuels CNG01 and CNG02 compared to the other fuels which follows as these fuel blends do not contain any NMHC constituents. The mean NMHC value for CNG01 and CNG02 was lower than CNG06 by over 200% with 90% confidence as indicated by blue values in Table 14. There was no statistical difference in bag-weighted NOx and CO results comparing each fuel to each other as shown in Table 16 and Table 17.

Almost every fuel comparison shows a statistical difference mean FE with greater than 90% confidence, except when comparing CNG07 to CNG02 and CNG03 as shown in Table 19. These three fuels had very similar Wobbe Indices that may explain this exception (from Figure 28).

Table 13. Bag THC Pairwise t-Test P-Value Results for the Test Vehicle Fleet

All Vehicles Paired t Test Analysis Bag HC (g/mi)							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		0.213957	0.152789	**0.093514**	0.110665	**0.088933**	0.135079
CNG02			0.760294	**0.042107**	0.244164	**0.056619**	0.847248
CNG03				0.103615	0.355463	**0.079311**	0.662848
CNG04					**0.098079**	0.482921	0.161373
CNG05						**0.095113**	0.195505
CNG06							0.154447
CNG07							
Summary							
Mean	0.06928	0.058433	0.06088	0.041583	0.05778	0.04005	0.068175
StDev	0.064793	0.052357	0.055263	0.0373	0.053505	0.034547	0.065848
Count	5	6	5	6	5	6	4
Mean Value Percent Difference							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		15.7%	12.1%	**40.0%**	16.6%	**42.2%**	1.6%
CNG02			-4.2%	**28.8%**	1.1%	**31.5%**	-16.7%
CNG03				31.7%	5.1%	**34.2%**	-12.0%
CNG04					**-38.9%**	3.7%	-63.9%
CNG05						**30.7%**	-70.2%
CNG06							-70.2%
CNG07							

Red values indicate ≥95% confidence means are not equal
Blue values indicate ≥90% confidence means are not equal

Table 14. Bag NMHC Pairwise t-Test P-Value Results for the Test Vehicle Fleet

All Vehicles Paired t Test Analysis Bag NMHC (g/mi)							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		0.517417	0.146267	0.102525	0.148546	**0.098499**	0.198219
CNG02			0.119386	**0.068419**	0.173498	**0.055306**	0.426836
CNG03				0.124025	0.7573	**0.087625**	0.16106
CNG04					0.848661	0.265244	0.137325
CNG05						0.672922	0.13523
CNG06							0.130678
CNG07							
Summary							
Mean	0.00244	0.0025333	0.00466	0.0075333	0.00742	0.0084833	0.003525
StDev	0.0010922	0.0018683	0.0036936	0.0070744	0.0061157	0.0075558	0.0021884
Count	5	6	5	6	5	6	4
Mean Value Percent Difference							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		-3.8%	-91.0%	-208.7%	-204.1%	**-247.7%**	-44.5%
CNG02			-83.9%	**-197.4%**	-192.9%	**-234.9%**	-39.1%
CNG03				-61.7%	-59.2%	**-82.0%**	24.4%
CNG04					1.5%	-12.6%	53.2%
CNG05						-14.3%	58.4%
CNG06							58.4%
CNG07							

Red values indicate ≥95% confidence means are not equal
Blue values indicate ≥90% confidence means are not equal

Table 15. Bag CH_4 Pairwise t-Test P-Value Results for the Test Vehicle Fleet

All Vehicles Paired t Test Analysis Bag CH4 (g/mi)							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		0.217715	0.139843	**0.091167**	0.113333	**0.090802**	0.140331
CNG02			0.465631	**0.046297**	**0.078766**	**0.054124**	1.0
CNG03				**0.083131**	0.307841	**0.078303**	0.458663
CNG04					0.17677	0.200698	0.150801
CNG05						0.168918	0.169777
CNG06							0.147671
CNG07							
Summary							
Mean	0.0716	0.059883	0.06026	0.036483	0.05398	0.033833	0.069275
StDev	0.068241	0.054238	0.055309	0.0325	0.055524	0.028979	0.068158
Count	5	6	5	6	5	6	4
Mean Value Percent Difference							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		16.4%	15.8%	**49.0%**	24.6%	**52.7%**	3.2%
CNG02			-0.6%	**39.1%**	**9.9%**	**43.5%**	-15.7%
CNG03				**39.5%**	10.4%	**43.9%**	-15.0%
CNG04					-48.0%	7.3%	-89.9%
CNG05						37.3%	-104.8%
CNG06							-104.8%
CNG07							

Red values indicate ≥95% confidence means are not equal
Blue values indicate ≥90% confidence means are not equal

Table 16. Bag NOx Pairwise t-Test P-Value Results for the Test Vehicle Fleet

All Vehicles Paired t Test Analysis Bag NOx (g/mi)							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		0.219631	0.218418	0.285133	0.227309	0.210183	0.207981
CNG02			0.303189	0.359102	0.262967	0.399767	0.215561
CNG03				0.437164	0.567927	0.200074	0.249355
CNG04					0.263361	0.327385	0.253583
CNG05						0.304802	0.21747
CNG06							0.430979
CNG07							
Summary							
Mean	0.09062	0.029167	0.0329	0.045383	0.03286	0.02705	0.025025
StDev	0.11362	0.022007	0.029586	0.054538	0.032271	0.020033	0.026873
Count	5	6	5	6	5	6	4
Mean Value Percent Difference							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		67.8%	63.7%	49.9%	63.7%	70.2%	72.4%
CNG02			-12.8%	-55.6%	-12.7%	7.3%	14.2%
CNG03				-37.9%	0.1%	17.8%	23.9%
CNG04					27.6%	40.4%	44.9%
CNG05						17.7%	7.5%
CNG06							7.5%
CNG07							

Red values indicate ≥95% confidence means are not equal
Blue values indicate ≥90% confidence means are not equal

Table 17. Bag CO Pairwise t-Test P-Value Results for the Test Vehicle Fleet

All Vehicles Paired t Test Analysis Bag CO (g/mi)							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		0.408696	0.363995	0.173636	0.364945	0.242077	0.162128
CNG02			0.538729	0.782175	0.484652	0.357051	0.148357
CNG03				0.460779	0.815726	0.136488	0.617251
CNG04					0.363397	0.29079	0.152935
CNG05						0.330942	0.5477
CNG06							0.738785
CNG07							
Summary							
Mean	0.29186	0.28398	0.39458	0.2785	0.3999	0.36578	0.5422
StDev	0.1176	0.1841	0.29318	0.15149	0.27303	0.28424	0.25987
Count	5	6	5	6	5	6	4
Mean Value Percent Difference							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		2.7%	-35.2%	4.6%	-37.0%	-25.3%	-85.8%
CNG02			-38.9%	1.9%	-40.8%	-28.8%	-90.9%
CNG03				29.4%	-1.3%	7.3%	-37.4%
CNG04					-43.6%	-31.3%	-94.7%
CNG05						8.5%	-48.2%
CNG06							-48.2%
CNG07							

Red values indicate ≥95% confidence means are not equal
Blue values indicate ≥90% confidence means are not equal

Table 18. Bag CO_2 Pairwise t-Test P-Value Results for the Test Vehicle Fleet

All Vehicles Paired t Test Analysis Bag CO2 (g/mi)							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		0.023142	0.011324	0.037836	0.083743	0.092858	0.074156
CNG02			0.0837	0.006046	0.06755	0.021449	0.043516
CNG03				0.00229	0.405848	0.022656	0.676478
CNG04					0.045769	0.720035	0.039478
CNG05						0.077748	0.65407
CNG06							0.079707
CNG07							
Summary							
Mean	406.636	357.193	394.538	378.038	393.888	378.91	441.823
StDev	251.255	228.137	245.524	238.864	238.837	244.12	249.778
Count	5	6	5	6	5	6	4
Mean Value Percent Difference							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		12.2%	3.0%	7.0%	3.1%	6.8%	-8.7%
CNG02			-10.5%	-5.8%	-10.3%	-6.1%	-23.7%
CNG03				4.2%	0.2%	4.0%	-12.0%
CNG04					-4.2%	-0.2%	-16.9%
CNG05						3.8%	-16.6%
CNG06							-16.6%
CNG07							

Red values indicate ≥95% confidence means are not equal
Blue values indicate ≥90% confidence means are not equal

Table 19. Bag FE Pairwise t-Test P-Value Results for the Test Vehicle Fleet

All Vehicles Paired t Test Analysis Bag FE (MPGe)							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		0.01135	0.014131	0.00907	0.034362	0.012802	0.043028
CNG02			0.01962	0.002656	0.007205	0.003651	0.598075
CNG03				0.003975	0.011998	0.011774	0.126221
CNG04					0.07248	0.007658	0.039302
CNG05						0.024969	0.052886
CNG06							0.049726
CNG07							
Summary							
Mean	19.726	23.008	22.614	26.06	23.306	27.958	18.998
StDev	10.028	10.504	11.576	11.826	11.621	12.86	10.749
Count	5	6	5	6	5	6	4
Mean Value Percent Difference							
	CNG01	CNG02	CNG03	CNG04	CNG05	CNG06	CNG07
CNG01		-16.6%	-14.6%	-32.1%	-18.1%	-41.7%	3.7%
CNG02			1.7%	-13.3%	-1.3%	-21.5%	17.4%
CNG03				-15.2%	-3.1%	-23.6%	16.0%
CNG04					10.6%	-7.3%	27.1%
CNG05						-20.0%	32.1%
CNG06							32.1%
CNG07							

Red values indicate ≥95% confidence means are not equal
Blue values indicate ≥90% confidence means are not equal

7.2 Statistical Analysis of Individual Vehicle Effects

Statistical models were developed to further determine if some of the fuel effects on individual vehicles were statistically significant, discussed in Section 6. Figure 60 below shows mean value responses for each vehicle. CNG07 was excluded for Vehicle B as both tests recorded gasoline operation during the cold start of Phase 1.

The test plan had only up to 2 replicates x 7 fuels = 14 total observations that may be used to explore individual vehicle effects. Therefore the purpose of the individual vehicle models was to analyze the most obvious fuel effect trends, including FE for Vehicles A, B and C and NOx emissions from Vehicle C. The independent variables were Methane Number and Wobbe Index, and dependent variables were FE and Bag NOx. Polynomial models were developed to confirm the statistical validity of the conclusions being drawn for individual vehicles.

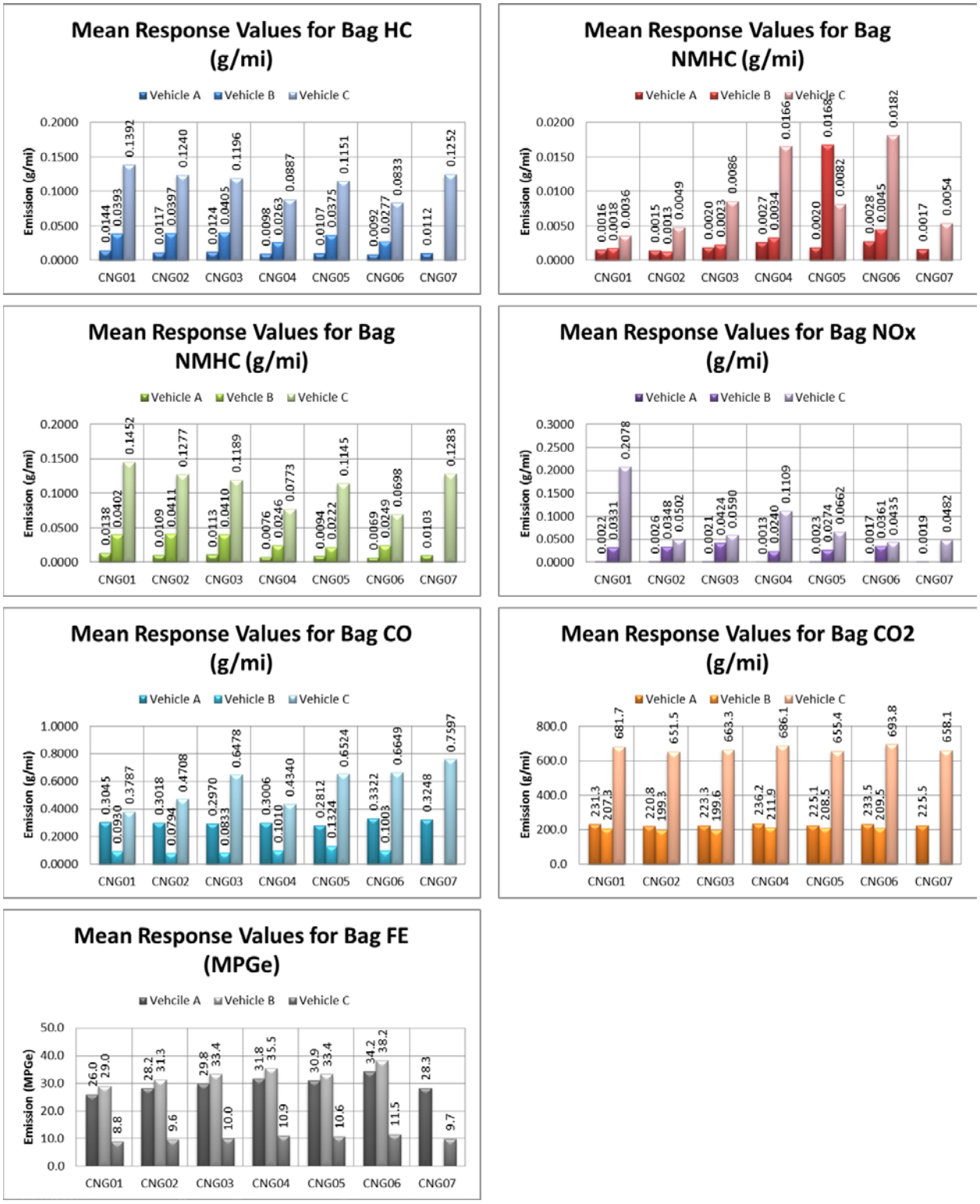


Figure 60. Mean Response Values for Each Test Vehicle

Mean Value (y-hat) models were developed for the effect of MN and WI on fuel economy for all vehicles as shown in Figure 61, Figure 62, and Figure 63. All terms included in the models shown here had p-values less than 0.05, indicating good model fidelity. All models exhibit increasing FE with increasing Wobbe Index and decreasing methane number. Vehicles A and B's models predict very linear trends, whereas Vehicle C has a second order sensitivity to methane number.

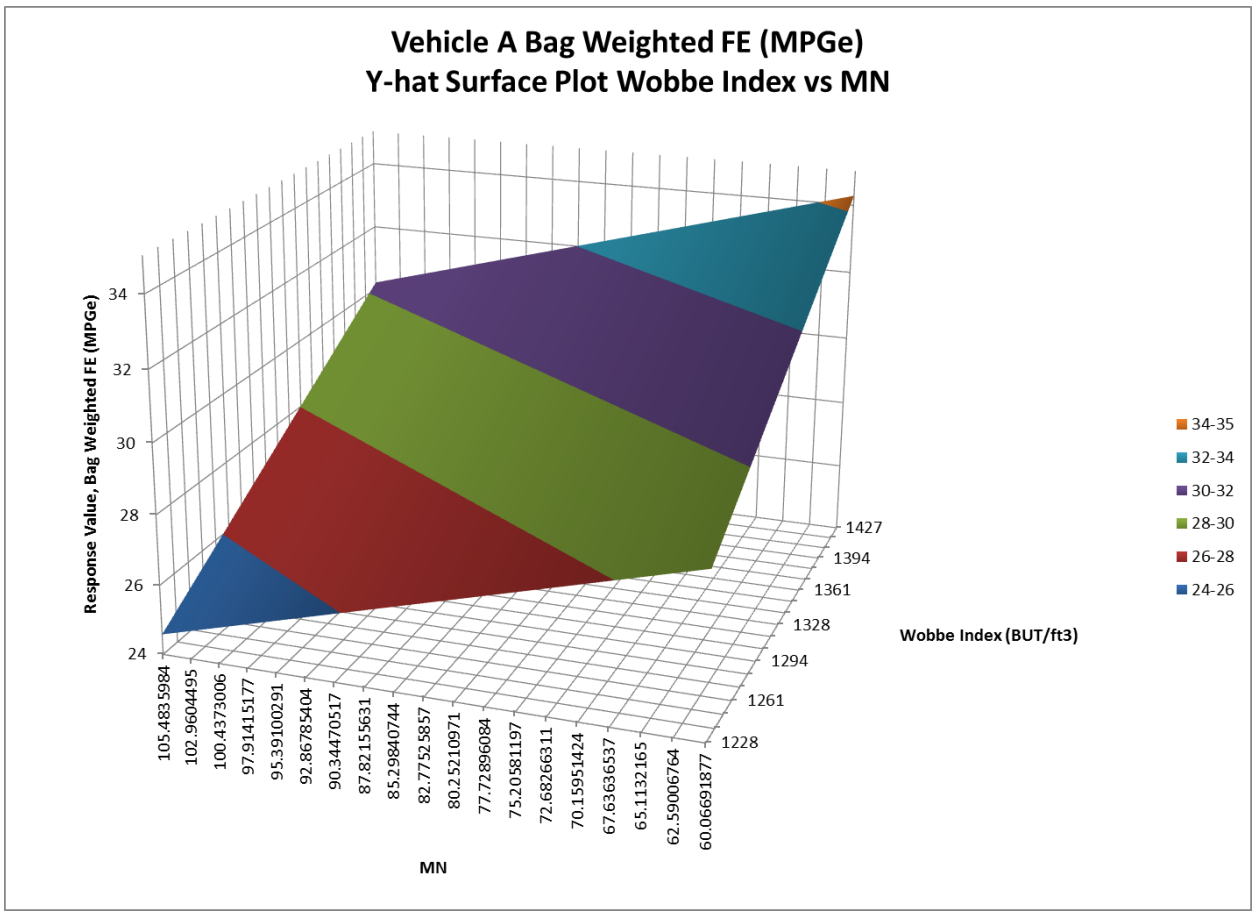


Figure 61. Vehicle A Bag-Weighted FE Mean Value Surface Plot Wobbe Index vs. MN

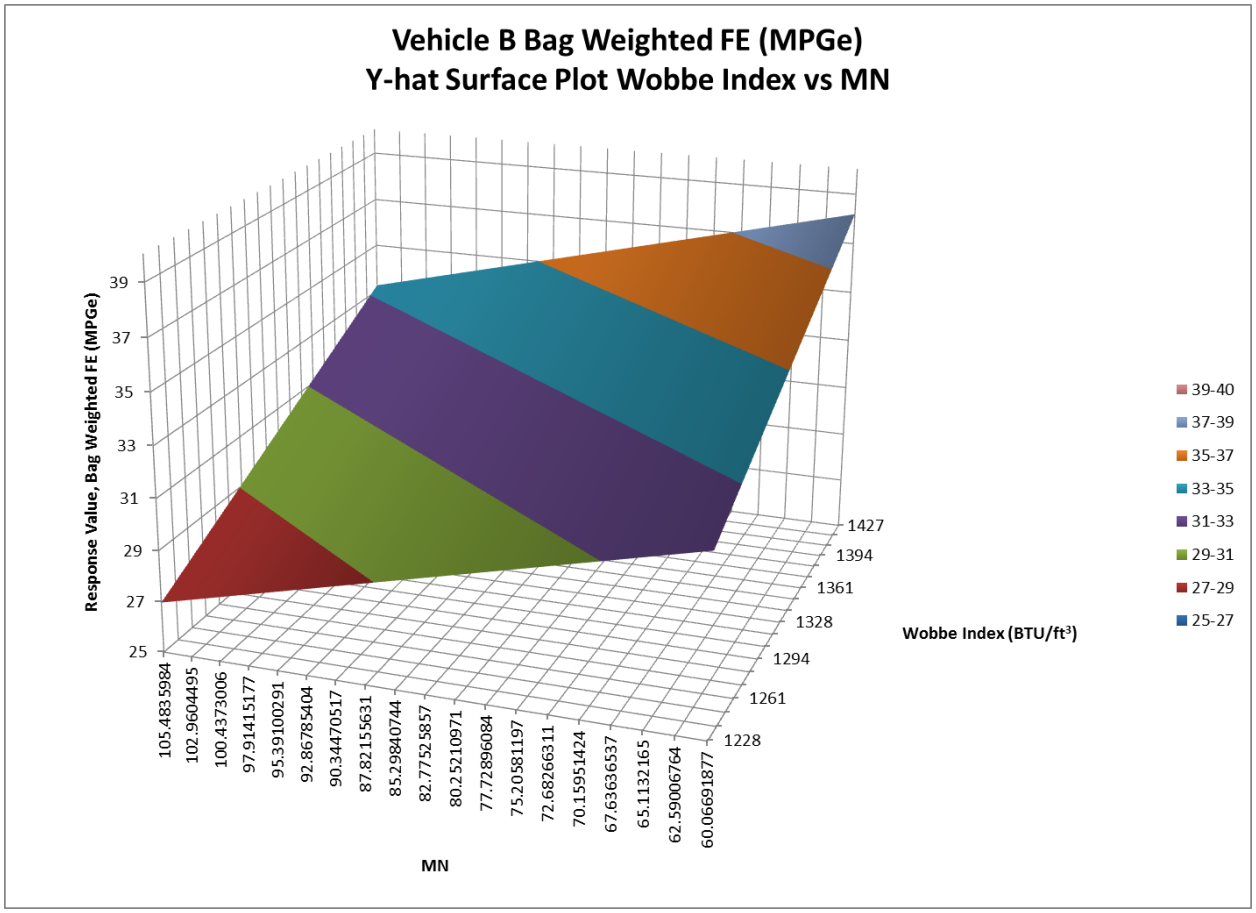


Figure 62. Vehicle B Bag-Weighted FE Mean Value Surface Plot Wobbe Index vs. MN

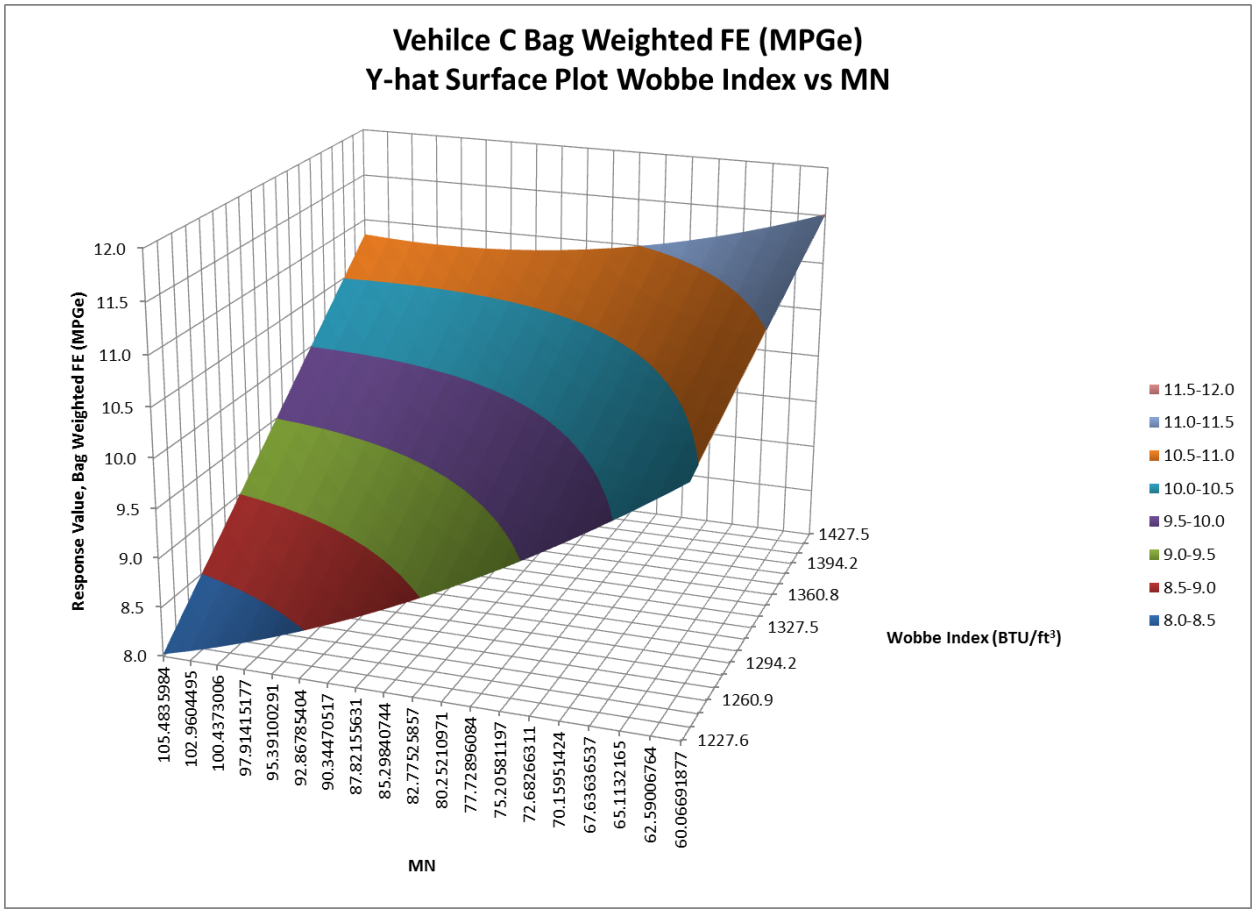


Figure 63. Vehicle C Bag-Weighted FE Mean Value Surface Plot Wobbe Index vs. MN

For Vehicle C, the effect of MN and Wobbe Index on NOx emissions was statistically significant with greater than 95% confidence. A strong second order relationship was observed against Wobbe Index and a linear trend was predicted against methane number (Figure 64).

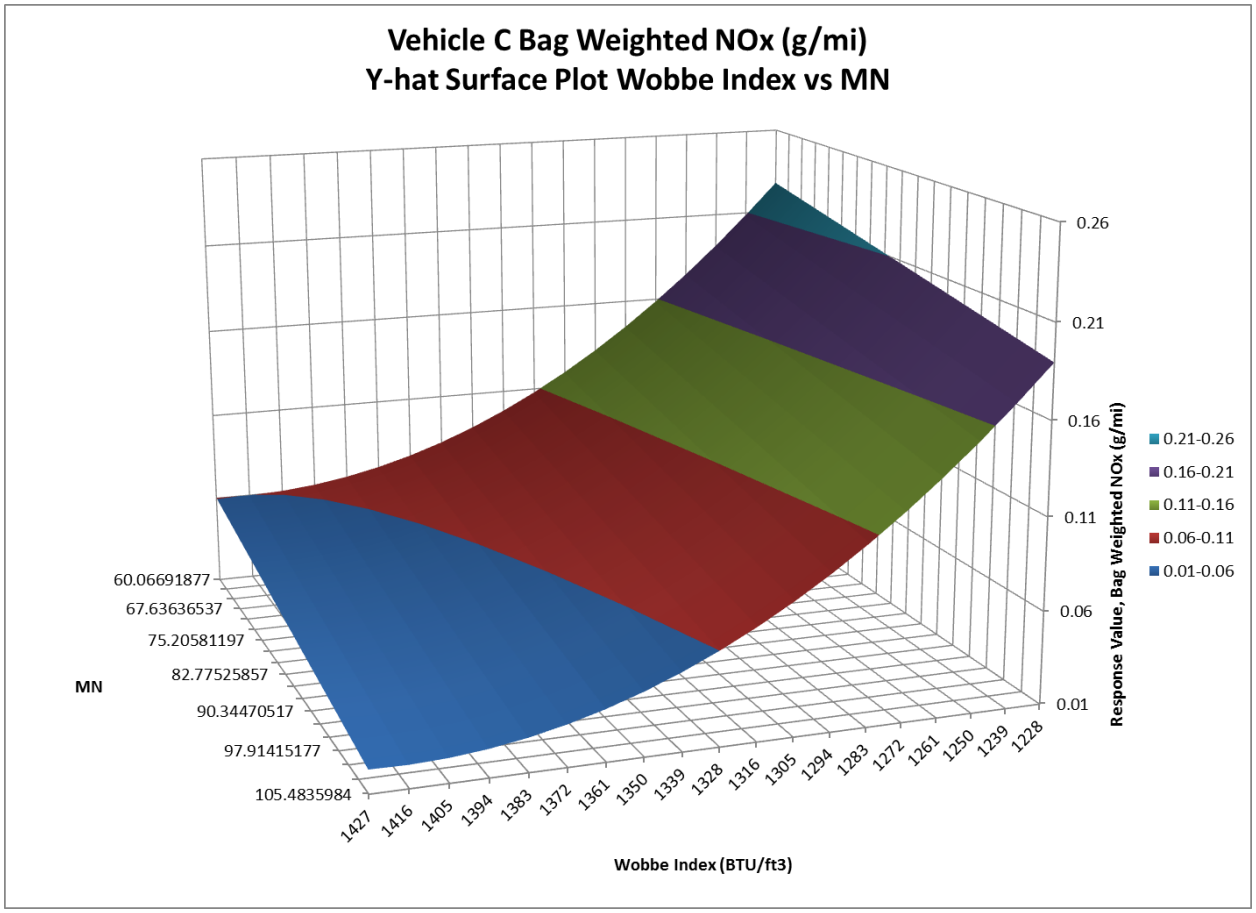


Figure 64. Vehicle C Bag-Weighted NOx Mean Value Surface Plot Wobbe Index vs. MN

8.0 Knock Investigation #1

During the EPEFE/WOT preconditioning cycles at 100°F ambient temperature, vehicle CAN data were recorded to observe the commanded ignition timing from cylinder one. The EPEFE/WOT cycle was used as preconditioning for the emissions test sequence to allow the ECU to adjust to the change in fuel quality and ensure uniform catalyst conditioning.

Data analysis was performed on the second half of the WOT cycle for all fuels tested to quantify a possible reduction in ignition timing with the lowest MN fuels compared to the highest MN fuels. This testing was grouped together with the base emission test cycles to minimize the time for test setup, fuel use, and cost. Figure 65 below shows the EPEFE drive trace.

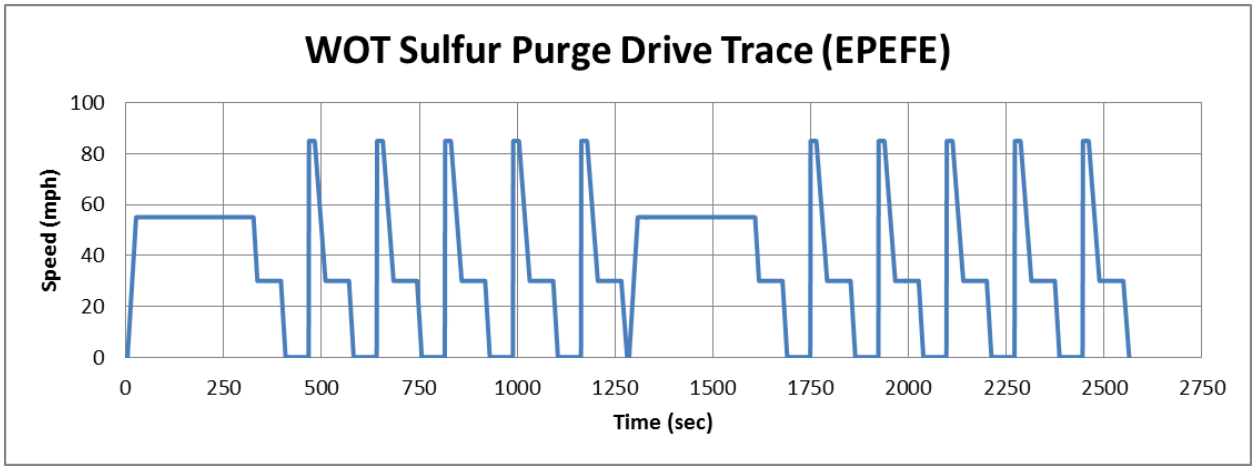


Figure 65. EPEFE (WOT) Drive Trace

Data were analyzed at discrete locations in the drive trace on the last 85 mph hill. This gave the vehicle's control system the ability to adapt to the fuel quality over two 65mph cruises, nine wide-open-throttle accelerations, and nine steady state cruises at 85mph and 30mph. Ignition timing values were noted at peak power and peak torque during WOT acceleration, 85mph steady state cruise, and 30mph steady state cruise for each vehicle. An example of the analyzed points for Vehicle A is shown below in Figure 66. The WOT peak power datum point was evaluated for Vehicle A in 2nd gear and 5500 RPM, for Vehicle B in 3rd gear at 5500 RPM, and Vehicle C in 3rd gear at 5000 RPM. The WOT peak torque datum point was evaluated for Vehicle A in 2nd gear at 4300 RPM and for Vehicle C at 4000 RPM. Although Vehicle B's peak torque occurred from 1500 to 4500 RPM, wheel slip occurred at WOT on the chassis dynamometer in the first two gears. By third gear Vehicle B gained traction and no longer had wheel slip at WOT. After shifting from second gear at 6000 RPM the engine speed only dropped to 4000 RPM in third gear. 4200 RPM in 3rd gear was selected as Vehicle B's WOT peak torque RPM as it was the lowest RPM with no wheel spin and the turbocharger re-spooled after the shift event.

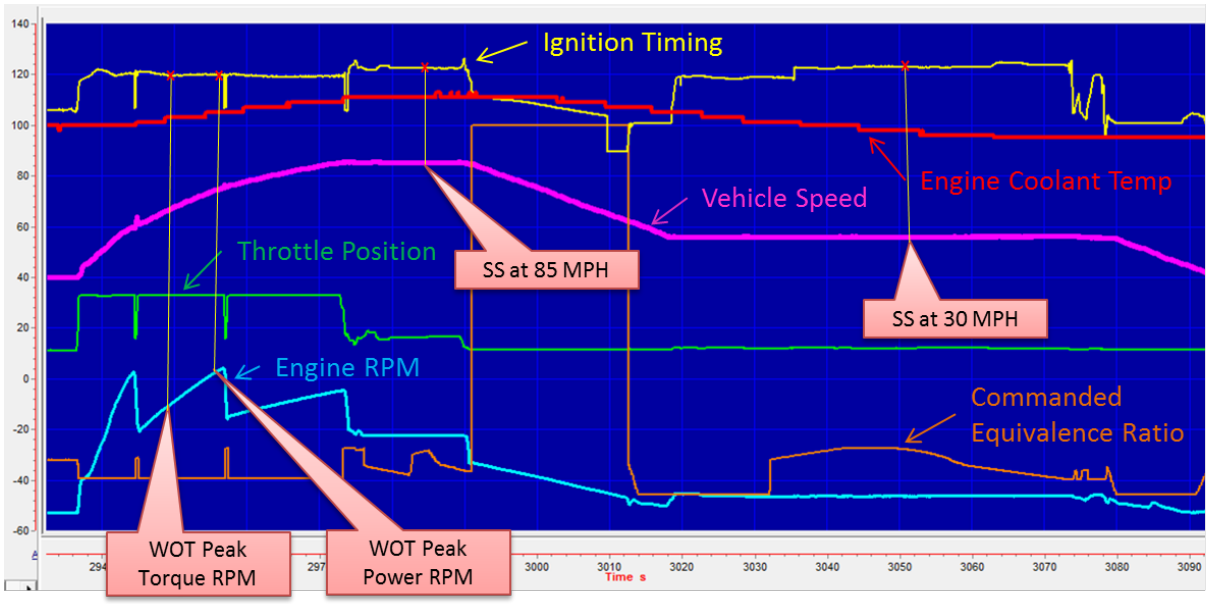


Figure 66. Vehicle A EPEFE CNG04_run2 INCA Example

Figure 67 below charts the four discrete data points for duplicates of each of the seven fuels. Knock was not detected at the peak power, peak torque, 85mph, or 30mph conditions when comparing ignition timing advance to methane number against each fuel for any of the vehicles. This conclusion is inferred because the control systems did not identify any knock and did not adjust ignition timing advance for the lower methane number fuels.

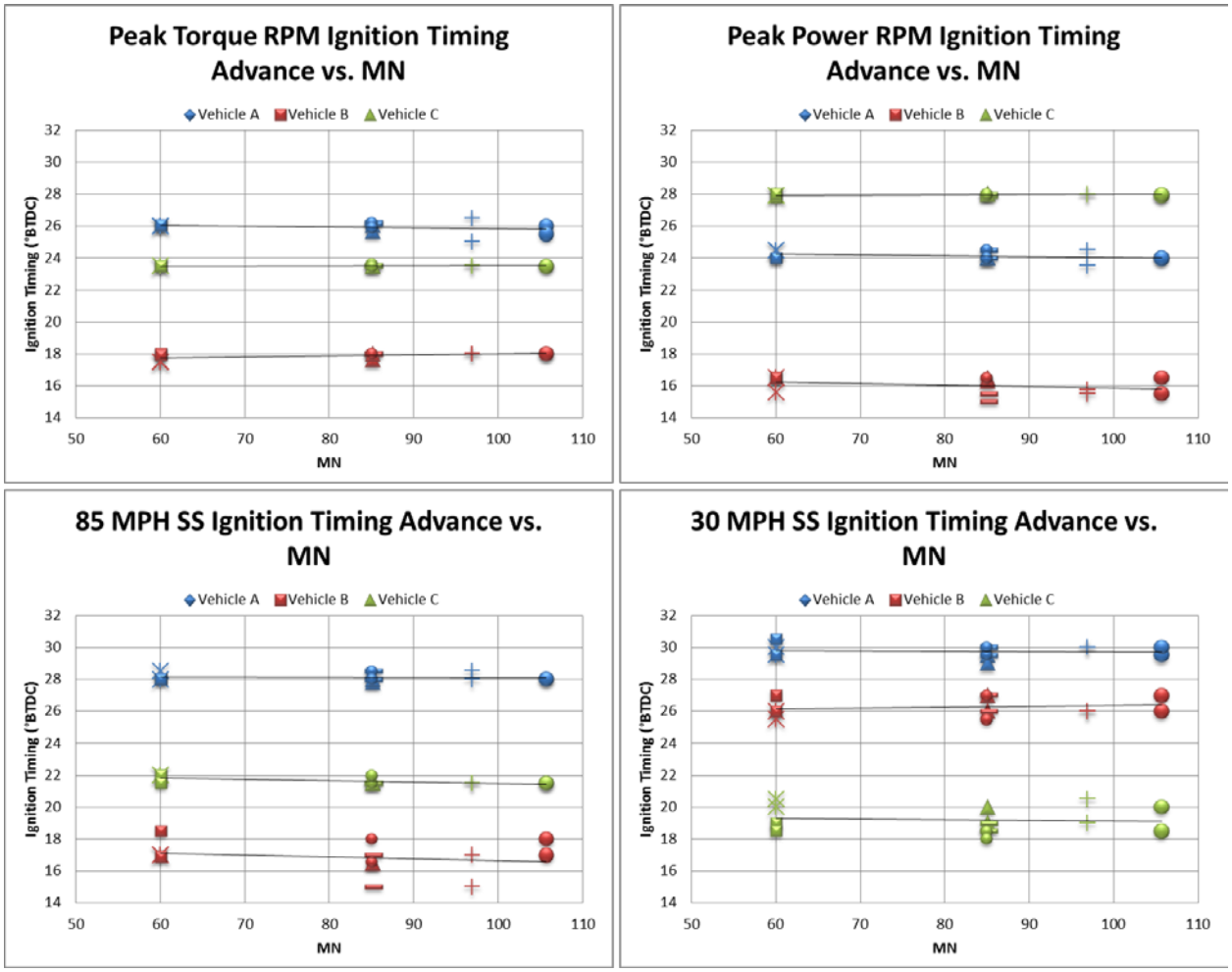


Figure 67. Ignition Timing Advance vs. MN (Peak Torque, Peak Power, 85mph SS, 30mph SS)

9.0 Knock Investigation #2

9.1 Set-Up and Test Procedure

A pseudo steady state engine RPM knock investigation was performed on all vehicles utilizing a spark plug mounted cylinder pressure transducer and A&D Redline CAS II combustion analyzer. Timing triggers for cylinder pressure sampling were generated from the stock 60-2 timing wheels by soldering a BNC connector onto the crank angle sensor harness for both Vehicle A and Vehicle B. Wire piercing probes were utilized on the easily accessible crank angle sensor harness on Vehicle C. Good engineering judgment was used for procurement of the spark plug with pressure transducer to achieve the correct heat range, gap, and protrusion to closely match the OEM spark plug. The engine's ignition coil/spark plug wire arrangement remained intact without modification. The cylinder pressure signal wire egress was afforded on Vehicle's A and B with an eccentric adapter and on Vehicle C with an ignition wire extension.

To minimize the modifications required to capture in-cylinder data, spark plug mounted pressure transducers were used with specifications closely matching the OEM spark plug as shown in Table 20 below. The Kistler spark plugs used the Bosch heat range scale which is listed as the last number in the Kistler part number.

Table 20. OEM Spark Plug Specifications with Kistler Equivalent

Manufacturer	Vehicle A	Vehicle B	Vehicle C
OEM Spark Plug Mfg:	NGK	Bosch	NGK
OEM Spark Plug P/N:	SILKR8B8DS	BOM 06E905612 R1 DH	ILZFR5E 8D
Resistor Type (y/n)	Y	Y	Y
Seat (flat/conical)	Flat	Flat	Flat
Gap (mm)	0.8	0.8	0.7
Hex Size (in.)	5/8"	5/8"	5/8"
Thread Ø (mm)	14	12	14
Thread pitch (mm)	1.25	1.25	1.25
Thread reach (mm)	19	19	26.7
Heat Range (NGK)	8	6	5
Heat Range (Bosch)	4	6	8
Resistor Type (y/n)	Y	Y	Y
Kistler Measuring Plug	6115BFD34	6115BFD16	6117BCD39

The heat ranges selected closely matched the OEM plugs to minimize influence of changing this in-cylinder component for the knock investigation. A comparison of the OEM and Kistler plugs and are shown below in Figure 68. Installation of the spark plugs for Vehicle A and Vehicle B required an offset extension be installed on the Kistler plug to regain eccentricity of the terminal nut and use the OEM ignition coils. Standoffs were utilized to securely mount the coils. Vehicle C's installation did not require an offset extension, but instead required two ignition wire length adapters with the dual-plug OEM ignition coil secured outside of its original location as shown in Figure 69.

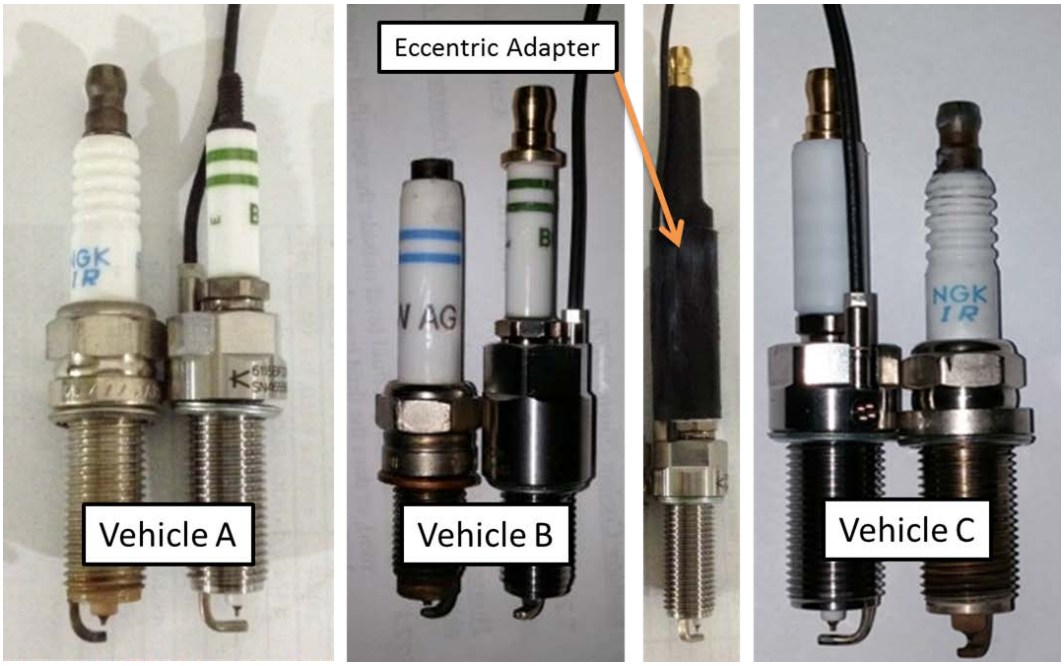


Figure 68. OEM and Kistler Spark Plugs (Vehicle A, Vehicle B, Vehicle C)

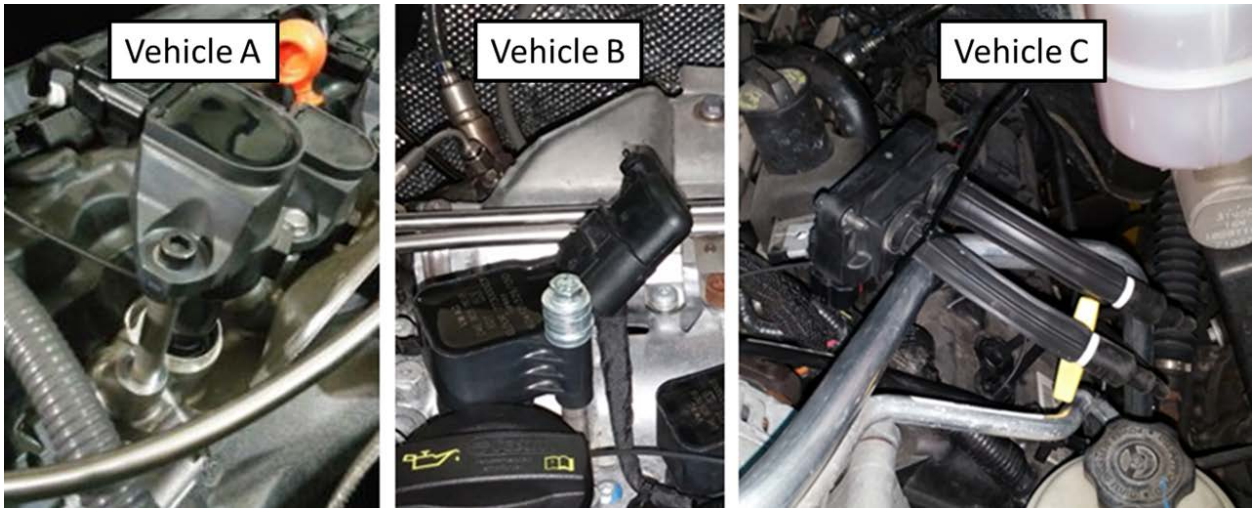


Figure 69. Ignition Coil Standoff (Vehicle A, Vehicle B, Vehicle C)

The Volkswagen Golf TGI is shown with the A&D Redline II CAS unit in Figure 70. Cylinder pressure data was collected by manually triggering the recording just prior to the load transient.

Figure 70. Volkswagen Golf TGI on Site 3 with CAS

A steady state engine RPM was selected at peak engine torque with the chassis dynamometer set in speed control mode. The transmission gear selector was put into a fixed position to prevent influence from the transmission changing gears. The engine was brought from near zero-load to full-load in a fast step change and data were collected during this transient over 100 engine cycles.

