CRC Report No. E-129

ALTERNATIVE OXYGENATE EFFECTS ON EMISSIONS

May 2019

COORDINATING RESEARCH COUNCIL, INC.
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Alternative Oxygenate Effects on Emissions

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SGS Aurora is an accredited laboratory, in certification with
ISO 14001:2004, and ISO 17025:2005 for performing vehicle and engine emissions tests.
Orion Registrar, Inc. Certificate Number 1014098.
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ACCREDITED 1975-01

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Abbreviations and Acronyms

AKI ..... Antiknock Index (octane number)
ASTM ..... American Society for Testing and Materials
CAFE ..... Corporate Average Fuel Economy
CFR ..... Code of Federal Regulations
CH_4 ..... Methane
CLD ..... Chemiluminescent Detector
cm ..... Centimeter
CO ..... Carbon Monoxide
CO_2 ..... Carbon Dioxide
COA ..... Certificate of Analysis
CRC ..... Coordinating Research Council
CREE ..... Carbon related exhaust emissions
CVT ..... Continuously Variable Transmission

DHA ..... Detailed Hydrocarbon Analysis
GHG ..... Green-house Gas
FID ..... Flame Ionization Detector
FTP ..... Federal Test Procedure
EPA ..... Environmental Protection Agency
ETOH ..... Ethanol
E0..... Neat gasoline (not containing ethanol)
E10..... Gasoline containing 10 vol% ethanol
E15..... Gasoline containing 15 vol% ethanol
ETW ..... Equivalent Test Weight
FBP ..... Final Boiling Point
Fuel C..... Non-oxygenated hydrocarbon fuel with low propensity for PM formation re-blended to match the original "Fuel C" used in the CRC E-94-2 program
g..... Gram
GDI ..... Gasoline Direct Injection
hr ..... Hour
HoV..... Heat of Vaporization
IBP ..... Initial Boiling Point
IBUT ..... Isobutanol (i-Butanol)
ISO ..... International Organization for Standardization
km..... Kilometer
kPaA ..... Kilopascal (absolute)
lbs ..... pounds
MAF ..... Mass Air Flow
µg ..... Microgram
MHz ..... Mega hertz
MPH..... Miles per hour
MTBE ..... Methyl Tert-Butyl Ether
N_2O ..... Nitrous Oxide
NA ..... Naturally Aspirated
NDIR ..... Non-dispersive infrared
nm ..... Nanometer
NMHC ..... Non-methane hydrocarbons
NMOG ..... Non-methane organic gas
NO_x ..... Oxides of Nitrogen ($NO + NO_2$)
O_3..... Ozone
OBDII ..... On-board Diagnostics II
OFCEAS..... Optical Feedback Cavity Enhanced Absorption Spectroscopy
pm ..... Picometer
PM ..... Particulate Matter
PMI ..... Particulate Matter Index
PTFE..... Polytetrafluoroethylene
RPM..... Revolutions per minute (engine speed)
s ..... second
SAE ..... Society of Automotive Engineering
SEE..... Standard Error of the Estimate
SIDI ..... Spark-Induced Direct-Injected
SRC ..... Standard Road Cycle
TC ..... Turbocharger (Turbocharged)
THC ..... Total Hydrocarbons

UDDS ..... Urban Dynamometer Driving Schedule
v..... Volt
vol%..... Volume percent
VP ..... Vapor Pressure at 100 °F
VW..... Volkswagen
wt%..... Weight percent

Acknowledgments

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Robert Crawford of Rincon Ranch Consulting (Tucson, AZ) conducted the statistical analysis of the data, under independent contract with CRC. That work was incorporated into this report as Section 8 and the last part of the Executive Summary. Jim Lyons of Trinity Consultants (Sacramento, CA) assisted in the interpretation of the results from the perspective of emission control design and operation.

The authors also acknowledge funding and technical support from the working members of the Coordinating Research Council (CRC) Emissions Committee.

1. Executive Summary

The continued demand for improvement in the fuel-efficiency of the automobile engine has greatly influenced the market share of engine technologies such as engine down-sizing and the use of turbochargers. The Corporate Average Fuel Economy (CAFE) and Green-House Gas (GHG) emissions regulations currently in place will only encourage the expansion of these engine strategies to meet these ever more stringent standards. In addition, gasoline blended with 10% ethanol by volume comprises more than 95%[1] of the currently available commercial vehicle fuel sold. Automotive manufacturers have focused their engine calibrations and designs on meeting CAFE and GHG targets using all available combinations of engine-technologies and fuel-blends. There is an interest in evaluating the impact of higher ethanol-blends as well as gasoline blended with other types of oxygenates on the tailpipe emissions and fuel economy of motor vehicles using these technologies.

This study evaluated the tailpipe emissions of four model year 2012-2013 light-duty gasoline vehicles equipped with in-line 4-cylinder spark-ignited direct-injected engines with various size, charge-air and transmission configurations and represented of a range of automotive manufacturers including: Volkswagen, Honda and General Motors.

Eight fuels were used for testing during this project. A base non-oxygenated regular grade gasoline that would be rated low for its propensity to form PM was re-blended for this study to conform to the specifications of Fuel C in the CRC E-94-2 assessment of particulate emissions from spark-ignited, direct-injected (SIDI) vehicles. Six different oxygenated fuels were created by splash-blending varying amounts of ethanol, i-butanol, and MTBE with non-oxygenate Fuel C described above to achieve two different levels for oxygen content (nominally 3.5 wt% and 5.5 wt%) with each oxygenated fuel. The eighth fuel was a non-oxygenated certification gasoline compliant with the Tier 2 fuel specifications described in 40 CFR Part 86 for the Federal Test Procedure ("Cert Fuel") and was used in baseline testing at the beginning and end of the study to monitor any change in vehicle performance.

Tailpipe emissions were collected at least twice for each vehicle/fuel combination using the LA92 Unified Cycle. Fuel conditioning and testing protocols were followed according to the previous CRC E-94-2 program. In addition to the E-94-2 testing protocols, tailpipe emissions were collected over triplicate FTP cycles at the beginning and end of the test program to evaluate potential drift in any of the test vehicles, analyzers or procedures.

The addition of oxygenates reduced the four-vehicle, fleet average emission rates of THC, CO, NO_x, NMHC, N_2O and PM in comparison to the non-oxygenated base fuel (Fuel C) as shown in Figure 1-1. The fuel containing 10% ethanol was observed to have a much smaller influence on a change in fleet average tailpipe emissions when compared to the effects associated with the other five oxygenated test fuels.

[1] U.S. Energy Information Administration. (2016, May 4). *Today in Energy*. Retrieved from EIA: https://www.eia.gov/todayinenergy/detail.php?id=26092

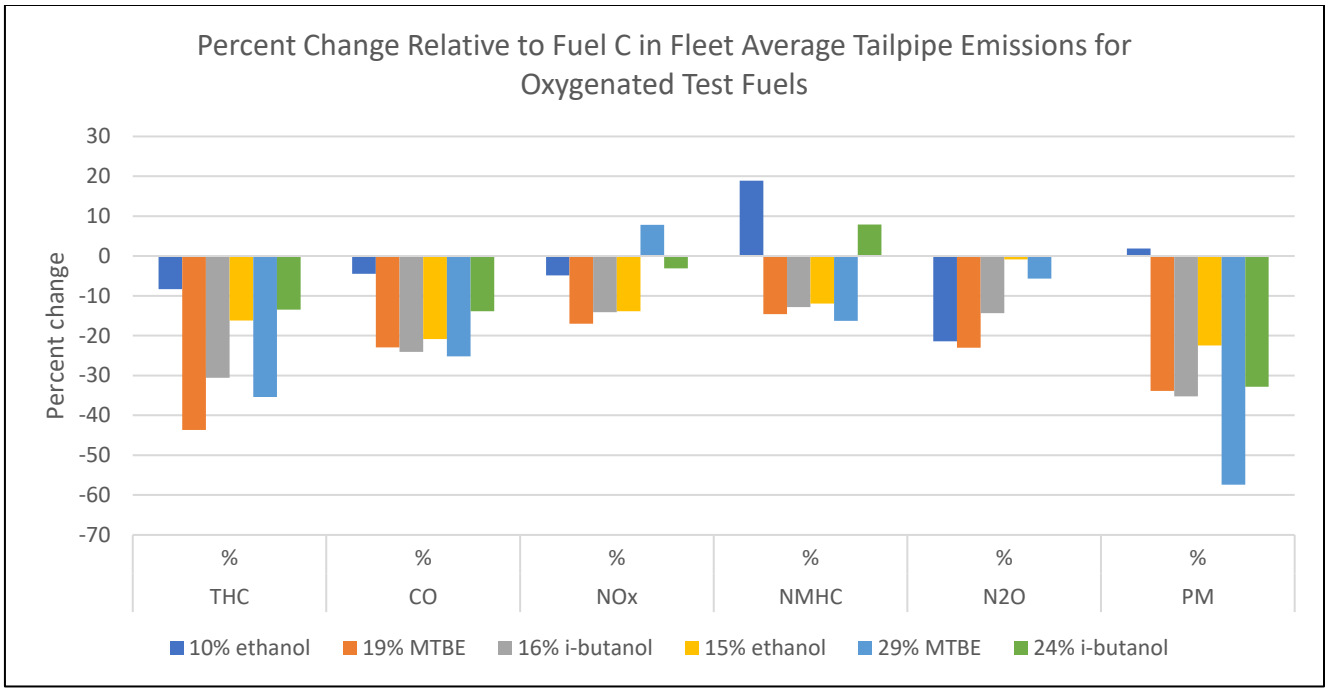

Figure 1-1 Percent Change in Fleet Average Tailpipe Emissions

The propensity of a fuel to increase PM emissions was characterized in this study by the PMI (Particulate Matter Index), which calculates an index value based on a detailed speciation of hydrocarbons in the fuel and selected characteristics of each compound. In the case of i-butanol, the reported PMI of 24% i-butanol (1.09) was inconsistent with the PMI expected as a result of splash-blending the base non-oxygenated test fuel (Fuel C) and thereby diluting the individual i-value components of the base fuel. Figure 1-2 shows that the dilution of the base non-oxygenated Fuel C is the predominant source in the reduction of PMI for all oxygenated test fuels in this study with the exception of 24% i-butanol.

Even though the reported PMI for 24% i-butanol was inconsistent with the expected PMI, this study observed that the fleet average tailpipe PM emissions for all test fuels were consistent with the calculated PMI values. Figure 1-3 shows the correlation of the percent change in fleet average PM emissions versus the corresponding percent change in PMI relative to each fuel-blend's smallest oxygen containing varietal with R^2 of 0.993, as shown with the black-dashed trendline. If the intercept is fixed at zero (representing that no change in PMI would result in no change in PM emissions), the R^2 value is 0.9736 as shown with the blue-dotted trendline. The addition of oxygen by wt% with respect to the 10% ethanol and 19% MTBE oxygenates reduced their PMI by 6.5% and 11.7%, respectively. The fleet average PM emissions for 15% ethanol and 29% MTBE decreased by 23.9% and 35.6% when compared to 10% ethanol and 19% MTBE. In contrast, the addition of more oxygen wt% with respect to the 16% i-butanol oxygenate slightly raised its PMI by 2.1%. The fleet average PM emissions for 24% i-butanol increased by 3.7% when compared to 16% i-butanol. The correlation shown in Figure 1-3 supports the relationship between PMI and PM emissions and further supports the accuracy in the PMI calculations as a result of this study.

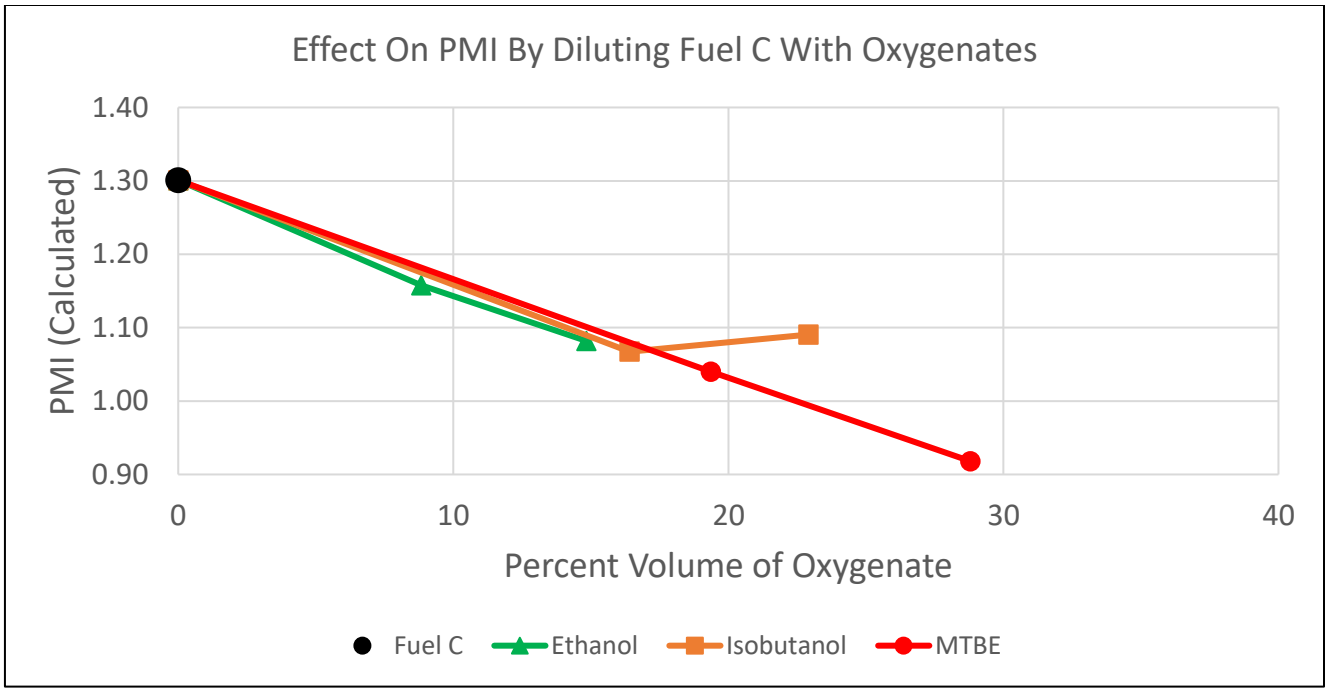

Figure 1-2 Effect on PMI by Diluting Fuel C with Oxygenates

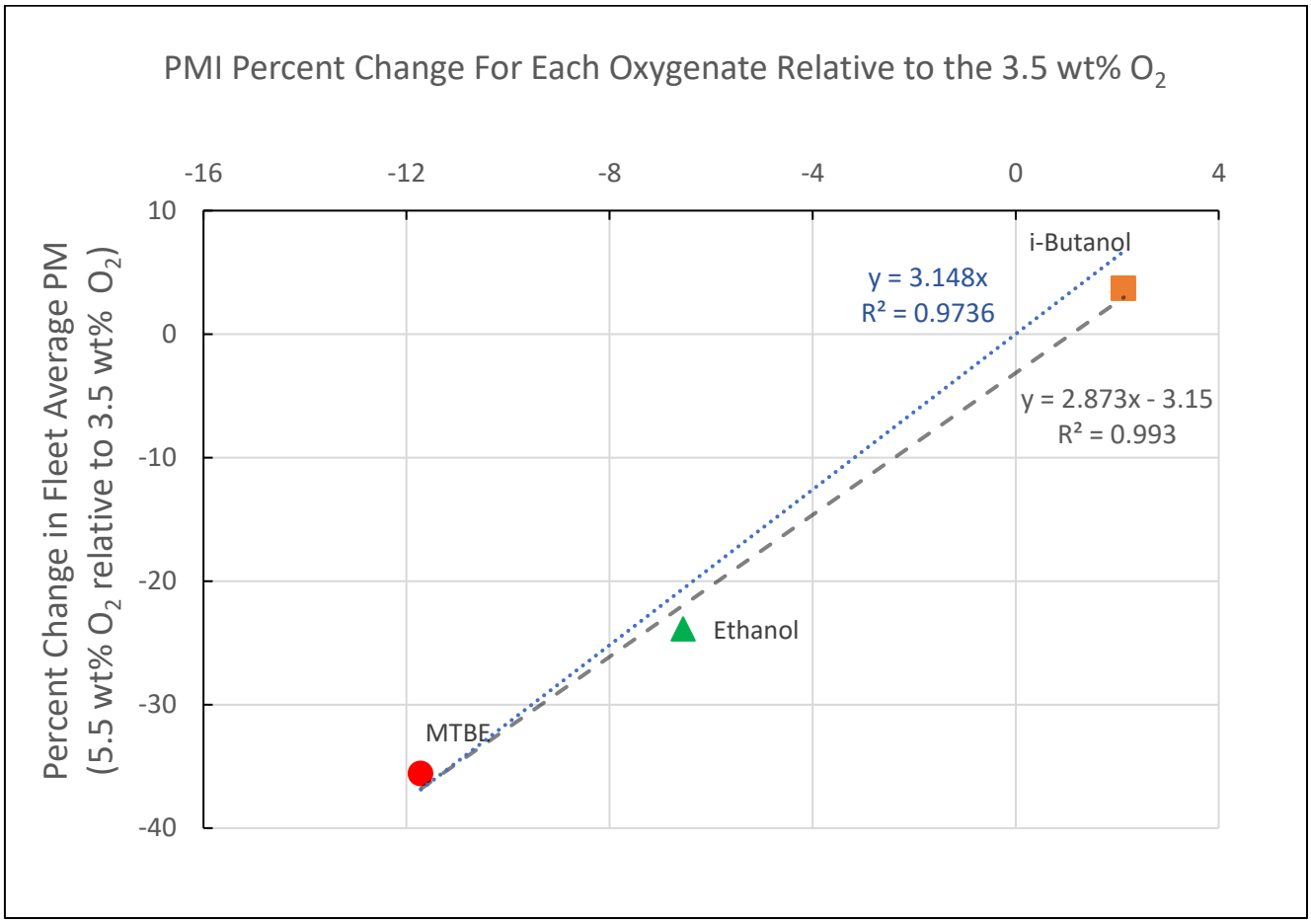

Figure 1-3 Percent Change in PMI versus Percent Change in Average PM

After completion of the testing, Rincon Ranch Consulting conducted a statistical analysis under independent contract with CRC to understand the effect of the fuels on the particulate and gaseous emissions of the test fleet. The analysis developed statistical estimates of the average emissions of the four-vehicle test fleet to address two chief questions:

- Which characteristics of the experimental fuels are most influential in determining the emissions of the test fleet?
- How do emissions of the test fleet respond to the different levels of oxygen content and the three oxygenate types used in the experimental fuels?

Six different particulate and gaseous pollutants were examined: LA92 Phase 1 PM and weighted-average PM emissions over the LA92 cycle plus the weighted-average LA92 emissions of HC, CO, NOx, and CO_2. In this, emissions of the oxygenated fuels were compared to emissions from Fuel C, the base fuel from which the others were blended. Fuel C was a regular grade gasoline with a low propensity for PM emissions (PMI = 1.30).

Table 1-1 summarizes how the emissions of the test fleet are related to characteristics of the oxygenated fuels. With respect to how PM emissions of the test fleet respond to oxygen content and the three oxygenate types, the study found the following:

- The 10% ethanol fuel reduces Phase 1 PM and LA92 PM emissions by 7% and 1%, respectively, compared to Fuel C but the differences are not large enough to be statistically significant.
- Phase 1 LA92 and LA92 PM emissions from the 10% ethanol fuel are higher than would be expected from its PMI and oxygen content, although the difference from the emissions trend line with PMI is not statistically significant.
- Except for the 10% ethanol fuel, the other oxygenated fuels significantly reduce PM emissions compared to Fuel C. The 15% ethanol and the two i-butanol fuels reduce Phase I PM emissions by 33–35%, while the two MTBE fuels reduce emissions by 44–58%. LA92 PM emissions are reduced by 31–54%, with the greatest reduction (54%) occurring for the 29% MTBE fuel.
- Except for the 10% ethanol fuel, the oxygenated fuels reduced the Phase 1 LA92 PM and LA92 PM emissions (compared to Fuel C) in proportion to the amount of oxygenate blended, whether measured as the volumetric percent of oxygenate or as the PMI. This is because oxygenates dilute Fuel C's gasoline hydrocarbons with compounds that make low (nearly zero) contributions to the PMI. The same is true for the 10% ethanol fuel, but its PM emissions are not reduced by proportional amounts.