The crank-angle resolved cylinder pressure trace was captured at light load, step change transient, and full load at the engine speed corresponding to peak torque. An engine knock condition is readily observed in the crank-angle resolved cylinder pressure shape characteristic, appearing as a rapidly oscillating pressure wave during the power stroke (so called “dinosaur back”). Other data were post-processed to identify knock, including the maximum pressure rise rate, knock intensity, and comparisons of ignition timing.

Testing was performed with the highest and the lowest MN fuels to compare the best and worst case knock tendency. Fuel CNG02 was selected as the highest quality fuel having a MN of 105.66 and the least amount of higher hydrocarbons (0%). Fuel CNG06 was selected as the poorest quality fuel with a MN of 60.06, the largest concentration of higher hydrocarbons (19.9%), and the least concentration of inert gasses (2.3%) of the low MN fuels. The higher hydrocarbons have lower auto-ignition temperatures and provide less margin to avoid in-cylinder knock.

Vehicle A was advertised to make peak torque of 106 ft-lbs at 4300 RPM. Normally, an engine’s knock resistance is lowest at the engine speed associated with peak torque. This puts the highest amount of fresh air in the cylinder along with the longest residence time near TDC. A steady state speed of 41 mph with the transmission selector position in ‘D2’ generated an engine speed of 4200 RPM at full load. Vehicle C was advertised making peak torque of 400 ft-lbs at 4000 RPM. A road speed of 55 mph in

3rd gear was selected to perform the no-load to WOT test. One aspect of the automatic transmissions in Vehicles A and C was that the torque converters were not in full lock-up when minimal load is applied. Therefore, a slight increase in engine speed is seen during the transient event before the torque converter was near or at full lock.

Vehicle B was advertised making peak torque of 147 ft-lbs from 1500-4500 RPM. Since the engine RPM effects the transient response of the turbocharger, a no-load to WOT sweep was performed to determine the engine speed best suited for this knock investigation. Based on the transient response of the turbocharger the minimum response time to achieve peak torque during the WOT transient was 1.5 seconds measured at 2525 RPM as shown in Figure 71 below. Lower engine speeds did not produce as much torque as 2525 RPM and took as much as 4.2 seconds at 1500 RPM for the turbocharger to achieve its target boost pressure. Higher engine speeds slightly reduced the transient response, but will reduce the charge residence time near TDC, reducing knock tendency. The optimum engine speed with the highest engine torque and reasonable load response was selected to be 2525 RPM for this investigation.

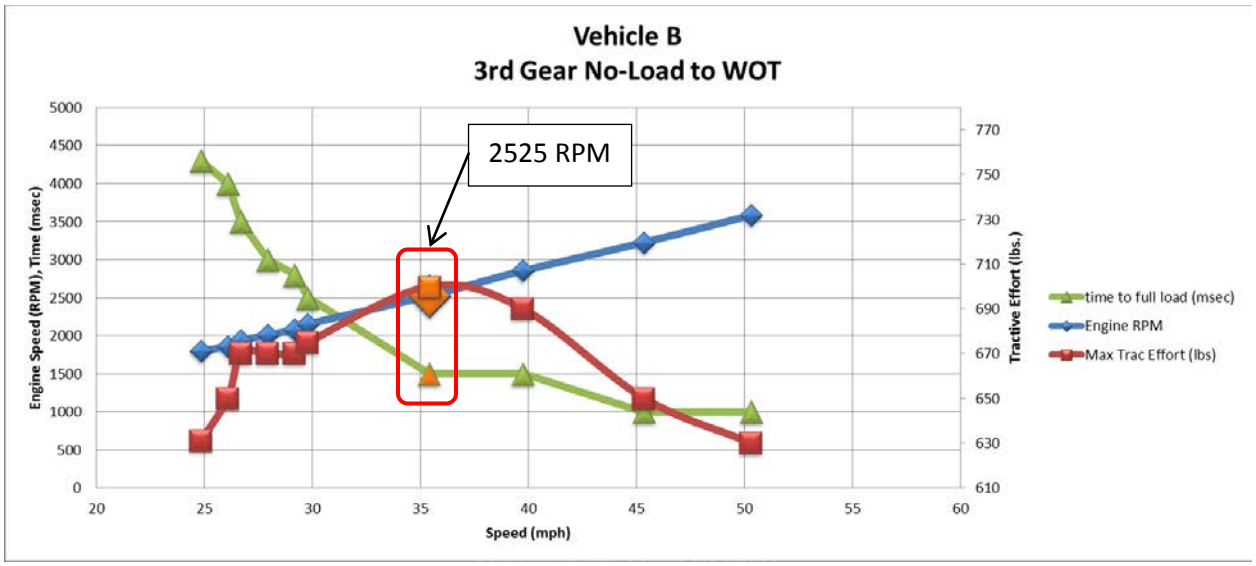


Figure 71. Vehicle B No-Load to WOT Response

The test sequence listed below was followed for each vehicle to capture the zero to full load transient on the highest and lowest MN fuels (CNG02 at 105.48 and CNG06 at 60.07).

1. Two LA92 preconditioning cycles on CNG02
2. Drive vehicle up to target speed and shift into target gear with the chassis dynamometer in speed control mode
3. Maintain light load (less than 50%) on vehicle to attain stable engine coolant and exhaust temperatures (>2 minutes)
4. Apply load to the engine such that the measured dyno torque is near zero ft.-lbs
5. Apply full load as fast as possible, hold for 5 seconds after maximum load is reached
6. Let off throttle and bring vehicle back to idle
7. Turn off car and change to CNG06
8. Drive vehicle up to target speed and shift into target gear with the chassis dynamometer in speed control mode
9. Maintain light load (less than 50%) on vehicle to attain stable engine coolant and exhaust temperatures (>2 minutes)
10. Apply load to the engine such that the measured dyno torque is near zero ft.-lbs.
11. Apply full load as fast as possible, hold for 5 seconds after maximum load is reached
12. Let off throttle and bring vehicle back to idle
13. Vehicle CAN data are collected with ETAS INCA ODX during the entire procedure and CAS recording is initialized ~2 seconds prior to the WOT event to capture the load transient.
14. Post-process cylinder pressure data to identify if knock is present with the following criteria.
    a. Maximum Pressure Rise Rate (MPRR) greater than 10 bar per °CA
    b. Measureable change in knock intensity between CNG02 and CNG06
    c. Measureable change in knock intensity squared between CNG02 and CNG06

9.2 Knock Investigation Results

INCA screenshots are shown in Figure 72, Figure 73, and Figure 74 with a time aligned overlay of the zero to full load transient events for all three vehicles using CNG02 and CNG06. Figure 72 shows the the ignition timing step change for Vehicle A went from 32°BTDC to 26°BTDC for both events, indicating the control system did not make any changes to spark timing between the two fuels. The calculated absolute load value went from approximately 16% to 60% for both tests.

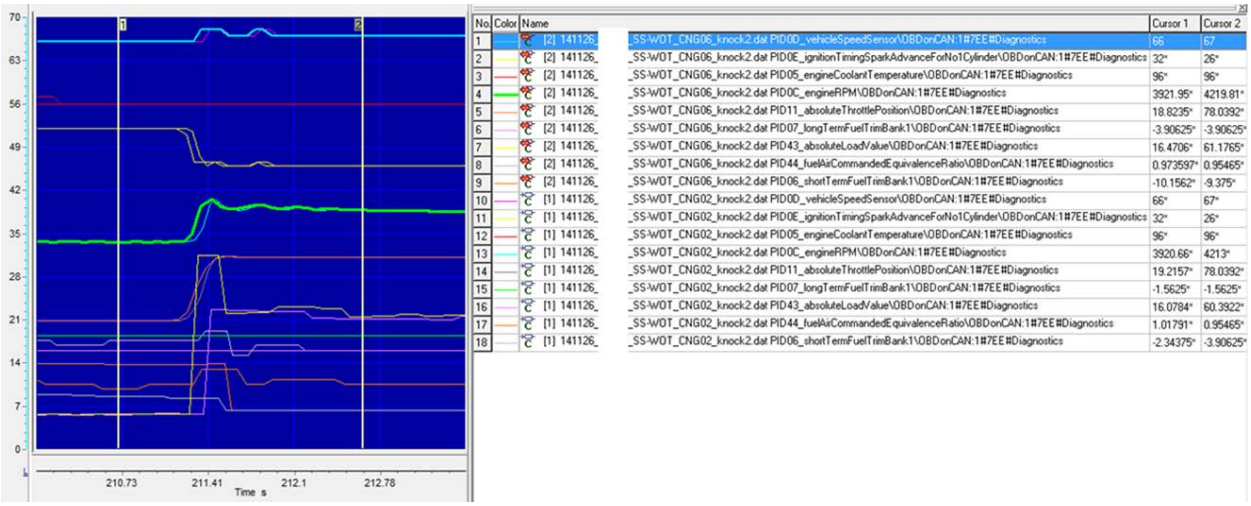


Figure 72. INCA Screenshot (Vehicle A, CNG02 vs. CNG06)

Figure 73 shows the ignition timing step change for Vehicle B went to 10.5°BTDC at full load for both events, indicating the control system did not make any changes to spark timing between the two fuels once the system reached full load. The calculated absolute load value went from approximately 15% to 132% for both tests.

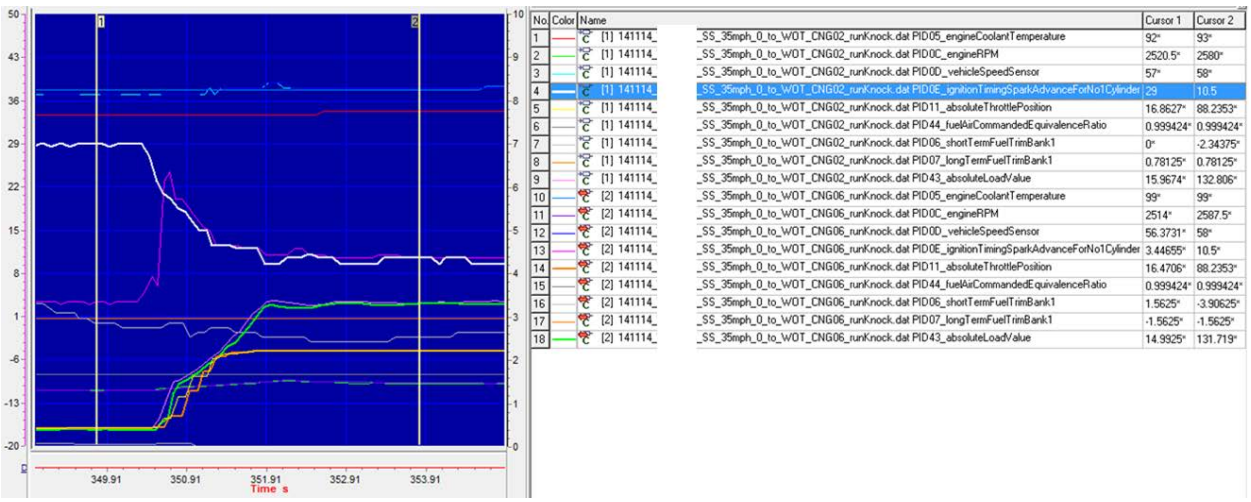


Figure 73. INCA Screenshot (Vehicle B, CNG02 vs. CNG06)

Figure 74 shows Vehicle C's ignition timing step change went from 24.5°BTDC to 24°BTDC for both events, indicating the control system did not make any changes to spark timing between the two fuels. The calculated absolute load value went from approximately 38% to 75% for both tests.

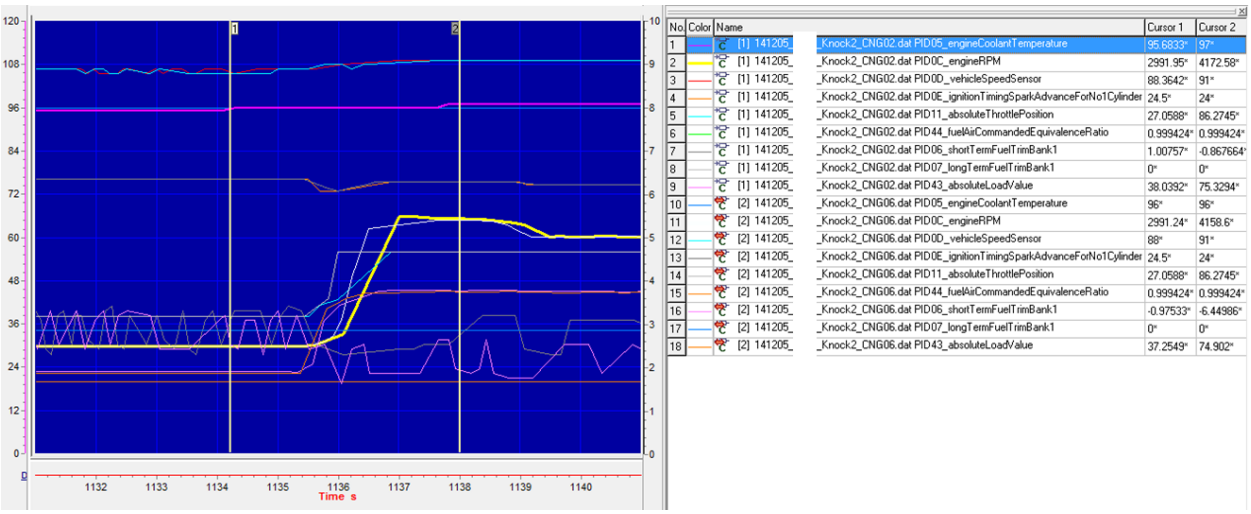


Figure 74. INCA Screenshot (Vehicle C, CNG02 vs. CNG06)

Results of the cylinder pressure data from Vehicle A are presented below in Figure 75. Displayed at left are waterfall plots of the cylinder pressure over 70 cycles. Displayed at right are peak cylinder pressure (MaxPress), maximum pressure rise rate (MPRR), and indicated mean effective pressure (IMEP) over 100 engine cycles. For this and subsequent plots in this section, the graphs at right are in the time domain and were intentionally not time-aligned for data visualization purposes.

The step change in load generated an IMEP step from approximately 2 bar to 9 bar over five engine cycles. The maximum pressure rise rate for both test fuels did not exceed 4 bar/degree and was well below the selected threshold of 10 bar/degree guideline that would indicate knock. Comparing CNG02 to CNG06, the maximum peak cylinder pressure increased from 65 bar to 72.8 bar, maximum peak pressure rise rate from 2.73 bar/deg to 3.54 bar/deg, and maximum IMEP from 9.02 bar to 9.29 bar. The 81mm cylinder bore of Vehicle A should knock (or ring) around 7.04kHz. Nothing was found in this frequency spectrum that would indicate a knocking cylinder for either fuel tested. Vehicle A's combination of compression ratio (12.7:1), valve timing, EGR, and ignition timing proved robust to knocking on these two fuels at a barometric pressure of 84 kPa.

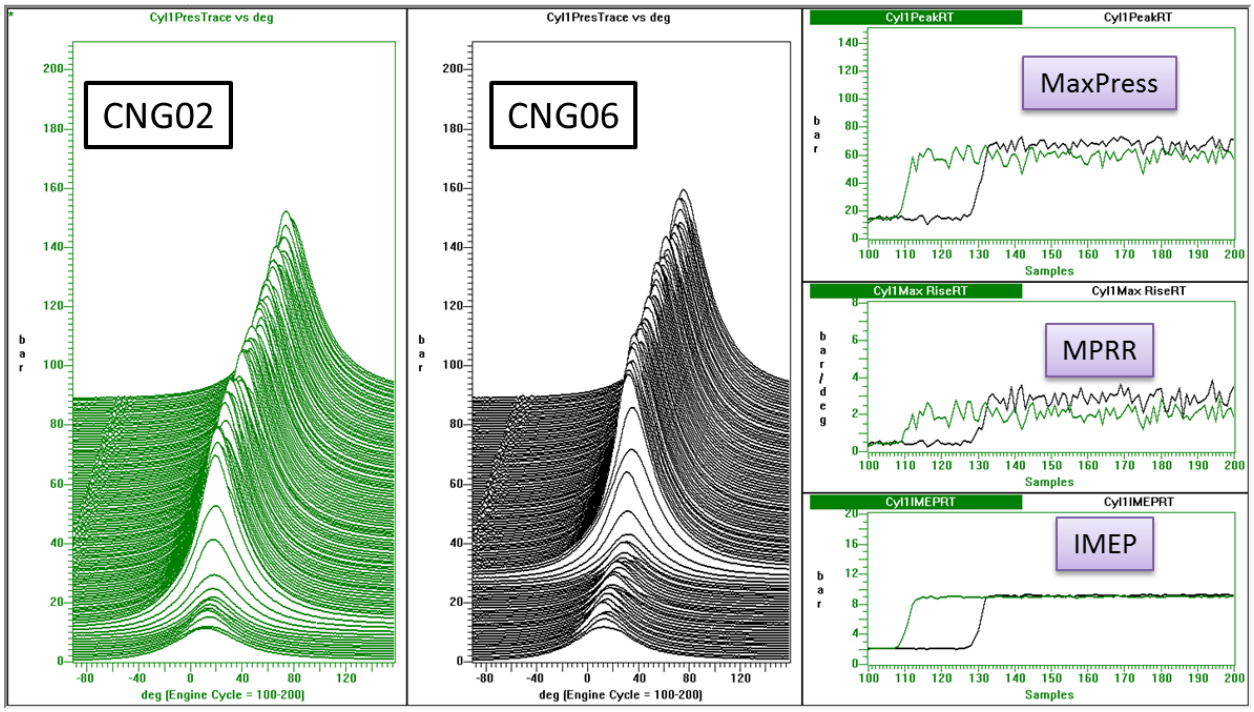


Figure 75. Vehicle A Cylinder Pressure Transient CNG02 (green) vs. CNG06 (black)

Results of the cylinder pressure data from Vehicle B are presented below in Figure 76. The step change in load generated an IMEP step from approximately 2 bar to 18.6 bar over 40 engine cycles. The maximum pressure rise rate for both test fuels did not exceed 7.5 bar/degree and was well below the selected threshold of 10 bar/degree that would indicate knock. Comparing CNG02 to CNG06, the maximum peak cylinder pressure increased from 100.7 bar to 110.4 bar, maximum peak pressure rise rate from 6.02 bar/deg to 7.35 bar/deg, and maximum IMEP from 18.64 bar to 19.05 bar. The 76.5mm cylinder bore of Vehicle B should knock (or ring) around 7.45kHz. Nothing was found in this frequency spectrum that would indicate a knocking cylinder for either fuel tested. Vehicle B's combination of compression ratio (10.5:1), boost pressure, valve timing, EGR, and ignition timing proved robust to knocking on these two fuels at a barometric pressure of 84 kPa.

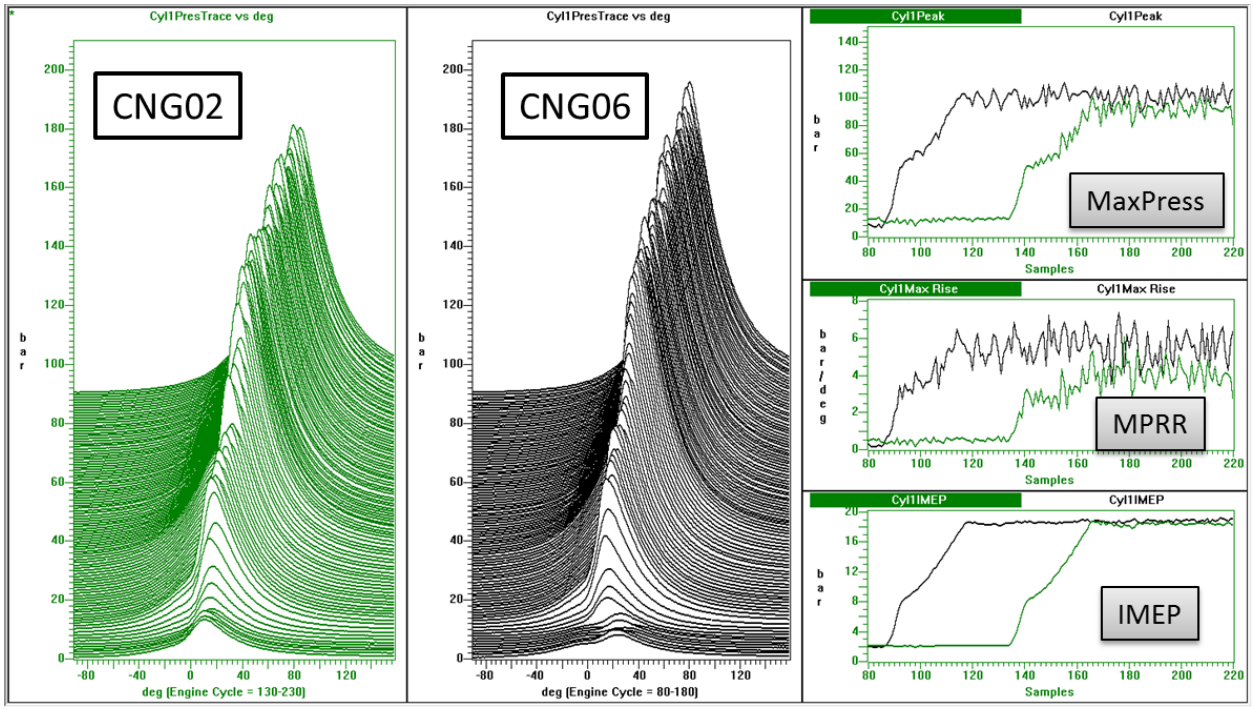


Figure 76. Vehicle B Cylinder Pressure Transient CNG02 (green) vs. CNG06 (black)

Results of the cylinder pressure data from Vehicle C are presented below in Figure 77. The step change in load generated an IMEP step from approximately 5 bar 10.7 bar over 10 engine cycles. The maximum pressure rise rate for both test fuels did not exceed 4 bar/degree and was well below the selected threshold of 10 bar/degree that would indicate knock. Comparing CNG02 to CNG06, the maximum peak cylinder pressure increased from 65.3 bar to 67.7 bar, maximum peak pressure rise rate from 3.17 bar/deg to 3.98 bar/deg, and maximum IMEP from 10.73 bar to 10.97 bar. The 99.5mm cylinder bore of Vehicle C should knock (or ring) around 5.73kHz. Nothing was found in this frequency spectrum that would indicate a knocking cylinder for either fuel tested. Vehicle C's combination of compression ratio (10.5:1), valve timing, EGR, and ignition timing proved robust to knocking on these two fuels at a barometric pressure of 84 kPa.

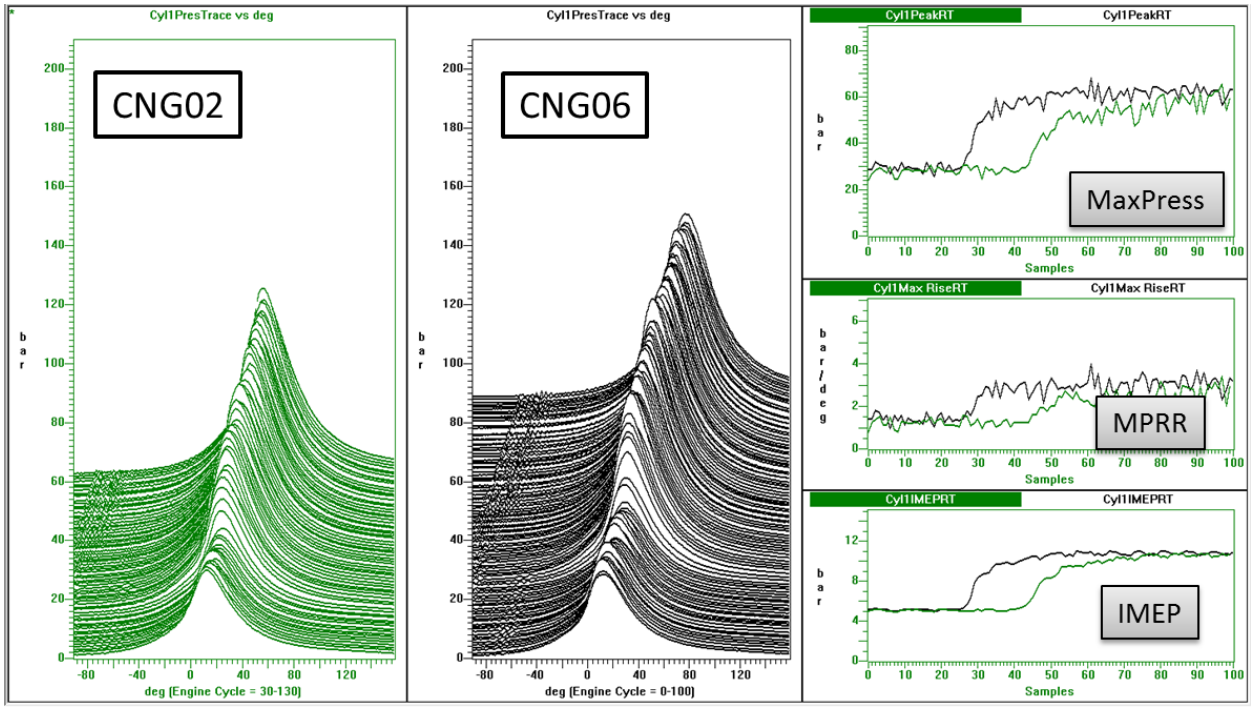


Figure 77. Vehicle C Cylinder Pressure Transient CNG02 (green) vs. CNG06 (black)

Each vehicle had a slight increase in peak cylinder pressure, maximum cylinder pressure rise rate, and IMEP with the lower methane number CNG06 fuel which also had higher Wobbe Index. Figure 78 below shows Vehicle A experienced a 10.7% increase in maximum peak pressure and a 22.9% increase in maximum cylinder pressure rise rate. IMEP increased by more than 2% for all three vehicles while operating on CNG06.

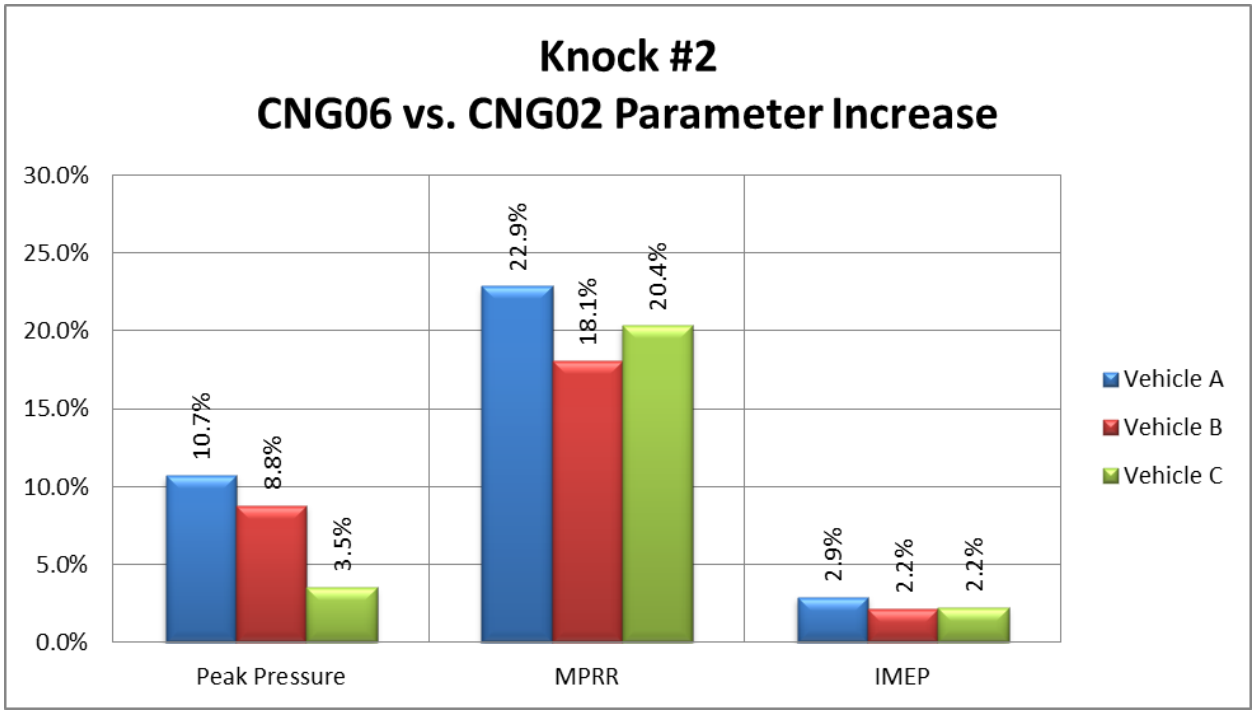


Figure 78. CNG06 vs. CNG02 Parameter Increase

9.3 Additional Knock Investigation - Environmental Conditions and Engine Speed Sweeps

The maximum IMEP of the naturally aspirated vehicles was reduced by approximately 17% at SGS's test lab located at high altitude near Denver, compared to sea level labs (101.325 kPa vs. 84 kPa barometric pressure). Vehicle A's IMEP at peak torque theoretically dropped from 11.3 bar to 9.4 bar and Vehicle C's dropped from 12.0 bar to 9.9 bar. The turbocharged control strategy for Vehicle B may target an absolute load the same or higher than what is commanded at sea level conditions, but was unknown. The reduction in mean effective pressure equates to lower peak cylinder pressure and temperature that will reduce knock tendency. Another item to note is that the bi-fuel vehicle's engine compression ratios must accommodate both gasoline and CNG operation, leaving room for increased efficiency with higher compression ratio if the engine were dedicated to CNG operation only. Vehicle A has the highest compression ratio of the vehicle group at 12.7:1 and is a dedicated CNG vehicle. Even so, it did not experience knock during the load step change transient.

Additional testing was conducted on Vehicle C utilizing SGS BASE™ (Balancing Altitude Simulation Equipment) shown below in Figure 79. This modular air handling system was used to simulate different altitude and ambient temperature conditions to explore knock potential. To achieve higher pressures than the local barometric pressure, the system compresses the intake air to the engine. To achieve pressures lower than the local barometric pressure, the system creates a slight vacuum to the engine intake system. The pressure is dynamically balanced at the intake, exhaust, and crankcase, correctly simulating variable altitudes and the corresponding effects that barometric pressure has on engine breathing, gas exchange, combustion, exhaust pollutant formation, fuel consumption, and pumping losses.

Figure 79. Balancing Altitude Simulation Equipment™ (BASE™)

9.3.1 Vehicle C Knock Investigation #2 with BASE™, Altitude Effects

Increasing the in-cylinder pressure and temperature can lead to increased propensity for engine knock. To create a worst-case knock scenario the BASE™ system was installed on Vehicle C and set to sea level pressure (101.3 kPa) and elevated intake air temperature (35°C). An additional test cycle was run with the poorer-quality CNG06 producing cylinder pressure data shown in Figure 82 below. The step change in load generated an IMEP step from 5 bar to 11.0 bar at local altitude (84kPa/25C, green) compared to 5 bar to 13.7 bar at low altitude (101kPa/35C, black) over 10 engine cycles. The maximum pressure rise rate for both test fuels did not exceed 5 bar/degree and is well below the selected threshold of 10 bar/degree that would indicate knock.

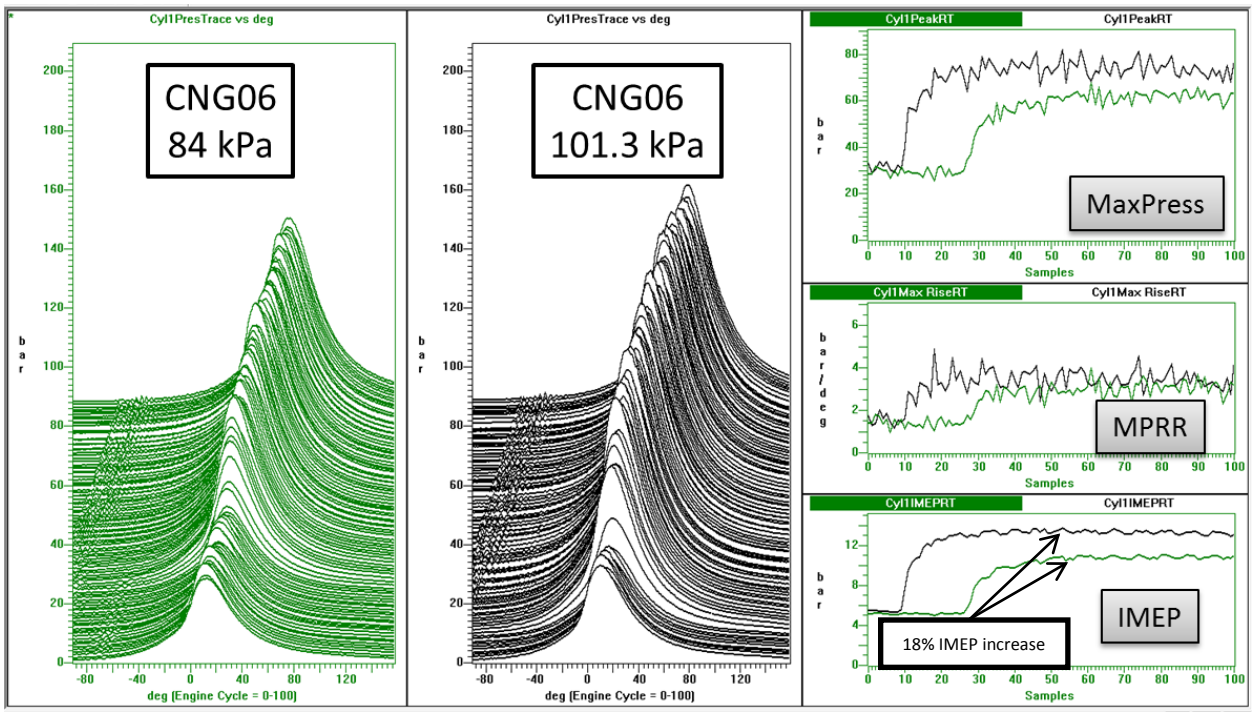


Figure 80. Vehicle C Cylinder Pressure Transient at 84kPa/25C and 101kPa/35C for CNG06 Fuel

9.3.2 Vehicle C Knock Investigation #2 with BASE™, Fuel Effects

Both CNG02 and CNG06 were tested with BASE™ set to 101.3 kPa and 35°C. Comparing CNG02 to CNG06, the maximum peak cylinder pressure increased from 76.2 bar to 81.7 bar, maximum peak pressure rise rate from 3.82 bar/deg to 4.89 bar/deg, and maximum IMEP from 13.23 bar to 13.74 bar. The 99.5mm cylinder bore of Vehicle C should knock (or ring) around 5.73kHz. Nothing was found in this frequency spectrum that would indicate a knocking cylinder for either fuel tested. Vehicle C's combination of compression ratio (10.5:1), valve timing, EGR, and ignition timing proved robust to knocking on these two fuels at a barometric pressure of 101.325 kPa and 35°C intake air temperature.

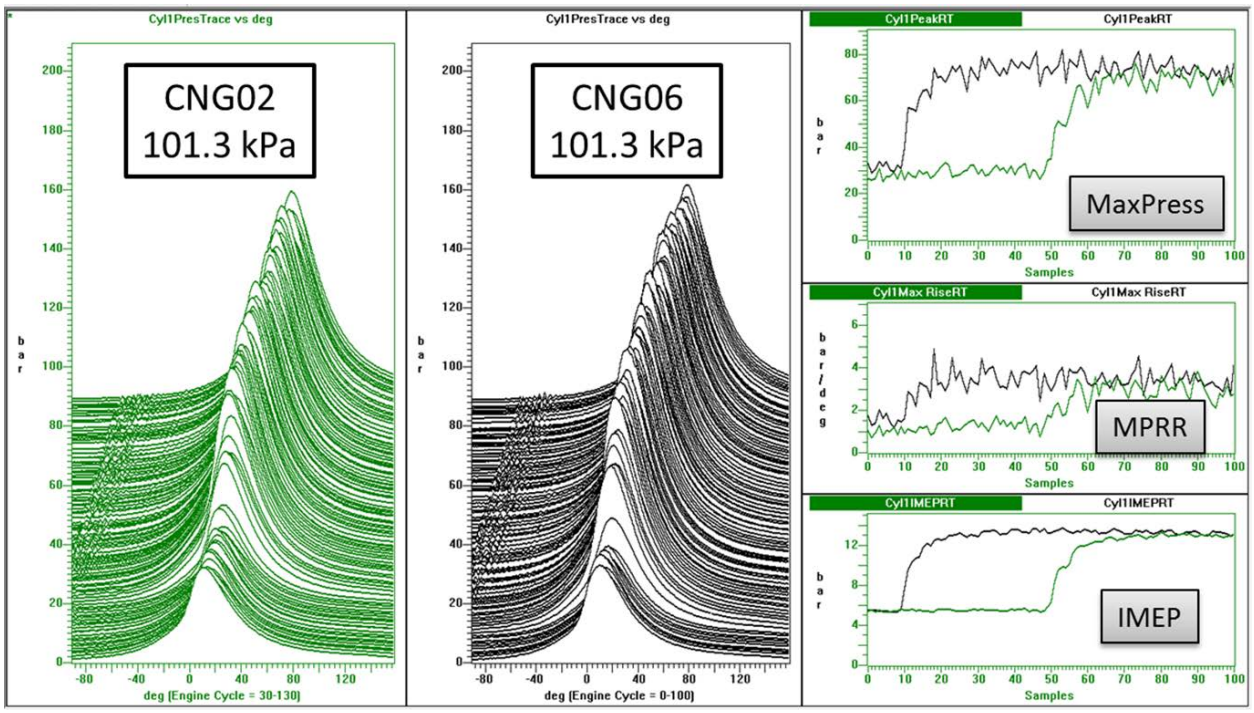


Figure 81. Vehicle C Cylinder Pressure Transient CNG02 (green) vs. CNG06 (Black) with BASE™

Comparing CAN data in Figure 82, the ignition timing step change went from 24.5°BTDC to 23.5°BTDC for both events, indicating the control system did not make any changes to spark timing between the two fuels. The higher load with BASE™ resulted in the absolute load parameter changing from approximately 38% to 91.4% for both tests. Compared to the tests at 84 kPa barometric pressure, Vehicle C commanded 0.5 degrees less spark advance at this higher WOT load.

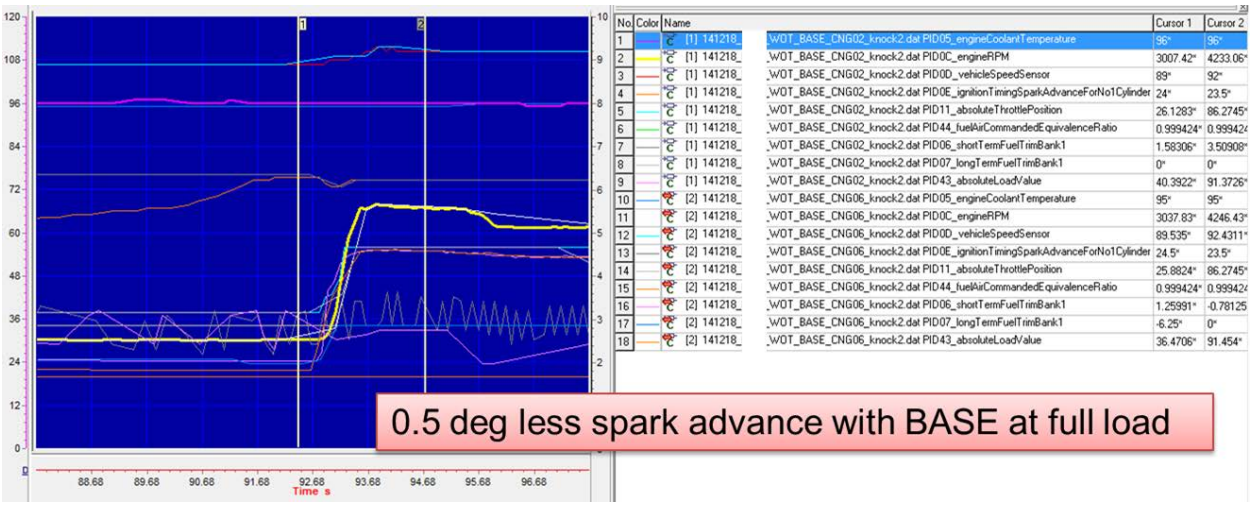


Figure 82. INCA Screenshot (Vehicle C, CNG02 vs. CNG06) with BASE

9.3.3 Vehicle C Knock Investigation #2 with BASE™, CNG06, Engine Speed Sweep

To further explore the engine operating map and resistance to knock, Vehicle C was tested on CNG06 with the transmission fixed in fourth gear and fixed engine speeds from 1900 to 2900 RPM in 200 RPM increments. The same test procedure was repeated, but BASE™ was again used to set the barometric pressure to 101.3 kPa and the intake air temperature to 35°C. Figure 83 below shows peak pressure, maximum cylinder pressure rise rate, and IMEP per cycle for the 6 data points taken during the RPM sweep. Knock was not seen during any of the test cycle, again indicating the vehicle configuration and calibration is robust to this fuel for the test conditions given.

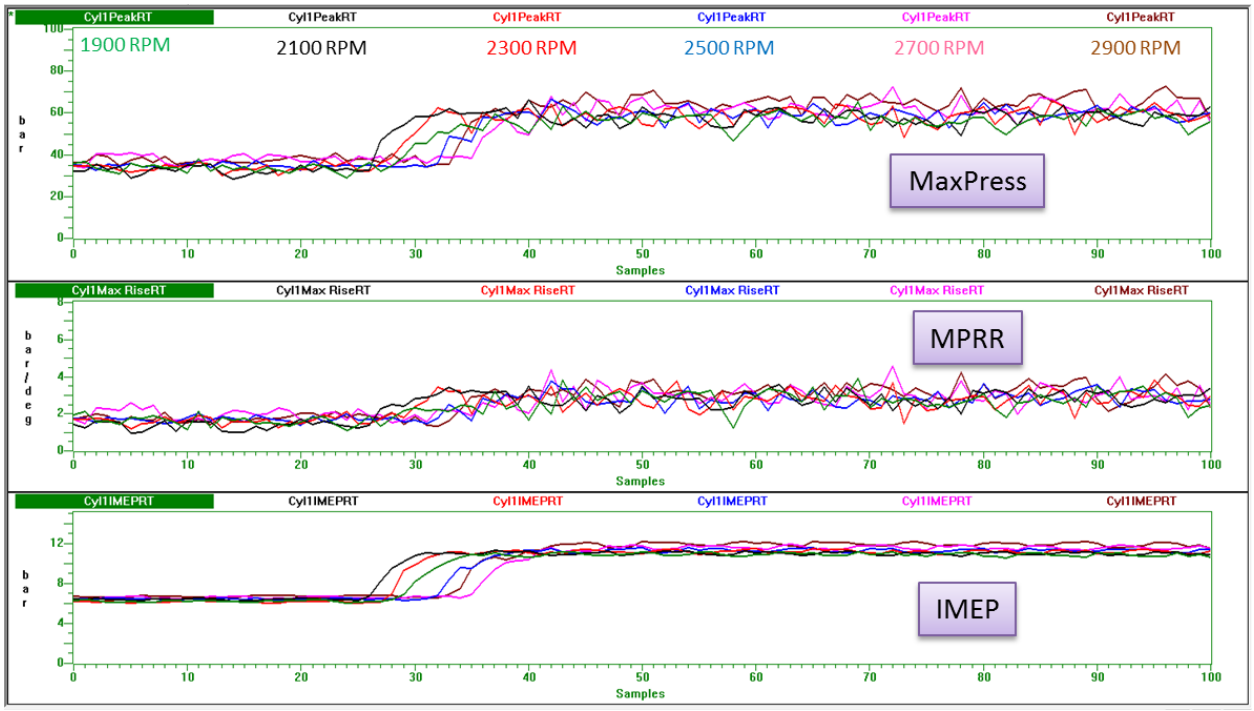


Figure 83. Vehicle C Load Transient Engine Speed Sweep with BASE™, CNG06

9.3.4 Vehicle A Knock Investigation #2, CNG06, Engine Speed Sweep

Vehicle A was further tested at various engine speeds at 84 kPa barometric pressure. With the transmission gear selector in second gear, vehicle speed was set to repeat the test at fixed engine speeds from 2040 RPM to 4300 RPM. Figure 84 below shows peak pressure, maximum cylinder pressure rise rate, and IMEP per cycle for the 8 data points taken during the RPM sweep. Knock was not seen during any of the test cycle, again indicating the vehicle configuration and calibration is robust to this fuel for the test conditions given.

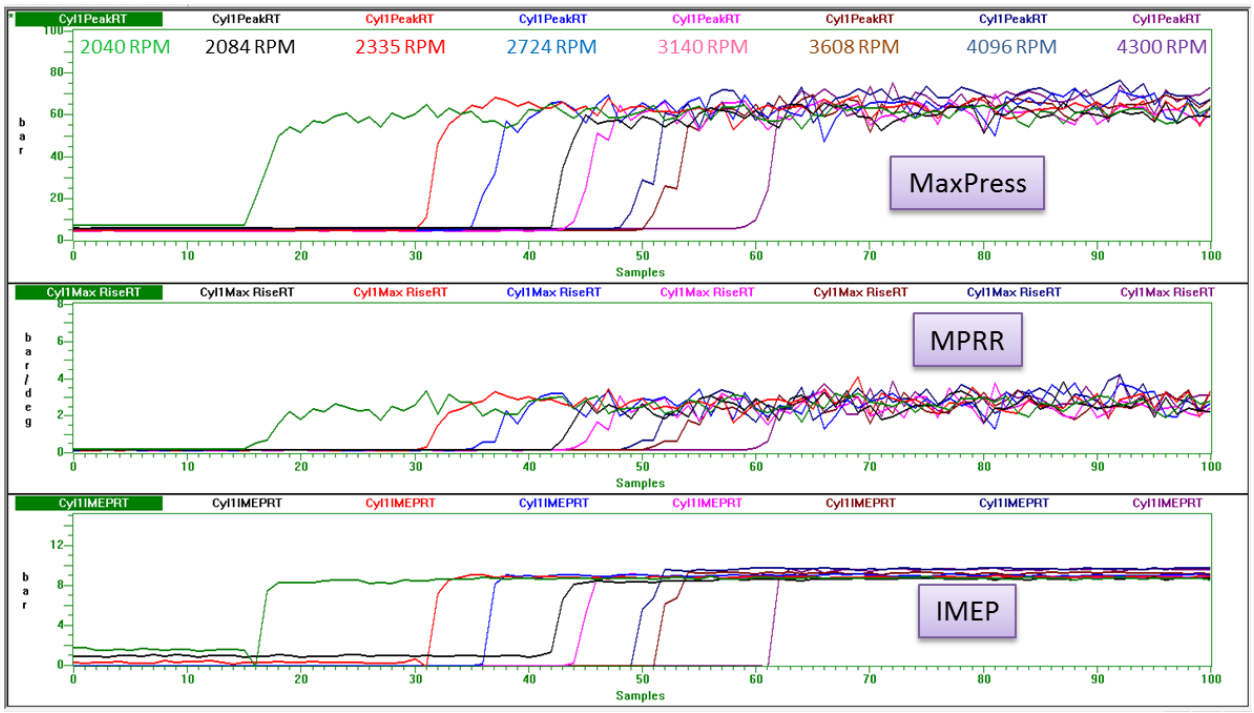


Figure 84. Vehicle A Load Transient Engine Speed Sweep, CNG06

10.0 Conclusions

Conclusions from this investigation are as follows:

1. The bag-weighted fuel economy, in miles per gasoline gallon equivalent (MPGe), varied in direct proportion to the Wobbe Index for all vehicles in the study. This effect was expected due to different energy content of the test fuels.
2. NOx and CO bag-weighted emissions from Vehicle A and Vehicle B were unaffected by the fuel type.
3. NOx engine-out-weighted emissions increased with higher Wobbe Index fuels for all three vehicles tested.
4. HC and CH_4 bag emissions increased with lower Wobbe Index fuels for all three vehicles tested.
5. Of the three vehicles in the study, Vehicle C was most affected by fuel type.
    a. When run on the fuel with lowest Wobbe Index (CNG01), bag-weighted NOx emissions increased by over 300% compared to the average CNG fuel (CNG07). For all tests the lowest Wobbe Index fuel produced highest NOx emissions during the Phase 2 stabilized portion of the LA92 cycle.
    b. CO bag-weighted emissions decreased for the lowest Wobbe Index fuel.
    c. Methane emissions increased by over 50% for the lowest Wobbe Index fuel.
    d. The effects appeared to be catalyst-conversion related as the trends were less apparent from engine-out emissions data.
6. A statistical analysis for all vehicles pooled together revealed:
    a. The effect of fuel type on mean bag-weighted fuel economy was significant with 95% confidence.
    b. The effect of fuel type on mean bag-weighted NOx and CO was not statistically significant.
    c. The effect of fuel type on mean bag-weighted CH_4 and total THC emissions was significant with 95% confidence.
7. Engine knock was not observed for either Knock Investigation #1 or #2, indicating that the combination of compression ratio, EGR, ignition timing, and valve timing employed on these vehicles can accommodate the lowest methane number fuel under the conditions tested.