The result for the 10% ethanol fuel is consistent with a continuation of the ethanol effect observed in the previous E-94-2 and E-94-3 studies, where the ethanol effect was statistically significant. In contrast, the 15% ethanol fuel and the fuels oxygenated with i-butanol and MTBE lead to PM emissions levels that are fully consistent with their PMIs. The cause of the 10% ethanol effect is not fully understood, nor why the 15% ethanol and the other oxygenated fuels display different emissions behavior.

For the gaseous pollutants, LA92 HC emissions respond to fuels in much the same way as PM, but the percentage reductions are smaller and more scatter is present around the primary trend, consistent with the presence of other influences on gaseous HC emissions. LA92 CO emissions are reduced in proportion to the oxygen content of the fuels, being reduced by about 15% at 3.5 wt% oxygen and about 20% at 5.5 wt% oxygen compared to Fuel C. LA92 NOx emissions are unchanged by oxygen content or oxygenate type. LA92 CO_2 emissions are reduced in comparison to Fuel C in proportion to the oxygenate use, because the oxygenated compounds contain less carbon per kJ of energy than Fuel C. LA92 CO_2 emissions are reduced by about 4 g/mi for each 10 vol% of added oxygenate (or by about 1.2% of Fuel C's CO_2 emissions of 345.8 g/mi).

Table 1-1 Relationship of Emission Changes to Characteristics of the E-129 Fuels

Phase 1 PM	The 10 vol% ethanol fuel does not significantly reduce emissions below Fuel C and appears to lead to higher emissions than expected from its PMI. The other oxygenated fuels significantly reduce PM emissions in response to the dilution of gasoline hydrocarbons by the addition of oxygenated molecules.
LA92 PM	
LA92 HC	Emissions respond much like PM
LA92 CO	Emissions are reduced in proportion to the oxygen content (wt%) of the fuels.
LA92 NOx	Emissions are unchanged by the oxygenated fuels.
LA92 CO_2	Emissions are reduced in proportion to the volumetric use of oxygenate.

The findings of this study with respect to PM emissions can be summarized as:

- With the exception of the 10% ethanol fuel, the oxygenated fuels in this study significantly reduced the Phase 1 and LA92 PM emissions of the test fleet in comparison to Fuel C. The 10% ethanol fuel did not significantly reduce emissions.
- For the three oxygenates considered here, the dilution of Fuel C's gasoline hydrocarbons with oxygenate compounds of low PM potential is the *primary* reason that oxygenated fuels reduced PM emissions.
- The 10% ethanol fuel deviates from the linear relationship between PM emissions and PMI, although not by a statistically significant amount in this sample. The consistency of its emission differences across pollutants is consistent with the hypothesis that 10% ethanol may exert a *secondary* influence on emissions.

When the emissions trends in this study are compared to those of CRC E-94-2, the E-129 fuels continue the trend of decreasing PM emissions with decreasing PMI, with the emissions difference narrowing as PMI decreases. In the prior study, 10% ethanol was found to increase LA92 Phase 1 PM emissions above the level of neat gasoline (not containing ethanol) of equal PMI. In this study, the PM emissions of the 10% ethanol fuel are above, but closer to, the extended E0 trend line with emissions, consistent with a continued narrowing of the 10% ethanol effect at lower PMI values.

While some trends are clear, three fuel effects are not understood at present:

- Why the 10% ethanol fuel increases PM emissions in comparison to E0 fuels of equal PMI value.
- Why the 15% ethanol fuel does not display the same emissions behavior as 10% ethanol.
- Why the 15% ethanol fuel and the fuels oxygenated with i-butanol and MTBE follow the PMI trend line for E0 fuels that was established in the prior CRC E-94-2 study, rather than being offset above like the 10% ethanol fuel.

Further research into oxygenate fuel effects on PM emissions is needed to resolve these unanswered questions. The most pressing need is to formulate a set of well-defined hypotheses for how other variables, including physical and chemical properties of the oxygenates, might explain the unresolved fuel effects. The design of emission and fuel control systems and their calibrations for operation on fuels containing 3.5 wt% versus 5.5 wt% oxygen should also be considered. Testing of MY2017 and newer vehicles could shed additional light on PM emissions for fuels up to the E15 level, as most current vehicles are approved by their manufacturers for operation with 15% ethanol gasoline blends.

2. Introduction and Objective

This program is a continuation of the CRC No. E-94-2 study which evaluated the impact on tailpipe emissions of spark-ignited direct-injected vehicles using fuels with varying Particulate Matter Index (PMI), ethanol concentration, and antiknock index (AKI). Automotive manufacturers continue research methods to comply with the Corporate Average Fuel Economy (CAFE) and Green-House Gas (GHG) emissions standards for current and future model year light-duty vehicles by utilizing engine technologies to reduce carbon related exhaust emissions (CREE). Some examples of these engine technologies include spark-ignited direct-injection (SIDI), down-sizing, and turbocharging.

The objective of CRC No. E-129 is to evaluate tailpipe emissions of four SIDI vehicles operated on a set of fuels formulated by splash-blending 3 oxygenates at different concentrations into a base hydrocarbon non-oxygenated gasoline re-blended to conform to Fuel C from the CRC No. E-94-2 test program. The measured tailpipe emissions on each of the 6 gasoline/oxygenate blends were compared relative to those measured on the non-oxygenated base hydrocarbon fuel. Ethanol, methyl tert-butyl ether (MTBE), and i-butanol served as the three different oxygenates. Each oxygenate was individually splash-blended to create two different test fuels that targeted an overall nominal total oxygen content of 3.5% and 5.5% by weight.

3. Laboratory Specifications and Instrumentation

All testing for this project was performed at the SGS laboratory in Columbus, Indiana (“SGS Columbus”) which is 100-120 meters above sea-level. SGS Columbus is an ISO 9001 accredited laboratory and regularly performs chassis emissions testing under 40 CFR Part 86 and 40 CFR Part 1066 testing protocols. Prior to the start of this program SGS provided all relevant documentation containing laboratory compliance information according to 40 CFR Part 1066. All preconditioning and emission testing was performed on the same Horiba 48-inch single roll chassis dynamometer to reduce variability.

Exhaust emissions were diluted using a constant volume sampler (CVS) and were collected into bags for analysis. Exhaust sampling and procedures were conducted according to the testing protocols described in 40 CFR Part 86 Subpart B and 40 CFR Part 1066. Conventional exhaust emissions were measured with the measurement technologies listed in Table 3-1.

Table 3-1 Exhaust Emission Measurement Methods

Constituent	Method
Carbon Monoxide (CO) Carbon Dioxide (CO_2)	Non-dispersive infrared (NDIR)
Total Hydrocarbon (THC) Methane (CH_4)	Flame-ionization detector (FID)
Oxides of Nitrogen (NO_x)	Chemiluminescent detector (CLD)
Nitrous Oxide (N_2O)	Optical Feedback Cavity Enhanced Absorption Spectroscopy (OFCEAS)
Particulate Matter (PM)	Gravimetric Analysis

Horiba 200 series analyzers were used to measure CO, CO_2, THC, CH_4 and NO_x. CO and CO_2 were measured using AIA-210 analyzers which have a repeatability of ±1% of full scale. CO and CO_2 measurements utilized infrared absorption filters in the energy bandwidth that CO and CO_2 absorb electromagnetic radiation. THC and CH_4 were measured using FIA-220 and GFA-220 analyzers and each have a repeatability of ±1% of full scale. THC measurements were made with a flame ionization detector which monitored the current change as the exhaust sample was consumed through the flame. CH_4 measurements were made in a similar fashion to THC with the addition of a gas chromatography column that separates CH_4 from non-CH_4 hydrocarbons. NO_x was measured using a CLA-220 analyzer whereby direct measurements of NO_2 are made as a result of gas-phase reaction of NO and O_3.

N_2O was measured using a Semtech® LASAR which utilizes Optical Feedback Cavity Enhanced Absorption Spectroscopy (OFCEAS) whereby the frequency of an emitted laser and the enclosed cavity are equal. This increases laser purity and enables self-stabilization of the spectrometer. The injected laser bandwidth is 0.01 MHz which produces single scans of 100ms and peak-to-peak noise of 4.10^{-10} Absorbance Units. A continuous current ramp is applied to the laser emission wavelength which yields a continuous spectrum up to 400 data points and an optical resolution of 1.12 pm (0.005 cm^{-1}) at 1,500 nm (6,666 cm^{-1}).

Particulate Matter (PM) was sampled using 47mm polytetrafluoroethylene (PTFE) filter media and sampling conditions consistent with the protocols described in 40 CFR Part 1065. Individual filter media were used for emission test cycles with multiple test intervals or phases (One filter media was used for an individual phase). The final results were calculated using the equations described in 40 CFR Part 1066. The sample air flow rate across the filter media targeted 100 cm/s and maintained a temperature of 47° C (±5° C). Proportional sample flow was verified for each test according to the SEE method described in 40 CFR Part 1065.545. The time-weighted dilution factor for each emission test was verified according to the testing protocols in 40 CFR Part 1066 which require a value between 7:1 and 20:1 for vehicle chassis testing. Time-weighted dilution factor examples are shown in Table 3-2 for a single, vehicle-trace cycle combination. An in-house clean room was used for the weighing of the PM filter media. The construction and environmental controls of the clean room complied with the requirements described in 40 CFR Part 1065. PM background of the facility was monitored during the months of June and July by sampling tunnel blanks according to the procedure described in 40 CFR Part 1066.110. The tunnel flow rate and the length of sampling were twice as large compared to the testing conditions in this program for Phase 1 of the LA92 to simulate a worse-case PM background. Tunnel blank results were 1-3 µg which correspond to 0.7-1.7% PM mass relative to the 10mg/mi standard and are within the allowable correction value according the regulation. Based on these tunnel blanks, PM filter weights were not corrected. OBDII channels were recorded continuously at 1Hz during dynamometer operation using the OBDLink SX tool. Table 3-3 lists the targeted OBDII signals that were recorded if they were available.

Table 3-2 Time-weighted dilution factors

Vehicle	Time-weighted Dilution Factor	
	FTP	LA92
VW Jetta	17	14
Honda Accord	18	15
2.5L Chevrolet Malibu	15	12
2.0L Chevrolet Malibu	15	12

Table 3-3 OBDII measured signals

1) Absolute Throttle Position (%)	12) Long Term Fuel Trim – Bank 1 (%)
2) Relative Throttle Position (%),	13) Long Term Fuel Trim – Bank 2 (%)
3) Absolute Throttle Position B (%)	14) Engine RPM (RPM)
4) Commanded Throttle Actuator Control (%)	15) Vehicle Speed (km/hr)
5) Intake Manifold Absolute Pressure (kPaA),	16) Calculated Load Value (%)
6) MAF (g/s)	17) Engine Coolant Temperature (Deg C)
7) Ignition Timing Advance Cyl. #1 (Degrees),	18) Commanded Evaporative Purge (%)
8) Bank 1 – Sensor 1 lambda (Wide Range O2S)	19) Bank 1 – Sensor 1 O2 Voltage (v)
9) Absolute Load Value (%)	20) Intake Air Temp (Deg C)
10) Short Term Fuel Trim – Bank 1 (%)	21) Commanded Equivalence Ratio
11) Short Term Fuel Trim – Bank 2 (%)	

4. Vehicle Model Description and Selection

CRC selected four vehicles for this present study to represent a subset of technologies and range of emissions from the previous E-94-2 study. The vehicles were preselected by CRC from the pool of the twelve original candidate vehicle models tested during the previous E-94-2 testing program. All four vehicles selected were equipped with inline four-cylinder engines with gasoline direct injection (GDI) fuel systems. Two vehicles were equipped with turbocharged engines and two were naturally aspirated. Three vehicles were 2013 model year and one vehicle was 2012 model year. All vehicles were equipped with automatic transmissions; three vehicles had six-speed transmissions and one vehicle had a continuously variable transmission (CVT). A summary of each vehicle and their technologies is shown in Table 4-1.

Each vehicle received a chassis road-load derivation using either the EPA Test Car database and the EPA Certification database to select the inertia weight and road-load coefficients. Vehicles were matched in these two databases by engine family, evaporative family, driveline and ETW to select the proper road-load targets. In the case of the VW Jetta, no matching vehicle was found. Instead, the same engine family in the EPA Test Car database was listed as a VW Eos and the declared road-load targets were verified by the manufacturer to use for the VW

Jetta. A summary of the vehicle road-load targets and database source is shown in Table 4-2. SGS determined the road-load setting coefficients by performing the SAE J2264 procedure for chassis dynamometer simulation of road-load using coastdown techniques. These road-load settings were used throughout the entirety of the project and were monitored each week by measuring consecutive coastdowns. These coastdown results are shown in Figure 9-1 through Figure 9-4 in the Appendix. Pictures of each test vehicle are shown in Figure 4-1.

Each vehicle received a randomized letter assignment A, B, C, or D. These vehicle identifiers are used for the remainder of the report so that the results are blinded to obscure any connection between a single vehicle and the datasets.

Table 4-1 Description of Vehicle Technologies and Characteristics

Vehicle make	Volkswagen	Honda	Chevrolet	Chevrolet
Vehicle model	Jetta - GLI	Accord	Malibu	Malibu
Model year	2012	2013	2013	2013
Engine Family	CADXJ02.03UA	DHNXV02.4FB3	DGMXV02.5001	DGMXV02.0021
Evaporative Family	CADXR0110238	DHNXR0121VEA	DGMXR0133810	DGMXR0133810
Engine Displacement	2.0L Turbocharged I4	2.4L Naturally Aspirated I4	2.5L Naturally Aspirated I4	2.0L Turbocharged I4
Transmission	6-speed Automatic	CVT	6-speed Automatic	6-speed Automatic
Mileage (miles)	8,943	22,509	25,534	27,332
Emission Group	EPA Tier 2 Bin 5	EPA Tier 2 Bin 5	EPA Tier 2 Bin 4	EPA Tier 2 Bin 4
ETW (lbs)	3500	3625	4000	4000

Table 4-2 Description of vehicle road-load coefficients

Car	2012 VW Jetta	2013 Honda Accord	2013 Chevrolet Malibu 2.5 L NA	2013 Chevrolet Malibu 2.0 L Turbo
VIN	3VW467AJ4CM463483	1HGCR2F85DA207500	1G11C5SAXDF321649	1G11J5SXXDF302657
Engine Family	CADXJ02.03UA	DHNXV02.4FB3	DGMXV02.5001	DGMXV02.0021
EVAP Family	CADXR0110238	DHNXR0121VEA	DGMXR0133810	DGMXR0133810
ETW (lbs)	3500	3625	4000	4000
Target A (lbs)	28.551	46.59	38.08	34.12
Target B (lbs/mph)	0.20546	-0.5204	0.2259	0.2082
Target C (lbs/mph^2)	0.016762	0.02512	0.01944	0.01908
Dyno Set A (lbs)	-4.36	9.811	11.1	19.04
Dyno Set B (lbs/mph)	0.5204	0.02896	-0.0837	0.0452
Dyno Set C (lbs/mph^2)	0.01358	0.017002	0.01967	0.01944
Source	EPA Test Car	EPA Cert Database	EPA Cert Database	EPA Test Car

Figure 4-1 Pictures of test vehicles

Figure 4-1 (Top left): VW Jetta turbocharged. (Top right): 2.0L Chevrolet Malibu turbocharged. (Bottom left): Honda Accord narturally aspirated. (Bottom right): 2.5L Chevrolet Malibu natrually aspirated.

5. Test Fuels

The test fuels for E-129 were selected and provided by CRC. A base non-oxygenated regular grade gasoline was re-blended by Gage Products Company for this study to conform to the specifications of the Fuel C in the CRC E-94-2 assessment of particulate emissions from SIDI vehicles. Fuel C was a low AKI, low PMI fuel base hydrocarbon. CRC approved the use of Fuel C for E-129 after it was re-blended to match the original fuels specifications used in CRC E-94-2. Six oxygenated fuels were then created by Gage Products Company by splash-blending varying amounts of ethanol, i-butanol, and MTBE with Fuel C to achieve two different levels for oxygen content (nominally 3.5 wt% and 5.5 wt%). The oxygenate concentrations (by volume) of the six splash-blended fuels included 10% ethanol, 15% ethanol, 19% methyl tert-butyl ether, 29% methyl tert-butyl ether, 16% i-butanol, and 24% i-butanol. Baseline emissions for each vehicle were recorded over triplicate FTP Cycles at the beginning and at the end of the program using non-oxygenated certification gasoline (Cert Fuel). A comparison of pertinent selected properties of the eight test fuels is shown in Table 5-1. Values for additional fuel properties of each test fuel can be found in the certificates of analysis (COA) in the Appendix. In total, 49 drums of test fuel were delivered to SGS Columbus, in April 2018, containing the base hydrocarbon and each splash-blended oxygenate. Nine additional drums of certification gasoline were also delivered for the Baseline Emission tests. Fuel drums were stored inside the SGS Columbus laboratory where environmental conditions are controlled to meet exhaust emissions testing requirements of 68-86 °F (temperature) and 25-75 grains/lb (absolute humidity). Fuel drums placed inside cooling jackets two days before being used so that the dispensed fuel was 50 °F.

Table 5-1 Test Fuel Comparison

Test Method			Cert Fuel	Fuel C	10% ethanol	19% MTBE	16% i-butanol	15% ethanol	29% MTBE	24% i-butanol
Carbon Content	**ASTM D5291**	**Wt%**	86.4	85.93	82.24	82.37	82.15	80.53	80.6	80.35
Hydrogen Content	**ASTM D5291**	**Wt%**	13.61	14.07	14.07	14.1	14.05	13.98	14.04	14.02
Oxygen Content	**ASTM D4815**	**Wt%**	0	0	3.7	3.54	3.79	5.49	5.37	5.63
Specific Gravity	**ASTM D4052**	**-**	0.7412	0.7382	0.7427	0.7395	0.748	0.7452	0.7402	0.7533
AKI	**[(R+M)/2]**	**-**	92.5	88.2	91.7	92.6	90.8	92.8	94.4	91.7
PMI	**Honda Eq.**	**-**	1.27	1.3	1.16	1.04	1.07	1.08	0.92	1.09
Net Heat of Combustion	**ASTM D240**	**BTU/lb**	18765.9	18637.2	17906.3	17927.8	17803.1	17532.2	17777.3	17437.7

5.1.Randomization of Test Fuels and Vehicles

The test fuel order was randomized in order to reduce serial effects on the emissions results. The four vehicles were paired into two groups of two. Each group of vehicles was assigned a random order for each of the test fuels so that two vehicles tested with the same fuel each week and two different fuels were tested across all four vehicles with the exception of the Baseline Emissions. Table 5-2 shows the groupings of each vehicle pair and their assigned driver.

Table 5-2 Test vehicle and driver pairings

Vehicle Pair	Driver
Vehicle A, D	1
Vehicle B, C	2

The randomized order of testing by test fuels, vehicles and testing week is shown in Table 5-3. The testing schedule overlapped with two national holidays during which no testing was conducted due to the length of the preconditioning sequence and the required cadence in between emissions tests. The same two drivers were used for all emission tests to reduce any human influence on the test results. One driver was assigned to Vehicle A and Vehicle D; the other driver was assigned to Vehicle B and Vehicle C. If a driver was unavailable, then the assigned vehicles were not tested that week and were scheduled for a later time.

Table 5-3 Test fuel order for each vehicle pair

Week	Vehicles A, D	Fuel		Week	Vehicles B, C	Fuel
0	Cert fuel	A		0	Cert fuel	A
1	19% MTBE	G		1	15% ethanol	C
2	10% ethanol	F		2	19% MTBE	G
3	29% MTBE	H		3	16% i-butanol	D
4	Base fuel	B		4	29% MTBE	H
5	24% i-butanol	E		5	10% ethanol	F
6	16% i-butanol	D		6	Base Fuel	B
7	15% ethanol	C		7	24% i-butanol	E
8	Cert fuel	A		8	Cert fuel	A

5.2.PMI Deviation for i-Butanol

The dilution of Fuel C with the oxygenates is the primary reason for the reduction of PMI. When the oxygenates are splash-blended into Fuel C there should be a proportional decrease in PMI as a function of the volume displaced by the added oxygenate. This proportional relationship is shown in Figure 5-1 for all test fuels except 24% i-butanol. The 24% i-butanol was retested for a detailed hydrocarbon analysis (DHA) analysis and the PMI value recalculated in case there was an error in the blending process. The DHA analysis confirmed that i-butanol was added with 24% by volume and that the calculated PMI was 1.09. The reported PMI of 1.09 for 24% i-butanol deviates from the expectation that adding more i-butanol to Fuel C should reduce the PMI to a greater extent. However, the actual PM emissions measured in this study confirm the reported PMI for all test fuels, including 24% i-butanol.