11.0 References

CRC PC-2-12, *Compressed Natural Gas Vehicle Fuel Survey*, Coordinating Research Council, Alpharetta, GA, USA, www.crc.org, May 27, 2014

U.S. Code of Federal Regulations, Title 40: *Transportation*, Part 86 – *Control of Air Pollution from Mobile Sources*, Part 600 – Fuel Economy and Greenhouse Gas Exhaust Emissions of Motor Vehicles, Subpart B – Fuel Economy and Carbon-Related Exhaust Emission Test Procedures www.ecfr.gov, December 11, 2014.

ASTM Standard D1945-03(2010), *Standard Test Method for Analysis of Natural Gas by Gas Chromatography*, ASTM International, West Conshohocken, Pennsylvania, USA, www.astm.org, March 2010.

ASTM Standard D3588-98(2011), *Standard Practice for Calculating Heat Value, Compressibility Factor, and Relative Density of Gaseous Fuels*, ASTM International, West Conshohocken, Pennsylvania, USA, www.astm.org, November 2011.

Ryan, T. W., and Callahan, T. J (Southwest Research Institute), *Effects of Gas Composition on Engine Performance and Emissions*, Gas Research Institute Topical Report GRI-92/0054, published by Gas Technology Institute, Des Plaines, Illinois, USA, www.gastechnology.org, December 1991.

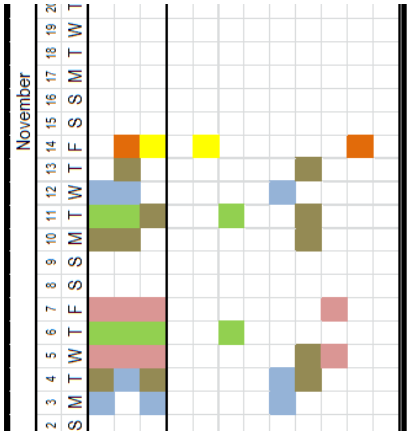
Ryan, T. W., Callahan, T. J., and King, S. R., "Engine Knock Rating of Natural Gases – Methane Number," *ASME Journal of Engineering for Gas Turbines and Power*, Volume 115, pp. 769-776, October 1993.

Davis, P., Peckham, M., "The Analysis of Gasoline Transient Emissions Behavior Using Fast Response Gas Analyzers", SAE Paper No. 2007-26-015, 2007.

Lee, Y.J., Kim, G.C., "Effect of Gas Composition on NGV Performance", Seoul 2000 FISITA World Automotive Congress, Paper F2000A174, June 12, 2000.

12.0 Appendices

12.1 Appendix 1: CRC E-109 Vehicle and Fuel Test Order, and Date of Emissions Test



12.2 Appendix 2: Properties for SGS Tank 3 T2SHED7.8 Gasoline

haltermannsolutions
fueling the world, one solution at a time

Telephone: (800) 969-2542

Product Information

FAX: (281) 457-1469

Johann Haltermann Ltd.

PRODUCT: HIGH ALTITUDE EMISSION FUEL
CFR 86. 113-04 Tier 2

PRODUCT CODE: HF0073

Batch No.: CD1421GP02
TMO NO.: 802765
Tank No.: 52
Date: 4/23/2014

TEST	METHOD	UNITS	SPECIFICATIONS			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°C	24		41	34
5%		°C				46
10%		°C	49		57	54
20%		°C				66
30%		°C				79
40%		°C				94
50%		°C	93		110	104
60%		°C				110
70%		°C				117
80%		°C				129
90%		°C	149		163	160
95%		°C				168
Distillation - EP		°C			213	185
Recovery		vol %		Report		97.0
Residue		vol %			2	1.1
Loss		vol %		Report		1.4
Gravity	ASTM D4052	°API		Report		60.0
Specific Gravity	ASTM D4052		0.734		0.744	0.739
Reid Vapor Pressure	ASTM D5191	kPa	52		55	55.9*
Sulfur	ASTM D5453	ppm wt	25		35	32
Lead	ASTM D3237	g/l			0.013	None Detected
Phosphorous	ASTM D3231	g/l			0.0013	None Detected
Composition, aromatics	ASTM D1319	vol %			35	26
Composition, olefins	ASTM D1319	vol %			10	1
Composition, saturates	ASTM D1319	vol %		Report		73
Oxidation Stability	ASTM D525	minutes	240			1000+
Copper Corrosion	ASTM D130				1B	1a
Gum content, washed	ASTM D381	mg/100mls			5	<0.5
Net Heat of Combustion	ASTM D240	btu/lb		Report		18363
Carbon	ASTM D5291	wt fraction		Report		0.8612
Research Octane Number	ASTM D2699		93			97
Motor Octane Number	ASTM D2700			Report		89
Sensitivity	D2699/2700		7.5			8.1

*Waived by Customer

APPROVED BY:

12.3 Appendix 3: Vehicle C ECU Scan Reports

Vehicle Scan Report

Year: 2014
Body: DJ
VIN: 3C6TR5J22EG100286
Odometer: 3364.6 miles

Date: Friday, September 26 2014 2:25:09 PM
CDA Version: 6.5.368
Device S/N: 12942
Device Platform: Vector

ECU Information

ECU	Can Req ID	Can Res ID	Part Number	Software Version | HEX	Hardware Version	Software PN	Variant	Version	ISO Code	VMM Version	Supplier	ENG File
ABS_PN	747	4C7	68212541AC	#0: 13.20.5	02.27.0C	#0: 68212541AC	40	06	-	1247	TRW	ABS-ABS_PN-40-4006-001
BCM_PN	620	504	68236153AB	#0: 13.35.49	10.20.0	#0: 68236152AB	40	11	-	1247	Continental	BCM-BCM_PN-40-4011-014
CMCM_PN	7BF	53F	68224531AB	#0: 2013.21.04	2012.45.01	#0: 13210484AA	80	16	-	-	Harman / Becker	RADIO-CMCM_PN-80-8003-000
DDM_PN	784	504	68155771AD	#0: 12.48.01	11.30.00	#0: 68155771AD	41	00	-	1210	Continental	DDM-DDM_PN-41-4100-008
DTCM_PN	74B	4CB	56029590AE	#0: 030108	1011	56029590AE	40	02	-	1131	Huntsville	DTCM-DTCM_PN-40-4002-004
HVAC_PN	783	503	68186216AB	#0: 2013.17.5	2013.18.04	#0: 68186216AB	42	01	-	1232	KDAC	HVAC-HVAC_PN-42-4201-003
ICS_PN	7BC	53C	1UJ96DX9AE	#0: 12.44.30	0C.26.42	#0: 14179681__	41	00	-	1223	TRW	ICS-ICS_PN-41-4100-007
IPC_PN	742	4C2	56054954AF	#0: 13.37.0	05.6.00	#0: 56054952AF	42	01	-	1247	00C6	IPC-IPC_PN-42-4201-003
ITBM_PN	754	4D4	68092732AE	#0: 13.11.31	0D.5.00	#0: 68092740AE	40	00	-	1223	Conti Temic	ITBM-ITBM_PN-40-4000-008
ORC_PN	744	4C4	68085883AF	#0: 13.12.0, #1: 13.19.0	12.37.2	#0: 10DT00D11, #1: DT00D11 21	42	01	-	1149	Bosch	ORC-ORC_PN-42-4201-008
PCM	7E0	7E8	68153863AF	#0: 090404	1A2F	68153863AF	42	C6	-	4712	Motorola	PCM-PCM-42-42C6-006
PDM_PN	785	505	68155770AD	#0: 12.48.01	11.30.00	#0: 68155770AD	41	00	-	1210	Continental	PDM-PDM_PN-41-4100-008
RFH_PN	740	4C0	68207773AD	#0: 13.31.1, #1: 13.31.1	0C.1A.01	#0: 14D50731AA, #1: 14D50731CA, #2: 5576AB445566778899AA	41	02	-	1247	TRW	RFH-RFH_PN-41-4102-002
SCCM_PN	763	4E3	68110739AC	#0: 11.38.0, #1: 11.38.0, #2: 11.38.1, #3: 11.2.1, #4: 11.2.1, #5: 11.2.1	2010.46.04	?	41	01	-	1117	Delphi	SCCM-SCCM_PN-41-4101-008

ENG files shown above in red indicate a Diagnostic Variant or ISO Code mismatch.

ENG files shown above in yellow indicate a Diagnostic Version mismatch.

Figure 85. Vehicle C OEM Calibration ECU Scan Report (Software PN: 68153863AF)

Vehicle Scan Report

Year: 2014
Body: DJ
VIN: 3C6TR5J22EG100286
Odometer: 3544.8 miles

Date: Friday, October 17 2014 12:08:45 PM
CDA Version: 6.5.368
Device S/N: 12942
Device Platform: Vector

ECU Information

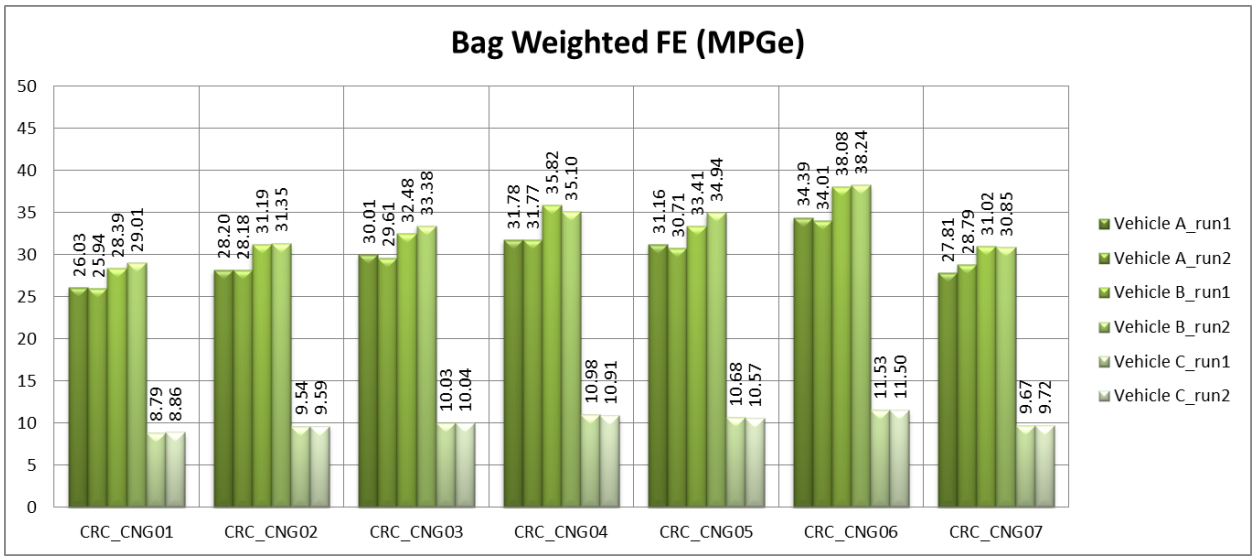
ECU	Can Req ID	Can Res ID	Part Number	Software Version | HEX	Hardware Version	Software PN	Variant	Version	ISO Code	VMM Version	Supplier	ENG File
ABS_PN	747	4C7	68212541AC	#0: 13.20.5	02.27.0C	#0: 68212541AC	40	06	-	1247	TRW	ABS-ABS_PN-40-4006-001
BCM_PN	620	504	68236153AB	#0: 13.35.49	10.20.0	#0: 68236152AB	40	11	-	1247	Continental	BCM-BCM_PN-40-4011-014
CMCM_PN	7BF	53F	68224531AB	#0: 2013.21.04	2012.45.01	#0: 13210484AA	80	16	-	-	Harman / Becker	RADIO-CMCM_PN-80-8003-000
DDM_PN	784	504	68155771AD	#0: 12.48.01	11.30.00	#0: 68155771AD	41	00	-	1210	Continental	DDM-DDM_PN-41-4100-008
DTCM_PN	74B	4CB	56029590AE	#0: 030108	1011	56029590AE	40	02	-	1131	Huntsville	DTCM-DTCM_PN-40-4002-004
HVAC_PN	783	503	68186216AB	#0: 2013.17.5	2013.18.04	#0: 68186216AB	42	01	-	1232	KDAC	HVAC-HVAC_PN-42-4201-003
ICS_PN	7BC	53C	1UJ96DX9AE	#0: 12.44.30	0C.26.42	#0: 14179681__	41	00	-	1223	TRW	ICS-ICS_PN-41-4100-007
IPC_PN	742	4C2	56054954AF	#0: 13.37.0	05.6.00	#0: 56054952AF	42	01	-	1247	00C6	IPC-IPC_PN-42-4201-003
ITBM_PN	754	4D4	68092732AE	#0: 13.11.31	0D.5.00	#0: 68092740AE	40	00	-	1223	Conti Temic	ITBM-ITBM_PN-40-4000-008
ORC_PN	744	4C4	68085883AF	#0: 13.12.0, #1: 13.19.0	12.37.2	#0: 10DT00D11, #1: DT00D11 21	42	01	-	1149	Bosch	ORC-ORC_PN-42-4201-008
PCM	7E0	7E8	68153863CN	#0: 090404	1A2F	68153863CN	42	C6	-	4712	Motorola	PCM-PCM-42-42C6-006
PDM_PN	785	505	68155770AD	#0: 12.48.01	11.30.00	#0: 68155770AD	41	00	-	1210	Continental	PDM-PDM_PN-41-4100-008
RFH_PN	740	4C0	68207773AD	#0: 13.31.1, #1: 13.31.1	0C.1A.01	#0: 14D50731AA, #1: 14D50731CA, #2: 5576AB445566778899AA	41	02	-	1247	TRW	RFH-RFH_PN-41-4102-002
SCCM_PN	763	4E3	68110739AC	#0: 11.38.0, #1: 11.38.0, #2: 11.38.1, #3: 11.2.1, #4: 11.2.1, #5: 11.2.1	2010.46.04	?	41	01	-	1117	Delphi	SCCM-SCCM_PN-41-4101-008

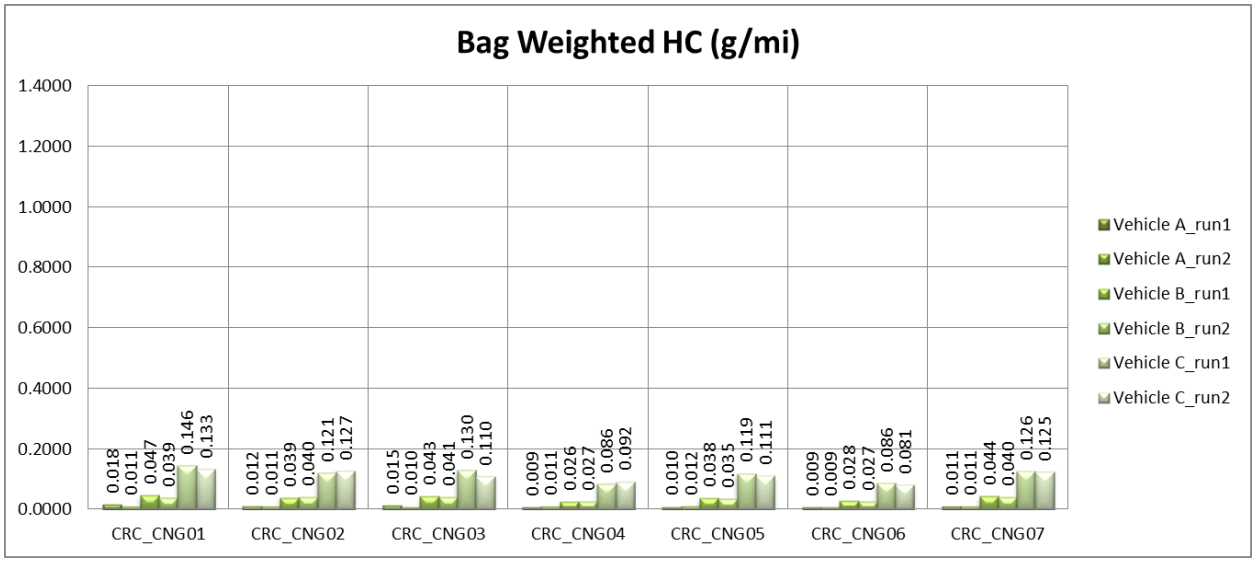
ENG files shown above in red indicate a Diagnostic Variant or ISO Code mismatch.

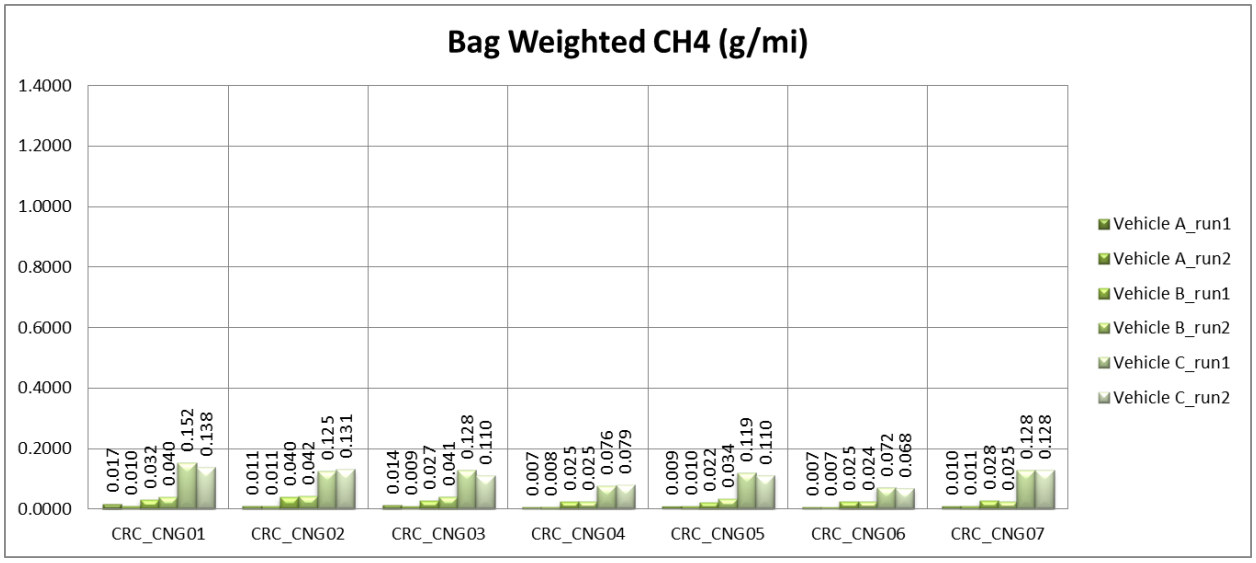
ENG files shown above in yellow indicate a Diagnostic Version mismatch.

Figure 86. Vehicle C Modified Calibration ECU Scan Report (Software PN: 68153863CN)

12.4 Appendix 4: Bag-Weighted Dataset Charts



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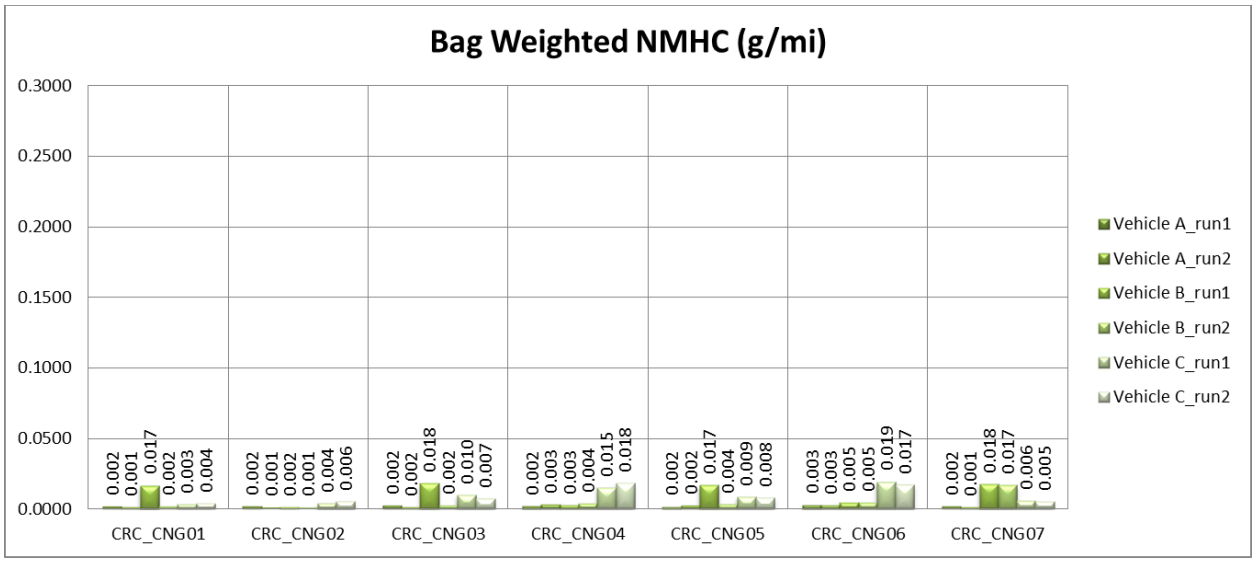
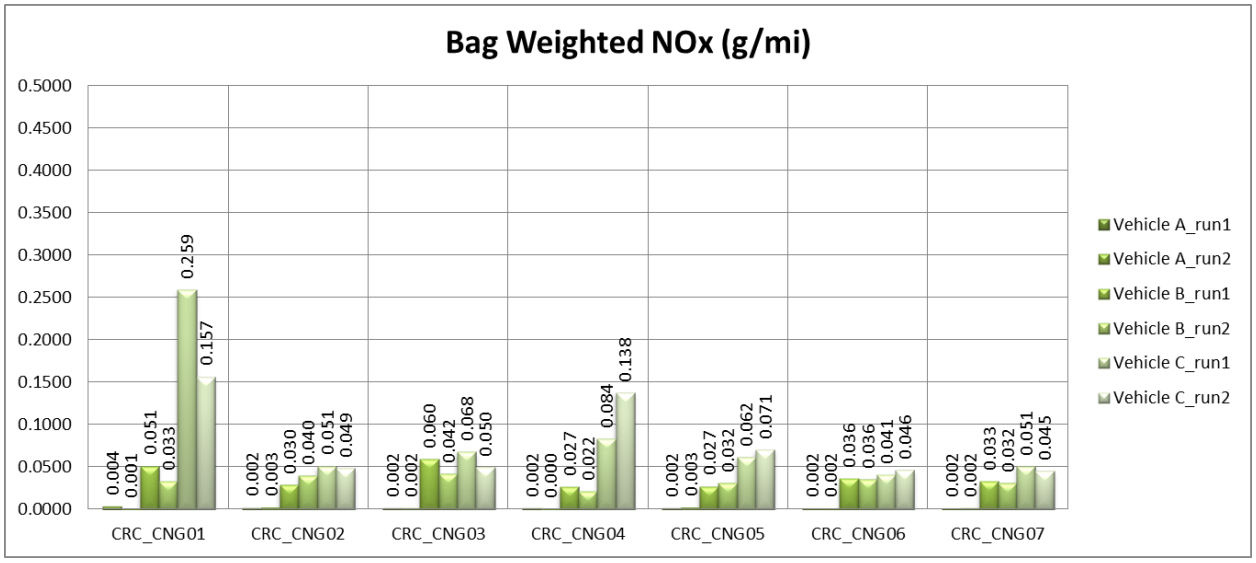
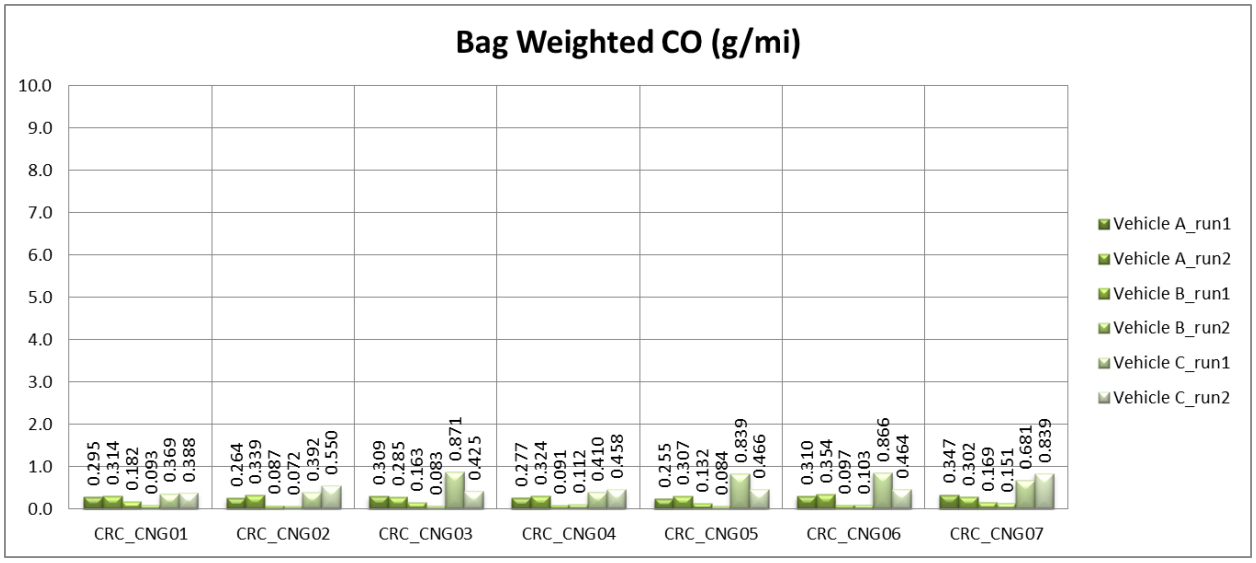
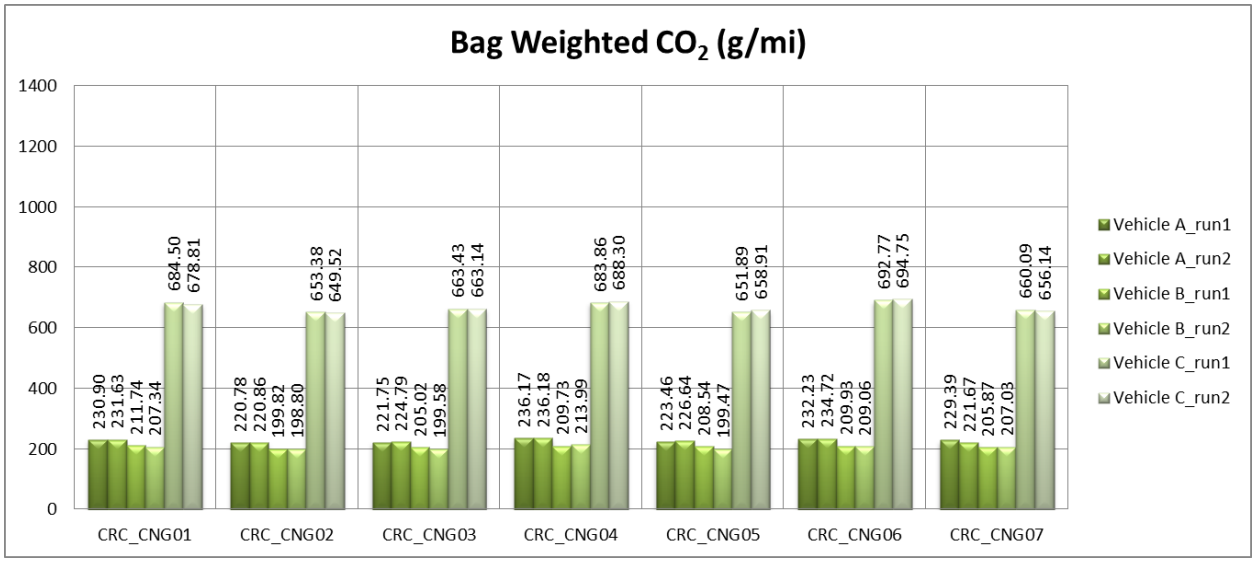
1.4000
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
0.017 0.010 0.032 0.040 0.152 0.138
0.011 0.011 0.040 0.042 0.125 0.131
0.014 0.009 0.027 0.041 0.128 0.110
0.007 0.008 0.025 0.025 0.076 0.079
0.009 0.010 0.022 0.034 0.119 0.110
0.007 0.007 0.025 0.024 0.072 0.068
0.010 0.011 0.028 0.025 0.128 0.128
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

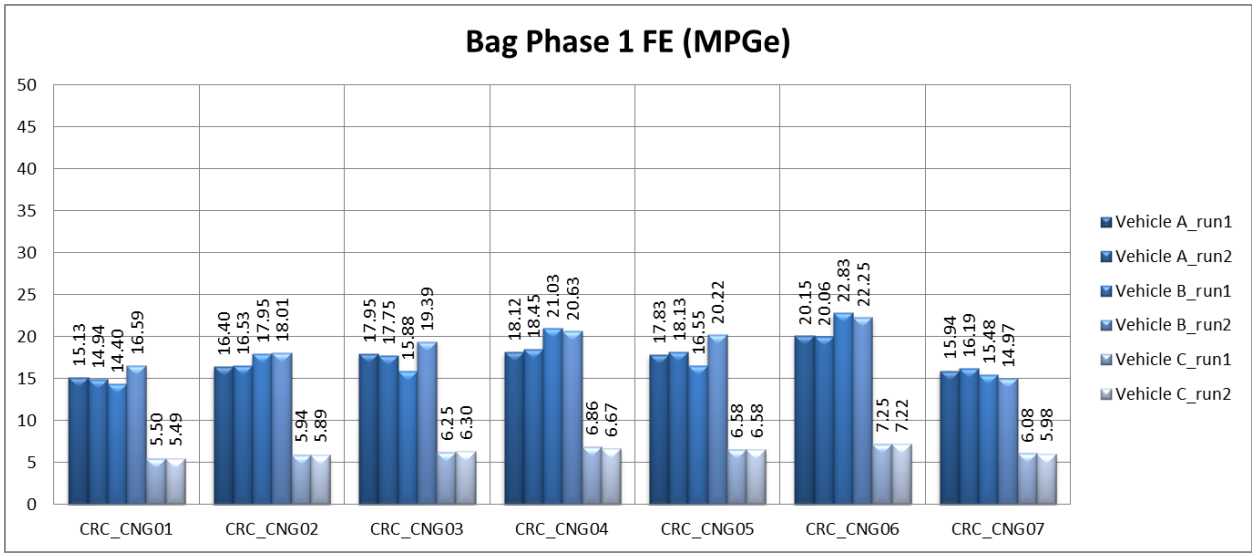

Bag Weighted NMHC (g/mi)
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0.002 0.001 0.017 0.002 0.003 0.004
0.002 0.001 0.002 0.001 0.004 0.006
0.002 0.002 0.018 0.002 0.010 0.007
0.002 0.003 0.003 0.004 0.015 0.018
0.002 0.002 0.017 0.004 0.009 0.008
0.003 0.003 0.005 0.005 0.019 0.017
0.002 0.001 0.018 0.017 0.006 0.005
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

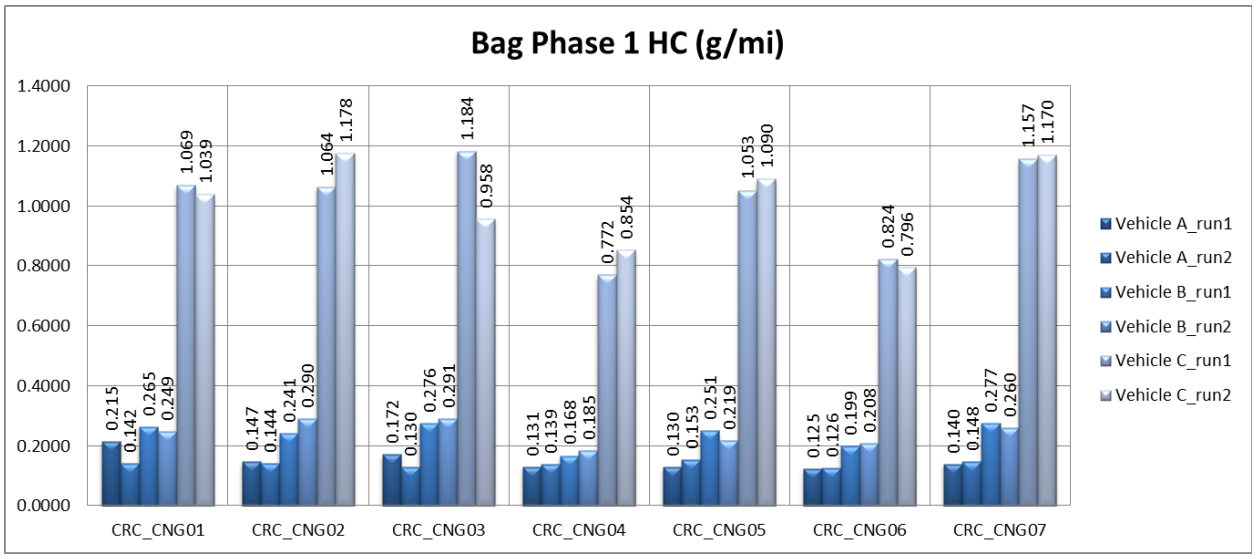

Bag Weighted NOx (g/mi)
0.5000
0.4500
0.4000
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0.004 0.001 0.051 0.033 0.259 0.157
0.002 0.003 0.030 0.040 0.051 0.049
0.002 0.002 0.060 0.042 0.068 0.050
0.002 0.000 0.027 0.022 0.084 0.138
0.002 0.003 0.027 0.032 0.062 0.071
0.002 0.002 0.036 0.036 0.041 0.046
0.002 0.002 0.033 0.032 0.051 0.045
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

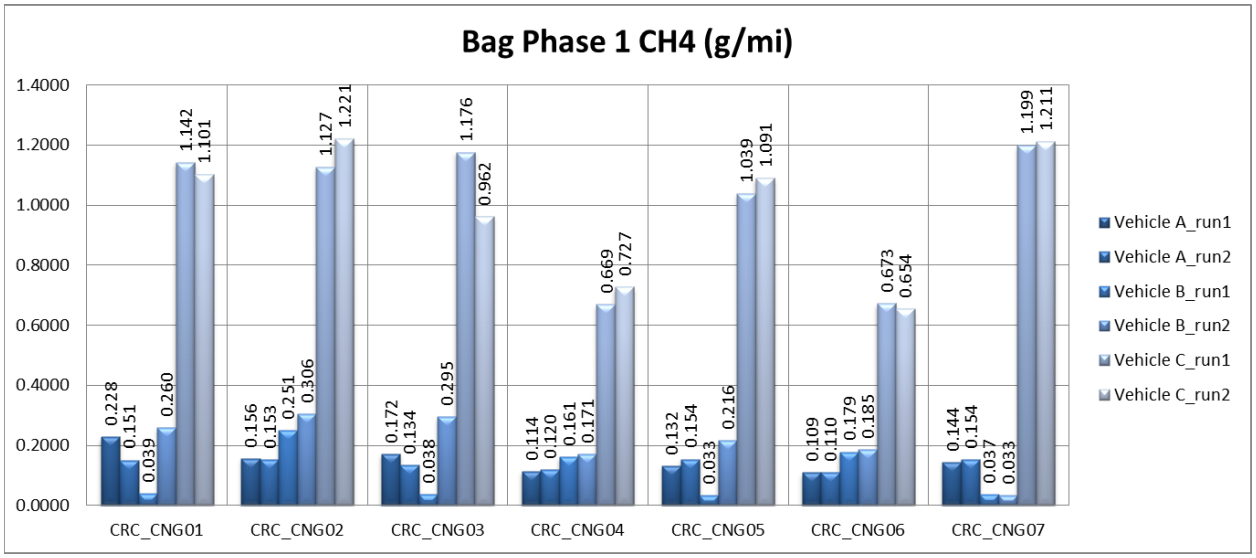

Bag Weighted CO (g/mi)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.295 0.314 0.182 0.093 0.369 0.388
0.264 0.339 0.087 0.072 0.392 0.550
0.309 0.285 0.163 0.083 0.871 0.425
0.277 0.324 0.091 0.112 0.410 0.458
0.255 0.307 0.132 0.084 0.839 0.466
0.310 0.354 0.097 0.103 0.866 0.464
0.347 0.302 0.169 0.151 0.681 0.839
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

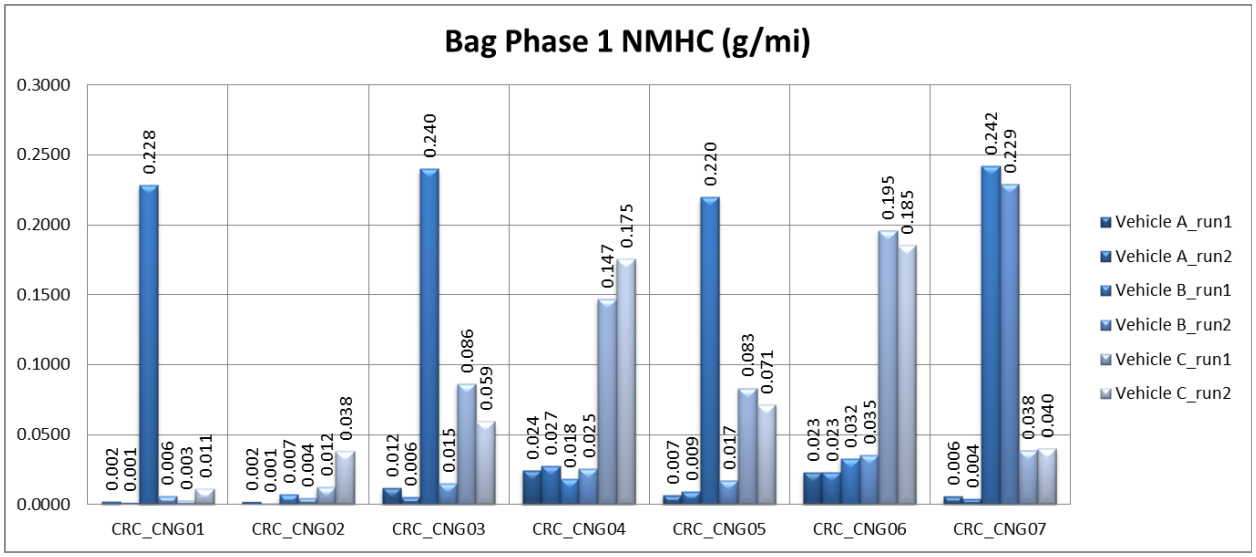

Bag Weighted CO_2 (g/mi)
1400
1200
1000
800
600
400
200
0
230.90
231.63
211.74
207.34
684.50
678.81
220.78
220.86
199.82
198.80
653.38
649.52
221.75
224.79
205.02
199.58
663.43
663.14
236.17
236.18
209.73
213.99
683.86
688.30
223.46
226.64
208.54
199.47
651.89
658.91
232.23
234.72
209.93
209.06
692.77
694.75
229.39
221.67
205.87
207.03
660.09
656.14
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

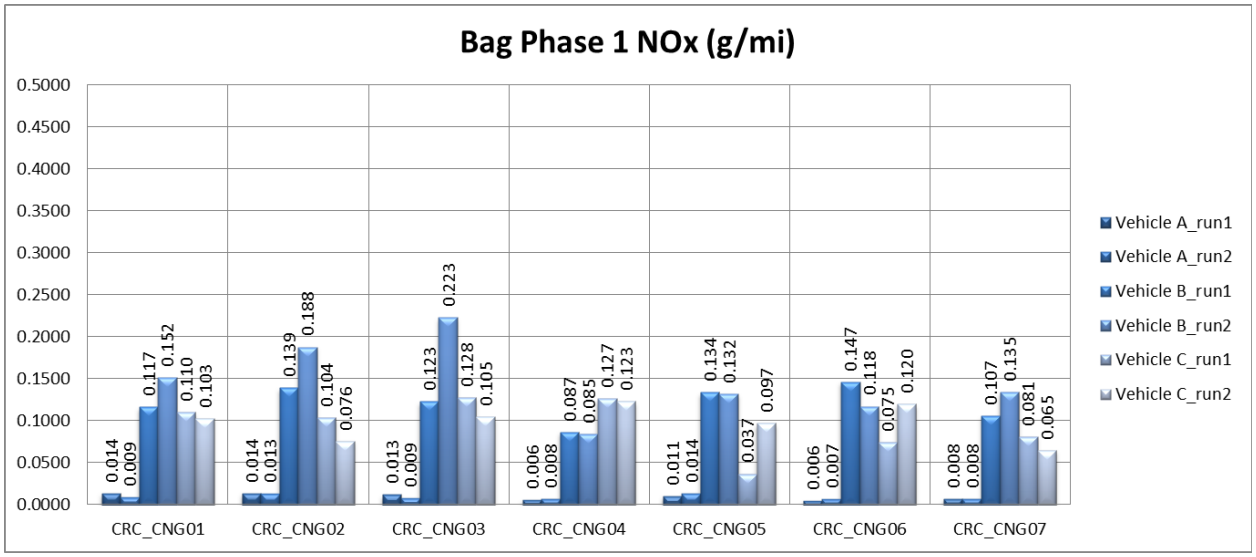
12.5 Appendix 5: Bag Phase 1 Dataset Charts

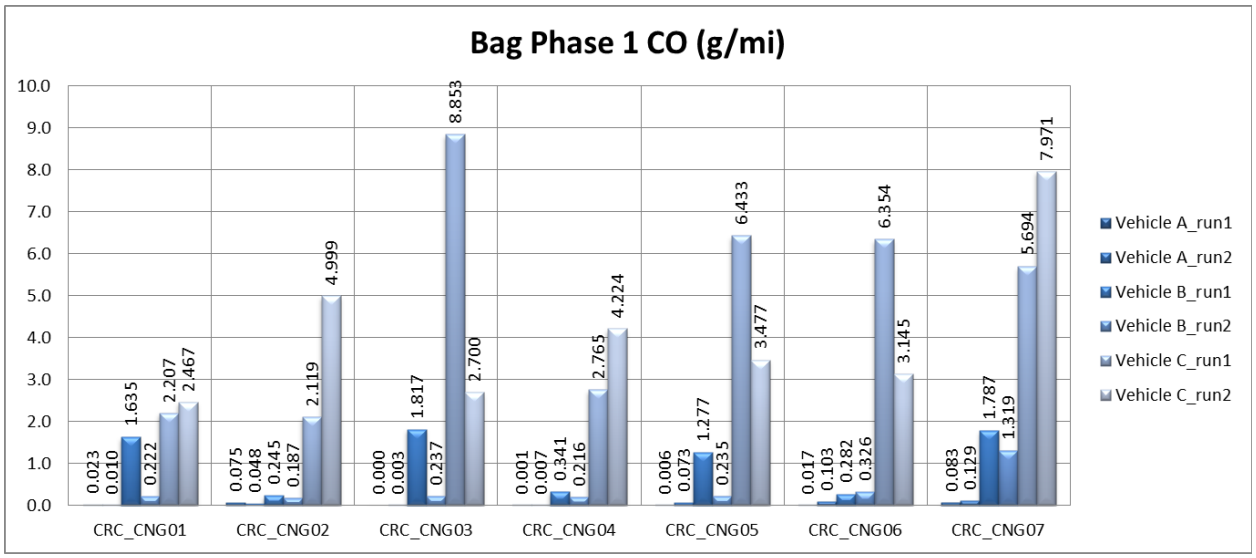


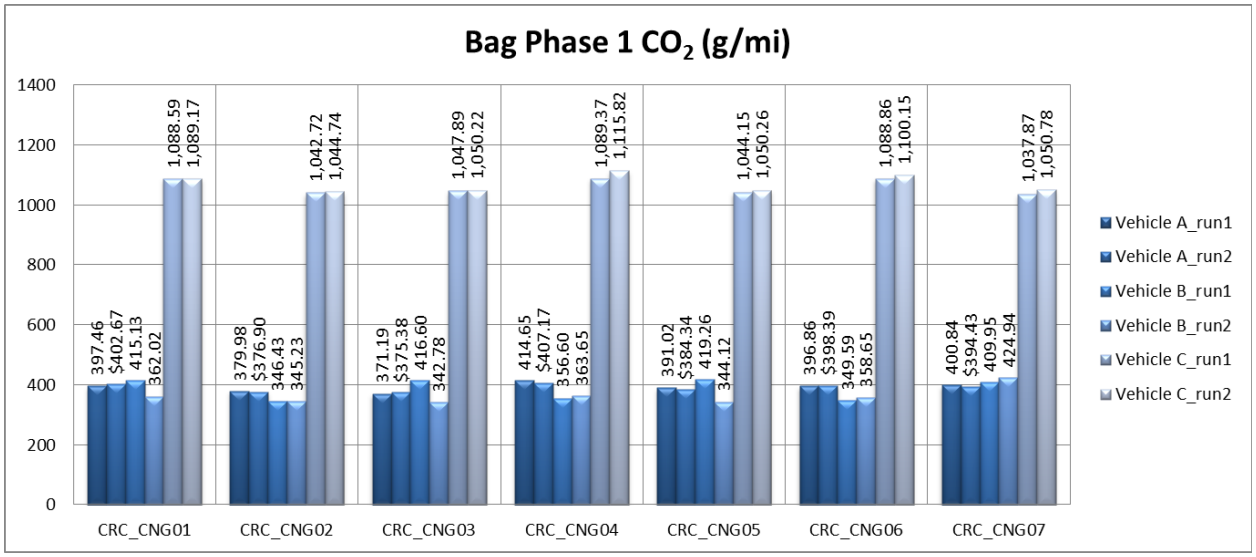



Bag Phase 1 CH4 (g/mi)
1.4000
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
0.228 0.151 0.039 0.260 1.142 1.101
0.156 0.153 0.251 0.306 1.127 1.221
0.172 0.134 0.038 0.295 1.176 0.962
0.114 0.120 0.161 0.171 0.669 0.727
0.132 0.154 0.033 0.216 1.039 1.091
0.109 0.110 0.179 0.185 0.673 0.654
0.144 0.154 0.037 0.033 1.199 1.211
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