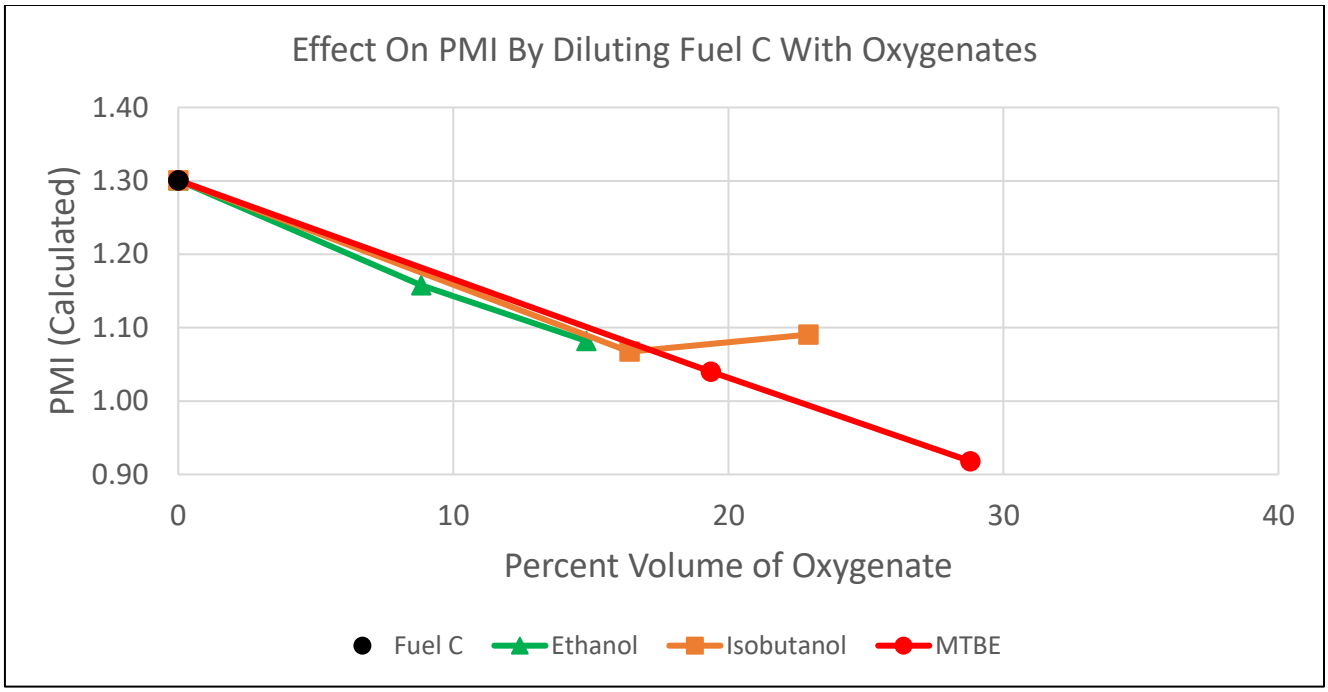

Figure 5-1 Effect on PMI by Diluting Fuel C with Oxygenates

Figure 5-2 shows the percent change in reported PMI between the lower concentration and higher concentration of each oxygenate and plots it against the percent change in actual PM emissions. For example, a 11.7% decrease in calculated PMI between 29% MTBE (0.92 PMI) and 19% MTBE (1.04 PMI) also shows a 35.6% decrease in PM fleet average emissions. Ethanol shows a similar relationship where the PMI decreased by 6.5% and the fleet average PM emissions also decreased by 23.9%. For i-butanol, this relationship is also observed between percent change in PMI and percent change in PM emissions. The percent change in PMI for i-butanol increased 2.1% and the actual fleet average PM emissions increased 3.7%. Two trendlines are shown in Figure 5-2 to describe the relationship. The gray-dashed line is a linear regression using all three data points. The blue-dotted line is fixed at the intercept to illustrate the relationship where no change in PMI would also show no change in PM emissions. The relationship between PMI and PM emissions has been well documented and based on the observed relationship in this study, there is high confidence in the calculated PMI for all test fuels.

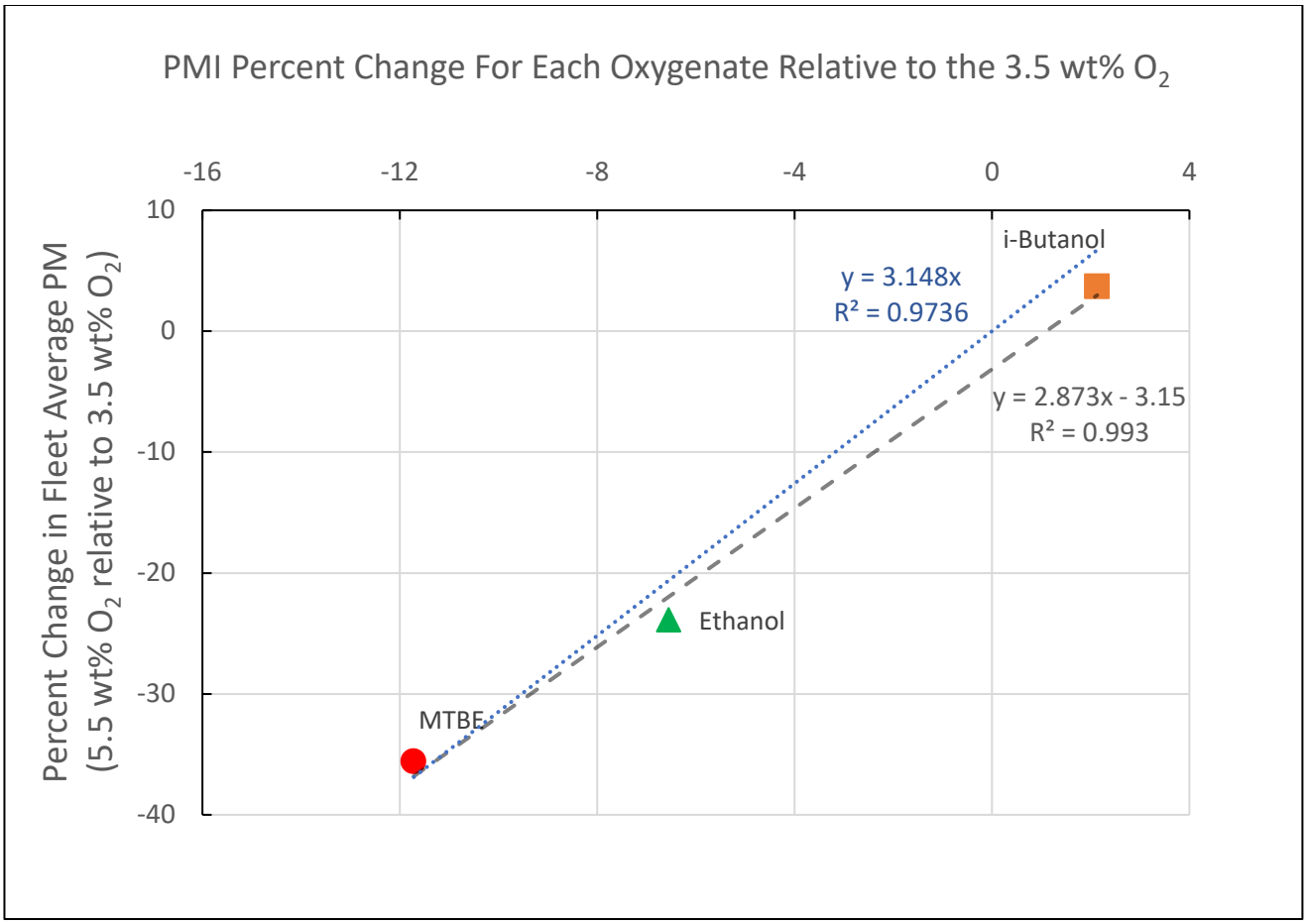

Figure 5-2 Percent Change in PMI versus Percent Change in Average PM

6. Vehicle Inspection, Fuel Change, Preconditioning and Test Procedure

Testing protocols, fuel conditioning and procedure control measures were identical to the previous CRC E-94-2 program. Testing protocols followed the relevant requirements described in 40 CFR Part 86, 40 CFR 1065 and 40 CFR 1066. Procedure control measures included the following; cadence in between vehicle operations that took place on the dynamometer, weekly coastdowns to verify consistent vehicle powertrain performance, fuel labeling and weekly verification before fuel was changed in a vehicle, quality assurance checks focused on 40 CFR 1066 and 40 CFR 1065 requirements for time weighted dilution factor and proportional PM sampling, and monitoring the PM background of the laboratory throughout the emission testing program. This section describes in detail the steps performed for each stage of conditioning and testing.

6.1.Vehicle Inspection

All vehicles arrived at the SGS Columbus laboratory in January 2018. Upon arrival, each vehicle received a full bumper to bumper inspection documenting the as-received condition of the vehicle. The vehicle inspection includes photographs of the exterior and interior of the vehicle. An OBDII scan of each vehicle was taken in order to document the following:

- Readiness Monitor status

- Malfunction Indicator Light: All of the vehicle MILs were OFF and the condition of the tires were satisfactory for testing on a dynamometer.
- Diagnostic Trouble Codes
- Mode 1 – Powertrain Diagnostic data
- Mode 6 – On-board Monitoring
- Mode 9 – Vehicle Information

6.1.1.Vehicle Preparation

The batteries for each vehicle were replaced since they were unable to maintain a stable charge. The exhaust tips for each vehicle arrived ready for emission testing with marmon-flanges welded from the previous project. A thermocouple was installed into the oil reservoir through the dipstick. Each vehicle received an oil change and oil filter change according to OEM recommendation. After the oil change, 250 miles were accumulated for each vehicle on the chassis dynamometer running the Standard Road Cycle (SRC).

6.1.2.Vehicle As-Received Testing (Check-out Test)

Each vehicle was tested over the Federal Test Procedure (FTP) in accordance with 40 CFR Part 86 to ensure that the test candidate was in compliance with the certification standard and was a fair representation of the respective emission test group. All four vehicles were found to be representative of their respective emission engine test group. These results are shown in Table 6-1.