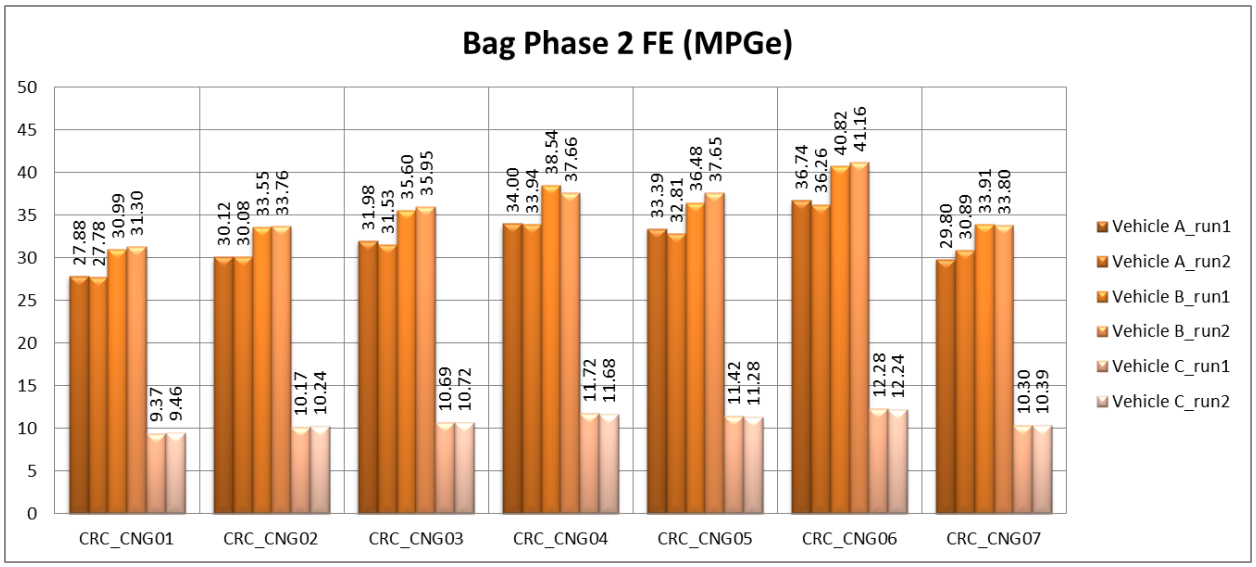

Bag Phase 1 NMHC (g/mi)
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0.002 0.001 0.228 0.006 0.003 0.011
0.002 0.001 0.007 0.004 0.012 0.038
0.012 0.006 0.240 0.015 0.086 0.059
0.024 0.027 0.018 0.025 0.147 0.175
0.007 0.009 0.220 0.017 0.083 0.071
0.023 0.023 0.032 0.035 0.195 0.185
0.006 0.004 0.242 0.229 0.038 0.040
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

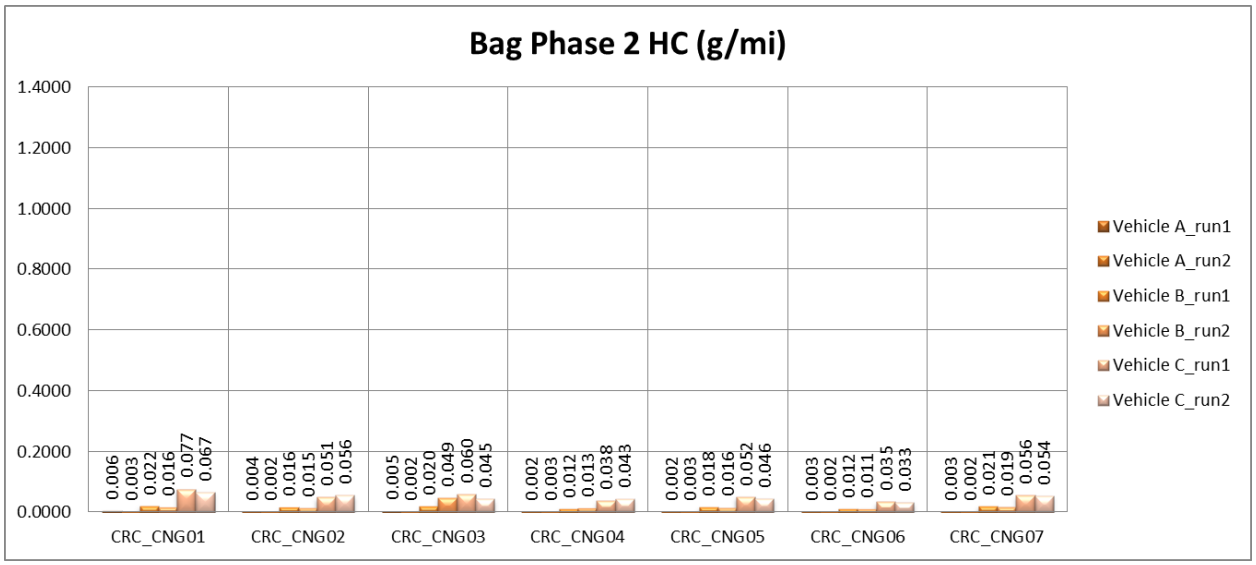

Bag Phase 1 NOx (g/mi)
0.5000
0.4500
0.4000
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0.014 0.009 0.117 0.152 0.110 0.103
0.014 0.013 0.139 0.188 0.104 0.076
0.013 0.009 0.123 0.223 0.128 0.105
0.006 0.008 0.087 0.085 0.127 0.123
0.011 0.014 0.134 0.132 0.037 0.097
0.006 0.007 0.147 0.118 0.075 0.120
0.008 0.008 0.107 0.135 0.081 0.065
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

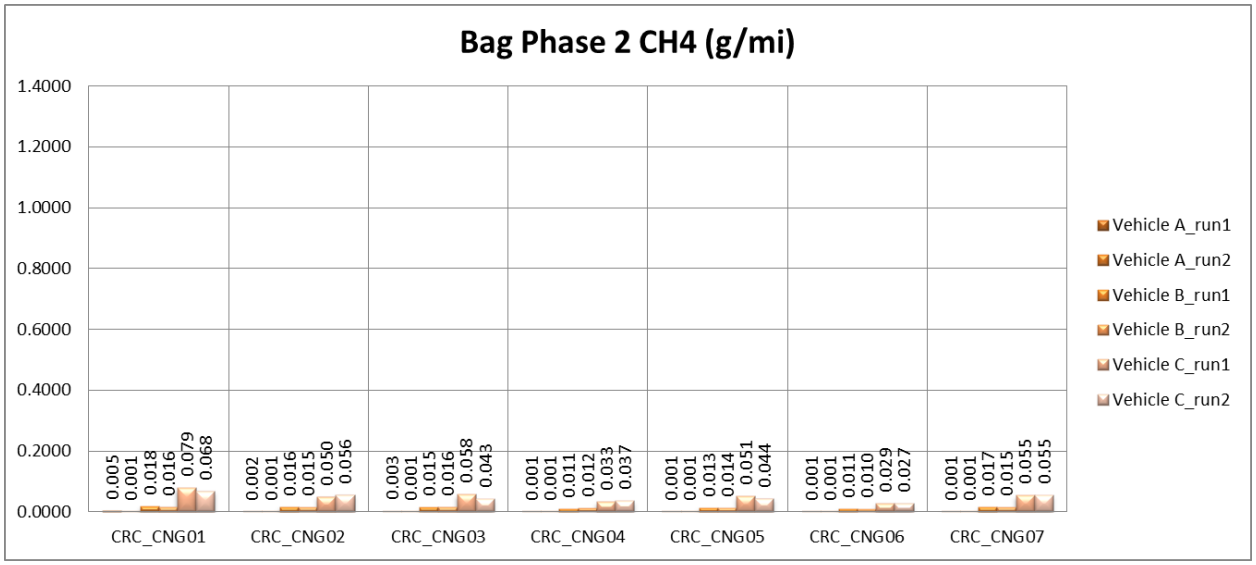

Bag Phase 1 CO (g/mi)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.023 0.010 1.635 0.222 2.207 2.467
0.075 0.048 0.245 0.187 2.119 4.999
0.000 0.003 1.817 0.237 8.853 2.700
0.001 0.007 0.341 0.216 2.765 4.224
0.006 0.073 1.277 0.235 6.433 3.477
0.017 0.103 0.282 0.326 6.354 3.145
0.083 0.129 1.787 1.319 5.694 7.971
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

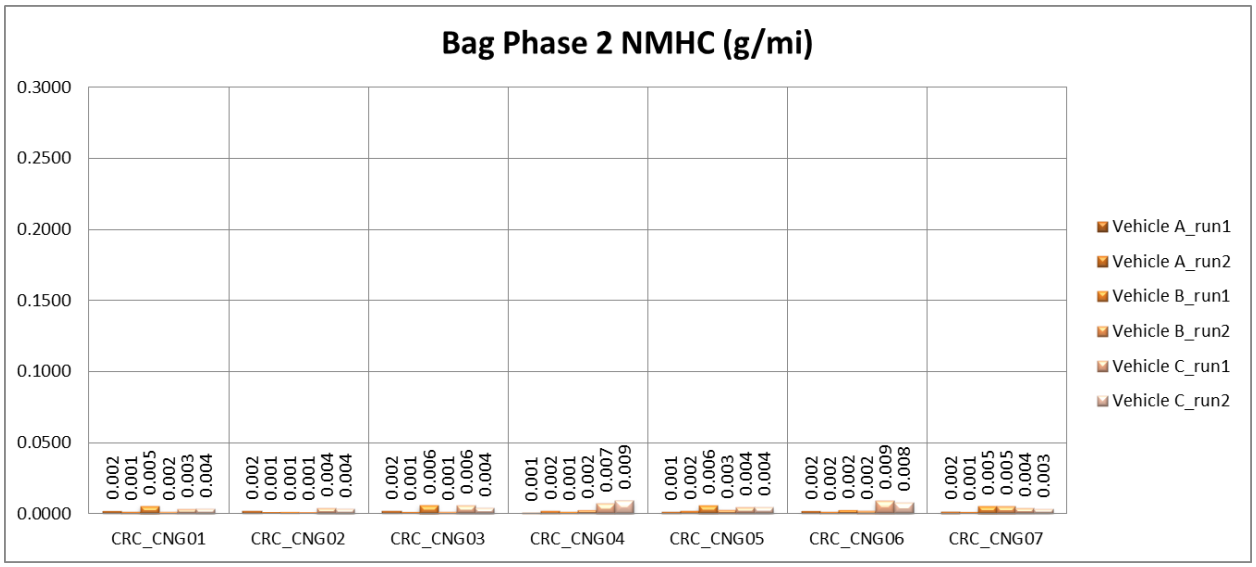

Bag Phase 1 CO_2 (g/mi)
1400
1200
1000
800
600
400
200
0
397.46
$402.67
415.13
362.02
1,088.59
1,089.17
379.98
$376.90
346.43
345.23
1,042.72
1,044.74
371.19
$375.38
416.60
342.78
1,047.89
1,050.22
414.65
$407.17
356.60
363.65
1,089.37
1,115.82
391.02
$384.34
419.26
344.12
1,044.15
1,050.26
396.86
$398.39
349.59
358.65
1,088.86
1,100.15
400.84
$394.43
409.95
424.94
1,037.87
1,050.78
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

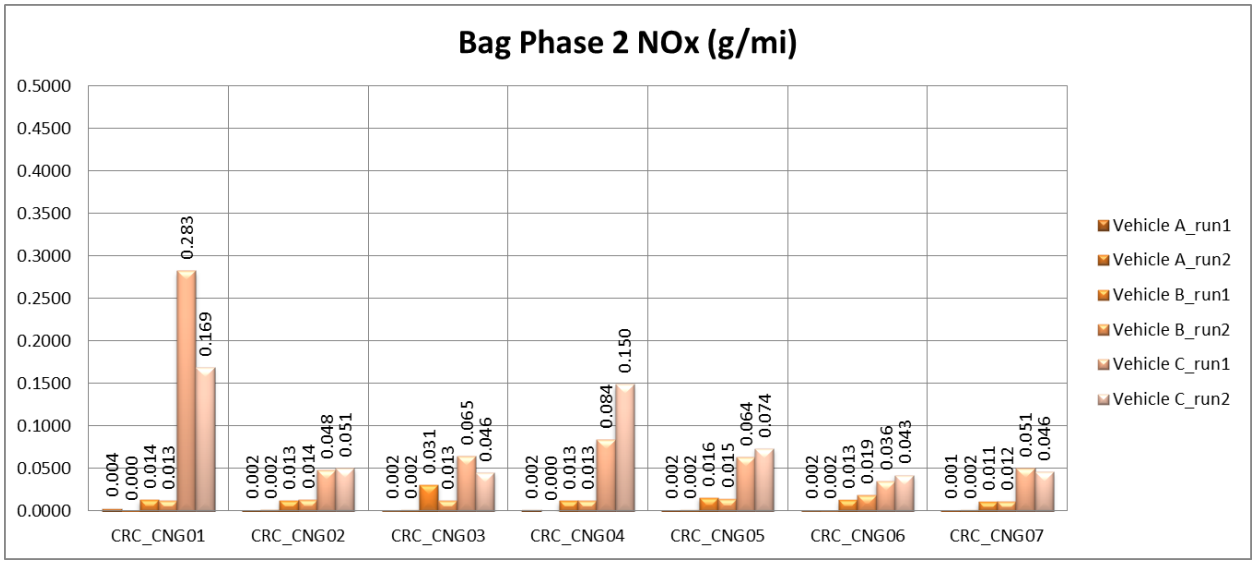
12.6 Appendix 6: Bag Phase 2 Dataset Charts

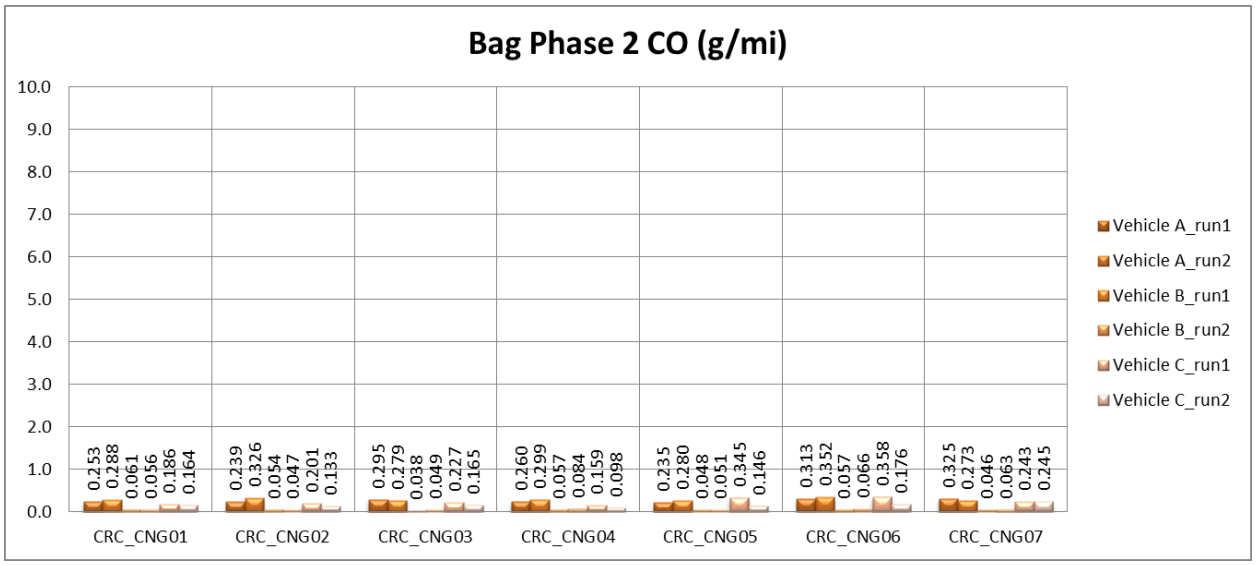


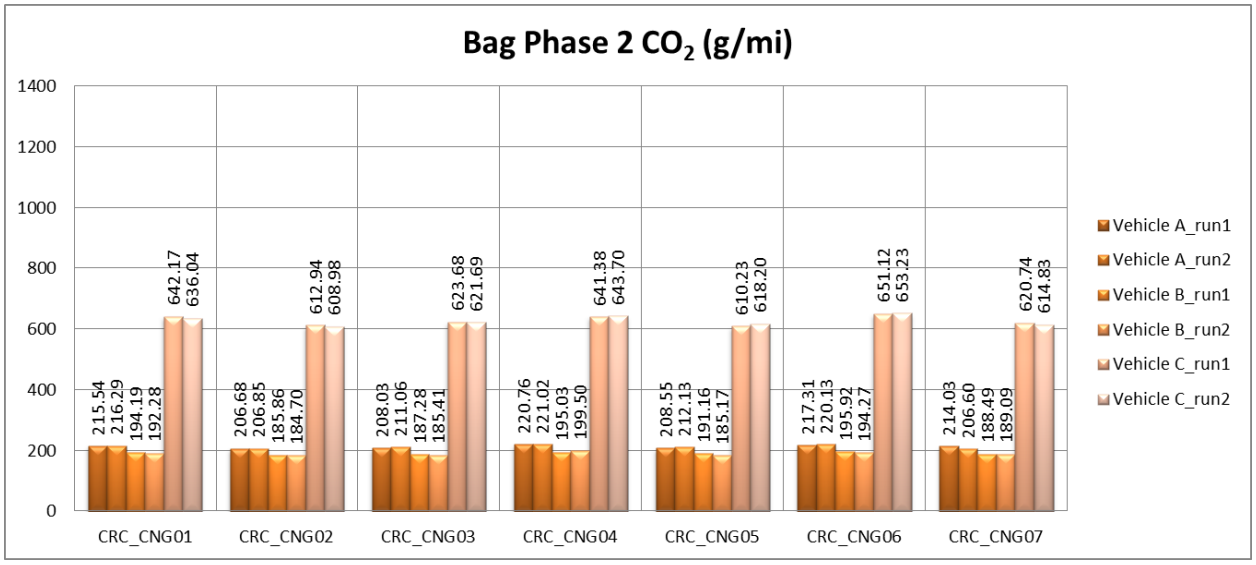



Bag Phase 2 CH4 (g/mi)
1.4000
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
0.005 0.001 0.018 0.016 0.079 0.068
0.002 0.001 0.016 0.015 0.050 0.056
0.003 0.001 0.015 0.016 0.058 0.043
0.001 0.001 0.011 0.012 0.033 0.037
0.001 0.001 0.013 0.014 0.051 0.044
0.001 0.001 0.011 0.010 0.029 0.027
0.001 0.001 0.017 0.015 0.055 0.055
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

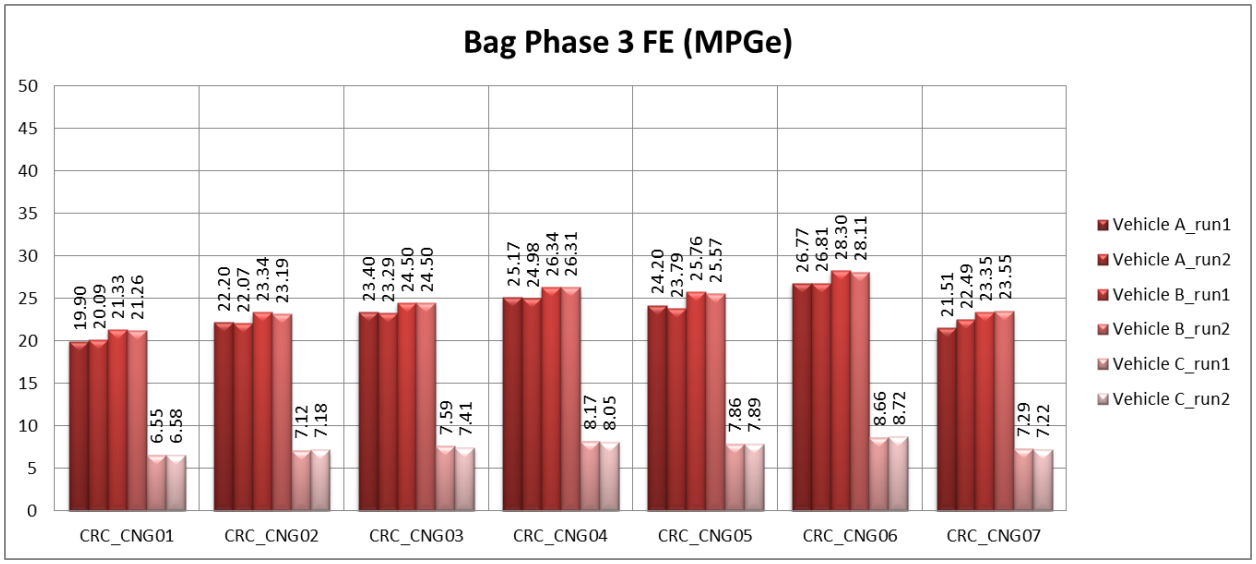

Bag Phase 2 NMHC (g/mi)
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0.002 0.001 0.005 0.002 0.003 0.004
0.002 0.001 0.001 0.001 0.004 0.004
0.002 0.001 0.006 0.001 0.006 0.004
0.001 0.002 0.001 0.002 0.007 0.009
0.001 0.002 0.006 0.003 0.004 0.004
0.002 0.002 0.002 0.002 0.009 0.008
0.002 0.001 0.005 0.005 0.004 0.003
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

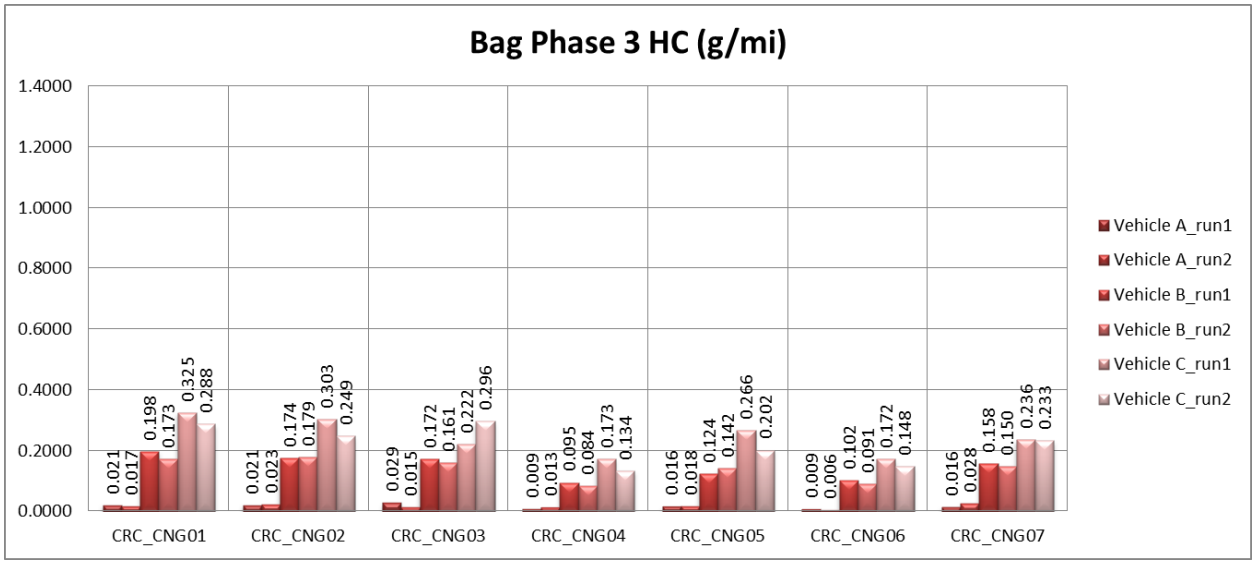

Bag Phase 2 NOx (g/mi)
0.5000
0.4500
0.4000
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0.004 0.000 0.014 0.013 0.283 0.169
0.002 0.002 0.013 0.014 0.048 0.051
0.002 0.002 0.031 0.013 0.065 0.046
0.002 0.000 0.013 0.013 0.084 0.150
0.002 0.002 0.016 0.015 0.064 0.074
0.002 0.002 0.013 0.019 0.036 0.043
0.001 0.002 0.011 0.012 0.051 0.046
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

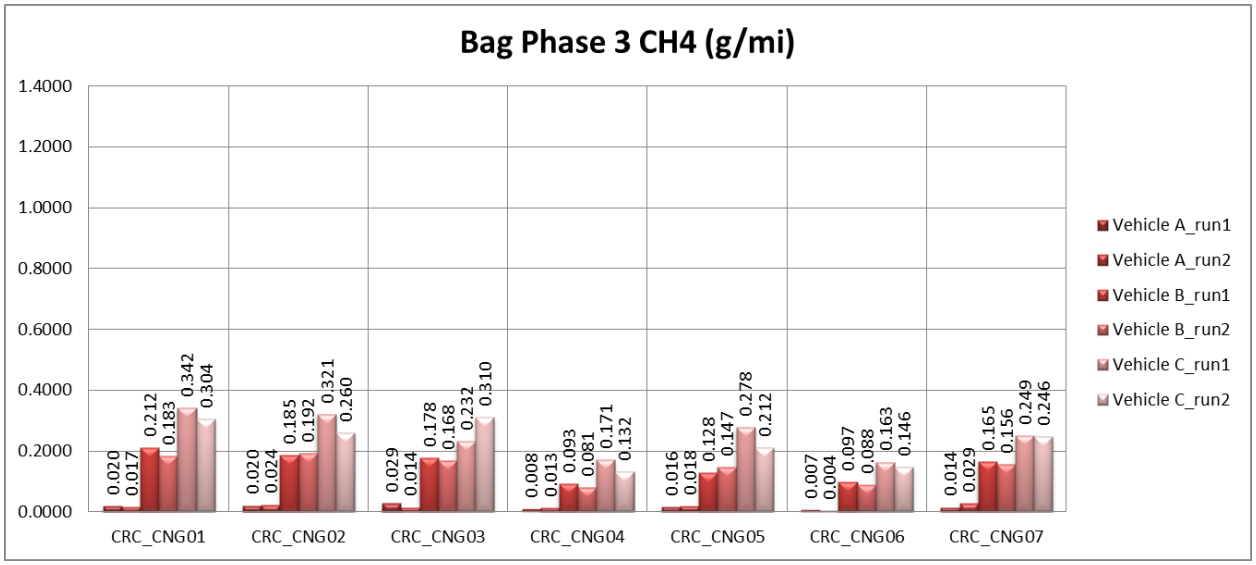

Bag Phase 2 CO (g/mi)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.253 0.288 0.061 0.056 0.186 0.164
0.239 0.326 0.054 0.047 0.201 0.133
0.295 0.279 0.038 0.049 0.227 0.165
0.260 0.299 0.057 0.084 0.159 0.098
0.235 0.280 0.048 0.051 0.345 0.146
0.313 0.352 0.057 0.066 0.358 0.176
0.325 0.273 0.046 0.063 0.243 0.245
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

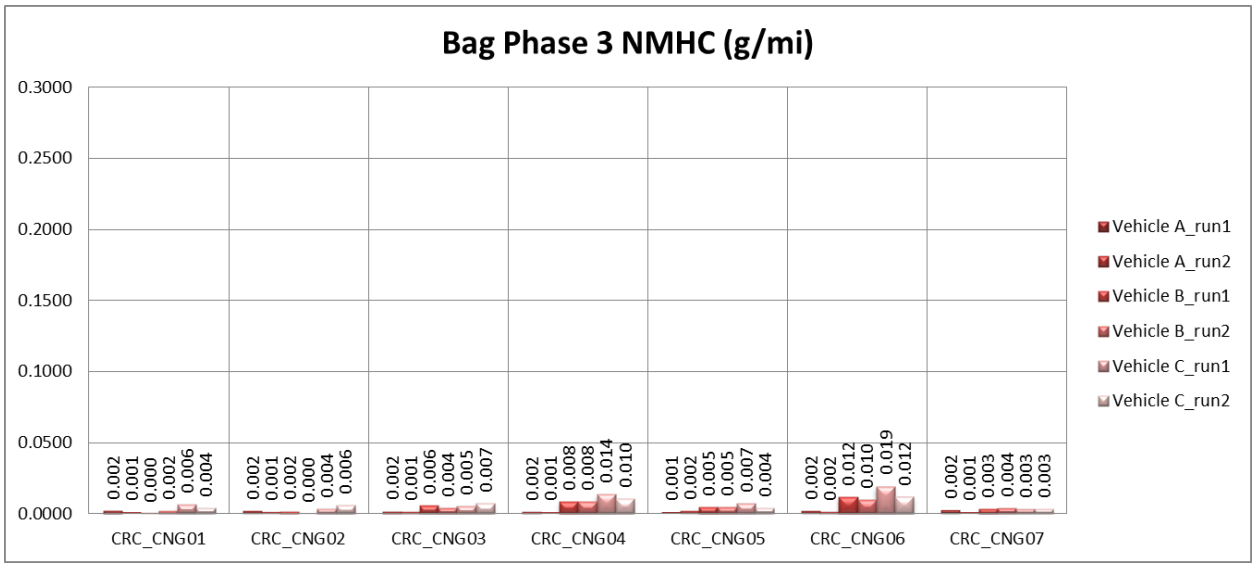

Bag Phase 2 CO_2 (g/mi)
1400
1200
1000
800
600
400
200
0
215.54
216.29
194.19
192.28
642.17
636.04
206.68
206.85
185.86
184.70
612.94
608.98
208.03
211.06
187.28
185.41
623.68
621.69
220.76
221.02
195.03
199.50
641.38
643.70
208.55
212.13
191.16
185.17
610.23
618.20
217.31
220.13
195.92
194.27
651.12
653.23
214.03
206.60
188.49
189.09
620.74
614.83
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

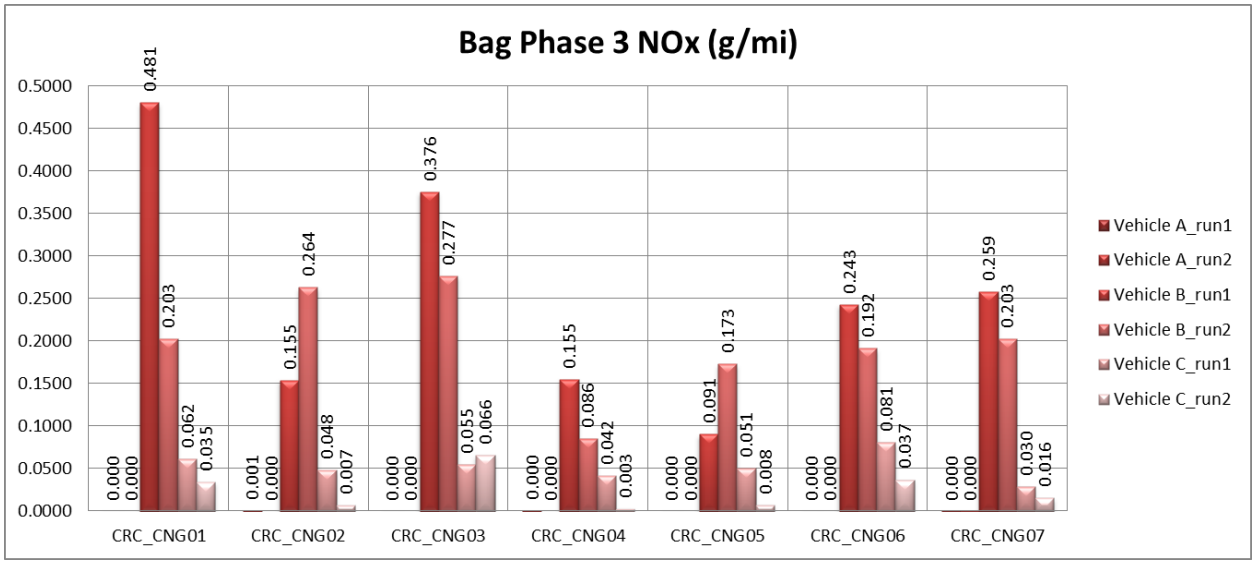
12.7 Appendix 7: Bag Phase 3 Dataset Charts

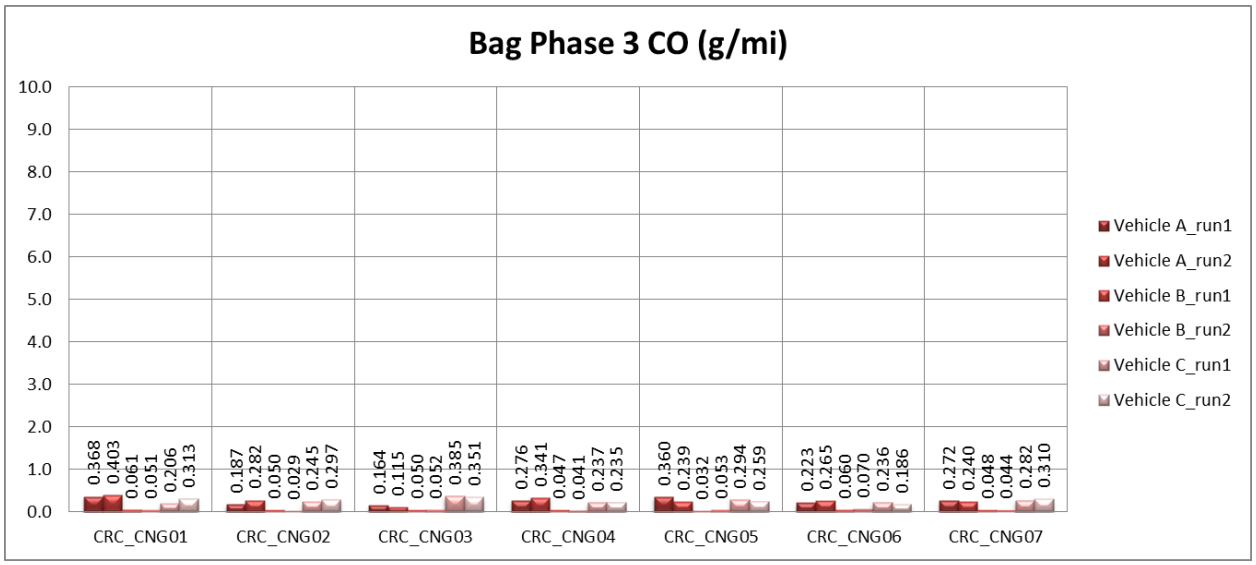


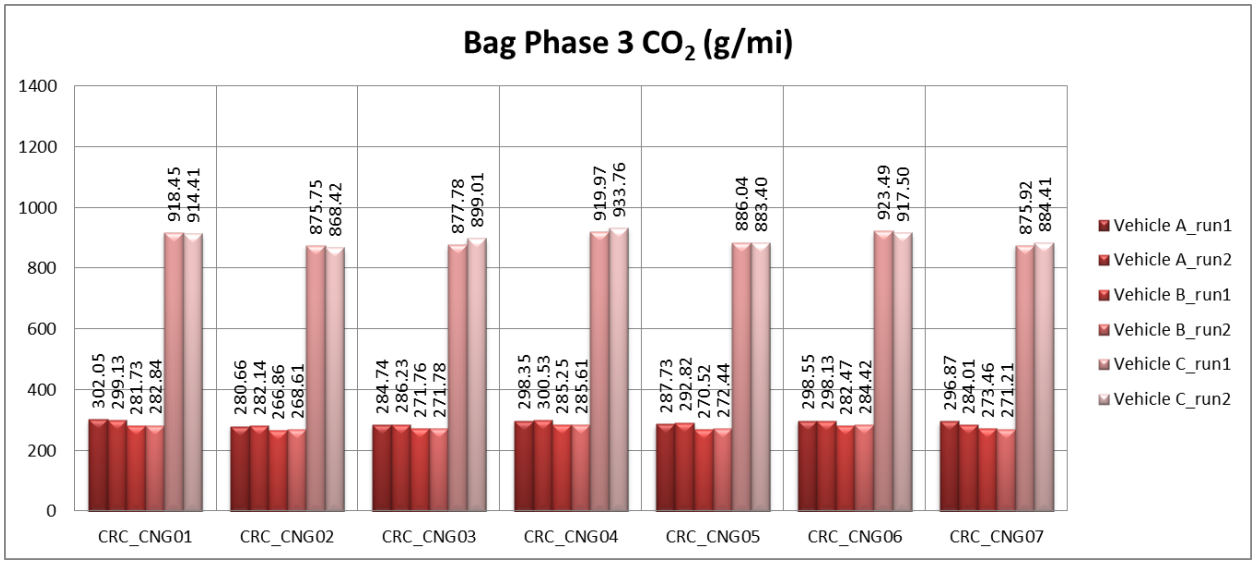



Bag Phase 3 CH4 (g/mi)
1.4000
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
0.020 0.017 0.212 0.183 0.342 0.304
0.020 0.024 0.185 0.192 0.321 0.260
0.029 0.014 0.178 0.168 0.232 0.310
0.008 0.013 0.093 0.081 0.171 0.132
0.016 0.018 0.128 0.147 0.278 0.212
0.007 0.004 0.097 0.088 0.163 0.146
0.014 0.029 0.165 0.156 0.249 0.246
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

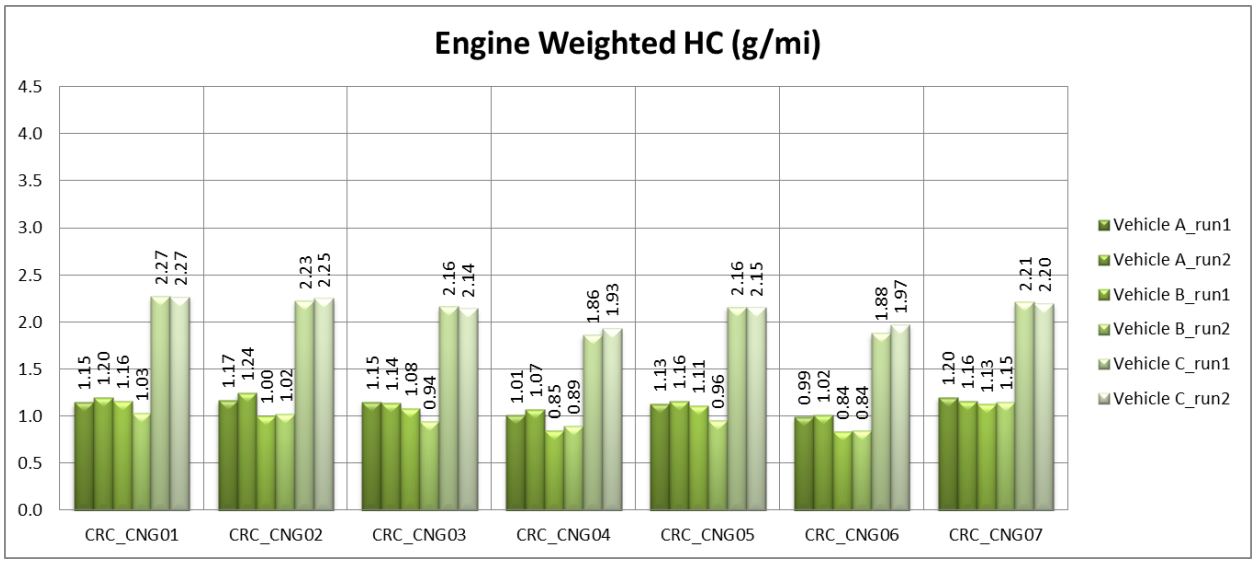

Bag Phase 3 NMHC (g/mi)
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0.002 0.001 0.000 0.002 0.006 0.004
0.002 0.001 0.002 0.000 0.004 0.006
0.002 0.001 0.006 0.004 0.005 0.007
0.002 0.001 0.008 0.008 0.014 0.010
0.001 0.002 0.005 0.005 0.007 0.004
0.002 0.002 0.012 0.010 0.019 0.012
0.002 0.001 0.003 0.004 0.003 0.003
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

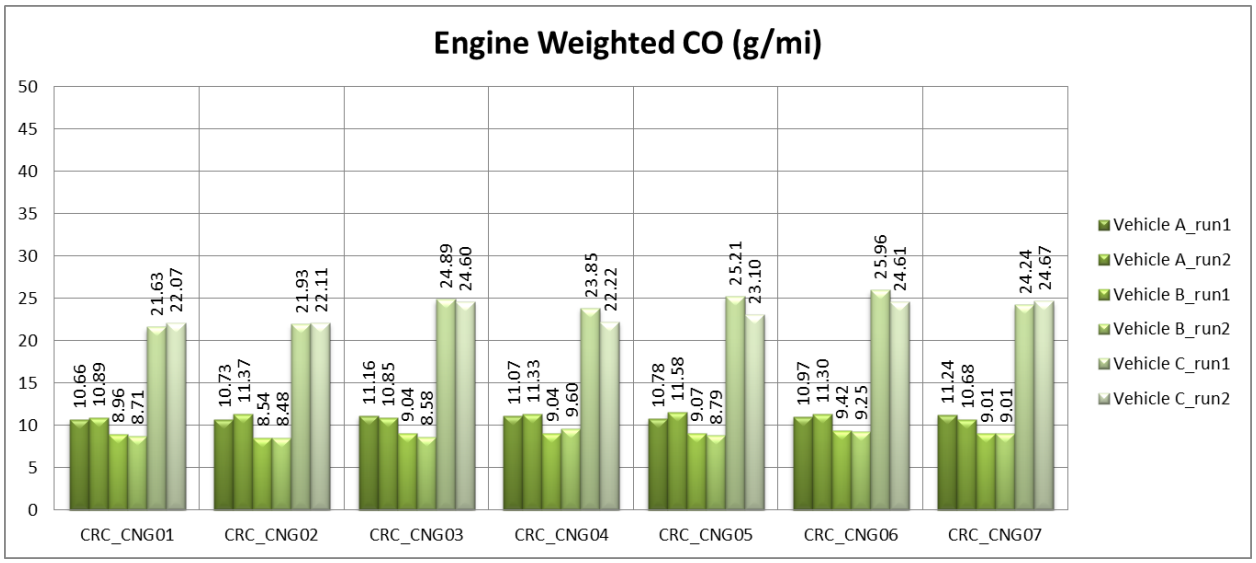

Bag Phase 3 NOx (g/mi)
0.5000
0.4500
0.4000
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0.000 0.000 0.481 0.203 0.062 0.035
0.001 0.000 0.155 0.264 0.048 0.007
0.000 0.000 0.376 0.277 0.055 0.066
0.000 0.000 0.155 0.086 0.042 0.003
0.000 0.000 0.091 0.173 0.051 0.008
0.000 0.000 0.243 0.192 0.081 0.037
0.000 0.000 0.259 0.203 0.030 0.016
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

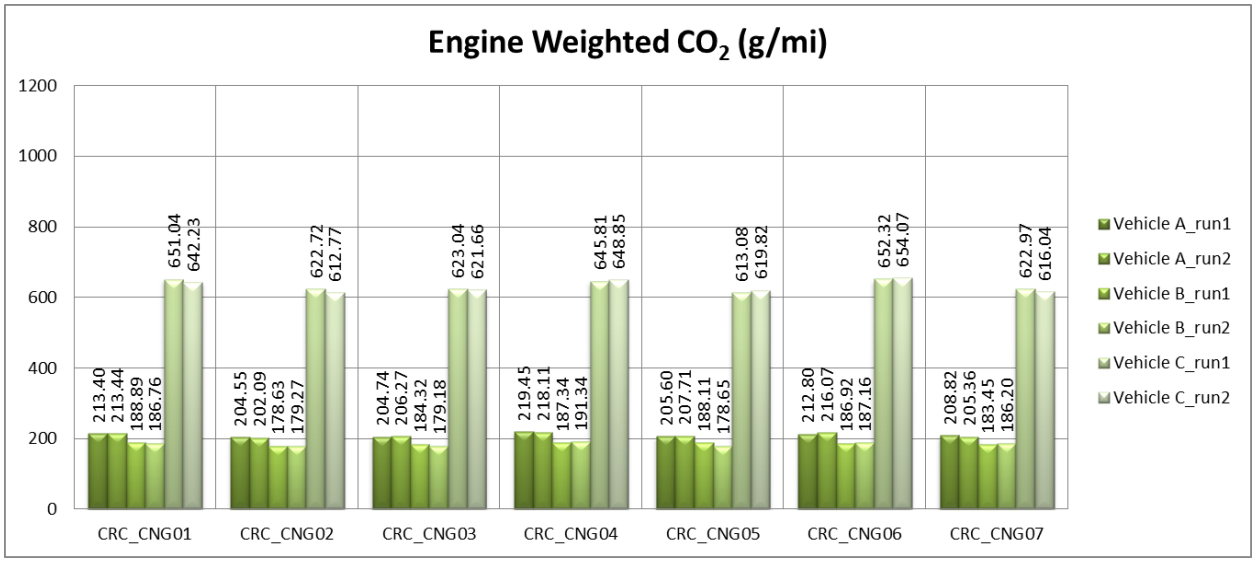

Bag Phase 3 CO (g/mi)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.368 0.403 0.061 0.051 0.206 0.313
0.187 0.282 0.050 0.029 0.245 0.297
0.164 0.115 0.050 0.052 0.385 0.351
0.276 0.341 0.047 0.041 0.237 0.235
0.360 0.239 0.032 0.053 0.294 0.259
0.223 0.265 0.060 0.070 0.236 0.186
0.272 0.240 0.048 0.044 0.282 0.310
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

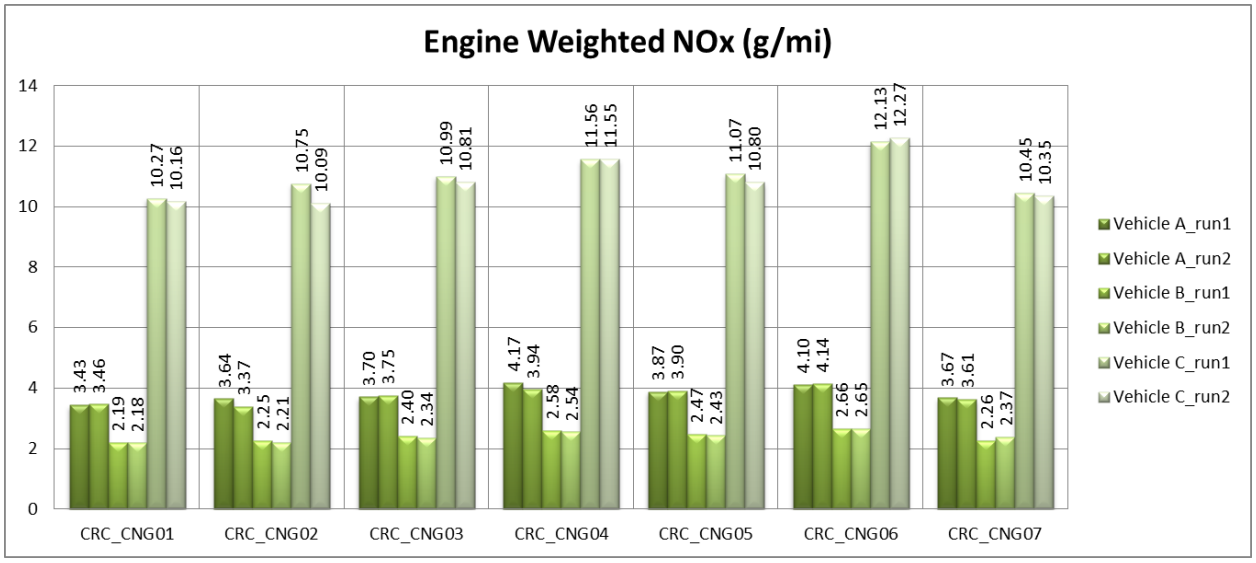

Bag Phase 3 CO_2 (g/mi)
1400
1200
1000
800
600
400
200
0
302.05
299.13
281.73
282.84
918.45
914.41
280.66
282.14
266.86
268.61
875.75
868.42
284.74
286.23
271.76
271.78
877.78
899.01
298.35
300.53
285.25
285.61
919.97
933.76
287.73
292.82
270.52
272.44
886.04
883.40
298.55
298.13
282.47
284.42
923.49
917.50
296.87
284.01
273.46
271.21
875.92
884.41
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

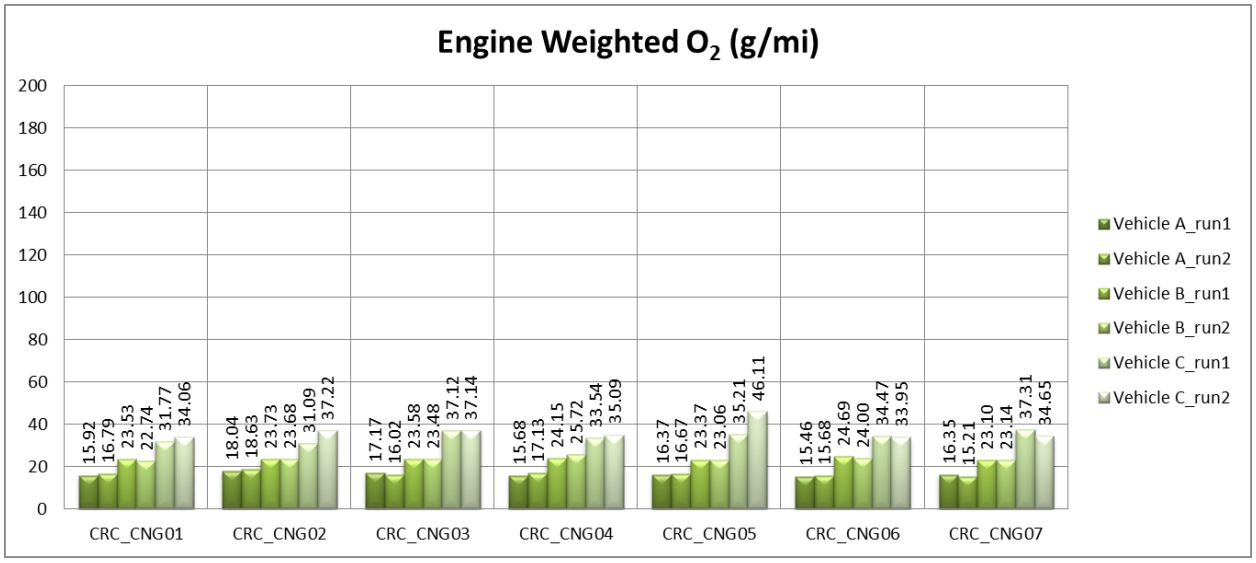
12.8 Appendix 8: Engine-Out-Weighted Dataset Chart

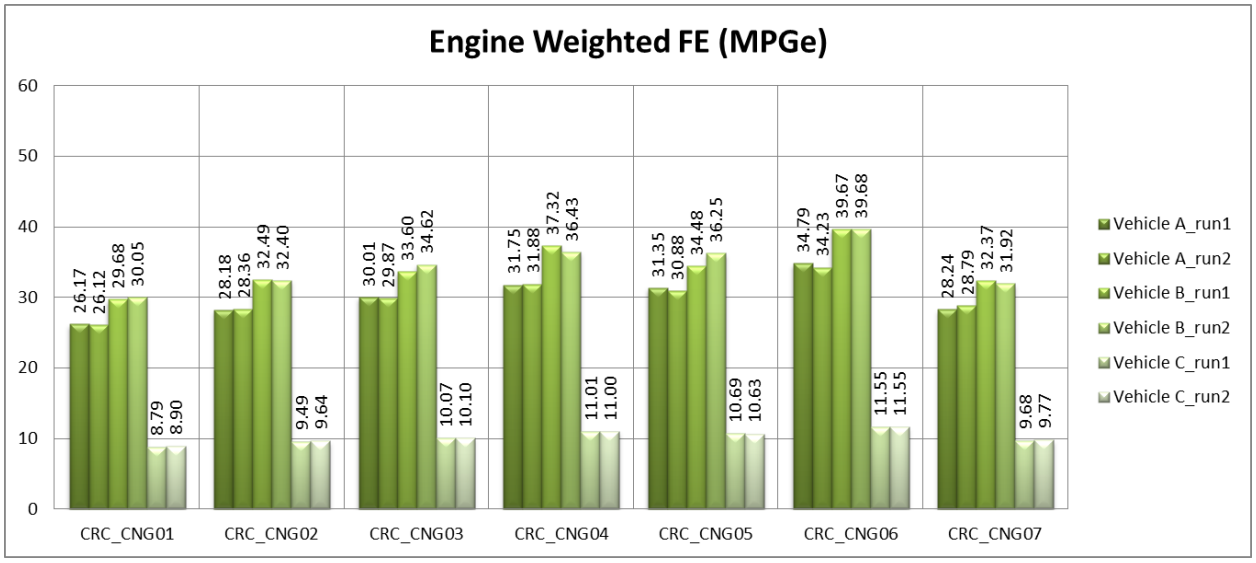




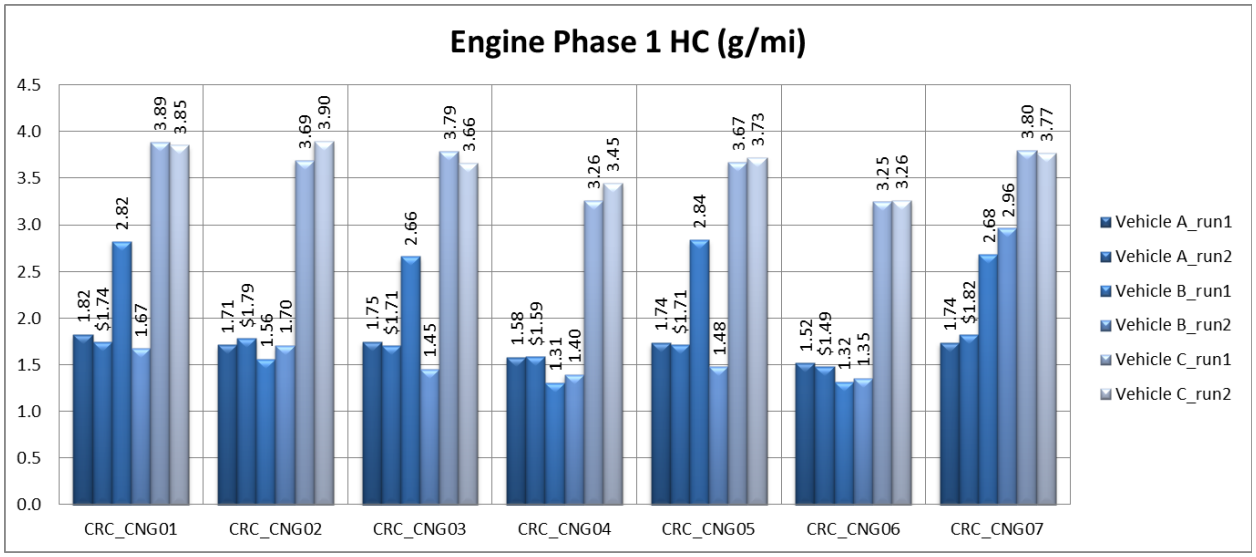

Engine Weighted CO_2 (g/mi)
1200
1000
800
600
400
200
0
213.40 213.44 188.89 186.76 651.04 642.23
204.55 202.09 178.63 179.27 622.72 612.77
204.74 206.27 184.32 179.18 623.04 621.66
219.45 218.11 187.34 191.34 645.81 648.85
205.60 207.71 188.11 178.65 613.08 619.82
212.80 216.07 186.92 187.16 652.32 654.07
208.82 205.36 183.45 186.20 622.97 616.04
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

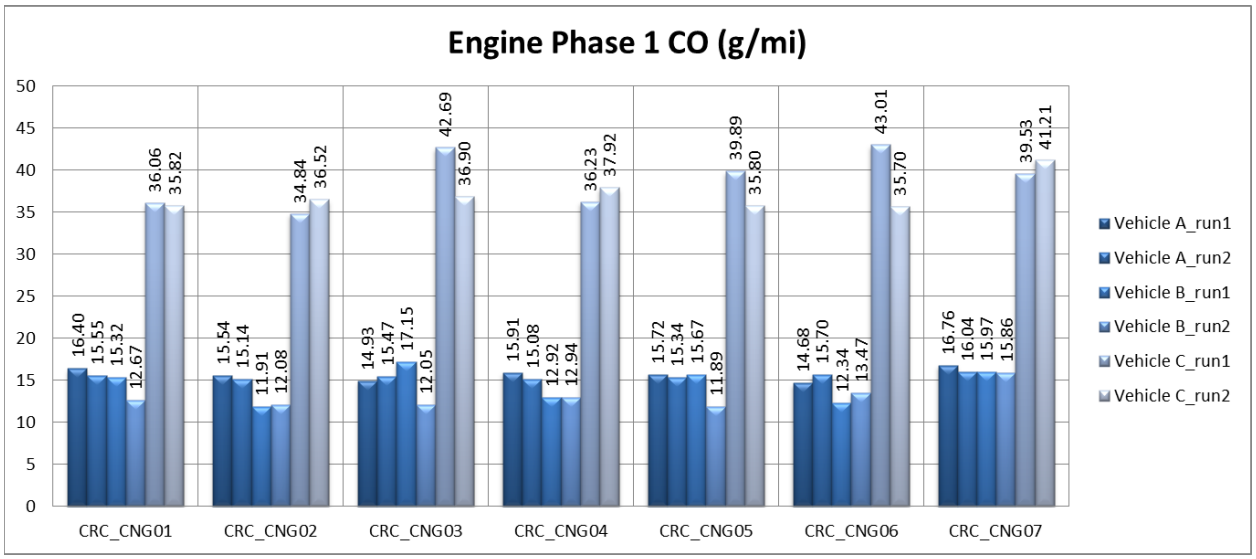

Engine Weighted NOx (g/mi)
14
12
10
8
6
4
2
0
3.43 3.46 2.19 2.18 10.27 10.16
3.64 3.37 2.25 2.21 10.75 10.09
3.70 3.75 2.40 2.34 10.99 10.81
4.17 3.94 2.58 2.54 11.56 11.55
3.87 3.90 2.47 2.43 11.07 10.80
4.10 4.14 2.66 2.65 12.13 12.27
3.67 3.61 2.26 2.37 10.45 10.35
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

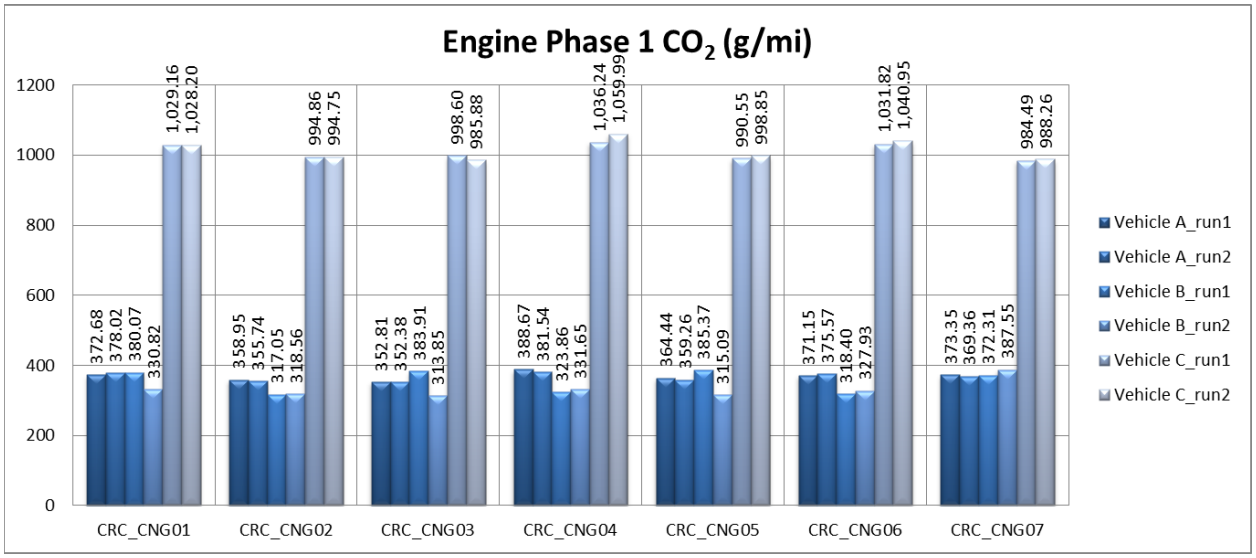

Engine Weighted O_2 (g/mi)
200
180
160
140
120
100
80
60
40
20
0
15.92 16.79 23.53 22.74 31.77 34.06
18.04 18.63 23.73 23.68 31.09 37.22
17.17 16.02 23.58 23.48 37.12 37.14
15.68 17.13 24.15 25.72 33.54 35.09
16.37 16.67 23.37 23.06 35.21 46.11
15.46 15.68 24.69 24.00 34.47 33.95
16.35 15.21 23.10 23.14 37.31 34.65
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

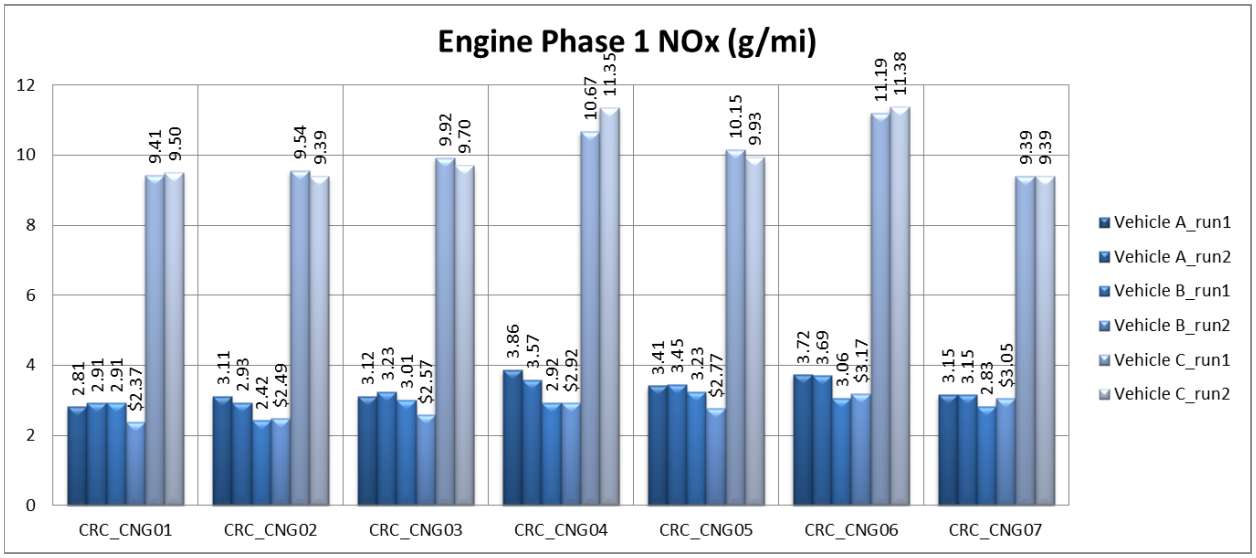

Engine Weighted FE (MPGe)
60
50
40
30
20
10
0
26.17 26.12 29.68 30.05 8.79 8.90
28.18 28.36 32.49 32.40 9.49 9.64
30.01 29.87 33.60 34.62 10.07 10.10
31.75 31.88 37.32 36.43 11.01 11.00
31.35 30.88 34.48 36.25 10.69 10.63
34.79 34.23 39.67 39.68 11.55 11.55
28.24 28.79 32.37 31.92 9.68 9.77
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

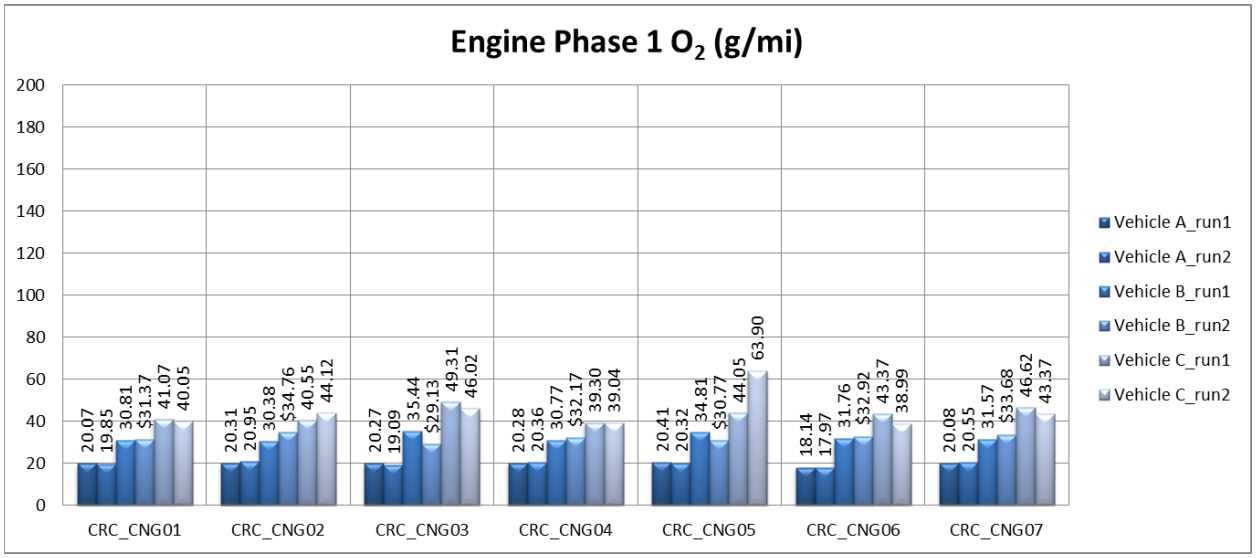
12.9 Appendix 9: Engine-Out Phase 1 Dataset Chart

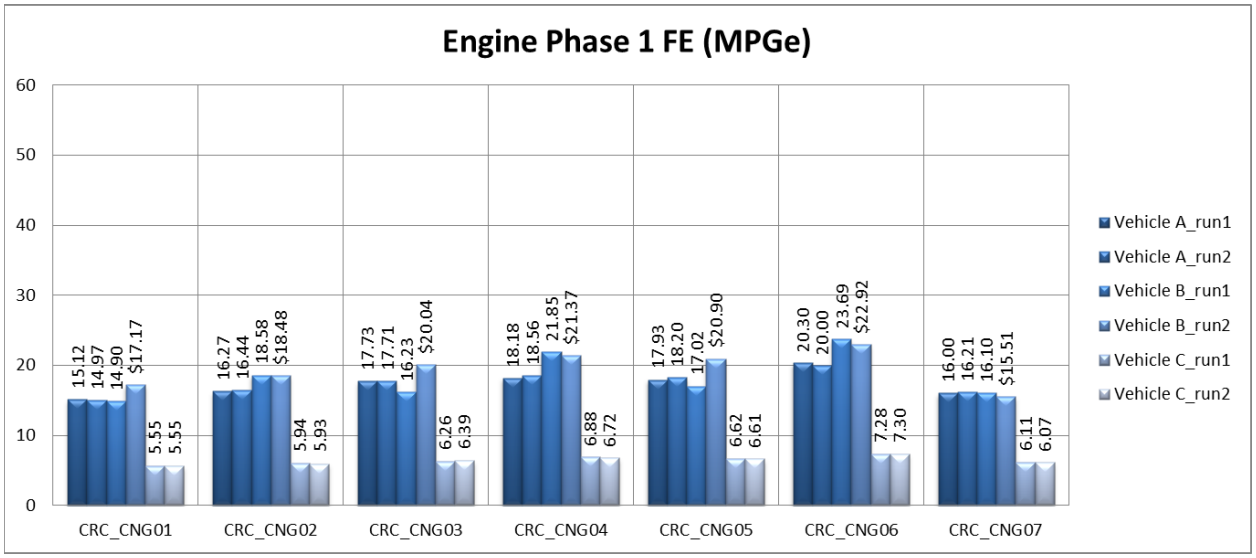




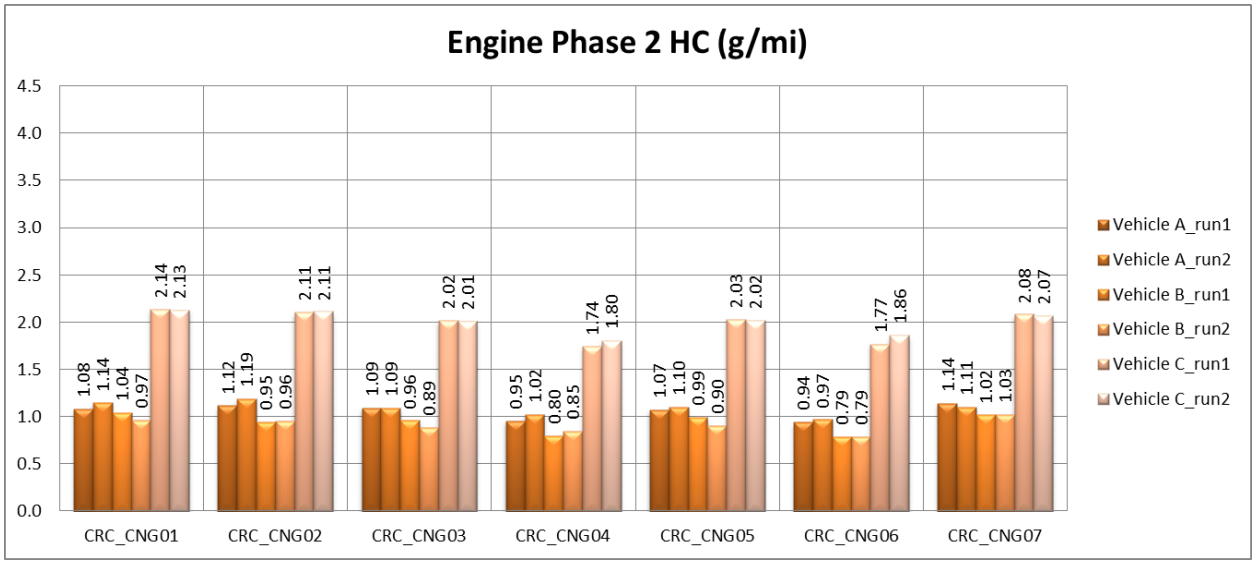

Engine Phase 1 CO_2 (g/mi)
1200
1000
800
600
400
200
0
372.68 378.02 380.07 330.82 1,029.16 1,028.20
358.95 355.74 317.05 318.56 994.86 994.75
352.81 352.38 383.91 313.85 998.60 985.88
388.67 381.54 323.86 331.65 1,036.24 1,059.99
364.44 359.26 385.37 315.09 990.55 998.85
371.15 375.57 318.40 327.93 1,031.82 1,040.95
373.35 369.36 372.31 387.55 984.49 988.26
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

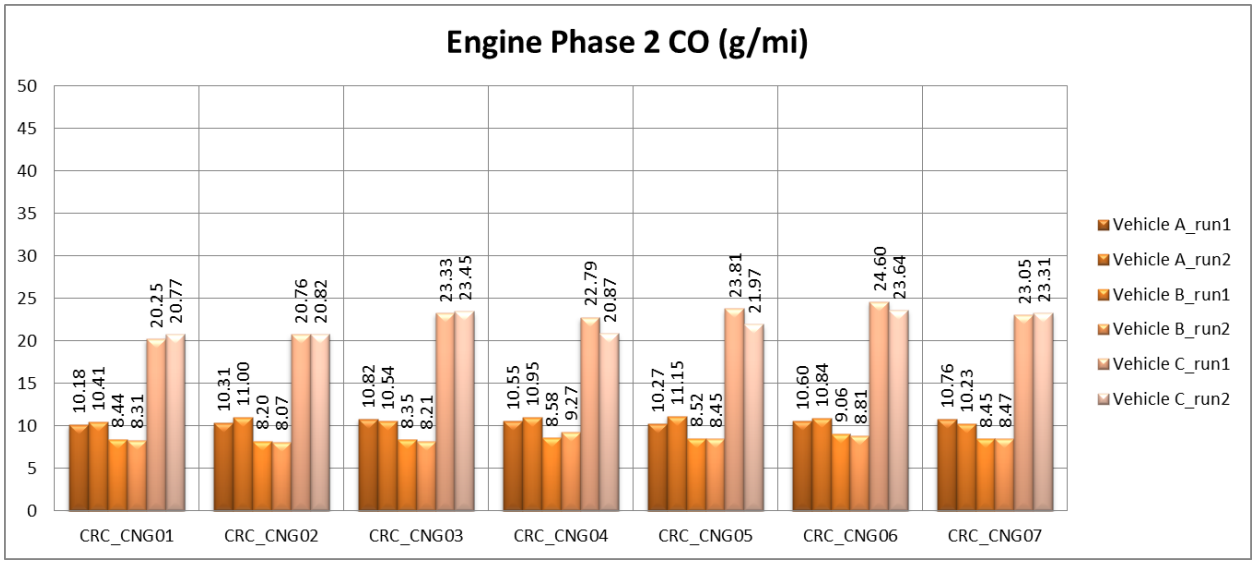

Engine Phase 1 NOx (g/mi)
12
10
8
6
4
2
0
2.81 2.91 2.91 $2.37 9.41 9.50
3.11 2.93 2.42 $2.49 9.54 9.39
3.12 3.23 3.01 $2.57 9.92 9.70
3.86 3.57 2.92 $2.92 10.67 11.35
3.41 3.45 3.23 $2.77 10.15 9.93
3.72 3.69 3.06 $3.17 11.19 11.38
3.15 3.15 2.83 $3.05 9.39 9.39
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

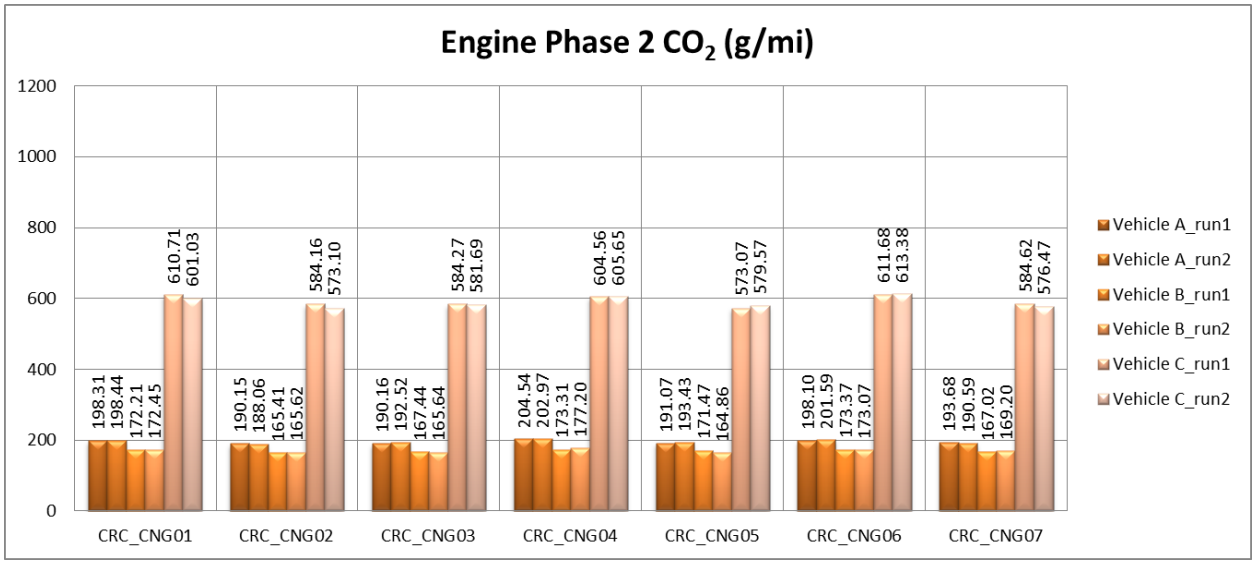

Engine Phase 1 O_2 (g/mi)
200
180
160
140
120
100
80
60
40
20
0
20.07 19.85 30.81 $31.37 41.07 40.05
20.31 20.95 30.38 $34.76 40.55 44.12
20.27 19.09 35.44 $29.13 49.31 46.02
20.28 20.36 30.77 $32.17 39.30 39.04
20.41 20.32 34.81 $30.77 44.05 63.90
18.14 17.97 31.76 $32.92 43.37 38.99
20.08 20.55 31.57 $33.68 46.62 43.37
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

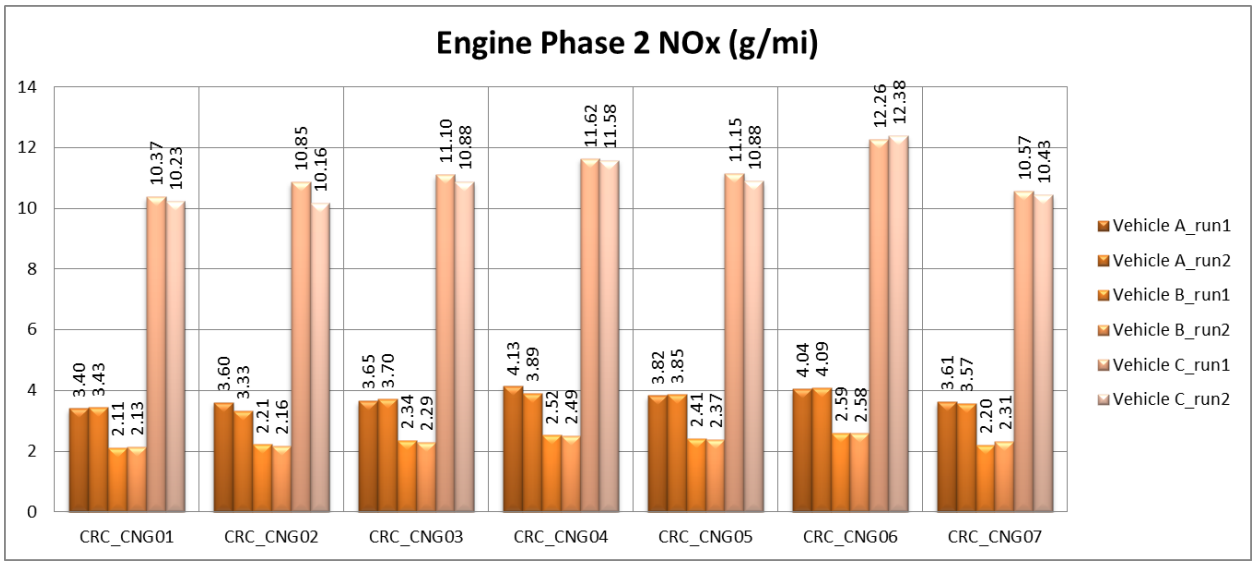

Engine Phase 1 FE (MPGe)
60
50
40
30
20
10
0
15.12 14.97 14.90 $17.17 5.55 5.55
16.27 16.44 18.58 $18.48 5.94 5.93
17.73 17.71 16.23 $20.04 6.26 6.39
18.18 18.56 21.85 $21.37 6.88 6.72
17.93 18.20 17.02 $20.90 6.62 6.61
20.30 20.00 23.69 $22.92 7.28 7.30
16.00 16.21 16.10 $15.51 6.11 6.07
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

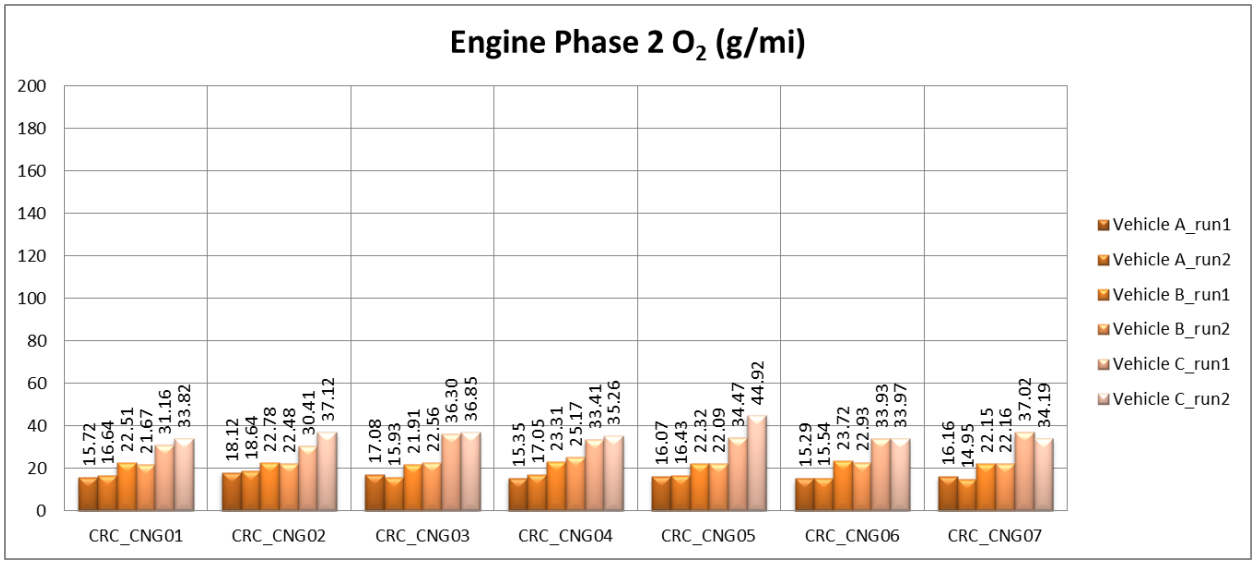
12.10 Appendix 10: Engine-Out Phase 2 Dataset Chart

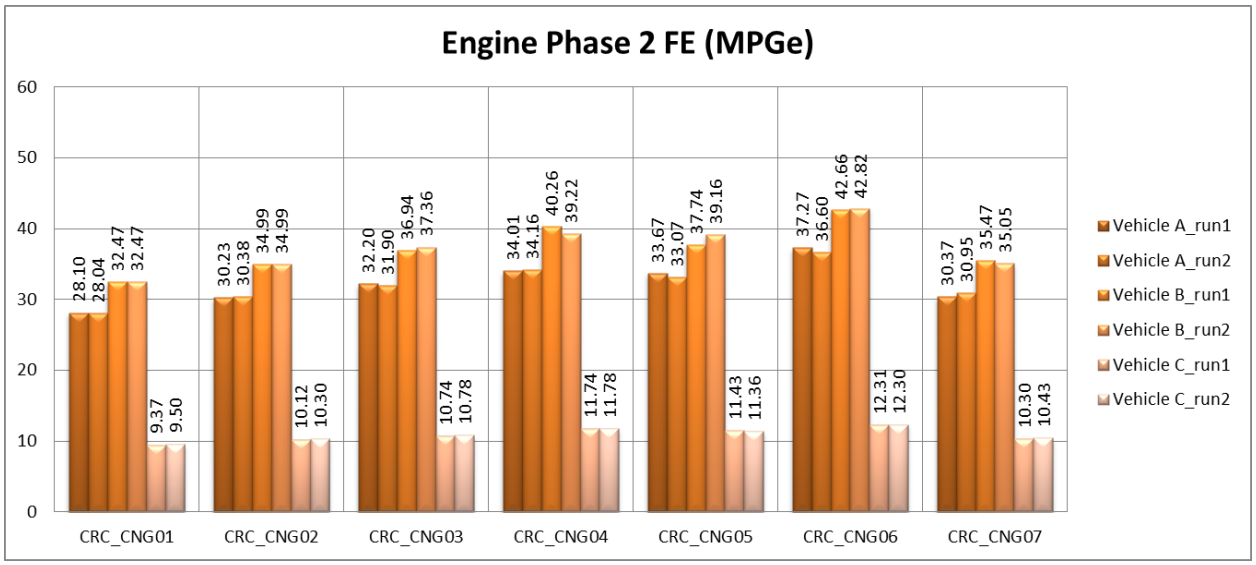




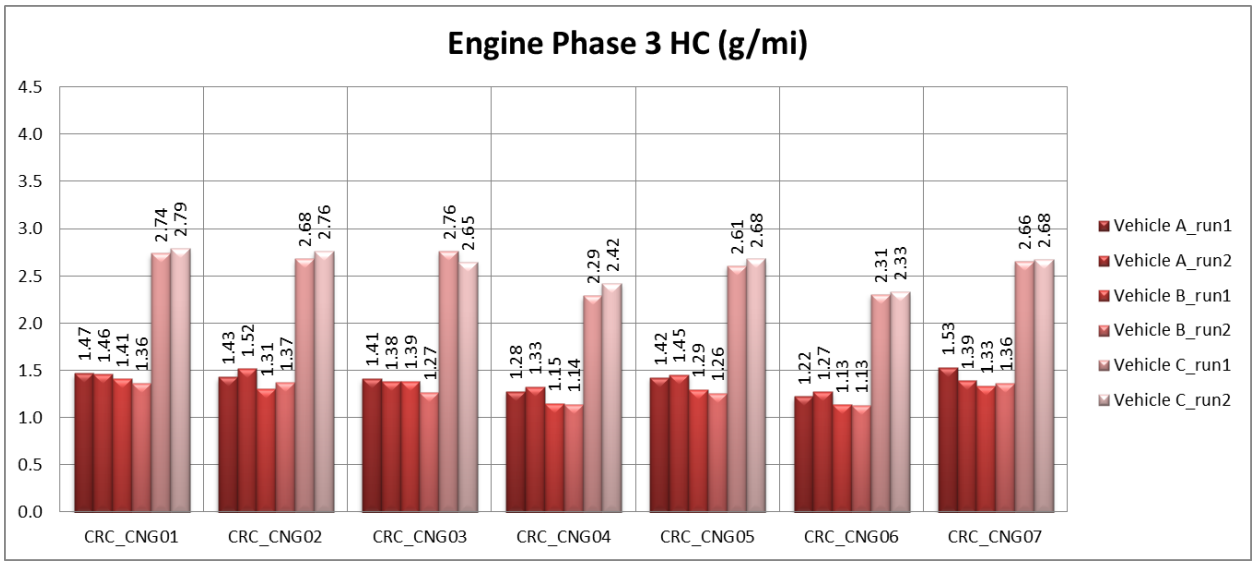

Engine Phase 2 CO_2 (g/mi)
1200
1000
800
600
400
200
0
198.31 198.44 172.21 172.45 610.71 601.03
190.15 188.06 165.41 165.62 584.16 573.10
190.16 192.52 167.44 165.64 584.27 581.69
204.54 202.97 173.31 177.20 604.56 605.65
191.07 193.43 171.47 164.86 573.07 579.57
198.10 201.59 173.37 173.07 611.68 613.38
193.68 190.59 167.02 169.20 584.62 576.47
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

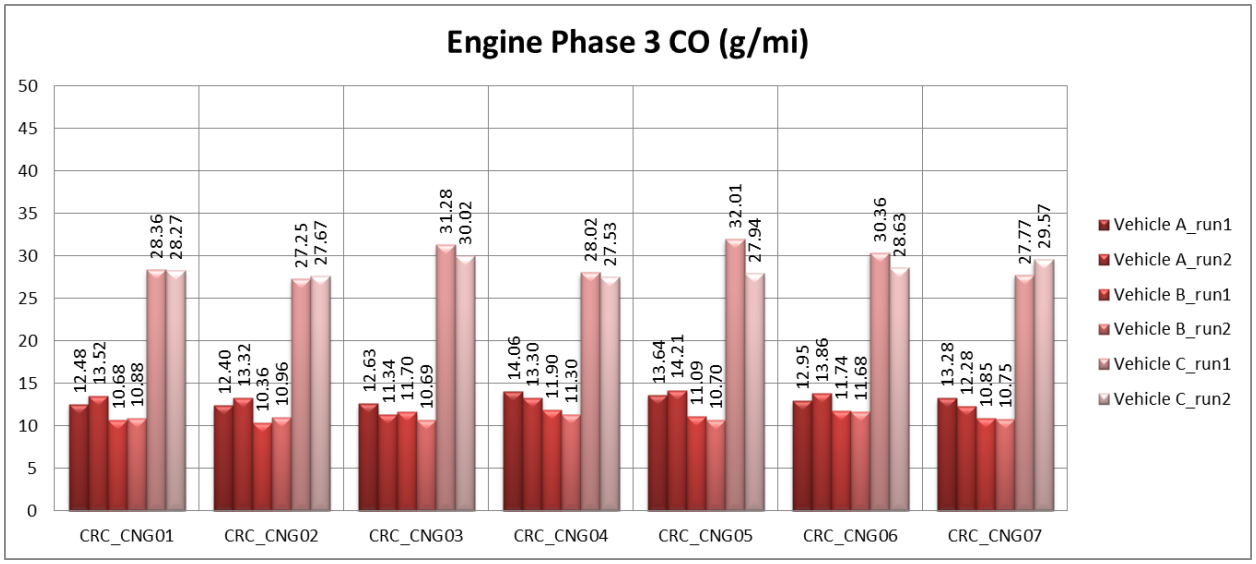

Engine Phase 2 NOx (g/mi)
14
12
10
8
6
4
2
0
3.40 3.43 2.11 2.13 10.37 10.23
3.60 3.33 2.21 2.16 10.85 10.16
3.65 3.70 2.34 2.29 11.10 10.88
4.13 3.89 2.52 2.49 11.62 11.58
3.82 3.85 2.41 2.37 11.15 10.88
4.04 4.09 2.59 2.58 12.26 12.38
3.61 3.57 2.20 2.31 10.57 10.43
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

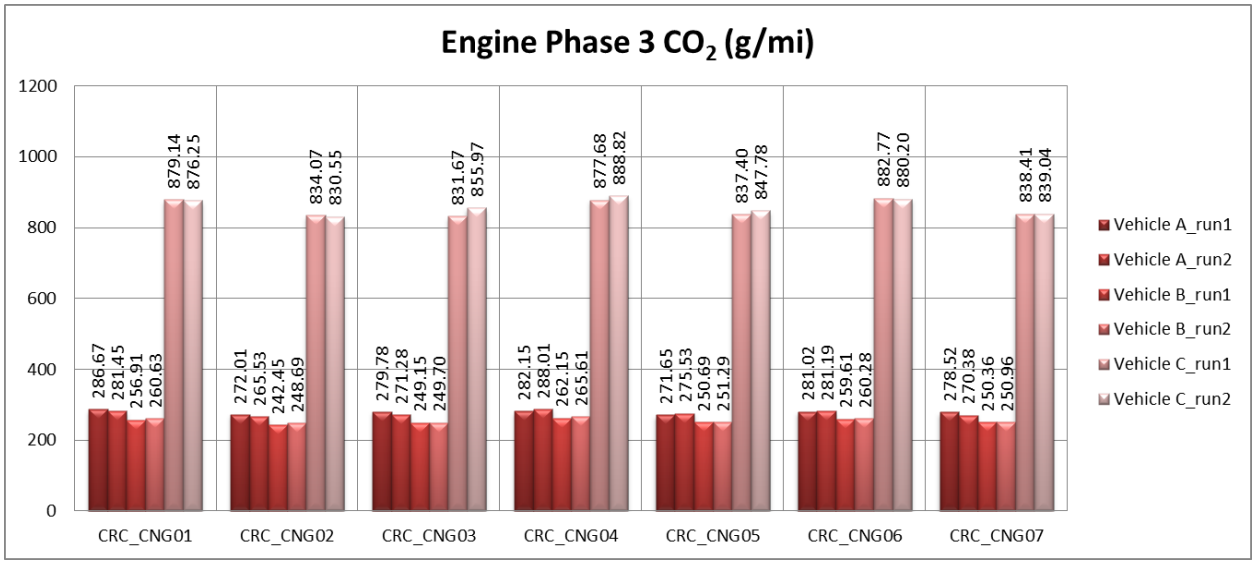

Engine Phase 2 O_2 (g/mi)
200
180
160
140
120
100
80
60
40
20
0
15.72 16.64 22.51 21.67 31.16 33.82
18.12 18.64 22.78 22.48 30.41 37.12
17.08 15.93 21.91 22.56 36.30 36.85
15.35 17.05 23.31 25.17 33.41 35.26
16.07 16.43 22.32 22.09 34.47 44.92
15.29 15.54 23.72 22.93 33.93 33.97
16.16 14.95 22.15 22.16 37.02 34.19
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

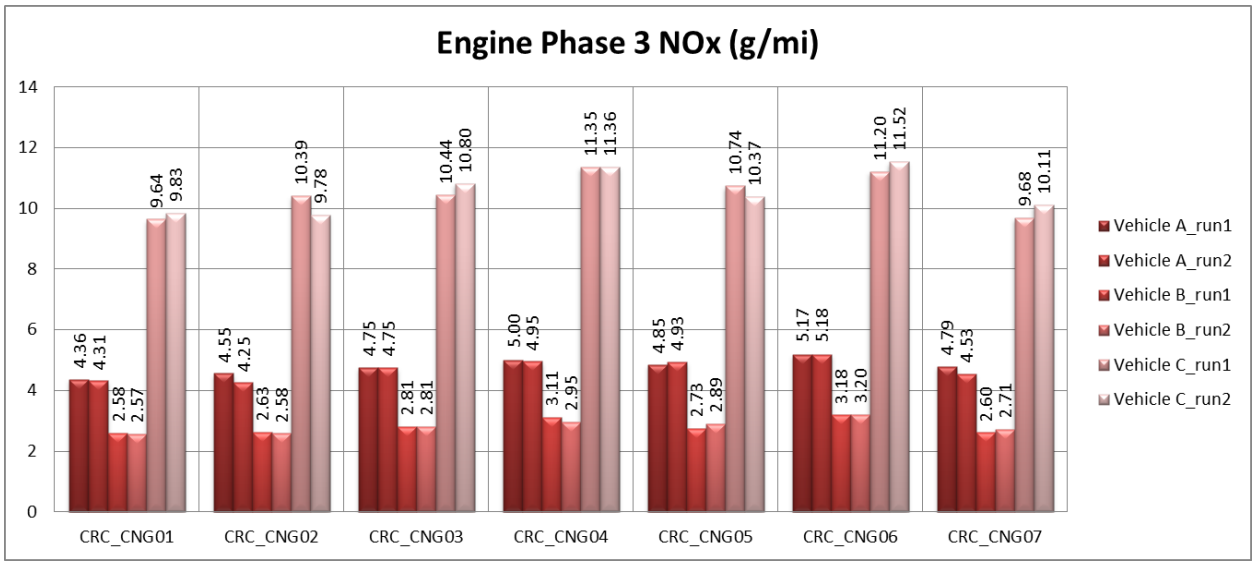

Engine Phase 2 FE (MPGe)
60
50
40
30
20
10
0
28.10 28.04 32.47 32.47 9.37 9.50
30.23 30.38 34.99 34.99 10.12 10.30
32.20 31.90 36.94 37.36 10.74 10.78
34.01 34.16 40.26 39.22 11.74 11.78
33.67 33.07 37.74 39.16 11.43 11.36
37.27 36.60 42.66 42.82 12.31 12.30
30.37 30.95 35.47 35.05 10.30 10.43
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