Table 6-1 As-received FTP Emissions test results and standards

VW Jetta TC (E94VW)				
Federal Tier 2 Bin 5	CO[g/mi]	NO_x[g/mi]	NMOG* [g/mi]	PM[mg/mi]
Certification Standard (50,000 miles)	3.400	0.050	0.075	10
Checkout Test Weighted Results on FTP-75	0.374	0.036	0.023	3.2
Honda Accord NA (HOA500)				
Federal Tier 2 Bin 5	CO[g/mi]	NO_x[g/mi]	NMOG* [g/mi]	PM[mg/mi]
Certification Standard (50,000 miles)	3.400	0.050	0.075	10
Checkout Test Weighted Results on FTP-75	0.252	0.007	0.030	1.1
2.5L Chevrolet Malibu NA (MLCH649)				
Federal Tier 2 Bin 4	CO[g/mi]	NO_x[g/mi]	NMOG* [g/mi]	PM[mg/mi]
Certification Standard (120,000 miles)	2.100	0.040	0.070	10
Checkout Test Weighted Results on FTP-75	0.580	0.011	0.010	4.9
2.0L Chevrolet Malibu TC (MLCH657)				
Federal Tier 2 Bin 4	CO[g/mi]	NO_x[g/mi]	NMOG* [g/mi]	PM[mg/mi]
Certification Standard (120,000 miles)	2.100	0.040	0.070	10
Checkout Test Weighted Results on FTP-75	0.582	0.009	0.021	2.1

*NMOG results calculated according to 40 CFR Part 86.1810-01(o): NMOG = NMHC*1.04

6.2.Fuel Change and Preconditioning

The fuel change procedure consisted of three fuel changes. The test fuel was initially drained from the tank through the filler neck to reduce the overall time spent on this procedure. The final amount of fuel was drained through the fuel rail. The fuel gauge and visual inspection of fuel flow were used to verify that the fuel tank was indeed empty. Fuel drums were conditioned to 50 °F using fuel jackets for two days prior to each fuel change. The temperature of the dispensed fuel was monitored by a thermocouple in the fuel nozzle and verified to be 50 °F during each fuel change. Each of three fuel changes filled the fuel tank to 40% capacity. After the first fuel change, the vehicle was taken to the test cell and completed the Sulfur Purge cycle shown in Figure 6-1. The Sulfur Purge cycle consists of two repeats of an initial steady-state operation at 55 mph and then five 0-85 mph events. Oil temperature was monitored during the Sulfur Purge cycle by a thermocouple placed through the oil dipstick and submerged into the oil reservoir. After the Sulfur Purge cycle, four vehicle coastdowns were performed from 70-30 mph. The third and fourth coastdowns were recorded and used as vehicle baselines during the program. Consecutive coastdowns needed to be within 0.5 seconds and each coastdown was required to be within ±7% of the running average during the program. The coastdowns results are shown in the Appendix. None of the vehicles were observed to violate the coastdown criteria. After the third and final fuel change, the vehicle was placed in soak for 24 hours between 68-86 °F and then placed back on the chassis dynamometer for a series of preconditioning drive cycles to allow the vehicle to properly adapt to the new fuel. The preconditioning drive cycles included consecutive Urban Driving Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Test, and US06 cycles ending with a 2-5 minute idle. The vehicle was placed back into soak for another 24 hours. A final preconditioning LA92 cycle was performed followed by a 24-hour soak.

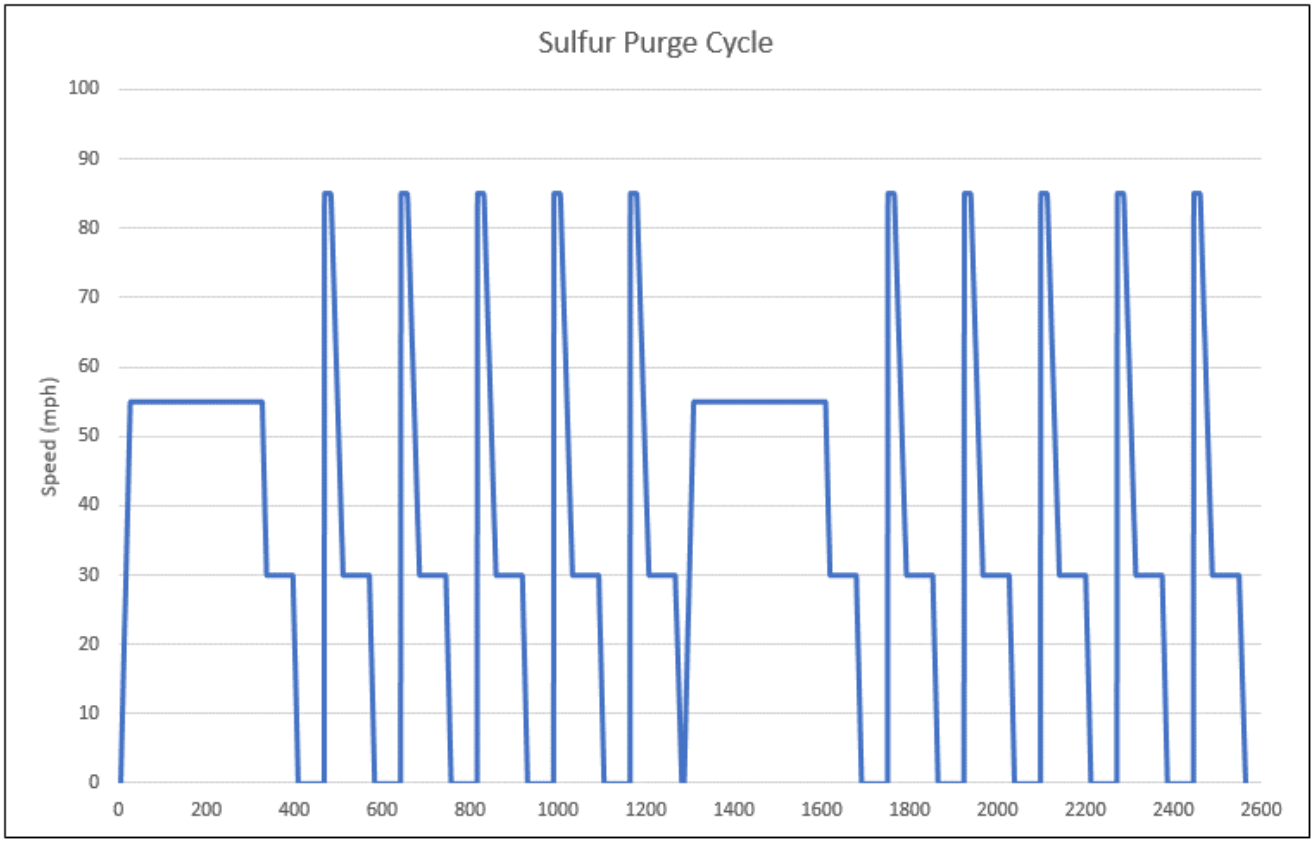

Figure 6-1 Sulfur Purge Cycle

6.3.Test Procedure

Triplicate FTP Cycles were performed with each vehicle using Cert Fuel at the beginning and end of the program to capture any vehicle performance drift. The FTP test results are known throughout this report as the "Baseline Emissions". The Baseline Emissions used the same preconditioning procedure documented in this section.

The Federal Test Procedure (FTP) for vehicle chassis emission testing is well documented in 40 CFR Part 86. The FTP drive cycle consists of three independent test-phase intervals and contains a ten-minute soak in between the second and third test-phases. Phase 1 and 3 of the FTP are each 505 seconds long. Phase 2 is 864 seconds long for a total of 1,874 seconds (31.2 minutes).

Tailpipe exhaust emissions were collected for all test fuels containing the base non-oxygenated gasoline (Fuel C) over the LA92 Unified Cycle for this program. The LA92 Unified Cycle used for this project has a similar structure to the FTP. The LA92 also has three test-phases with a ten-minute soak in between the second and third test-phases. Phase 1 and 3 of the LA92 are 300 seconds long. Phase 2 is 1,135 seconds long for a total of 1,735 seconds (28.9 minutes).

Graphical representations of the FTP and LA92 cycles are shown in Figure 6-2.