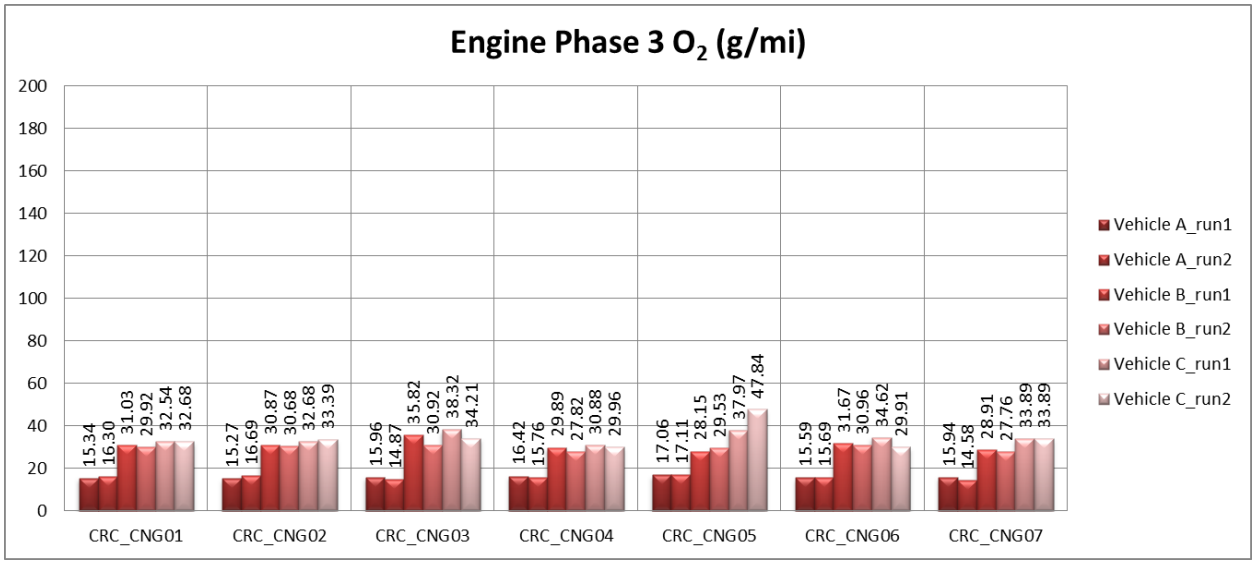
12.11 Appendix 11: Engine-Out Phase 3 Dataset Chart

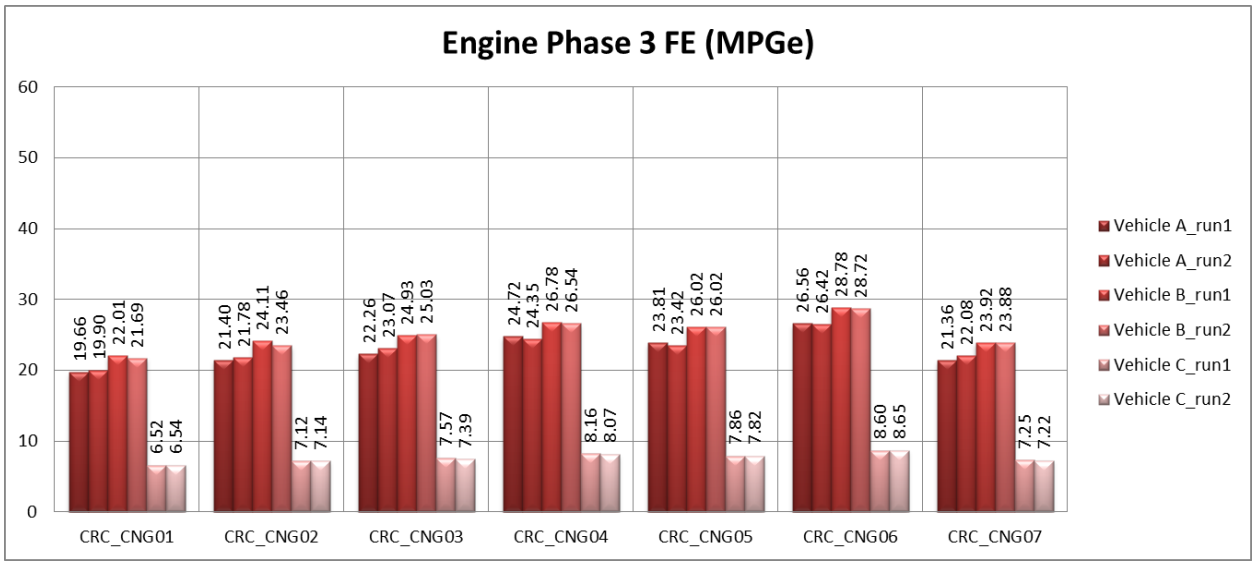




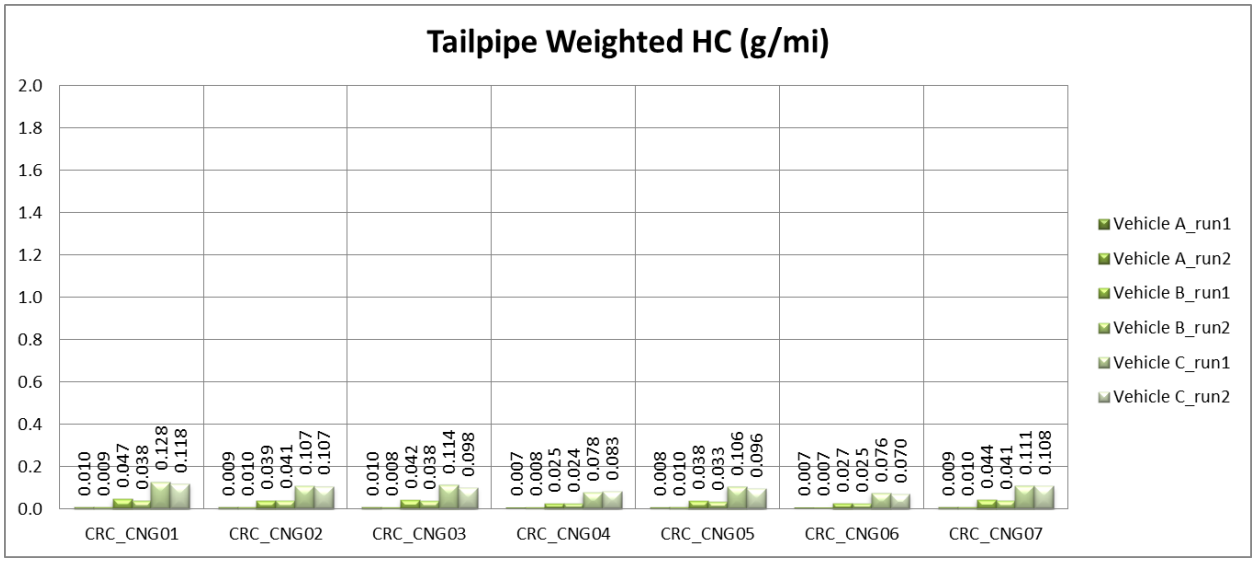

Engine Phase 3 CO_2 (g/mi)
1200
1000
800
600
400
200
0
286.67 281.45 256.91 260.63 879.14 876.25
272.01 265.53 242.45 248.69 834.07 830.55
279.78 271.28 249.15 249.70 831.67 855.97
282.15 288.01 262.15 265.61 877.68 888.82
271.65 275.53 250.69 251.29 837.40 847.78
281.02 281.19 259.61 260.28 882.77 880.20
278.52 270.38 250.36 250.96 838.41 839.04
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

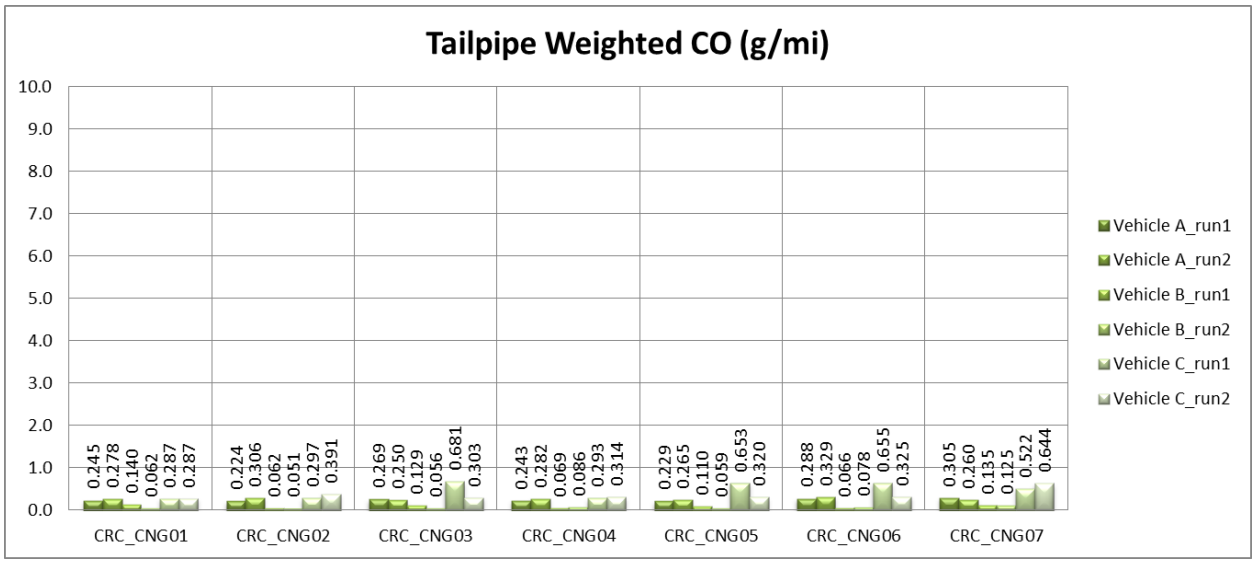

Engine Phase 3 NOx (g/mi)
14
12
10
8
6
4
2
0
4.36 4.31 2.58 2.57 9.64 9.83
4.55 4.25 2.63 2.58 10.39 9.78
4.75 4.75 2.81 2.81 10.44 10.80
5.00 4.95 3.11 2.95 11.35 11.36
4.85 4.93 2.73 2.89 10.74 10.37
5.17 5.18 3.18 3.20 11.20 11.52
4.79 4.53 2.60 2.71 9.68 10.11
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

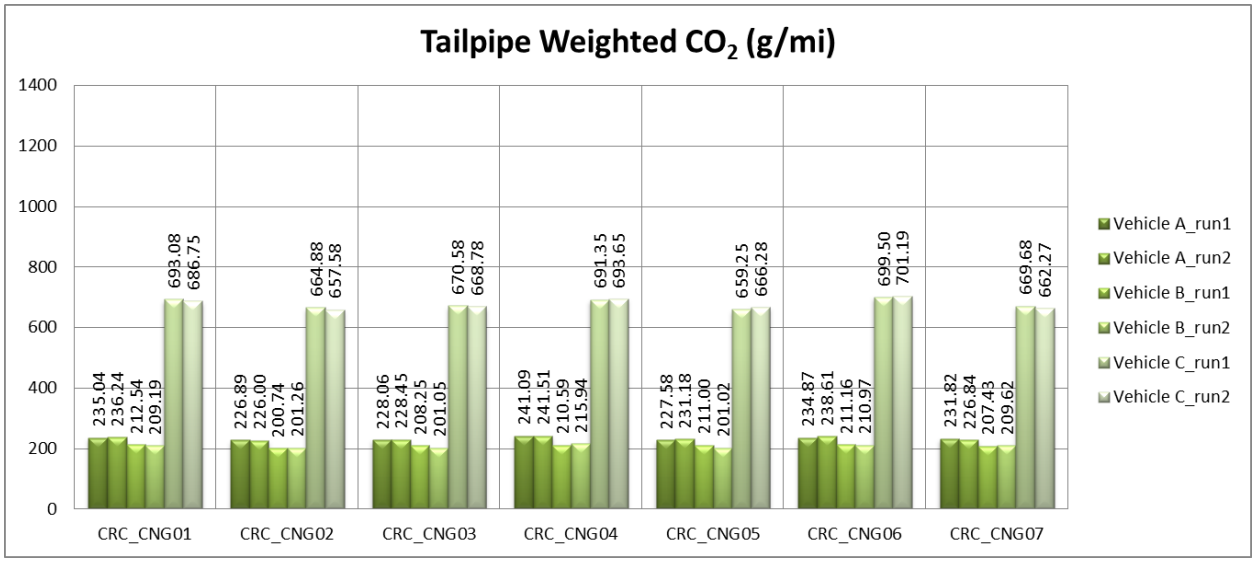

Engine Phase 3 O_2 (g/mi)
200
180
160
140
120
100
80
60
40
20
0
15.34 16.30 31.03 29.92 32.54 32.68
15.27 16.69 30.87 30.68 32.68 33.39
15.96 14.87 35.82 30.92 38.32 34.21
16.42 15.76 29.89 27.82 30.88 29.96
17.06 17.11 28.15 29.53 37.97 47.84
15.59 15.69 31.67 30.96 34.62 29.91
15.94 14.58 28.91 27.76 33.89 33.89
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

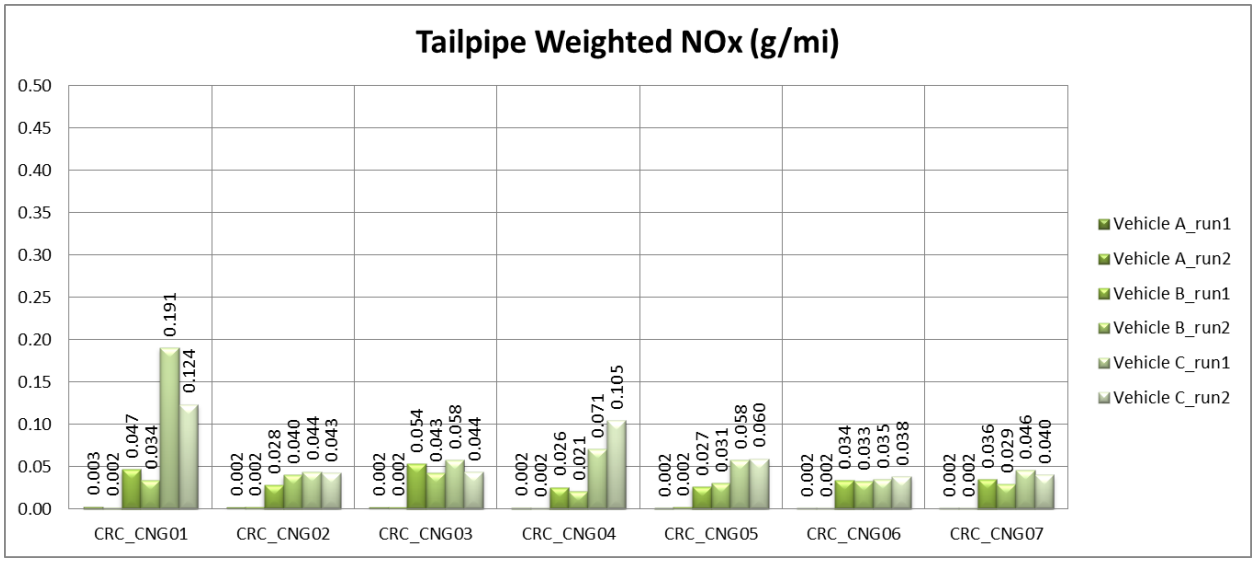

Engine Phase 3 FE (MPGe)
60
50
40
30
20
10
0
19.66 19.90 22.01 21.69 6.52 6.54
21.40 21.78 24.11 23.46 7.12 7.14
22.26 23.07 24.93 25.03 7.57 7.39
24.72 24.35 26.78 26.54 8.16 8.07
23.81 23.42 26.02 26.02 7.86 7.82
26.56 26.42 28.78 28.72 8.60 8.65
21.36 22.08 23.92 23.88 7.25 7.22
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

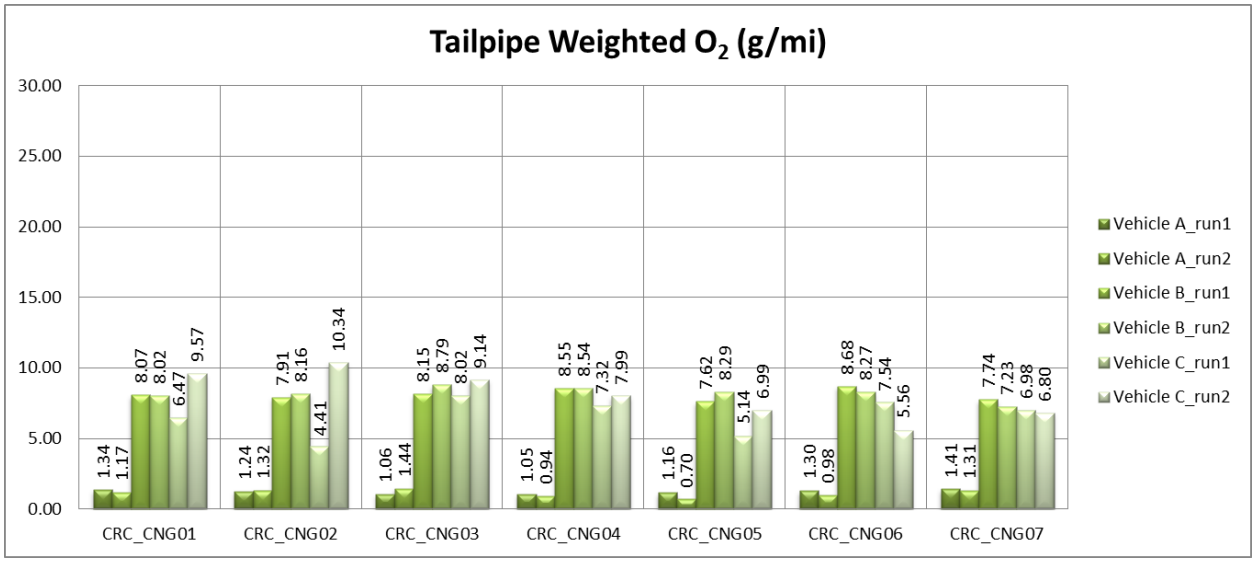
12.12 Appendix 12: Tailpipe-Weighted Dataset Charts

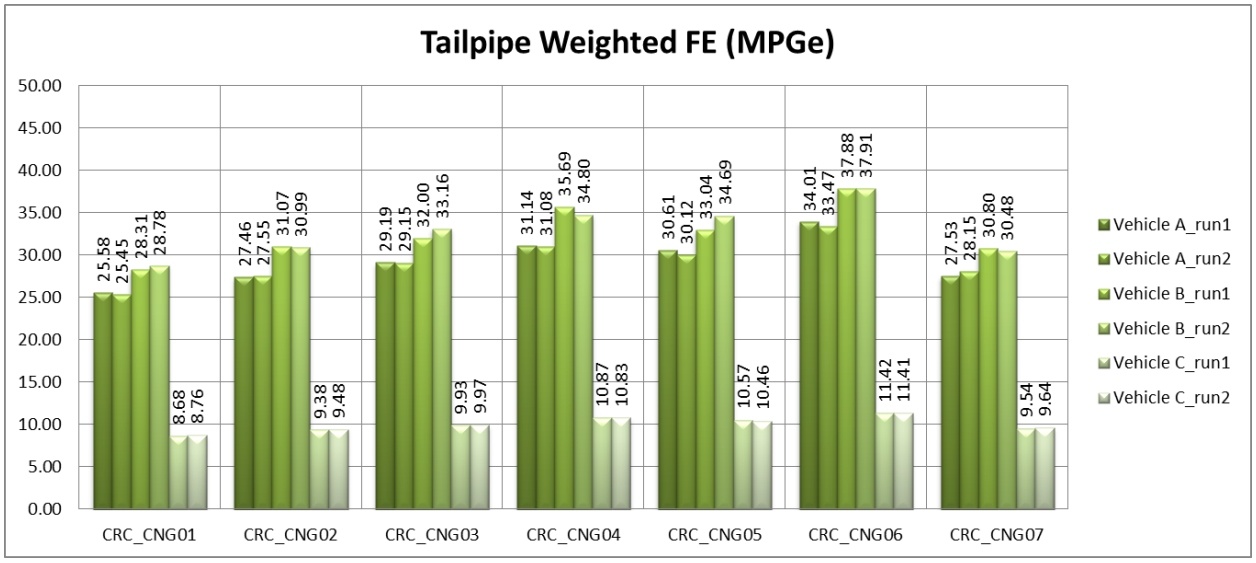




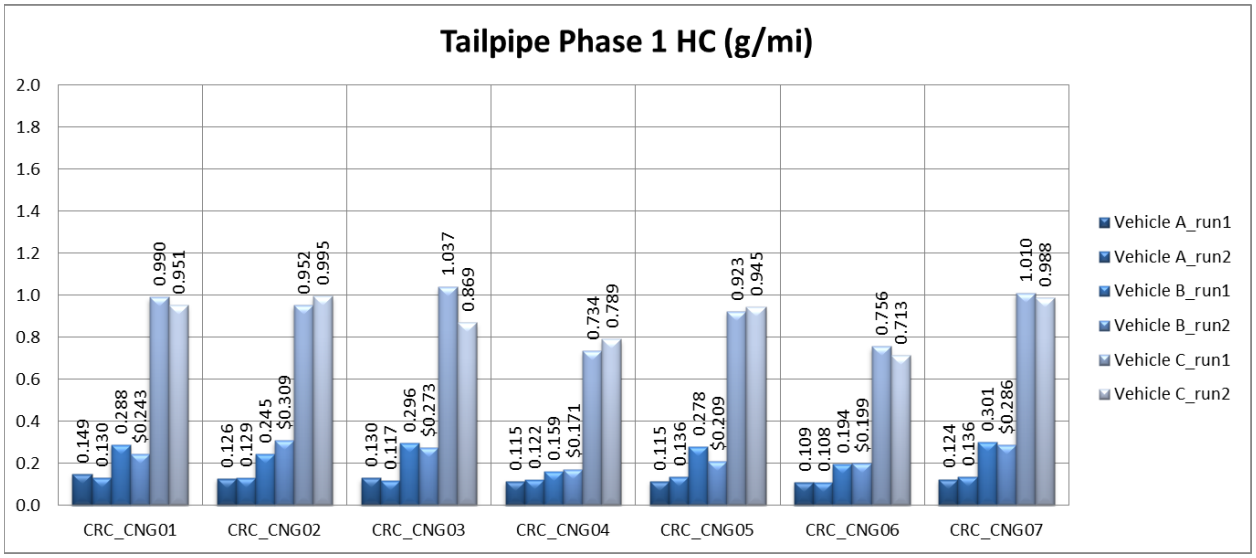

Tailpipe Weighted CO_2 (g/mi)
1400
1200
1000
800
600
400
200
0
235.04 236.24 212.54 209.19 693.08 686.75
226.89 226.00 200.74 201.26 664.88 657.58
228.06 228.45 208.25 201.05 670.58 668.78
241.09 241.51 210.59 215.94 691.35 693.65
227.58 231.18 211.00 201.02 659.25 666.28
234.87 238.61 211.16 210.97 699.50 701.19
231.82 226.84 207.43 209.62 669.68 662.27
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

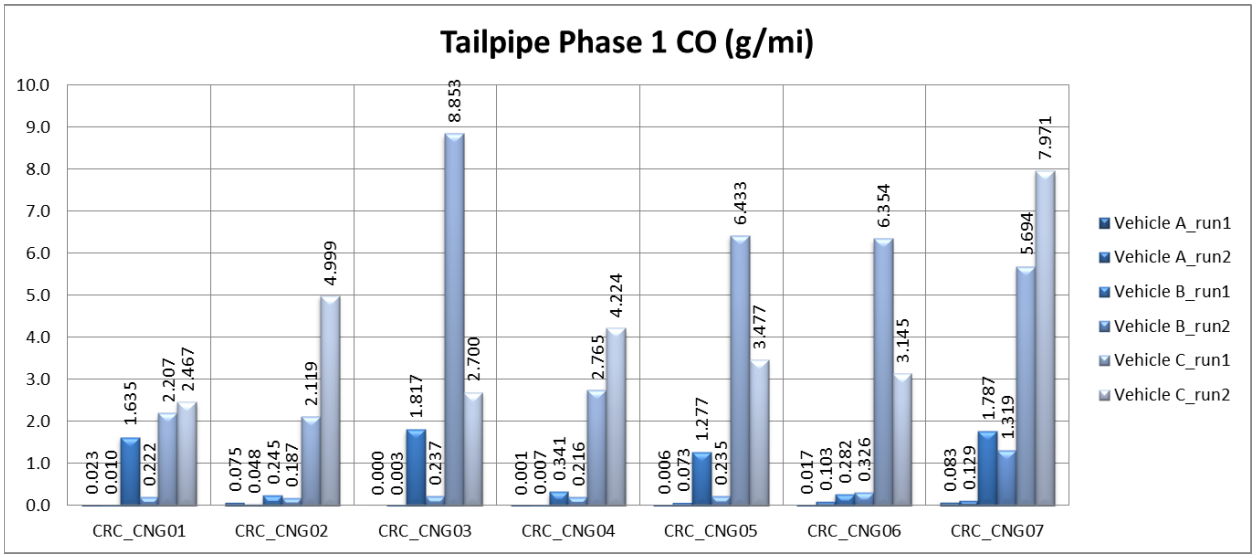

Tailpipe Weighted NOx (g/mi)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.003 0.002 0.047 0.034 0.191 0.124
0.002 0.002 0.028 0.040 0.044 0.043
0.002 0.002 0.054 0.043 0.058 0.044
0.002 0.002 0.026 0.021 0.071 0.105
0.002 0.002 0.027 0.031 0.058 0.060
0.002 0.002 0.034 0.033 0.035 0.038
0.002 0.002 0.036 0.029 0.046 0.040
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

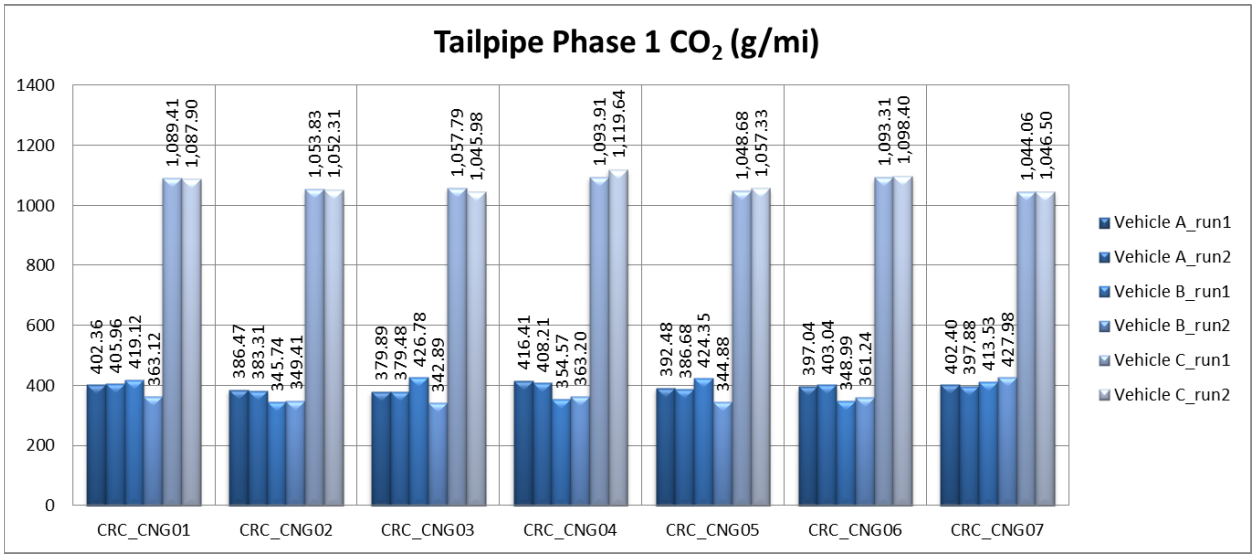

Tailpipe Weighted O_2 (g/mi)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1.34 1.17 8.07 8.02 6.47 9.57
1.24 1.32 7.91 8.16 4.41 10.34
1.06 1.44 8.15 8.79 8.02 9.14
1.05 0.94 8.55 8.54 7.32 7.99
1.16 0.70 7.62 8.29 5.14 6.99
1.30 0.98 8.68 8.27 7.54 5.56
1.41 1.31 7.74 7.23 6.98 6.80
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

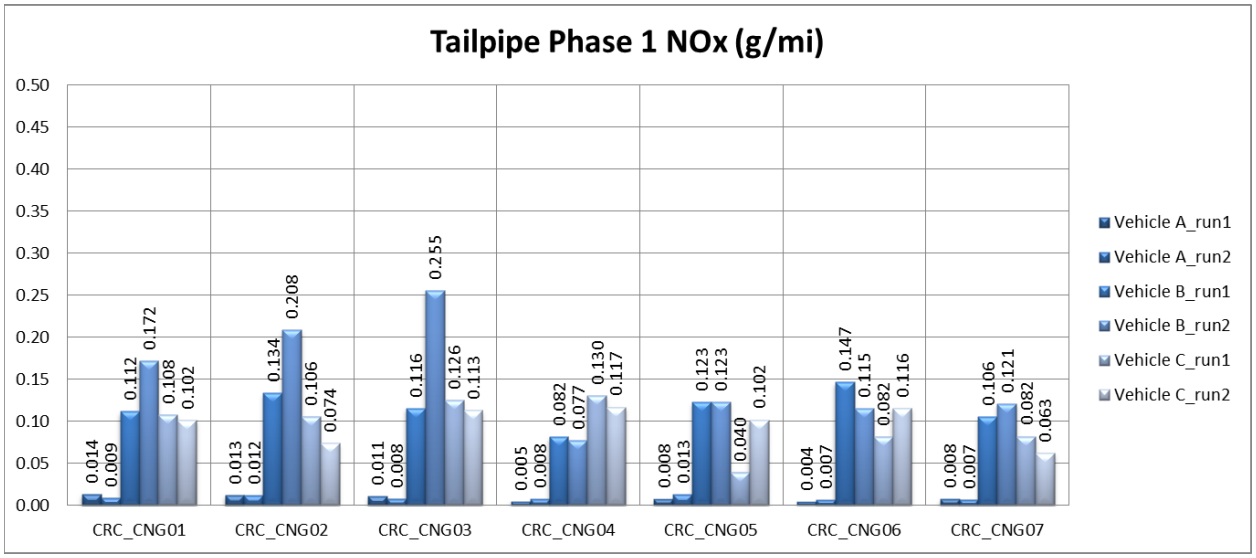

Tailpipe Weighted FE (MPGe)
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
25.58 25.45 28.31 28.78 8.68 8.76
27.46 27.55 31.07 30.99 9.38 9.48
29.19 29.15 32.00 33.16 9.93 9.97
31.14 31.08 35.69 34.80 10.87 10.83
30.61 30.12 33.04 34.69 10.57 10.46
34.01 33.47 37.88 37.91 11.42 11.41
27.53 28.15 30.80 30.48 9.54 9.64
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

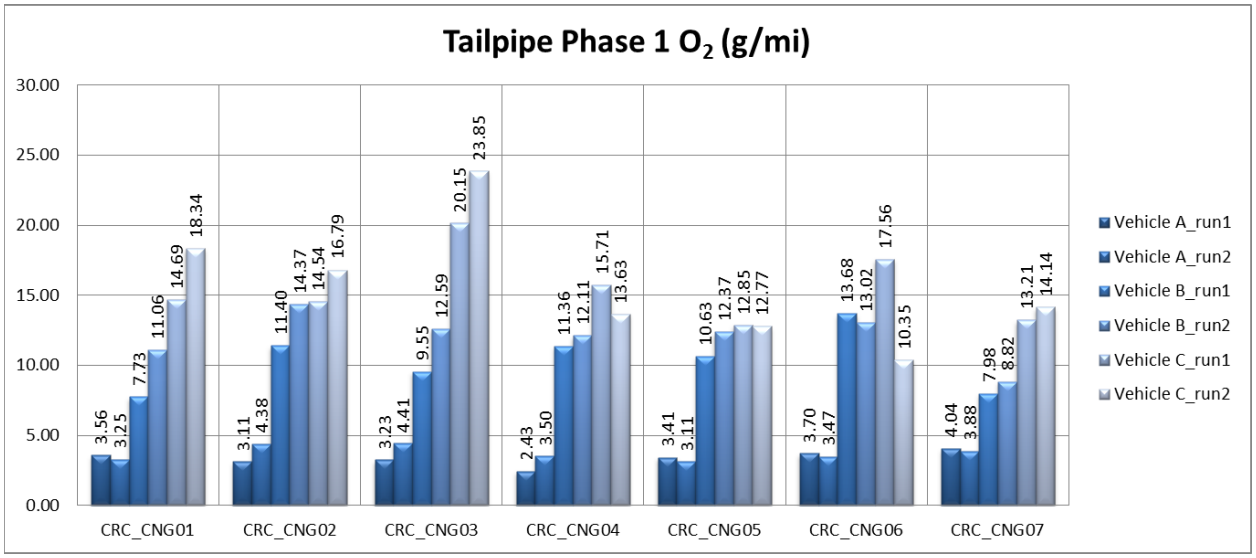
12.13 Appendix 13: Tailpipe Phase 1 Dataset Charts

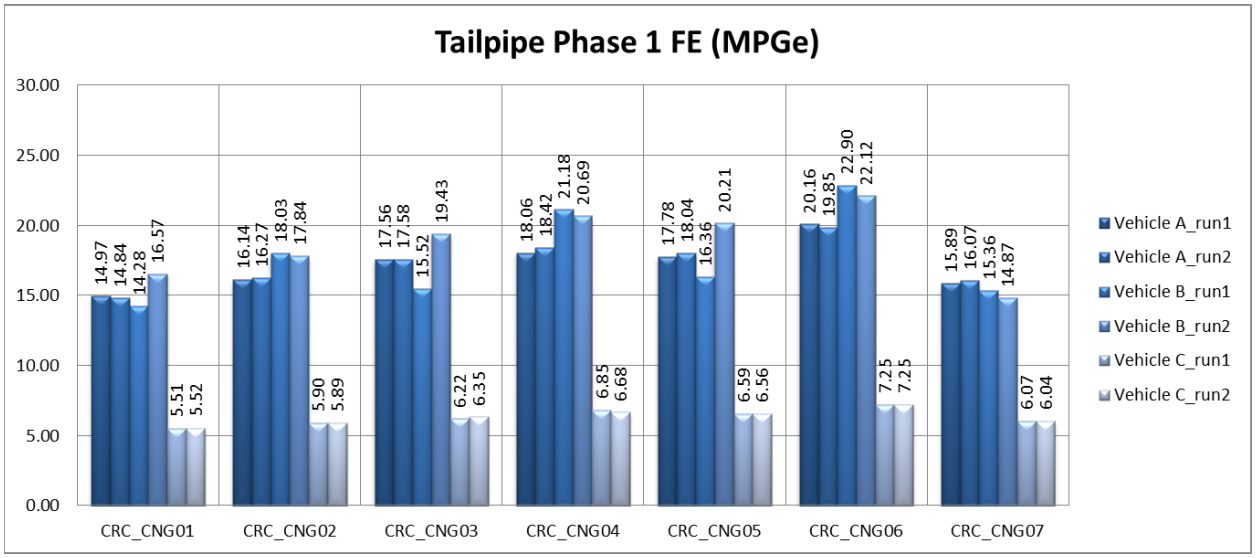




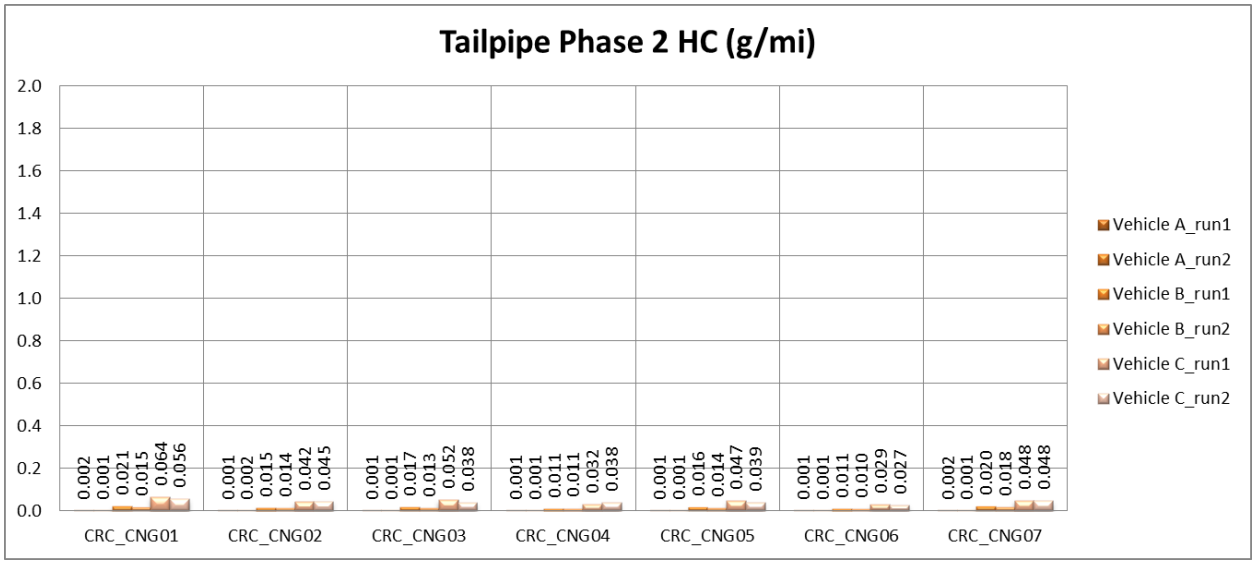

Tailpipe Phase 1 CO_2 (g/mi)
1400
1200
1000
800
600
400
200
0
402.36
405.96
419.12
363.12
1,089.41
1,087.90
386.47
383.31
345.74
349.41
1,053.83
1,052.31
379.89
379.48
426.78
342.89
1,057.79
1,045.98
416.41
408.21
354.57
363.20
1,093.91
1,119.64
392.48
386.68
424.35
344.88
1,048.68
1,057.33
397.04
403.04
348.99
361.24
1,093.31
1,098.40
402.40
397.88
413.53
427.98
1,044.06
1,046.50
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

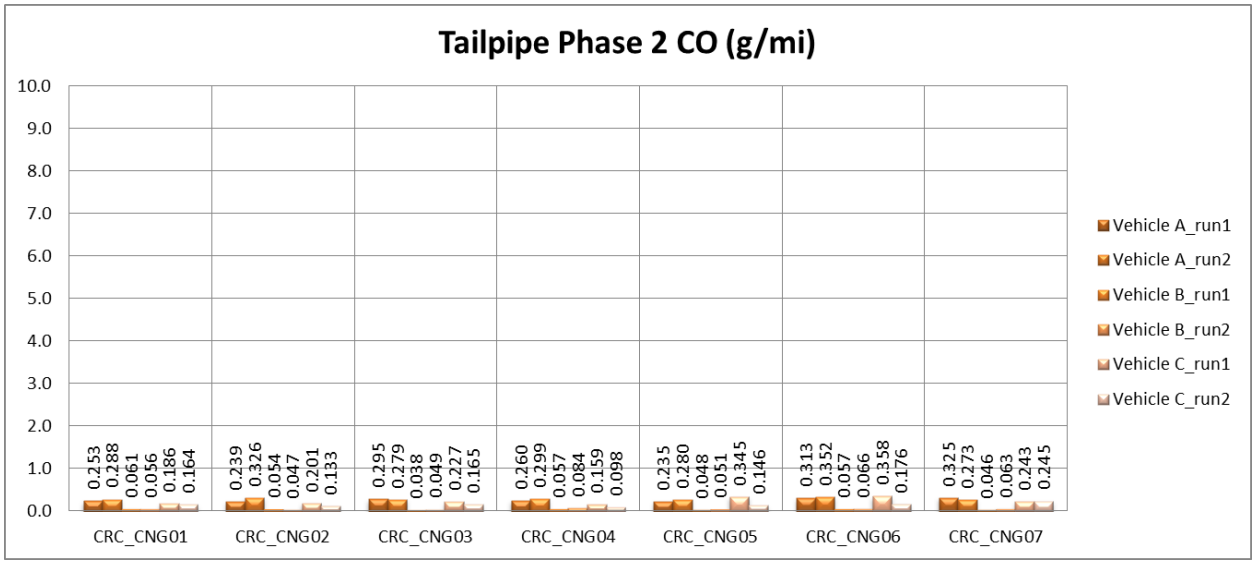

Tailpipe Phase 1 NOx (g/mi)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.014
0.009
0.112
0.172
0.108
0.102
0.013
0.012
0.134
0.208
0.106
0.074
0.011
0.008
0.116
0.255
0.126
0.113
0.005
0.008
0.082
0.077
0.130
0.117
0.008
0.013
0.123
0.123
0.040
0.102
0.004
0.007
0.147
0.115
0.082
0.116
0.008
0.007
0.106
0.121
0.082
0.063
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

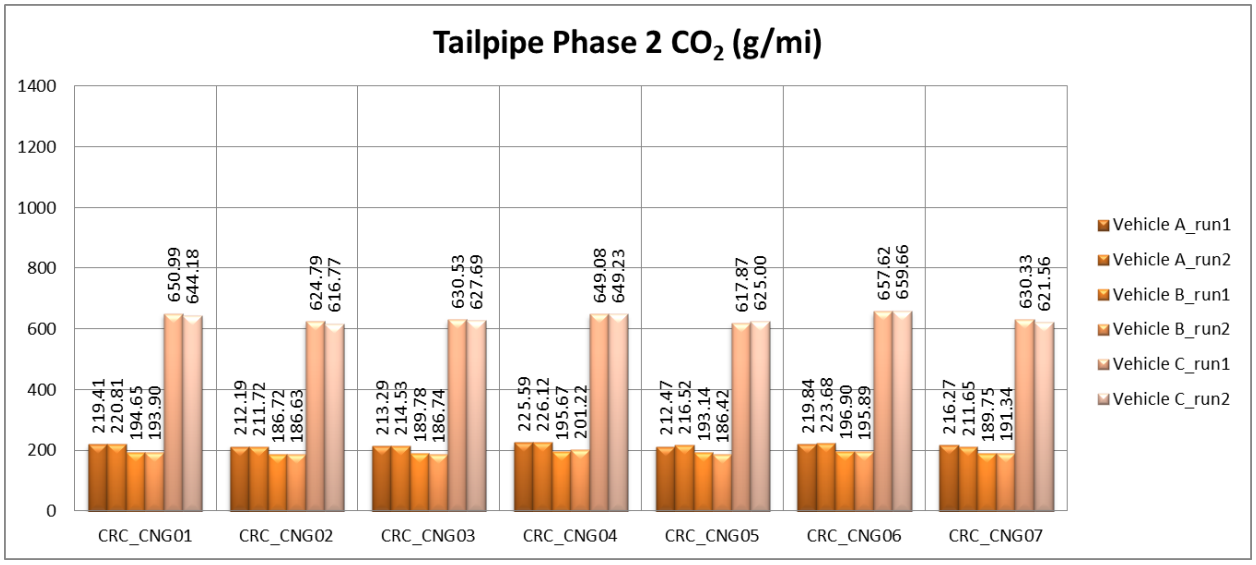

Tailpipe Phase 1 O_2 (g/mi)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
3.56 3.25 7.73 11.06 14.69 18.34
3.11 4.38 11.40 14.37 14.54 16.79
3.23 4.41 9.55 12.59 20.15 23.85
2.43 3.50 11.36 12.11 15.71 13.63
3.41 3.11 10.63 12.37 12.85 12.77
3.70 3.47 13.68 13.02 17.56 10.35
4.04 3.88 7.98 8.82 13.21 14.14
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

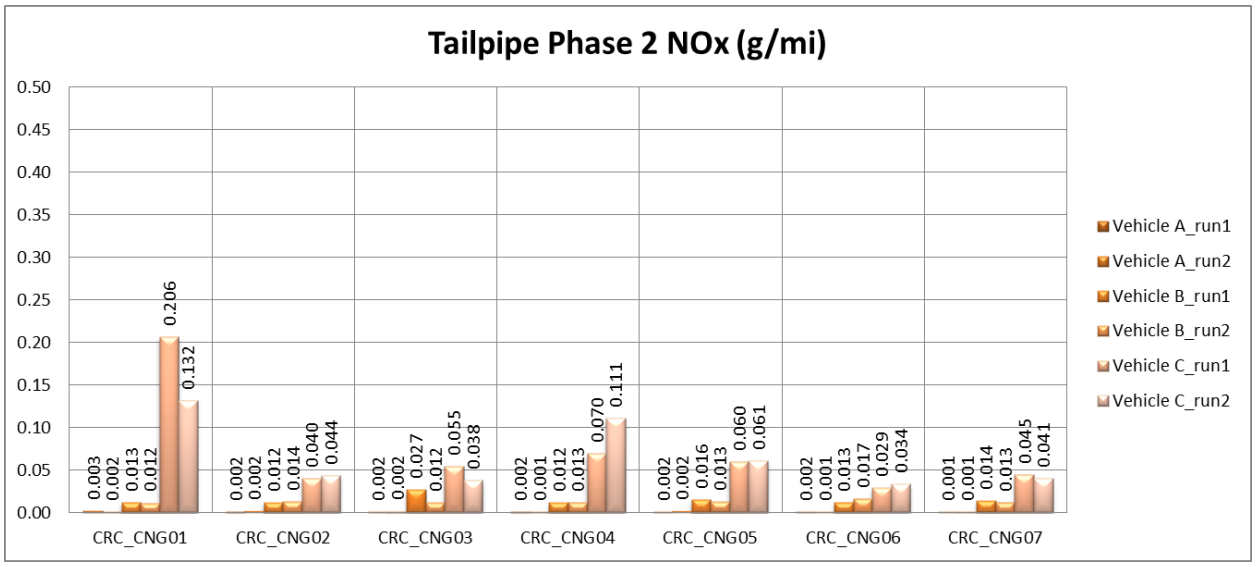

Tailpipe Phase 1 FE (MPGe)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
14.97 14.84 14.28 16.57 5.51 5.52
16.14 16.27 18.03 17.84 5.90 5.89
17.56 17.58 15.52 19.43 6.22 6.35
18.06 18.42 21.18 20.69 6.85 6.68
17.78 18.04 16.36 20.21 6.59 6.56
20.16 19.85 22.90 22.12 7.25 7.25
15.89 16.07 15.36 14.87 6.07 6.04
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