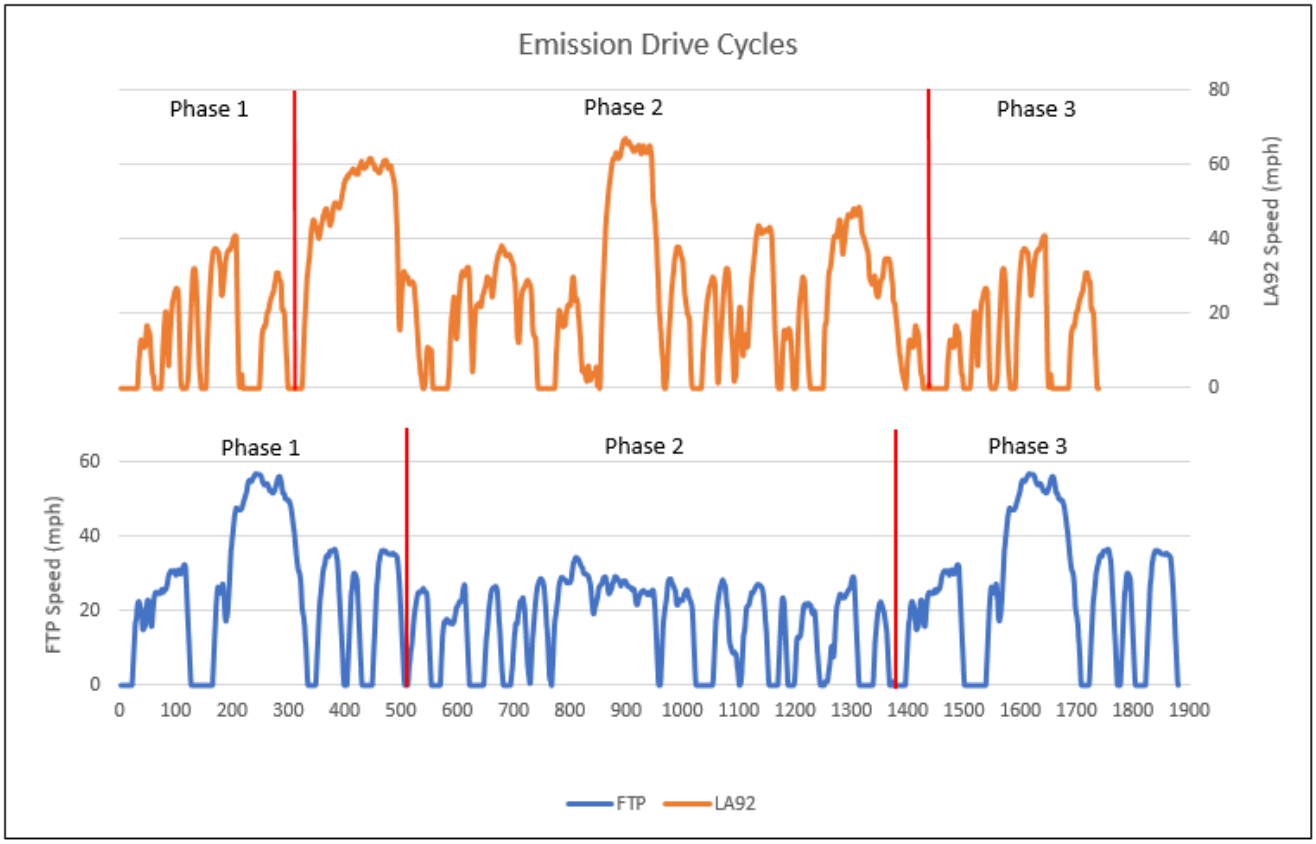

Figure 6-2 Emission Drive Cycles

The overall test flow diagram is shown in Figure 6-3.The full test program consisted of five separate categories of different procedures. These categories are shown in Figure 6-4. The Vehicle Setup/Preparation, Fuel Change and Vehicle Conditioning categories are described in Sections 6.1 and 6.2 of this report. The Iterative test category includes all emission testing where the LA92 drive cycle was performed. Each vehicle/fuel combination received a minimum of two consecutive LA92 emissions tests separated by a 24-hour soak. After the second LA92 was complete, the emission results for the first two tests were compared and checked for repeatability. If the repeatability for THC, CO, or NO_x was outside of the tolerance shown in Table 6-2, then the vehicle was placed back into a 24-hour soak and a third LA92 emission test was performed the following day. The Baseline Test category includes all emission testing where the FTP drive cycle was performed. Baseline Emission tests always performed three consecutive FTPs separated by 24-hour soaks since the results were used to capture and drift in vehicle performance.

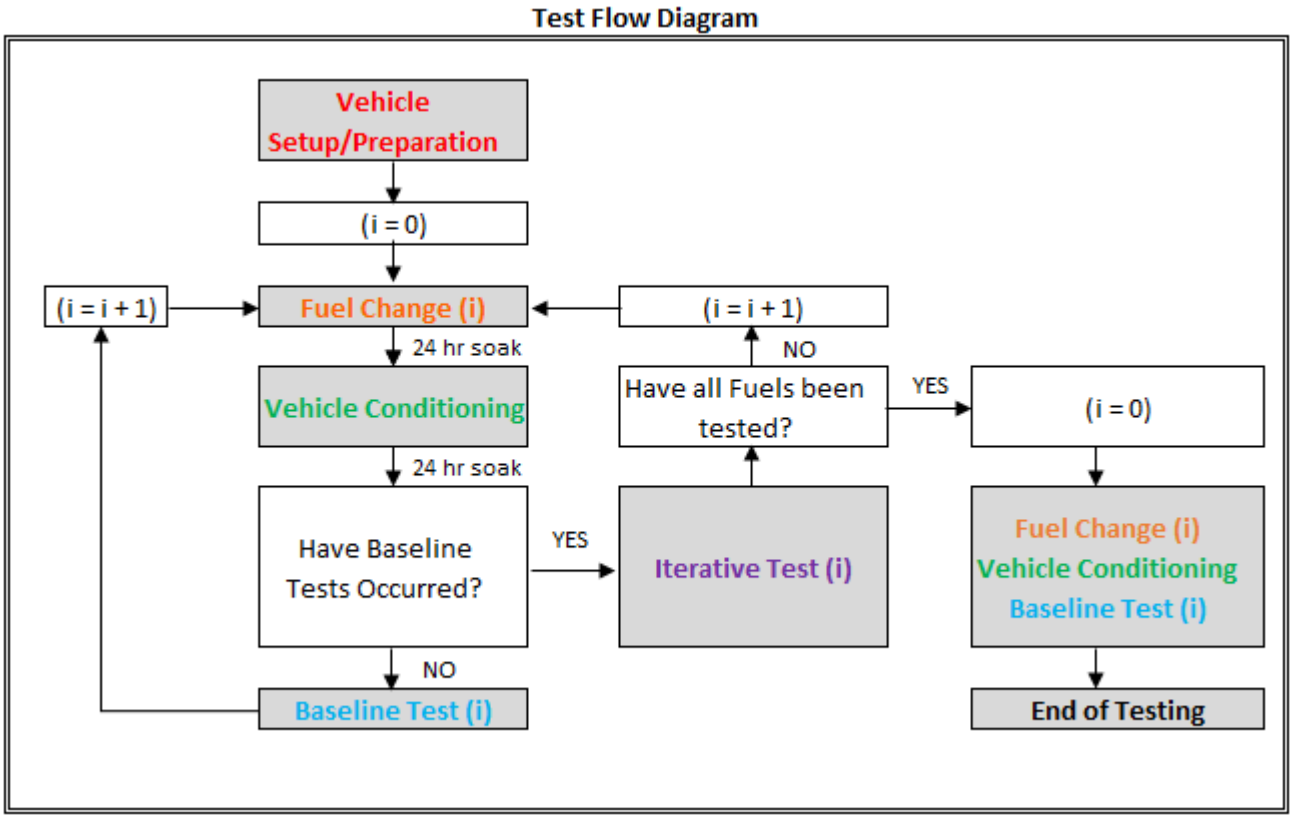

Figure 6-3 Overview of the Test Flow Diagram

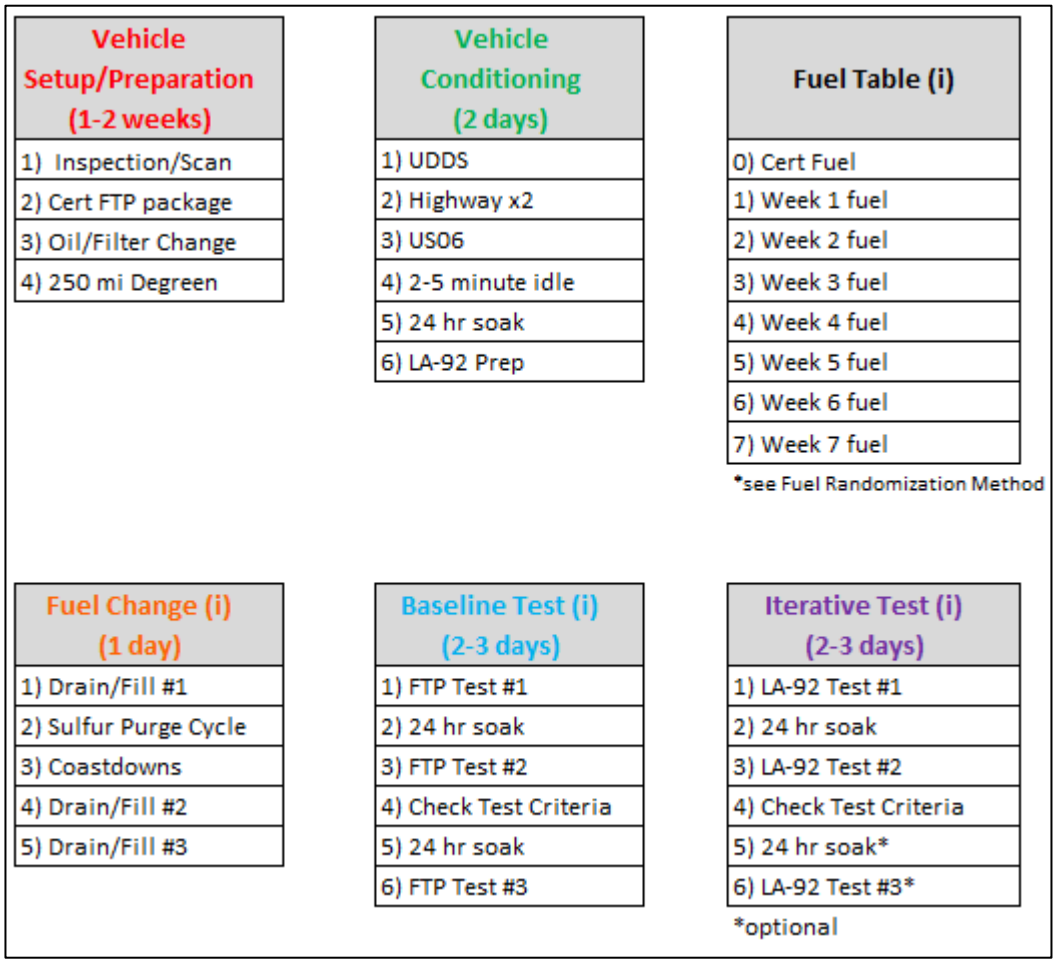

Figure 6-4 Category description for the Test Flow Diagram

Table 6-2 Test Repeatability Criteria

Repeatability Criteria	
Constituent	**Tolerance**
THC	±30%
CO	±50%
NOx	±50%

7. Results

7.1.Emission Results

A total of 89 emission tests were collected over the FTP and LA92 test cycles between May and August 2018. Average results for both the FTP and LA92 emission tests were calculated using the equation described in 40 CFR Part 86.144-94(a). Results presented in this section have been blinded using a randomized letter assignment for each vehicle. Letter assignments presented are A, B, C or D. Fuel results have not been blinded. Table 7-1 shows the number of test runs performed for each vehicle/fuel combination. A minimum of two test runs were collected based on the Test Repeatability Criteria shown in Section 6.3. Vehicle A received 5 test runs for the 19% MTBE oxygenate blend due to equipment error. The second test during the initial test sequence was void due to a sampling error and the results could not be salvaged. A third test was conducted during the initial test sequence and the comparison of the first and third tests were outside the tolerances for the Test Repeatability Criteria. It was decided to maintain the fuel test order and repeat the 19% MTBE testing on Vehicle A at the end of the project. During the repeat testing for Vehicle A on 19% MTBE, the first and second emissions test did not pass the criteria for test repeatability and a third test was performed.

Emission results presented in this section utilize all data collected from valid test runs. The mathematical averages were computed using the sample sizes or combination of sample sizes shown in Table 7-1. No attempt to discard outliers was performed on data in this section. The mathematical averages should not be confused with the estimated values calculated in Section 8 (Statistical Analysis) which documents the statistical approach of identifying and discarding potential outliers in the data set.