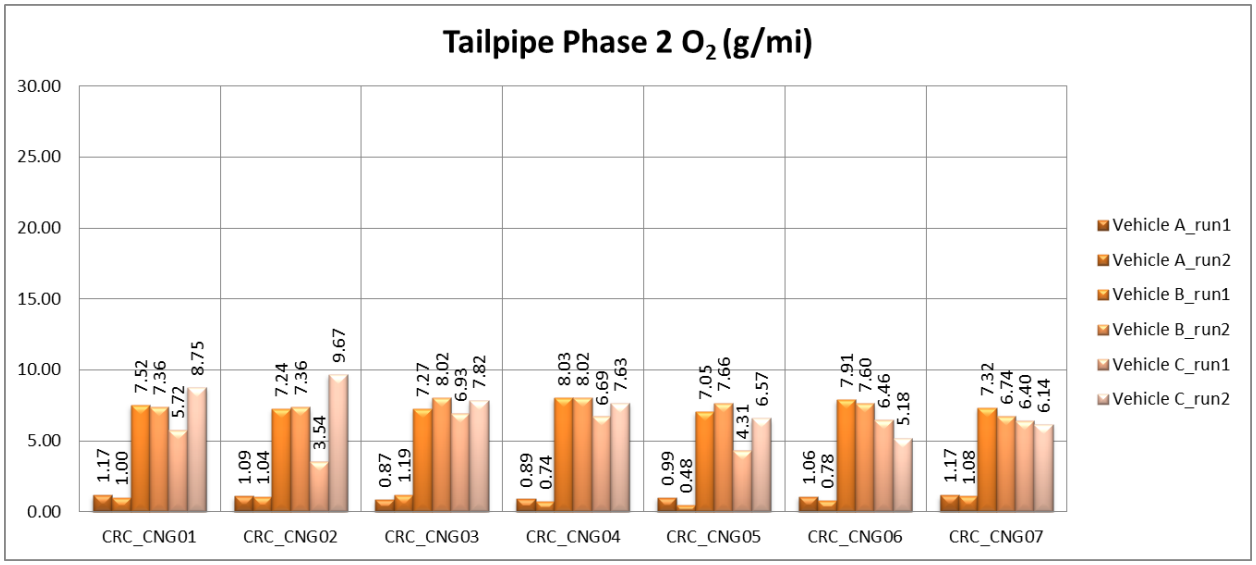
12.14 Appendix 14: Tailpipe Phase 2 Dataset Charts

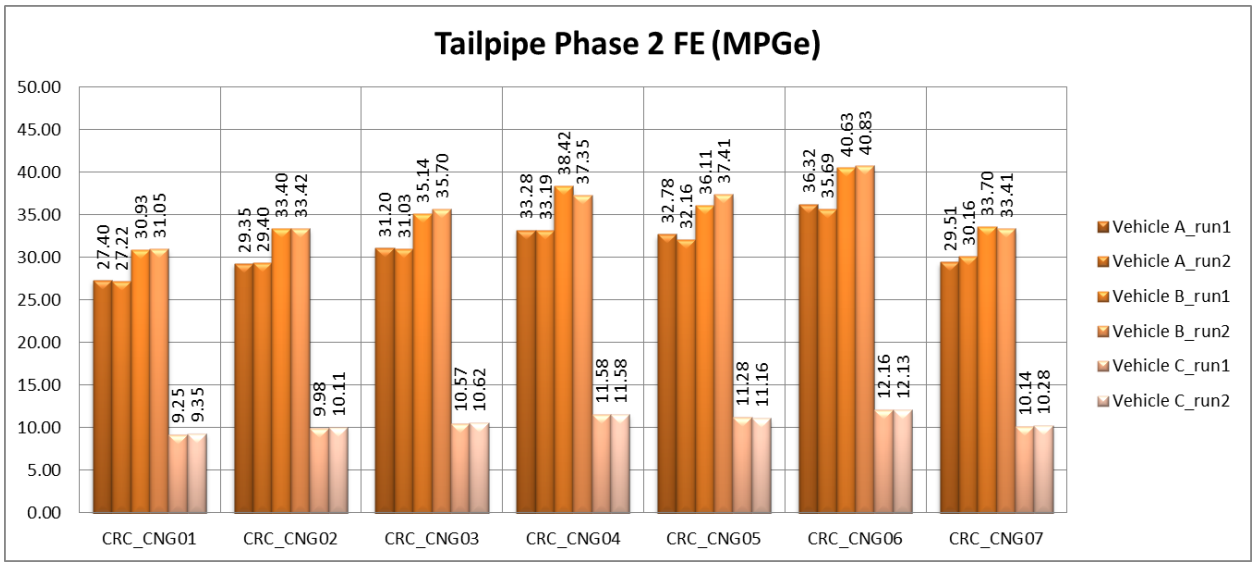




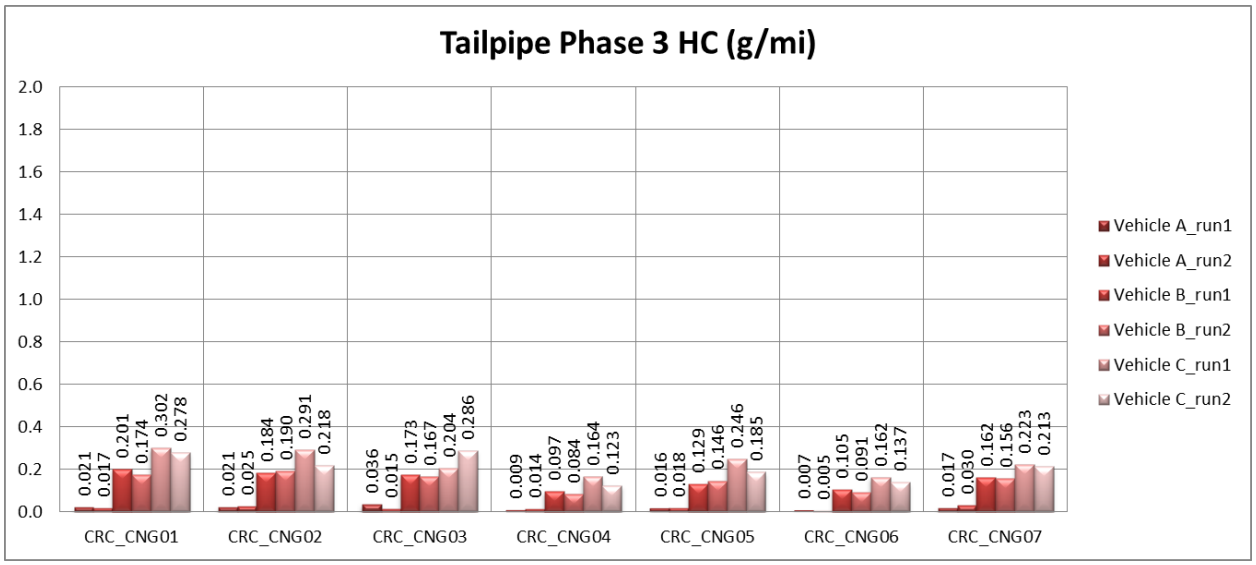

Tailpipe Phase 2 CO_2 (g/mi)
1400
1200
1000
800
600
400
200
0
219.41 220.81 194.65 193.90 650.99 644.18
212.19 211.72 186.72 186.63 624.79 616.77
213.29 214.53 189.78 186.74 630.53 627.69
225.59 226.12 195.67 201.22 649.08 649.23
212.47 216.52 193.14 186.42 617.87 625.00
219.84 223.68 196.90 195.89 657.62 659.66
216.27 211.65 189.75 191.34 630.33 621.56
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

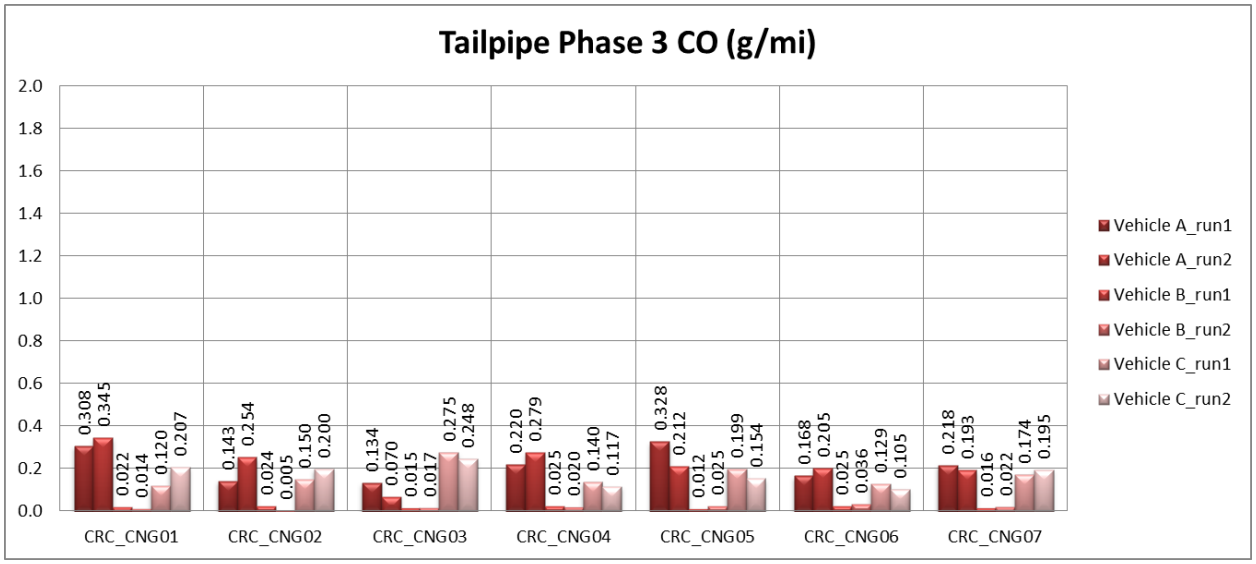

Tailpipe Phase 2 NOx (g/mi)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.003 0.002 0.013 0.012 0.206 0.132
0.002 0.002 0.012 0.014 0.040 0.044
0.002 0.002 0.027 0.012 0.055 0.038
0.002 0.001 0.012 0.013 0.070 0.111
0.002 0.002 0.016 0.013 0.060 0.061
0.002 0.001 0.013 0.017 0.029 0.034
0.001 0.001 0.014 0.013 0.045 0.041
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

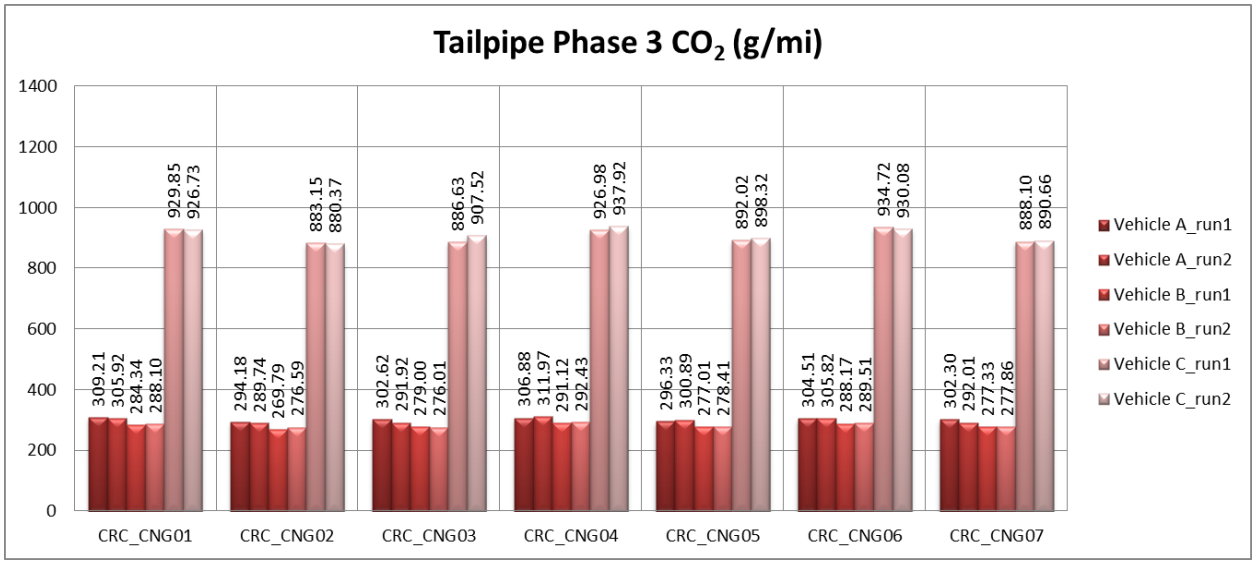

Tailpipe Phase 2 O_2 (g/mi)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1.17 1.00 7.52 7.36 5.72 8.75
1.09 1.04 7.24 7.36 3.54 9.67
0.87 1.19 7.27 8.02 6.93 7.82
0.89 0.74 8.03 8.02 6.69 7.63
0.99 0.48 7.05 7.66 4.31 6.57
1.06 0.78 7.91 7.60 6.46 5.18
1.17 1.08 7.32 6.74 6.40 6.14
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

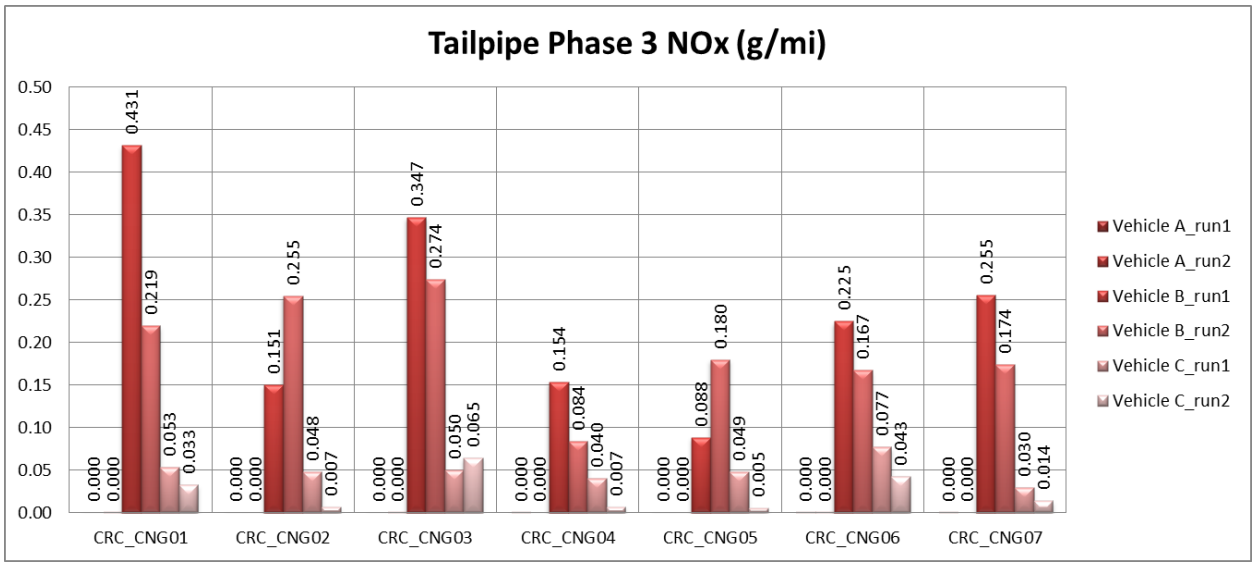

Tailpipe Phase 2 FE (MPGe)
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
27.40 27.22 30.93 31.05 9.25 9.35
29.35 29.40 33.40 33.42 9.98 10.11
31.20 31.03 35.14 35.70 10.57 10.62
33.28 33.19 38.42 37.35 11.58 11.58
32.78 32.16 36.11 37.41 11.28 11.16
36.32 35.69 40.63 40.83 12.16 12.13
29.51 30.16 33.70 33.41 10.14 10.28
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

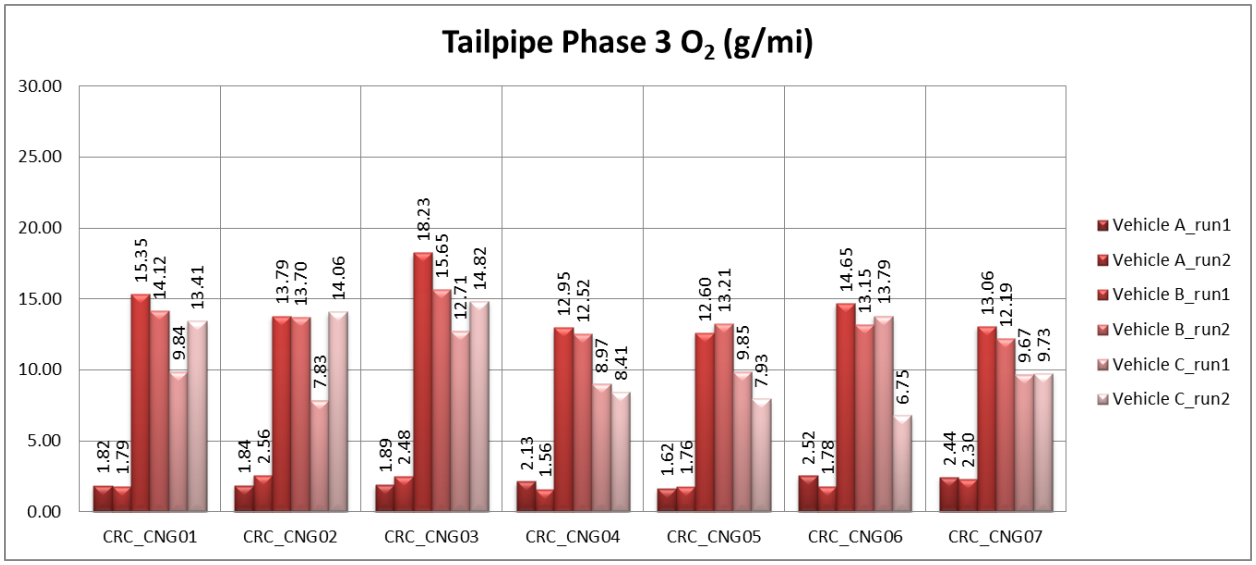
12.15 Appendix 15: Tailpipe Phase 3 Dataset Charts

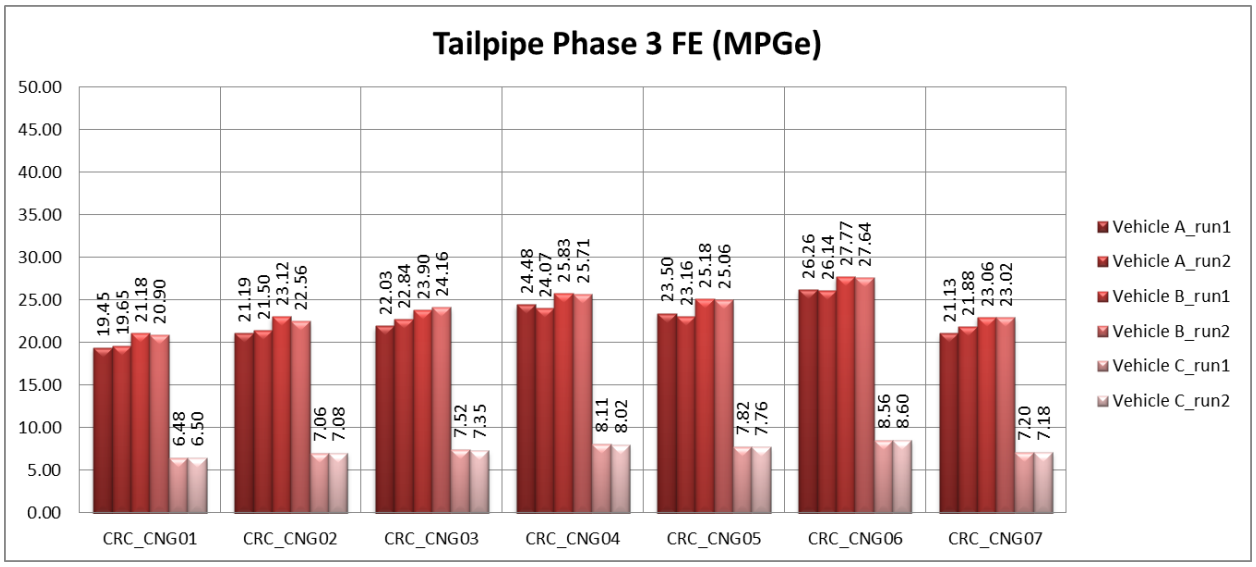




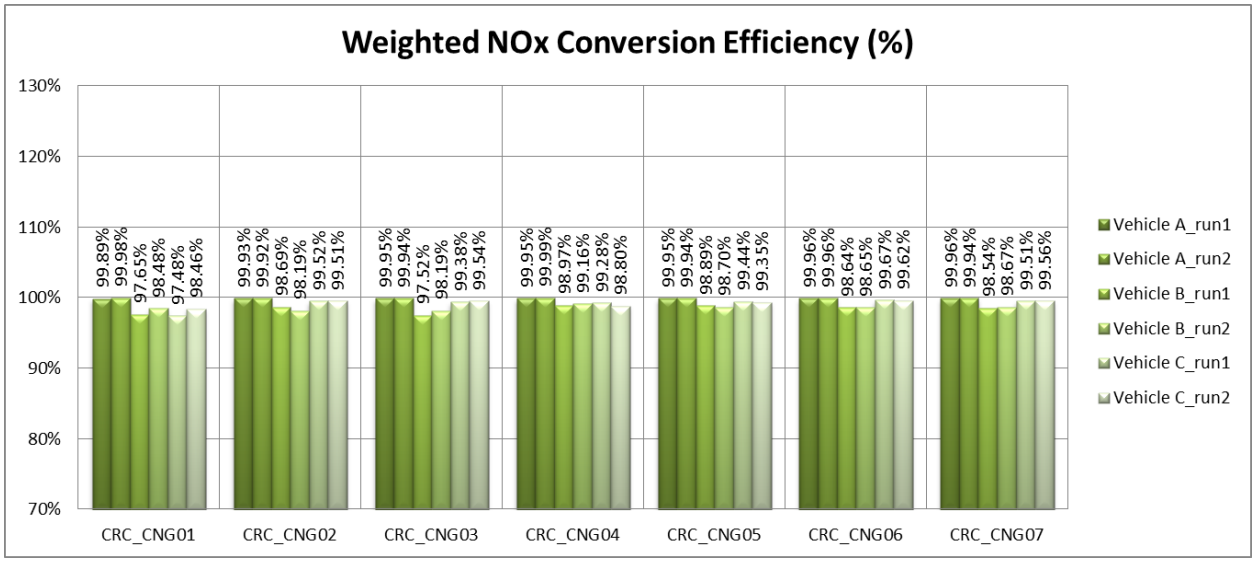

Tailpipe Phase 3 CO_2 (g/mi)
1400
1200
1000
800
600
400
200
0
309.21 305.92 284.34 288.10 929.85 926.73
294.18 289.74 269.79 276.59 883.15 880.37
302.62 291.92 279.00 276.01 886.63 907.52
306.88 311.97 291.12 292.43 926.98 937.92
296.33 300.89 277.01 278.41 892.02 898.32
304.51 305.82 288.17 289.51 934.72 930.08
302.30 292.01 277.33 277.86 888.10 890.66
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

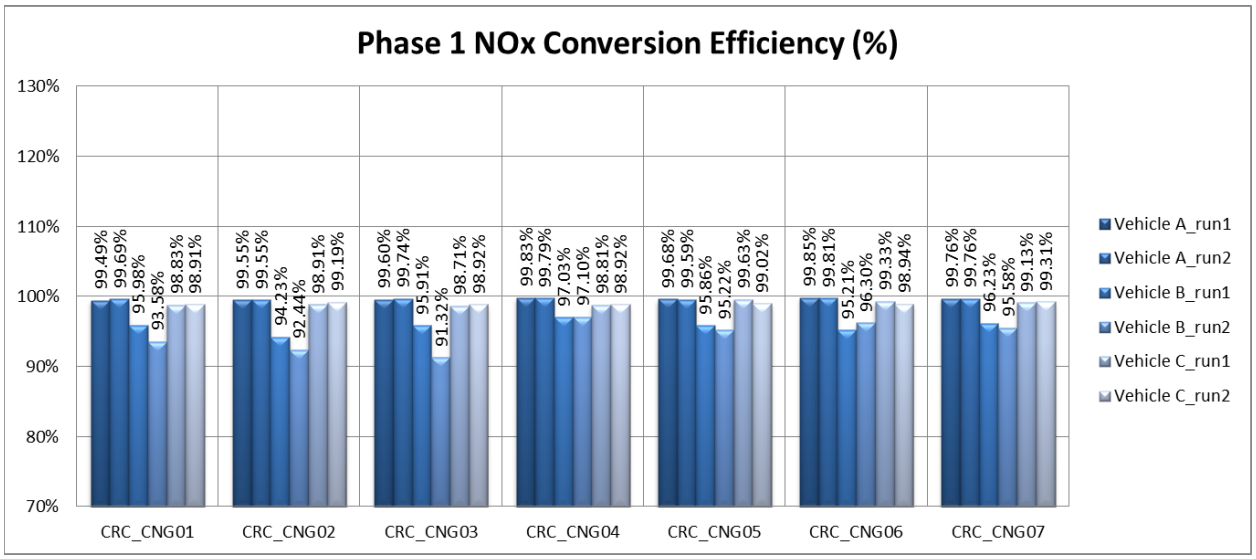

Tailpipe Phase 3 NOx (g/mi)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.000 0.000 0.431 0.219 0.053 0.033
0.000 0.000 0.151 0.255 0.048 0.007
0.000 0.000 0.347 0.274 0.050 0.065
0.000 0.000 0.154 0.084 0.040 0.007
0.000 0.000 0.088 0.180 0.049 0.005
0.000 0.000 0.225 0.167 0.077 0.043
0.000 0.000 0.255 0.174 0.030 0.014
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

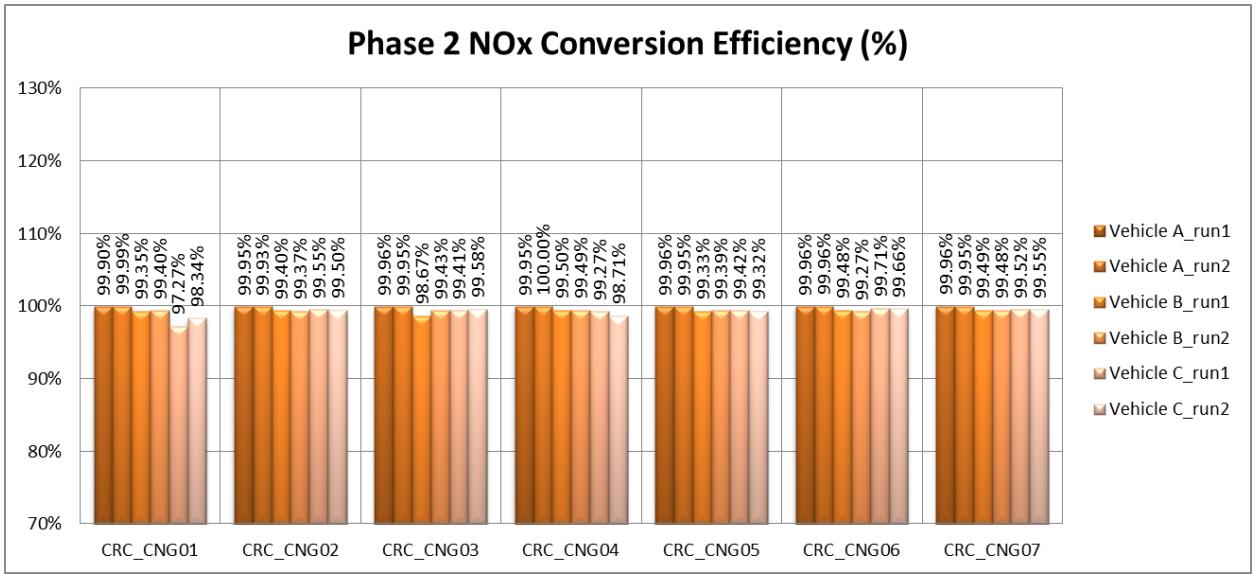

Tailpipe Phase 3 O_2 (g/mi)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1.82 1.79 15.35 14.12 9.84 13.41
1.84 2.56 13.79 13.70 7.83 14.06
1.89 2.48 18.23 15.65 12.71 14.82
2.13 1.56 12.95 12.52 8.97 8.41
1.62 1.76 12.60 13.21 9.85 7.93
2.52 1.78 14.65 13.15 13.79 6.75
2.44 2.30 13.06 12.19 9.67 9.73
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

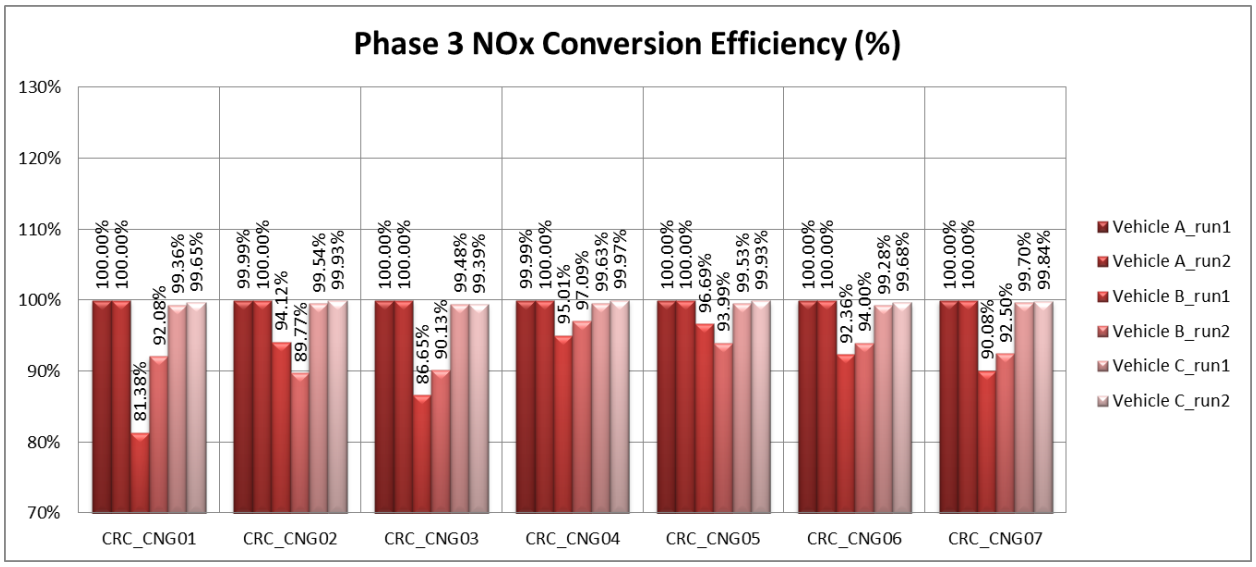

Tailpipe Phase 3 FE (MPGe)
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
19.45 19.65 21.18 20.90 6.48 6.50
21.19 21.50 23.12 22.56 7.06 7.08
22.03 22.84 23.90 24.16 7.52 7.35
24.48 24.07 25.83 25.71 8.11 8.02
23.50 23.16 25.18 25.06 7.82 7.76
26.26 26.14 27.77 27.64 8.56 8.60
21.13 21.88 23.06 23.02 7.20 7.18
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

12.16 Appendix 16: Weighted NOx Conversion Efficiency Dataset Charts

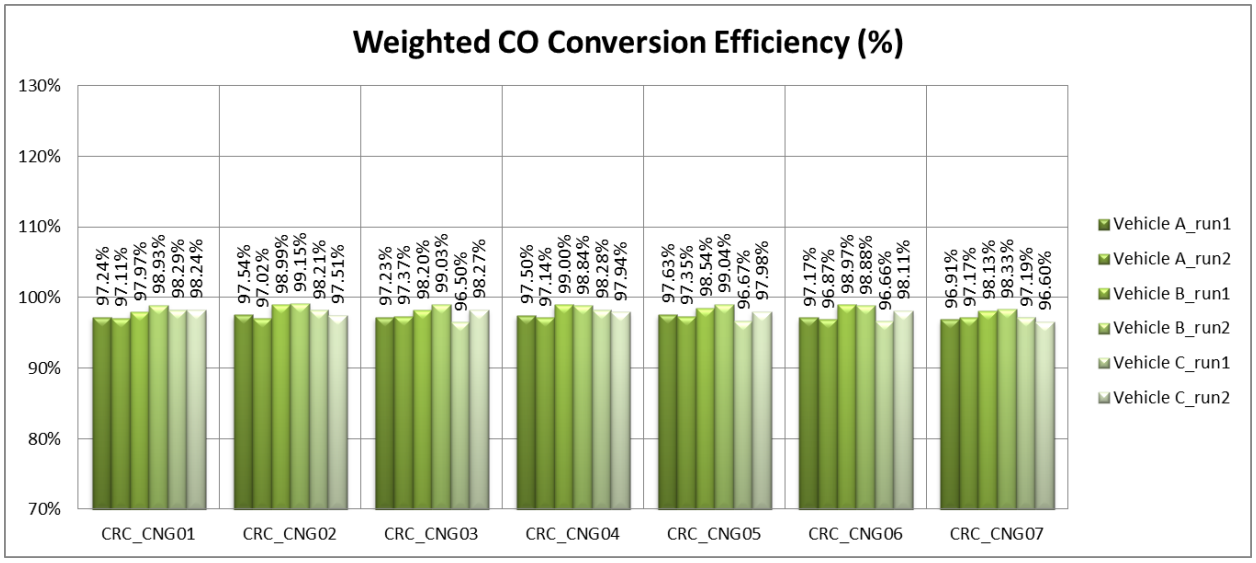


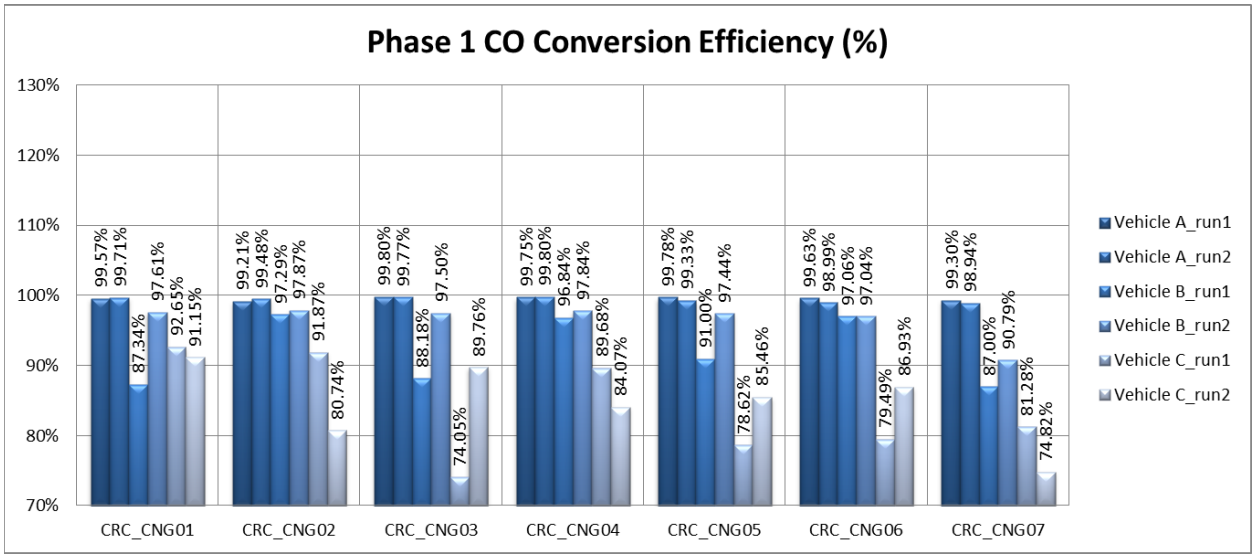


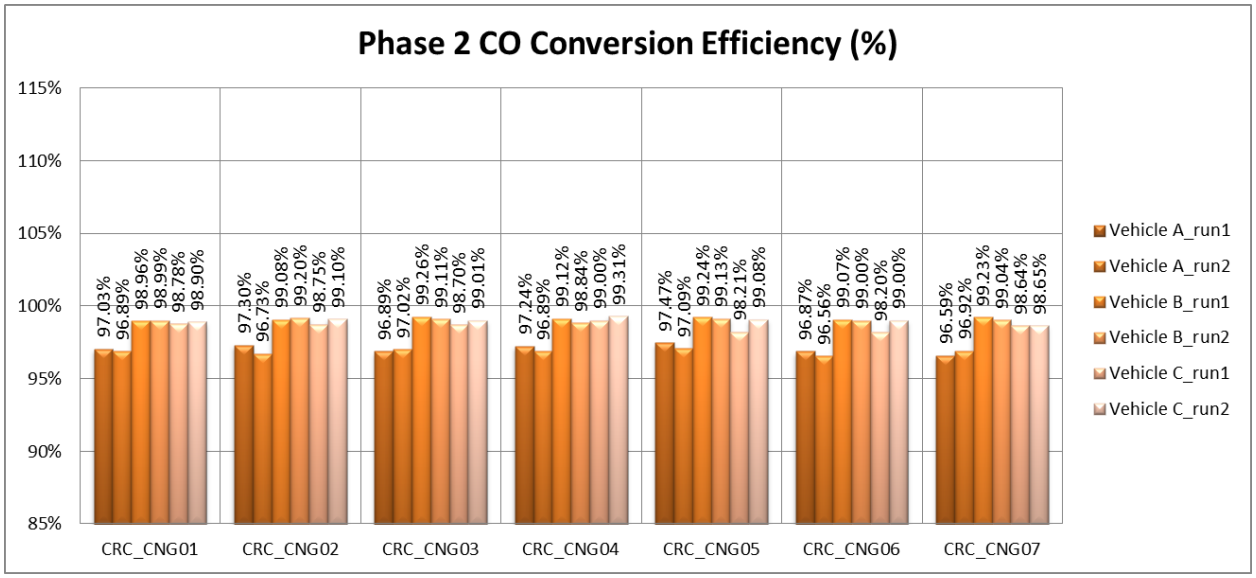

Phase 2 NOx Conversion Efficiency (%)
130%
120%
110%
100%
90%
80%
70%
99.90% 99.99% 99.35% 99.40% 97.27% 98.34%
99.95% 99.93% 99.40% 99.37% 99.55% 99.50%
99.96% 99.95% 98.67% 99.43% 99.41% 99.58%
99.95% 100.00% 99.50% 99.49% 99.27% 98.71%
99.96% 99.95% 99.33% 99.39% 99.42% 99.32%
99.96% 99.96% 99.48% 99.27% 99.71% 99.66%
99.96% 99.95% 99.49% 99.48% 99.52% 99.55%
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

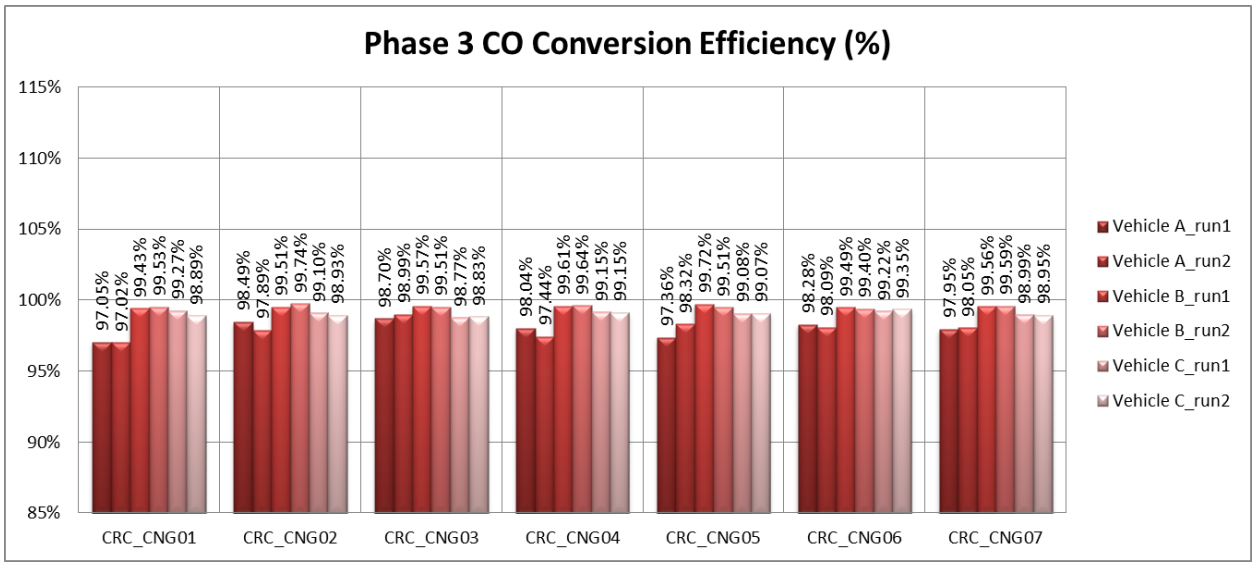

Phase 3 NOx Conversion Efficiency (%)
130%
120%
110%
100%
90%
80%
70%
100.00% 100.00% 81.38% 92.08% 99.36% 99.65%
99.99% 100.00% 94.12% 89.77% 99.54% 99.93%
100.00% 100.00% 86.65% 90.13% 99.48% 99.39%
99.99% 100.00% 95.01% 97.09% 99.63% 99.97%
100.00% 100.00% 96.69% 93.99% 99.53% 99.93%
100.00% 100.00% 92.36% 94.00% 99.28% 99.68%
100.00% 100.00% 90.08% 92.50% 99.70% 99.84%
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

12.17 Appendix 17: Weighted CO Conversion Efficiency Dataset Charts

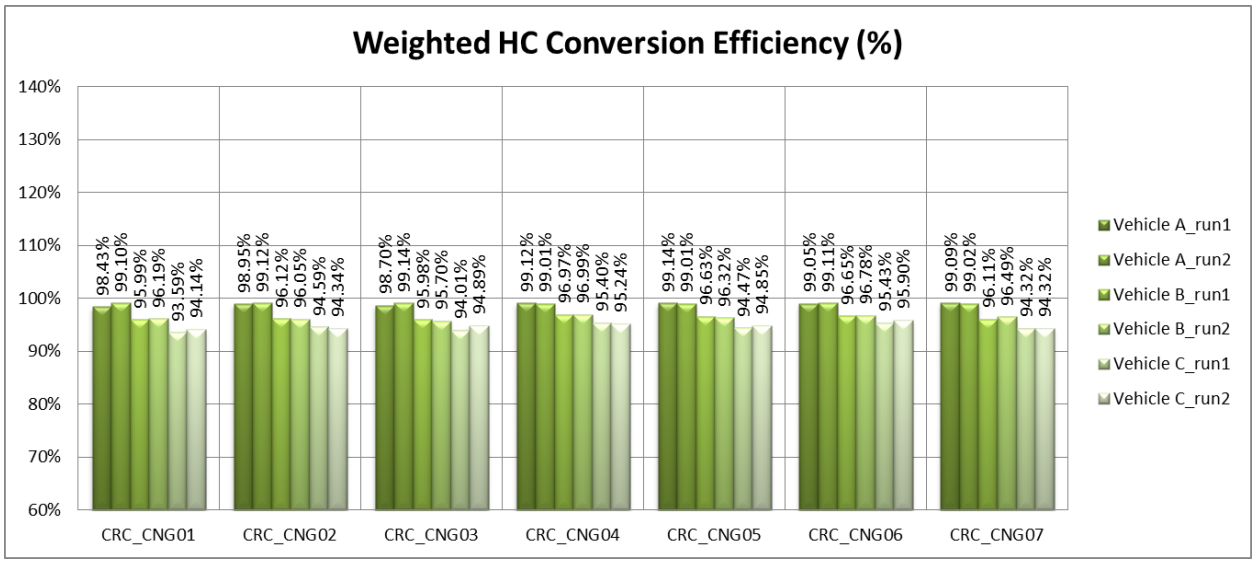


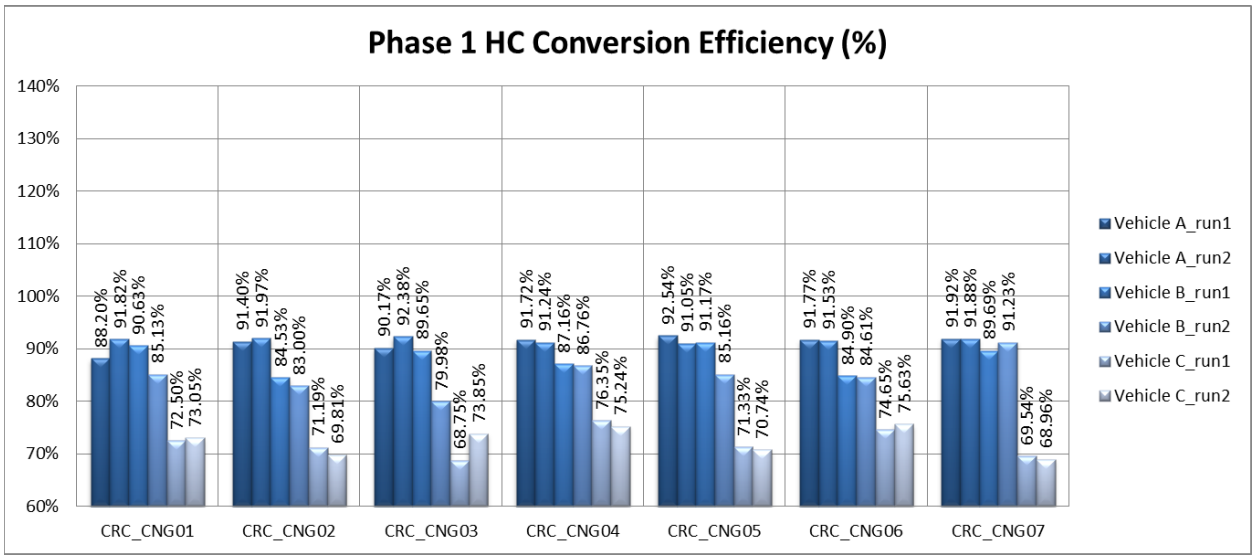


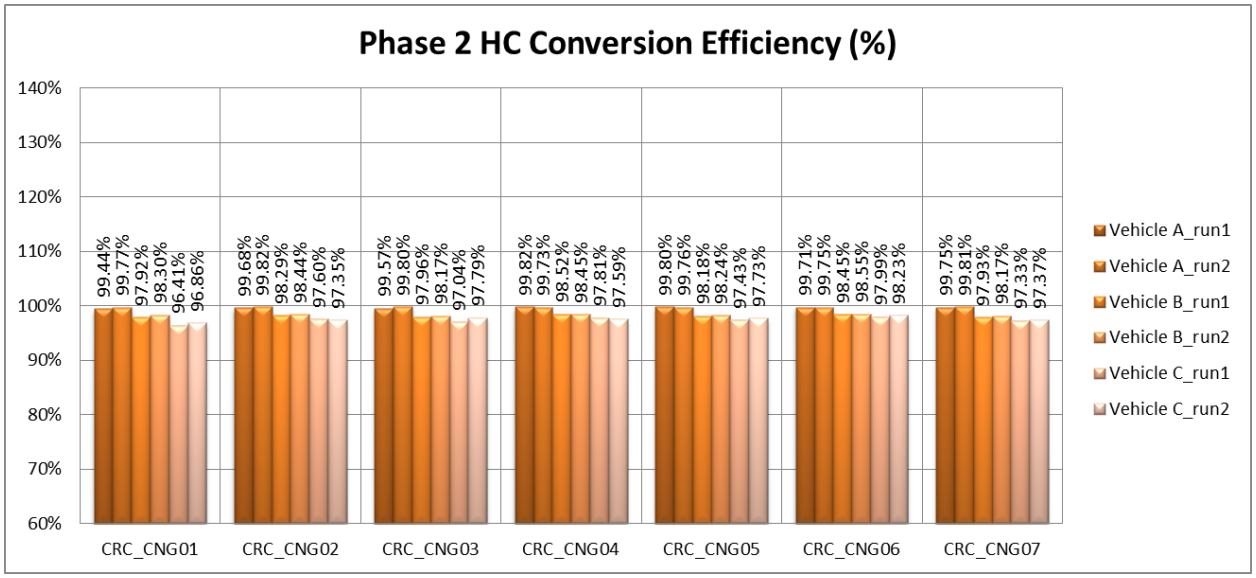

Phase 2 CO Conversion Efficiency (%)
115%
110%
105%
100%
95%
90%
85%
97.03% 96.89% 98.96% 98.99% 98.78% 98.90%
97.30% 96.73% 99.08% 99.20% 98.75% 99.10%
96.89% 97.02% 99.26% 99.11% 98.70% 99.01%
97.24% 96.89% 99.12% 98.84% 99.00% 99.31%
97.47% 97.09% 99.24% 99.13% 98.21% 99.08%
96.87% 96.56% 99.07% 99.00% 98.20% 99.00%
96.59% 96.92% 99.23% 99.04% 98.64% 98.65%
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

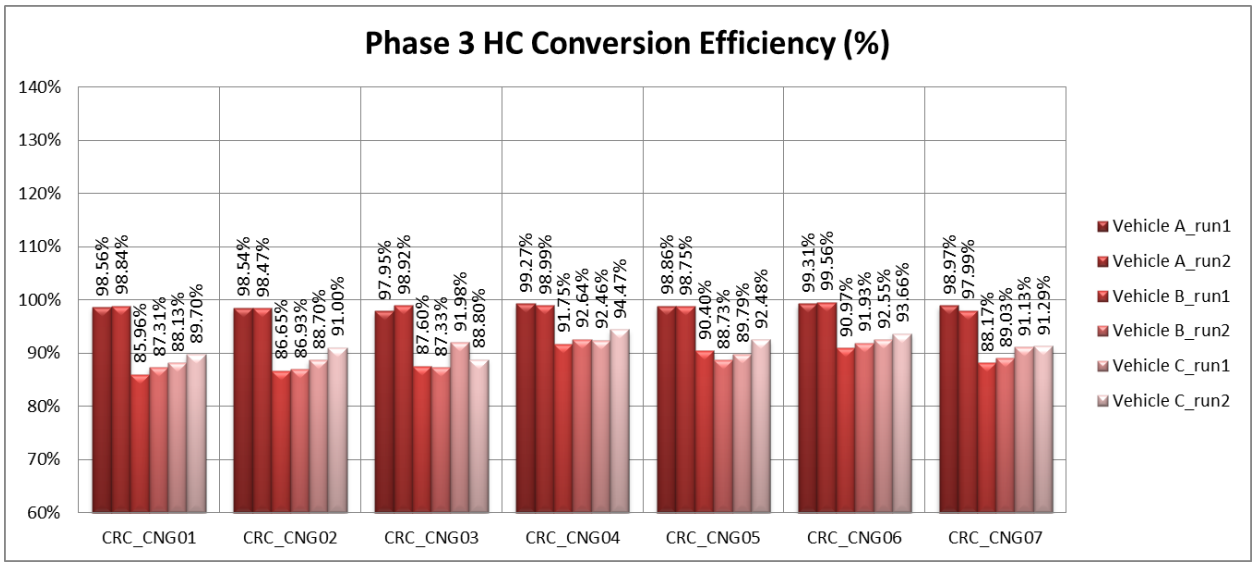

Phase 3 CO Conversion Efficiency (%)
115%
110%
105%
100%
95%
90%
85%
97.05% 97.02% 99.43% 99.53% 99.27% 98.89%
98.49% 97.89% 99.51% 99.74% 99.10% 98.93%
98.70% 98.99% 99.57% 99.51% 98.77% 98.83%
98.04% 97.44% 99.61% 99.64% 99.15% 99.15%
97.36% 98.32% 99.72% 99.51% 99.08% 99.07%
98.28% 98.09% 99.49% 99.40% 99.22% 99.35%
97.95% 98.05% 99.56% 99.59% 98.99% 98.95%
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

12.18 Appendix 18: Weighted THC Conversion Efficiency Dataset Charts

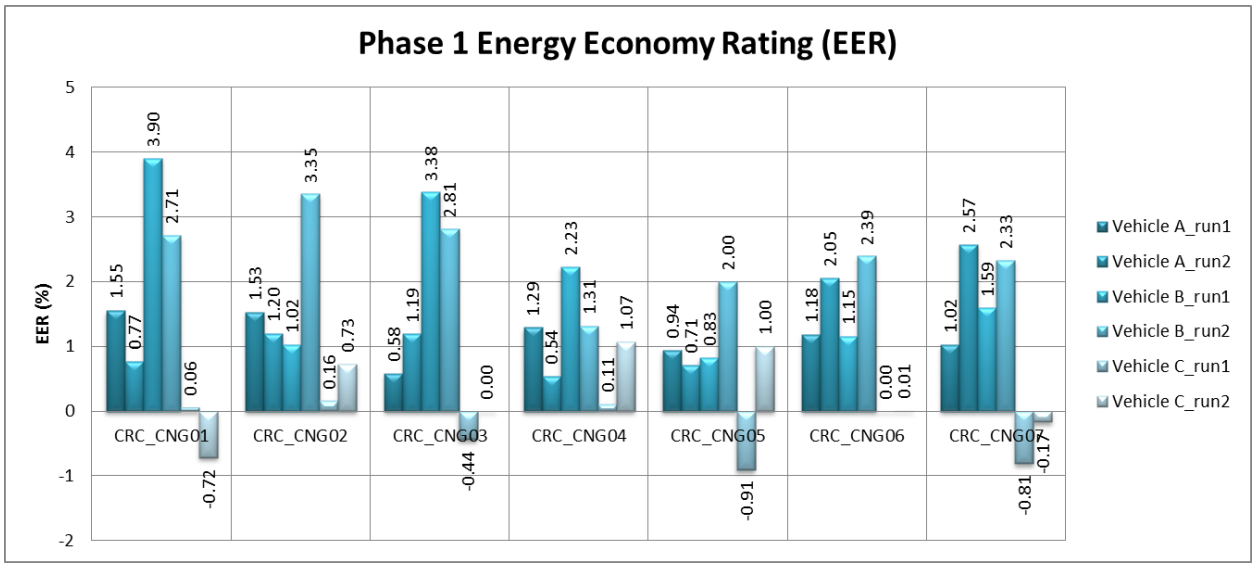


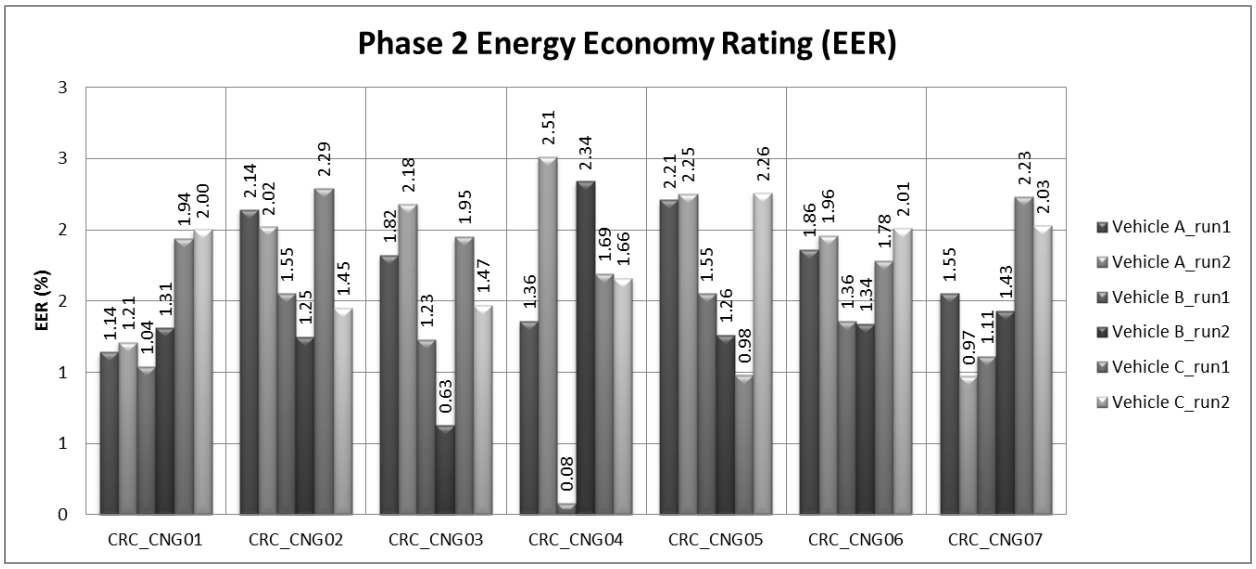


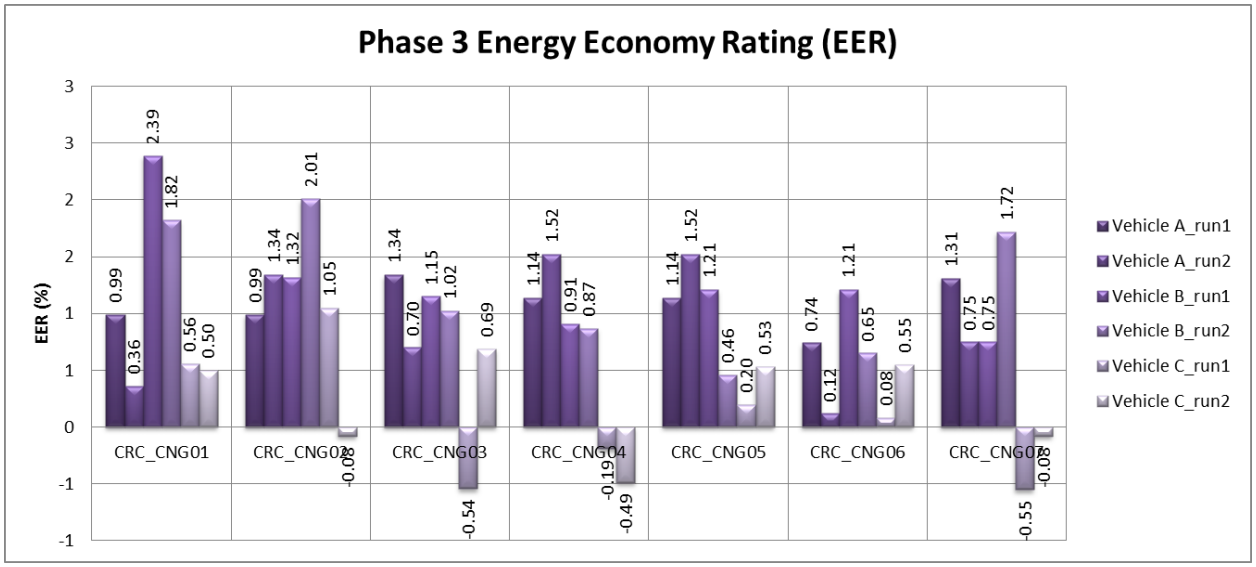

Phase 2 HC Conversion Efficiency (%)
140%
130%
120%
110%
100%
90%
80%
70%
60%
99.44% 99.77% 97.92% 98.30% 96.41% 96.86%
99.68% 99.82% 98.29% 98.44% 97.60% 97.35%
99.57% 99.80% 97.96% 98.17% 97.04% 97.79%
99.82% 99.73% 98.52% 98.45% 97.81% 97.59%
99.80% 99.76% 98.18% 98.24% 97.43% 97.73%
99.71% 99.75% 98.45% 98.55% 97.99% 98.23%
99.75% 99.81% 97.93% 98.17% 97.33% 97.37%
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2


Phase 3 HC Conversion Efficiency (%)
140%
130%
120%
110%
100%
90%
80%
70%
60%
98.56% 98.84% 85.96% 87.31% 88.13% 89.70%
98.54% 98.47% 86.65% 86.93% 88.70% 91.00%
97.95% 98.92% 87.60% 87.33% 91.98% 88.80%
99.27% 98.99% 91.75% 92.64% 92.46% 94.47%
98.86% 98.75% 90.40% 88.73% 89.79% 92.48%
99.31% 99.56% 90.97% 91.93% 92.55% 93.66%
98.97% 97.99% 88.17% 89.03% 91.13% 91.29%
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

12.19 Appendix 19: EPA 40CFR1066 EER Dataset Charts






Phase 3 Energy Economy Rating (EER)
EER (%)
3
3
2
2
1
1
0
-1
-1
0.99
0.36
2.39
1.82
0.56
0.50
0.99
1.34
1.32
2.01
1.05
-0.08
1.34
0.70
1.15
1.02
-0.54
0.69
1.14
1.52
0.91
0.87
-0.19
-0.49
1.14
1.52
1.21
0.46
0.20
0.53
0.74
0.12
1.21
0.65
0.08
0.55
1.31
0.75
0.75
1.72
-0.55
-0.08
CRC_CNG01
CRC_CNG02
CRC_CNG03
CRC_CNG04
CRC_CNG05
CRC_CNG06
CRC_CNG07
Vehicle A_run1
Vehicle A_run2
Vehicle B_run1
Vehicle B_run2
Vehicle C_run1
Vehicle C_run2

12.20 Appendix 20: Empact Analytical Certification Reports

EMPACT

NATURAL GAS ANALYSIS

PROJECT NO. :	**201410122**	ANALYSIS NO. :	**04**
COMPANY NAME :	**SGS AUTOMOTIVE**	ANALYSIS DATE:	OCTOBER 22, 2014
		SAMPLE DATE :	OCTOBER 21, 2014
ACCOUNT NO. :		CYLINDER NO. :	0840
NAME/DESCRIP :	SGS FUEL #1		
	BOTTLE #149765_		
FIELD DATA			
SAMPLED BY :	MARC HENDERSON	SAMPLE TEMP. :	74 F
SAMPLE PRES. :	1800 PSIG	AMBIENT TEMP.:	
COMMENTS :	SPOT; NO PROBE		
	VACUUM DRAWN ON CONNECTION PRIOR TO SAMPLE		

COMPONENTS	NORM. MOLE%	GPM @ **14.73**	GPM @ **14.696**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	1.01	-	-
NITROGEN	0.02	-	-
CO2	4.74	-	-
METHANE	94.23	-	-
ETHANE	0.00	0.000	0.000
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES+	0.00	0.000	0.000
TOTAL	100.00	0.000	0.000

BTU @ 60 DEG F	**14.73**	**14.696**
LOW NET DRY REAL=	860.7	858.7
NET SATURATED REAL=	845.7	843.7
HIGH GROSS DRY REAL =	955.9	953.7
GROSS SATURATED REAL =	939.3	937.1

RELATIVE DENSITY (AIR=1 @14.696 PSIA 60F) : 0.6063

COMPRESSIBILITY FACTOR : 0.99791

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

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EMPACT

NATURAL GAS ANALYSIS

PROJECT NO. :	**201410122**	ANALYSIS NO. :	**06**
COMPANY NAME :	**SGS AUTOMOTIVE**	ANALYSIS DATE:	OCTOBER 22, 2014
		SAMPLE DATE :	OCTOBER 21, 2014
ACCOUNT NO. :		CYLINDER NO. :	1668
NAME/DESCRIP :	SGS FUEL #2		
	BOTTLE #466446		
FIELD DATA			
SAMPLED BY :	MARC HENDERSON	SAMPLE TEMP. :	74 F
SAMPLE PRES. :	1800 PSIG	AMBIENT TEMP.:	
COMMENTS :	SPOT; NO PROBE		
	VACUUM DRAWN ON CONNECTION PRIOR TO SAMPLE		

COMPONENTS	NORM. MOLE%	GPM @ **14.73**	GPM @ **14.696**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.00	-	-
NITROGEN	0.72	-	-
CO2	0.52	-	-
METHANE	98.76	-	-
ETHANE	0.00	0.000	0.000
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES+	0.00	0.000	0.000
TOTAL	100.00	0.000	0.000

BTU @ 60 DEG F	**14.73**	**14.696**
LOW NET DRY REAL=	902.0	899.9
NET SATURATED REAL=	886.3	884.2
HIGH GROSS DRY REAL =	1001.8	999.4
GROSS SATURATED REAL =	984.4	982.0

RELATIVE DENSITY (AIR=1 @14.696 PSIA 60F) : 0.5628

COMPRESSIBILITY FACTOR : 0.99803

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

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NATURAL GAS ANALYSIS

PROJECT NO. :	**201410122**	ANALYSIS NO. :	**05**
COMPANY NAME :	**SGS AUTOMOTIVE**	ANALYSIS DATE:	OCTOBER 22, 2014
		SAMPLE DATE :	OCTOBER 21, 2014
ACCOUNT NO. :		CYLINDER NO. :	1691
NAME/DESCRIP :	SGS FUEL #3		
	BOTTLE #425272		
FIELD DATA			
SAMPLED BY :	MARC HENDERSON	SAMPLE TEMP. :	74 F
SAMPLE PRES. :	1800 PSIG	AMBIENT TEMP.:	
COMMENTS :	SPOT; NO PROBE		
	VACUUM DRAWN ON CONNECTION PRIOR TO SAMPLE		

COMPONENTS	NORM. MOLE%	GPM @ **14.73**	GPM @ **14.696**
HELIUM	0.01	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.47	-	-
NITROGEN	1.93	-	-
CO2	0.69	-	-
METHANE	92.61	-	-
ETHANE	0.00	0.000	0.000
PROPANE	4.29	1.182	1.179
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES+	0.00	0.000	0.000
TOTAL	100.00	1.182	1.179

BTU @ 60 DEG F	**14.73**	**14.696**
LOW NET DRY REAL=	945.9	943.7
NET SATURATED REAL=	929.5	927.3
HIGH GROSS DRY REAL =	1048.1	1045.7
GROSS SATURATED REAL =	1029.9	1027.5

RELATIVE DENSITY (AIR=1 @14.696 PSIA 60F) : 0.6139

COMPRESSIBILITY FACTOR : 0.99771

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

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NATURAL GAS ANALYSIS

PROJECT NO. :	**201410122**	ANALYSIS NO. :	**02**
COMPANY NAME :	**SGS AUTOMOTIVE**	ANALYSIS DATE:	OCTOBER 22, 2014
		SAMPLE DATE :	OCTOBER 21, 2014
ACCOUNT NO. :		CYLINDER NO. :	1705
NAME/DESCRIP :	SGS FUEL #4		
	BOTTLE #166681904		
FIELD DATA			
SAMPLED BY :	MARC HENDERSON	SAMPLE TEMP. :	74 F
SAMPLE PRES. :	1800 PSIG	AMBIENT TEMP.:	
COMMENTS :	SPOT; NO PROBE		
	VACUUM DRAWN ON CONNECTION PRIOR TO SAMPLE		

COMPONENTS	NORM. MOLE%	GPM @ **14.73**	GPM @ **14.696**
HELIUM	0.01	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	1.01	-	-
NITROGEN	4.76	-	-
CO2	2.30	-	-
METHANE	75.12	-	-
ETHANE	10.42	2.786	2.780
PROPANE	3.98	1.096	1.094
ISOBUTANE	0.01	0.003	0.003
N-BUTANE	1.94	0.611	0.610
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.45	0.163	0.163
HEXANES+	0.00	0.000	0.000
TOTAL	100.00	4.659	4.650

BTU @ 60 DEG F	**14.73**	**14.696**
LOW NET DRY REAL=	1024.9	1022.5
NET SATURATED REAL=	1007.1	1004.7
HIGH GROSS DRY REAL =	1131.0	1128.4
GROSS SATURATED REAL =	1111.3	1108.7

RELATIVE DENSITY (AIR=1 @14.696 PSIA 60F) : 0.7293
COMPRESSIBILITY FACTOR : 0.99691

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

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NATURAL GAS ANALYSIS

PROJECT NO. :	**201410122**	ANALYSIS NO. :	**01**
COMPANY NAME :	**SGS AUTOMOTIVE**	ANALYSIS DATE:	OCTOBER 21, 2014
		SAMPLE DATE :	OCTOBER 21, 2014
ACCOUNT NO. :		CYLINDER NO. :	1713
NAME/DESCRIP :	SGS FUEL GAS #5		
	BOTTLE #295730		
FIELD DATA			
SAMPLED BY :	MARC HENDERSON	SAMPLE TEMP. :	74 F
SAMPLE PRES. :	1800 PSIG	AMBIENT TEMP.:	
COMMENTS :	SPOT; NO PROBE		
	VACUUM DRAWN ON CONNECTION PRIOR TO SAMPLE		

COMPONENTS	NORM. MOLE%	GPM @ **14.73**	GPM @ **14.696**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.01	-	-
NITROGEN	0.01	-	-
CO2	0.00	-	-
METHANE	94.71	-	-
ETHANE	0.00	0.000	0.000
PROPANE	5.27	1.452	1.448
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES+	0.00	0.000	0.000
TOTAL	100.00	1.452	1.448

BTU @ 60 DEG F	**14.73**	**14.696**
LOW NET DRY REAL=	988.0	985.7
NET SATURATED REAL=	970.8	968.5
HIGH GROSS DRY REAL =	1094.3	1091.8
GROSS SATURATED REAL =	1075.3	1072.8

RELATIVE DENSITY (AIR=1 @14.696 PSIA 60F) : 0.6062

COMPRESSIBILITY FACTOR : 0.99759

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

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NATURAL GAS ANALYSIS

PROJECT NO. :	**201410122**	ANALYSIS NO. :	**03**
COMPANY NAME :	**SGS AUTOMOTIVE**	ANALYSIS DATE:	OCTOBER 22, 2014
		SAMPLE DATE :	OCTOBER 21, 2014
ACCOUNT NO. :		CYLINDER NO. :	1714
NAME/DESCRIP :	SGS FUEL #6		
	BOTTLE #1001304		
FIELD DATA			
SAMPLED BY :	MARC HENDERSON	SAMPLE TEMP. :	74 F
SAMPLE PRES. :	1800 PSIG	AMBIENT TEMP.:	
COMMENTS :	SPOT; NO PROBE		
	VACUUM DRAWN ON CONNECTION PRIOR TO SAMPLE		

COMPONENTS	NORM. MOLE%	GPM @ **14.73**	GPM @ **14.696**
HELIUM	0.01	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.00	-	-
NITROGEN	0.01	-	-
CO2	2.31	-	-
METHANE	77.83	-	-
ETHANE	13.82	3.695	3.687
PROPANE	4.01	1.104	1.102
ISOBUTANE	0.01	0.003	0.003
N-BUTANE	1.50	0.473	0.472
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.50	0.181	0.181
HEXANES+	0.00	0.000	0.000
TOTAL	100.00	5.456	5.445

BTU @ 60 DEG F	**14.73**	**14.696**
LOW NET DRY REAL=	1094.6	1092.1
NET SATURATED REAL=	1075.6	1073.1
HIGH GROSS DRY REAL =	1207.7	1204.9
GROSS SATURATED REAL =	1186.7	1183.9

RELATIVE DENSITY (AIR=1 @14.696 PSIA 60F) : 0.7158
COMPRESSIBILITY FACTOR : 0.99662

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

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NATURAL GAS ANALYSIS

PROJECT NO. :	**201410122**	ANALYSIS NO. :	**07**
COMPANY NAME :	**SGS AUTOMOTIVE**	ANALYSIS DATE:	OCTOBER 21, 2014
		SAMPLE DATE :	OCTOBER 21, 2014
ACCOUNT NO. :		CYLINDER NO. :	1720
NAME/DESCRIP :	SGS FUEL #7		
	BOTTLE #US-09545		
FIELD DATA			
SAMPLED BY :	MARC HENDERSON	SAMPLE TEMP. :	74 F
SAMPLE PRES. :	1800 PSIG	AMBIENT TEMP.:	
COMMENTS :	SPOT; NO PROBE		
	VACUUM DRAWN ON CONNECTION PRIOR TO SAMPLE		

COMPONENTS	NORM. MOLE%	GPM @ **14.73**	GPM @ **14.696**
HELIUM	0.00	-	-
HYDROGEN	0.00	-	-
OXYGEN/ARGON	0.00	-	-
NITROGEN	0.02	-	-
CO2	1.12	-	-
METHANE	96.65	-	-
ETHANE	2.21	0.591	0.590
PROPANE	0.00	0.000	0.000
ISOBUTANE	0.00	0.000	0.000
N-BUTANE	0.00	0.000	0.000
ISOPENTANE	0.00	0.000	0.000
N-PENTANE	0.00	0.000	0.000
HEXANES+	0.00	0.000	0.000
TOTAL	100.00	0.591	0.590

BTU @ 60 DEG F	**14.73**	**14.696**
LOW NET DRY REAL=	918.8	916.6
NET SATURATED REAL=	902.8	900.6
HIGH GROSS DRY REAL =	1019.8	1017.4
GROSS SATURATED REAL =	1002.1	999.7

RELATIVE DENSITY (AIR=1 @14.696 PSIA 60F) : 0.5764

COMPRESSIBILITY FACTOR : 0.99790

NOTE: REFERENCE GPA 2261(ASTM D1945 & ASME-PTC), 2145, & 2172 CURRENT PUBLICATIONS

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12.21 Appendix 21: Air Gas Certification Reports

Airgas

Airgas USA, LLC
616 Miller Cut Off Road
Laporte, TX 77571
(281) 842-6900 Fax: (281) 471-2518
www.airgas.com

CERTIFICATE OF ANALYSIS

Grade of Product: CERTIFIED STANDARD-SPEC

Customer:	HENDERSON , CO - SGS NORTH AMERICA		
Part Number:	X03ME94C300CPL6	Reference Number:	126-400413793-1
Cylinder Number:	W475945	Cylinder Volume:	274.0 CF
Laboratory:	ASG - LaPorte Mix (SAP) - TX	Cylinder Pressure:	1800 PSIG
Analysis Date:	Aug 19, 2014	Valve Outlet:	350
Lot Number:	126-400413793-1		

Expiration Date: Aug 19, 2017

Product composition verified by direct comparison to calibration standards traceable to N.I.S.T. weights and/or N.I.S.T. Gas Mixture reference materials.

ANALYTICAL RESULTS

Component	Requested Concentration	Actual Concentration (Mole %)	Analytical Uncertainty
OXYGEN	1.000 %	1.016 %	+/- 2%
CARBON DIOXIDE	4.700 %	4.716 %	+/- 2%
METHANE	94.30 %	94.27 %	+/- 2%

Permanent Notes: SGS AUTOMOTIVE FUEL 1

Notes:.
METHANE BALANCE = 94.2680%
PO # 335223
SGS AUTOMOTIVE FUEL 1
BTU @ 14.73 PSIA & 60 DEG F
WOBBE INDEX : 1228.4
BTU REPORT ADDENDUM ATTACHED

Approved for Release

Page 1 of 126-400413793-1

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La Porte, TX 77571
Phone: 281-842-6900 Fax: 281-471-2518
www.airgas.com

Customer Information

Customer Name	SGS NORTH AMERICA	Cylinder Number	W475945
Customer Rep		Cylinder Size	300
Address		Cylinder Pressure	1800 PSIG
City, State, Zip	HENDERSON , CO	CGA	350
Phone		Traceability (NIST)	741720-1
Customer PO#	335223	Certification Date	8/19/2014
Work Order	126-400413793-1	Expiration Date	8/19/2017
Part Number	X03ME94C300CPL6	Ticket Number	

Components and Concentrations

Pressure Base	14.73	100.0000%
CAS #	Component	Concentration
124-38-9	CARBON DIOXIDE	4.7160%
7782-44-7	OXYGEN	1.0160%
74-82-8	METHANE	94.2680%

BTU CALCULATION

	GROSS BTU	NET BTU	Relative Density
REAL, DRY	956.3	861.1	0.6060
REAL, SATURATED	940.0	846.4	0.6065
IDEAL, DRY	954.3	859.3	0.6050
IDEAL, SATURATED	937.7	844.3	0.6053
WOBBE INDEX	1228.4	1106.1	
COMPRESSIBILITY FACTOR (Dry) (Z Factor)		0.99790	
COMPRESSIBILITY FACTOR (Wet) (Z Factor)		0.99757	

Note: All reported values are calculated at 14.73 psia and 60°F in accordance with GPA Standard 2172.09 - "Calculation of Gross Heat Value, Relative Density and Compressibility Factor for Natural Gas Mixtures from Compositional Analysis"

SPECIAL INSTRUCTIONS

SGS AUTOMOTIVE FUEL 1

Approved By : _____ Date : 8/19/2014

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CERTIFICATE OF ANALYSIS

Grade of Product: CERTIFIED HYDROCARBON

Customer:	HENDERSON , CO - SGS NORTH AMERICA		
Part Number:	X03ME98C300CDN5	Reference Number:	126-400411188-1
Cylinder Number:	4147475Y	Cylinder Volume:	270.0 CF
Laboratory:	ASG - LaPorte Mix (SAP) - TX	Cylinder Pressure:	1800 PSIG
Analysis Date:	Aug 18, 2014	Valve Outlet:	350
Lot Number:	126-400411188-1	Expiration Date:	Aug 18, 2017

Traceability Statement: Hydrocarbon Process standards are NIST traceable either directly by weight or by comparison to Airgas laboratory standards that are directly NIST traceable by weight.

CERTIFIED CONCENTRATIONS

Component	Requested Concentration	Reported Mole %	Accuracy
CARBON DIOXIDE	0.5000 %	0.4891 %	+/- 2%
NITROGEN	0.7000 %	0.7020 %	+/- 2%
METHANE	98.80 %	98.81 %	+/- 2%

Permanent Notes:SGS AUTOMOTIVE FUEL 2

Notes:.
METHANE BALANCE = 98.8089%
PO # 335223
BTU @ 14.73 PSIA & 60 DEG F
WOBBE INDEX : 1336.5
BTU REPORT ADDENDUM ATTACHED

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Customer Information

Customer Name	SGS NORTH AMERICA	Cylinder Number	4147475Y
Customer Rep		Cylinder Size	300
Address		Cylinder Pressure	1800
City, State, Zip	HENDERSON , CO	CGA	350
Phone		Traceability (NIST)	741720-1
Customer PO#	335223	Certification Date	8/18/2014
Work Order	126-400411188-1	Expiration Date	8/18/2017
Part Number	X03ME98C300CDN5	Ticket Number	

Components and Concentrations

Pressure Base 14.73 100.0000%

CAS #	Component	Concentration
124-38-9	CARBON DIOXIDE	0.4891%
7727-37-9	NITROGEN	0.7020%
74-82-8	METHANE	98.8089%

BTU CALCULATION

	GROSS BTU	NET BTU	Relative Density
REAL, DRY	1002.3	902.4	0.5624
REAL, SATURATED	985.1	887.0	0.5636
IDEAL, DRY	1000.3	900.6	0.5615
IDEAL, SATURATED	982.9	885.0	0.5626
WOBBE INDEX	1336.5	1203.4	
COMPRESSIBILITY FACTOR (Dry) (Z Factor)		0.99802	
COMPRESSIBILITY FACTOR (Wet) (Z Factor)		0.99769	

Note: All reported values are calculated at 14.73 psia and 60°F in accordance with GPA Standard 2172.09 - "Calculation of Gross Heat Value, Relative Density and Compressibility Factor for Natural Gas Mixtures from Compositional Analysis"

SPECIAL INSTRUCTIONS

Approved By : _____ Date : 8/18/2014

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CERTIFICATE OF ANALYSIS

Grade of Product: CERTIFIED HYDROCARBON

Customer:	HENDERSON , CO - SGS NORTH AMERICA		
Part Number:	X05ME92C300CRC6	Reference Number:	126-400414939-1A
Cylinder Number:	425272	Cylinder Volume:	281.0 CF
Laboratory:	ASG - LaPorte Mix (SAP) - TX	Cylinder Pressure:	1800 PSIG
Analysis Date:	Aug 27, 2014	Valve Outlet:	350
Lot Number:	126-400414939-1A	Expiration Date:	Aug 27, 2017

Traceability Statement: Hydrocarbon Process standards are NIST traceable either directly by weight or by comparison to Airgas laboratory standards that are directly NIST traceable by weight.

CERTIFIED CONCENTRATIONS

Component	Requested Concentration	Reported Mole %	Accuracy
OXYGEN	0.5000 %	0.4847 %	+/- 2%
CARBON DIOXIDE	0.7000 %	0.6663 %	+/- 2%
NITROGEN	2.000 %	1.987 %	+/- 2%
PROPANE	4.300 %	4.352 %	+/- 2%
METHANE	Balance	Balance	

Permanent Notes: SGS AUTOMOTIVE FUEL 3

Notes:.
METHANE BALANCE = 92.5100%
PO # 335223
SGS AUTOMOTIVE FUEL 3
BTU @ 14.73 PSIA & 60 DEG F
WOBBE INDEX : 1337.7
BTU REPORT ADDENDUM ATTACHED

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Customer Information

Customer Name	SGS NORTH AMERICA	Cylinder Number	425272
Customer Rep		Cylinder Size	300
Address		Cylinder Pressure	1800 PSIG
City, State, Zip	HENDERSON , CO	CGA	350
Phone		Traceability (NIST)	741720-1
Customer PO#	335223	Certification Date	8/27/2014
Work Order	126-400414939-1A	Expiration Date	8/27/2017
Part Number	X05ME92C300CRC6	Ticket Number	

Components and Concentrations

Pressure Base	14.73	100.0000%
CAS #	Component	Concentration
7782-44-7	OXYGEN	0.4847%
124-38-9	CARBON DIOXIDE	0.6663%
7727-37-9	NITROGEN	1.9870%
74-98-6	PROPANE	4.3520%
74-82-8	METHANE	92.5100%

BTU CALCULATION

	GROSS BTU	NET BTU	Relative Density
REAL, DRY	1048.7	946.4	0.6145
REAL, SATURATED	1030.8	930.2	0.6149
IDEAL, DRY	1046.3	944.2	0.6134
IDEAL, SATURATED	1028.1	927.8	0.6135
WOBBE INDEX	1337.7	1207.3	
COMPRESSIBILITY FACTOR (Dry) (Z Factor)		0.99770	
COMPRESSIBILITY FACTOR (Wet) (Z Factor)		0.99735	

Note: All reported values are calculated at 14.73 psia and 60°F in accordance with GPA Standard 2172.09 - "Calculation of Gross Heat Value, Relative Density and Compressibility Factor for Natural Gas Mixtures from Compositional Analysis"

SPECIAL INSTRUCTIONS

SGS AUTOMOTIVE FUEL 3

Approved By : _____ Date : 8/27/2014

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CERTIFICATE OF ANALYSIS

Grade of Product: CERTIFIED HYDROCARBON

Customer:	HENDERSON , CO - SGS NORTH AMERICA		
Part Number:	X08ME75C300CNL2	Reference Number:	126-400410049-1
Cylinder Number:	W475941	Cylinder Volume:	315.0 CF
Laboratory:	ASG - LaPorte Mix (SAP) - TX	Cylinder Pressure:	1800 PSIG
Analysis Date:	Aug 26, 2014	Valve Outlet:	350
Lot Number:	126-400410049-1	Expiration Date:	Aug 26, 2017

Traceability Statement: Hydrocarbon Process standards are NIST traceable either directly by weight or by comparison to Airgas laboratory standards that are directly NIST traceable by weight.

CERTIFIED CONCENTRATIONS

Component	Requested Concentration	Reported Mole %	Accuracy
N PENTANE	0.5000 %	0.5013 %	+/- 2%
OXYGEN	1.000 %	1.000 %	+/- 2%
N BUTANE	2.000 %	1.999 %	+/- 2%
CARBON DIOXIDE	2.300 %	2.300 %	+/- 2%
PROPANE	4.000 %	4.000 %	+/- 2%
NITROGEN	4.700 %	4.700 %	+/- 2%
ETHANE	10.50 %	10.50 %	+/- 2%
METHANE	75.00 %	75.00 %	+/- 2%

Permanent Notes: SGS AUTOMOTIVE FUEL 4
MAINTAIN CYLINDER ABOVE 60F OR CALIBRATION ERROR MAY OCCUR.

Notes:.
METHANE BALANCE = 74.9997%
PO # 335223
SGS AUTOMOTIVE FUEL 4
BTU @ 14.73 PSIA & 60 DEG F
WOBBE INDEX : 1327.7
BTU REPORT ADDENDUM ATTACHED

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Customer Information

Customer Name	SGS NORTH AMERICA	Cylinder Number	W475941
Customer Rep		Cylinder Size	300
Address		Cylinder Pressure	1800 PSIG
City, State, Zip	HENDERSON , CO	CGA	350
Phone		Traceability (NIST)	741720-1
Customer PO#	335223	Certification Date	8/26/2014
Work Order	126-400410049-1	Expiration Date	8/26/2017
Part Number	X08ME75C300CNL2	Ticket Number	

Components and Concentrations

Pressure Base	14.73	100.0000%
CAS #	Component	Concentration
124-38-9	CARBON DIOXIDE	2.3000%
74-84-0	ETHANE	10.5000%
106-97-8	N BUTANE	1.9990%
109-66-0	N PENTANE	0.5013%
7727-37-9	NITROGEN	4.7000%
7782-44-7	OXYGEN	1.0000%
74-98-6	PROPANE	4.0000%
74-82-8	METHANE	74.9997%

BTU CALCULATION

	GROSS BTU	NET BTU	Relative Density
REAL, DRY	1135.4	1029.0	0.7314
REAL, SATURATED	1116.1	1011.5	0.7298
IDEAL, DRY	1131.9	1025.8	0.7294
IDEAL, SATURATED	1112.2	1007.9	0.7275
WOBBE INDEX	1327.7	1203.2	
COMPRESSIBILITY FACTOR (Dry) (Z Factor)		0.99688	
COMPRESSIBILITY FACTOR (Wet) (Z Factor)		0.99649	

Note: All reported values are calculated at 14.73 psia and 60°F in accordance with GPA Standard 2172.09 - "Calculation of Gross Heat Value, Relative Density and Compressibility Factor for Natural Gas Mixtures from Compositional Analysis"

SPECIAL INSTRUCTIONS

SGS AUTOMOTIVE FUEL 4

Approved By : _____ Date : 8/26/2014

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CERTIFICATE OF ANALYSIS

Grade of Product: CERTIFIED HYDROCARBON

Customer:	HENDERSON , CO - SGS NORTH AMERICA		
Part Number:	X02ME94C300CQ08	Reference Number:	126-400412626-1
Cylinder Number:	295730	Cylinder Volume:	286.0 CF
Laboratory:	ASG - LaPorte Mix (SAP) - TX	Cylinder Pressure:	1800 PSIG
Analysis Date:	Aug 19, 2014	Valve Outlet:	350
Lot Number:	126-400412626-1	Expiration Date:	Aug 19, 2017

Traceability Statement: Hydrocarbon Process standards are NIST traceable either directly by weight or by comparison to Airgas laboratory standards that are directly NIST traceable by weight.

CERTIFIED CONCENTRATIONS

Component	Requested Concentration	Reported Mole %	Accuracy
PROPANE	5.300 %	5.295 %	+/- 2%
METHANE	94.70 %	94.71 %	+/- 2%

Permanent Notes: SGS AUTOMOTIVE FUEL 5

Notes:
METHANE BALANCE = 94.705%
PO # 335223
SGS AUTOMOTIVE FUEL 5
BTU @ 14.73 PSIA & 60 DEG F
WOBBE INDEX : 1406.1
BTU REPORT ADDENDUM ATTACHED

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Customer Information

Customer Name	SGS NORTH AMERICA	Cylinder Number	295730
Customer Rep		Cylinder Size	300
Address		Cylinder Pressure	1800 PSIG
City, State, Zip	HENDERSON , CO	CGA	350
Phone		Traceability (NIST)	741720-1
Customer PO#	335223	Certification Date	8/19/2014
Work Order	126-400412626-1	Expiration Date	8/19/2017
Part Number	X02ME9E94C300CQ08	Ticket Number	

Components and Concentrations

Pressure Base 14.73

CAS #	Component	Concentration
74-98-6	PROPANE	5.2950%
74-82-8	METHANE	94.7050%

BTU CALCULATION

	GROSS BTU	NET BTU	Relative Density
REAL, DRY	1094.9	988.5	0.6064
REAL, SATURATED	1076.2	971.6	0.6069
IDEAL, DRY	1092.3	986.1	0.6052
IDEAL, SATURATED	1073.3	968.9	0.6055
WOBBE INDEX	1406.1	1269.4	
COMPRESSIBILITY FACTOR (Dry) (Z Factor)		0.99758	
COMPRESSIBILITY FACTOR (Wet) (Z Factor)		0.99722	

Note: All reported values are calculated at 14.73 psia and 60°F in accordance with GPA Standard 2172.09 - "Calculation of Gross Heat Value, Relative Density and Compressibility Factor for Natural Gas Mixtures from Compositional Analysis"

SPECIAL INSTRUCTIONS

SGS AUTOMOTIVE FUEL 5

Approved By : A J Sepulveda

Date : 8/19/2014

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CERTIFICATE OF ANALYSIS

Grade of Product: CERTIFIED HYDROCARBON

Customer:	HENDERSON , CO - SGS NORTH AMERICA		
Part Number:	X06ME77C300CX49	Reference Number:	126-400410051-1
Cylinder Number:	1001304	Cylinder Volume:	315.5 CF
Laboratory:	ASG - LaPorte Mix (SAP) - TX	Cylinder Pressure:	1800 PSIG
Analysis Date:	Aug 18, 2014	Valve Outlet:	350
Lot Number:	126-400410051-1	Expiration Date:	Aug 18, 2017

Traceability Statement: Hydrocarbon Process standards are NIST traceable either directly by weight or by comparison to Airgas laboratory standards that are directly NIST traceable by weight.

CERTIFIED CONCENTRATIONS

Component	Requested Concentration	Reported Mole %	Accuracy
N PENTANE	0.5000 %	0.5027 %	+/- 2%
N BUTANE	1.500 %	1.500 %	+/- 2%
CARBON DIOXIDE	2.300 %	2.303 %	+/- 2%
PROPANE	4.000 %	4.001 %	+/- 2%
ETHANE	13.90 %	13.90 %	+/- 2%
METHANE	77.80 %	77.79 %	+/- 2%

Notes:.
METHANE BALANCE = 77.7933%
PO # 335223
SGS AUTOMOTIVE FUEL 6
BTU @ 14.73 PSIA & 60 DEG F
WOBBE INDEX : 1428.2
BTU REPORT ADDENDUM ATTACHED

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Customer Information

Customer Name	SGS NORTH AMERICA	Cylinder Number	1001304
Customer Rep		Cylinder Size	300
Address		Cylinder Pressure	1800 PSIG
City, State, Zip	HENDERSON , CO	CGA	350
Phone		Traceability (NIST)	741720-1
Customer PO#	335223	Certification Date	8/18/2014
Work Order	126-400410051-1	Expiration Date	8/18/2017
Part Number	X06ME77C300CX49	Ticket Number	

Components and Concentrations

Pressure Base	14.73	100.0000%
CAS #	Component	Concentration
124-38-9	CARBON DIOXIDE	2.3030%
74-84-0	ETHANE	13.9000%
106-97-8	N BUTANE	1.5000%
109-66-0	N PENTANE	0.5027%
74-98-6	PROPANE	4.0010%
74-82-8	METHANE	77.7933%

BTU CALCULATION

	GROSS BTU	NET BTU	Relative Density
REAL, DRY	1208.3	1095.2	0.7159
REAL, SATURATED	1187.8	1076.5	0.7145
IDEAL, DRY	1204.2	1091.4	0.7137
IDEAL, SATURATED	1183.3	1072.4	0.7121
WOBBE INDEX	1428.2	1294.4	
COMPRESSIBILITY FACTOR (Dry) (Z Factor)		0.99661	
COMPRESSIBILITY FACTOR (Wet) (Z Factor)		0.99621	

Note: All reported values are calculated at 14.73 psia and 60°F in accordance with GPA Standard 2172.09 - "Calculation of Gross Heat Value, Relative Density and Compressibility Factor for Natural Gas Mixtures from Compositional Analysis"

SPECIAL INSTRUCTIONS

SGS AUTOMOTIVE FUEL 6

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CERTIFICATE OF ANALYSIS

Grade of Product: CERTIFIED HYDROCARBON

Part Number:	X03ME96C300C027	Reference Number:	126-400416507-1
Cylinder Number:	US-09545	Cylinder Volume:	275.0 CF
Laboratory:	ASG - LaPorte Mix (SAP) - TX	Cylinder Pressure:	1800 PSIG
Analysis Date:	Aug 25, 2014	Valve Outlet:	350
Lot Number:	126-400416507-1	Expiration Date:	Aug 25, 2017

Traceability Statement: Hydrocarbon Process standards are NIST traceable either directly by weight or by comparison to Airgas laboratory standards that are directly NIST traceable by weight.

CERTIFIED CONCENTRATIONS

Component	Requested Concentration	Reported Mole %	Accuracy
CARBON DIOXIDE	1.100 %	1.103 %	+/- 2%
ETHANE	2.200 %	2.218 %	+/- 2%
METHANE	96.70 %	96.68 %	+/- 2%

Permanent Notes: SGS AUTOMOTIVE FUEL 7

Notes:.
METHANE BALANCE = 96.679%
PO # 335223
SGS AUTOMOTIVE FUEL 7
BTU @ 14.73 PSIA & 60 DEG F
WOBBE INDEX : 1343.9
BTU REPORT ADDENDUM ATTACHED

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Customer Information

Customer Name	SGS NORTH AMERICA	**Cylinder Number**	US-09545
Customer Rep		**Cylinder Size**	300
Address		**Cylinder Pressure**	1800 PSIG
City, State, Zip	HENDERSON , CO	**CGA**	350
Phone		**Traceability (NIST)**	741720-1
Customer PO#	335223	**Certification Date**	8/25/2014
Work Order	126-400416507-1	**Expiration Date**	8/25/2017
Part Number	X03ME96C300C027	**Ticket Number**	

Components and Concentrations

Pressure Base	14.73	100.0000%
CAS #	Component	Concentration
74-84-0	ETHANE	2.2180%
124-38-9	CARBON DIOXIDE	1.1030%
74-82-8	METHANE	96.6790%

BTU CALCULATION

	GROSS BTU	NET BTU	Relative Density
REAL, DRY	1020.2	919.2	0.5763
REAL, SATURATED	1002.8	903.5	0.5773
IDEAL, DRY	1018.1	917.2	0.5753
IDEAL, SATURATED	1000.3	901.3	0.5761
WOBBE INDEX	1343.9	1210.8	
COMPRESSIBILITY FACTOR (Dry) (Z Factor)		0.99789	
COMPRESSIBILITY FACTOR (Wet) (Z Factor)		0.99756	

Note: All reported values are calculated at 14.73 psia and 60°F in accordance with GPA Standard 2172.09 - "Calculation of Gross Heat Value, Relative Density and Compressibility Factor for Natural Gas Mixtures from Compositional Analysis"

SPECIAL INSTRUCTIONS

SGS AUTOMOTIVE FUEL 7

Approved By : _____ Date : 8/18/2014