Table 7-1 Number of Tests Performed

All Vehicles Number of Tests Performed							
Vehicle	**-**	**-**		**Vehicle A**	**Vehicle B**	**Vehicle C**	**Vehicle D**
Measurement	**AKI**	**PMI**	**Cycle**	**No. of Tests**	**No. of Tests**	**No. of Tests**	**No. of Tests**
Fuel C (base hydrocarbon)	88.2	1.3	LA92	2	2	2	2
10% ethanol	91.7	1.16	LA92	3	2	2	3
19% MTBE	92.6	1.04	LA92	5	2	2	2
16% i-butanol	90.8	1.07	LA92	3	2	2	2
15% ethanol	92.8	1.08	LA92	2	2	2	3
29% MTBE	94.4	0.92	LA92	2	2	2	2
24% i-butanol	91.7	1.09	LA92	3	2	2	3
Certification Gasoline (Initial)	92.5	1.27	FTP	3	3	3	3
Certification Gasoline (Final)	92.5	1.27	FTP	3	3	3	3

7.2.Weighted Average Results

A summary of the average, weighted test results for each vehicle and test fuel combination is shown in Table 7-2 through Table 7-6. Figure 7-1 through Figure 7-13 show the vehicle average emissions side-by-side for each fuel. Fleet averages are also shown for emissions. Error bars represent the minimum and maximum result of an individual test. Error bars are not shown for the fleet average since the minimum and maximum results are already shown for each vehicle. Fuel categories are grouped by oxygen content. From left to right in each figure, Fuel C (non-oxygenated) on the far left, followed by the test fuels with 3.5 wt% oxygen, followed by the test fuels with 5.5 wt% oxygen, and ending with the certification gasoline categories on the far right. Graphical representations of the average test results for all phases are shown in Figure 9-13 through Figure 9-76 in the Appendix. The net filter gains for each test-phase were also recorded and are shown in the Table 9-1 through Table 9-4 of the Appendix.

Table 7-2 Vehicle A Weighted Average Test Results

Vehicle A Weighted Average Test Results								
Fuel	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**
-	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.012	0.333	0.022	0.010	1.6
10% ethanol	91.7	1.16	3.7	0.027	0.672	0.016	0.023	1.4
19% MTBE	92.6	1.04	3.54	0.018	0.458	0.013	0.014	1.7
16% i-butanol	90.8	1.07	3.79	0.013	0.378	0.015	0.010	1.4
15% ethanol	92.8	1.08	5.49	0.016	0.318	0.009	0.012	1.9
29% MTBE	94.4	0.92	5.37	0.014	0.323	0.020	0.011	1.7
24% i-butanol	91.7	1.09	5.63	0.021	0.551	0.012	0.017	1.3
Certification Gasoline (Initial)	92.5	1.27	0	0.029	0.568	0.011	0.023	1.4
Certification Gasoline (Final)	92.5	1.27	0	0.033	0.923	0.011	0.026	1.8

Table 7-3 Vehicle B Weighted Average Test Results

Vehicle B Weighted Average Test Results								
Fuel	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**
-	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.030	0.238	0.011	0.020	8.7
10% ethanol	91.7	1.16	3.7	0.022	0.150	0.008	0.014	4.6
19% MTBE	92.6	1.04	3.54	0.015	0.151	0.008	0.008	6.4
16% i-butanol	90.8	1.07	3.79	0.022	0.164	0.009	0.014	7.5
15% ethanol	92.8	1.08	5.49	0.017	0.114	0.013	0.009	7.6
29% MTBE	94.4	0.92	5.37	0.021	0.171	0.018	0.013	7.5
24% i-butanol	91.7	1.09	5.63	0.020	0.115	0.016	0.012	9.4
Certification Gasoline (Initial)	92.5	1.27	0	0.031	0.221	0.011	0.020	9.0
Certification Gasoline (Final)	92.5	1.27	0	0.031	0.220	0.010	0.020	12.5

Table 7-4 Vehicle C Weighted Average Test Results

Vehicle C Weighted Average Test Results								
Fuel	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**
-	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.013	0.783	0.008	0.008	1.3
10% ethanol	91.7	1.16	3.7	0.010	0.608	0.007	0.006	1.5
19% MTBE	92.6	1.04	3.54	0.009	0.755	0.008	0.005	1.5
16% i-butanol	90.8	1.07	3.79	0.009	0.654	0.006	0.005	1.2
15% ethanol	92.8	1.08	5.49	0.010	0.626	0.008	0.006	1.3
29% MTBE	94.4	0.92	5.37	0.010	0.698	0.008	0.006	1.3
24% i-butanol	91.7	1.09	5.63	0.010	0.598	0.008	0.006	1.3
Certification Gasoline (Initial)	92.5	1.27	0	0.016	0.658	0.009	0.008	1.7
Certification Gasoline (Final)	92.5	1.27	0	0.017	0.688	0.011	0.010	2.1

Table 7-5 Vehicle D Weighted Average Test Results

Vehicle D Weighted Average Test Results								
Fuel	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**
-	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.059	1.117	0.007	0.013	2.9
10% ethanol	91.7	1.16	3.7	0.038	0.788	0.012	0.014	4.0
19% MTBE	92.6	1.04	3.54	0.019	0.567	0.008	0.011	3.3
16% i-butanol	90.8	1.07	3.79	0.038	0.725	0.009	0.016	3.2
15% ethanol	92.8	1.08	5.49	0.043	0.760	0.011	0.015	3.7
29% MTBE	94.4	0.92	5.37	0.028	0.657	0.007	0.012	3.2
24% i-butanol	91.7	1.09	5.63	0.041	0.746	0.010	0.017	3.7
Certification Gasoline (Initial)	92.5	1.27	0	0.027	0.630	0.011	0.013	3.5
Certification Gasoline (Final)	92.5	1.27	0	0.036	0.688	0.019	0.014	6.3

Table 7-6 All Vehicles Weighted Average PM Results

All Vehicles Weighted Average PM Results							
Vehicle	**-**	**-**	**-**	**Vehicle A**	**Vehicle B**	**Vehicle C**	**Vehicle D**
Measurement	**AKI**	**PMI**	**Oxygen**	**PM**	**PM**	**PM**	**PM**
Units	**-**	**-**	**wt%**	**mg/mi**	**mg/mi**	**mg/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	1.0	0.7	2.5	2.5
10% ethanol	91.7	1.16	3.7	1.3	0.6	2.3	2.5
19% MTBE	92.6	1.04	3.54	1.0	0.4	1.7	1.4
16% i-butanol	90.8	1.07	3.79	0.8	0.3	1.9	1.3
15% ethanol	92.8	1.08	5.49	0.9	0.3	2.1	1.7
29% MTBE	94.4	0.92	5.37	0.8	0.3	0.8	0.9
24% i-butanol	91.7	1.09	5.63	0.7	0.5	2.3	1.2
Certification Gasoline (Initial)	92.5	1.27	0	3.0	0.7	4.1	2.9
Certification Gasoline (Final)	92.5	1.27	0	2.1	0.9	4.1	3.1

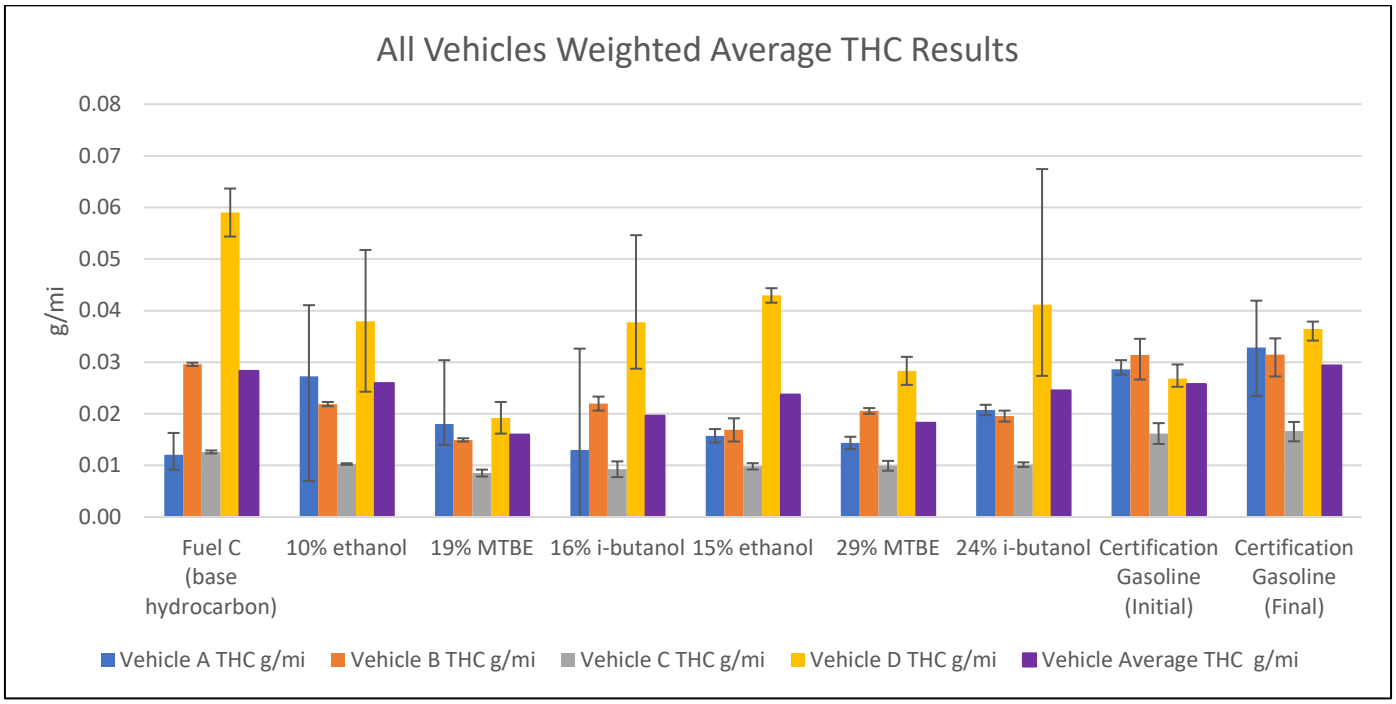

Figure 7-1 Weighted average THC emissions for each vehicle

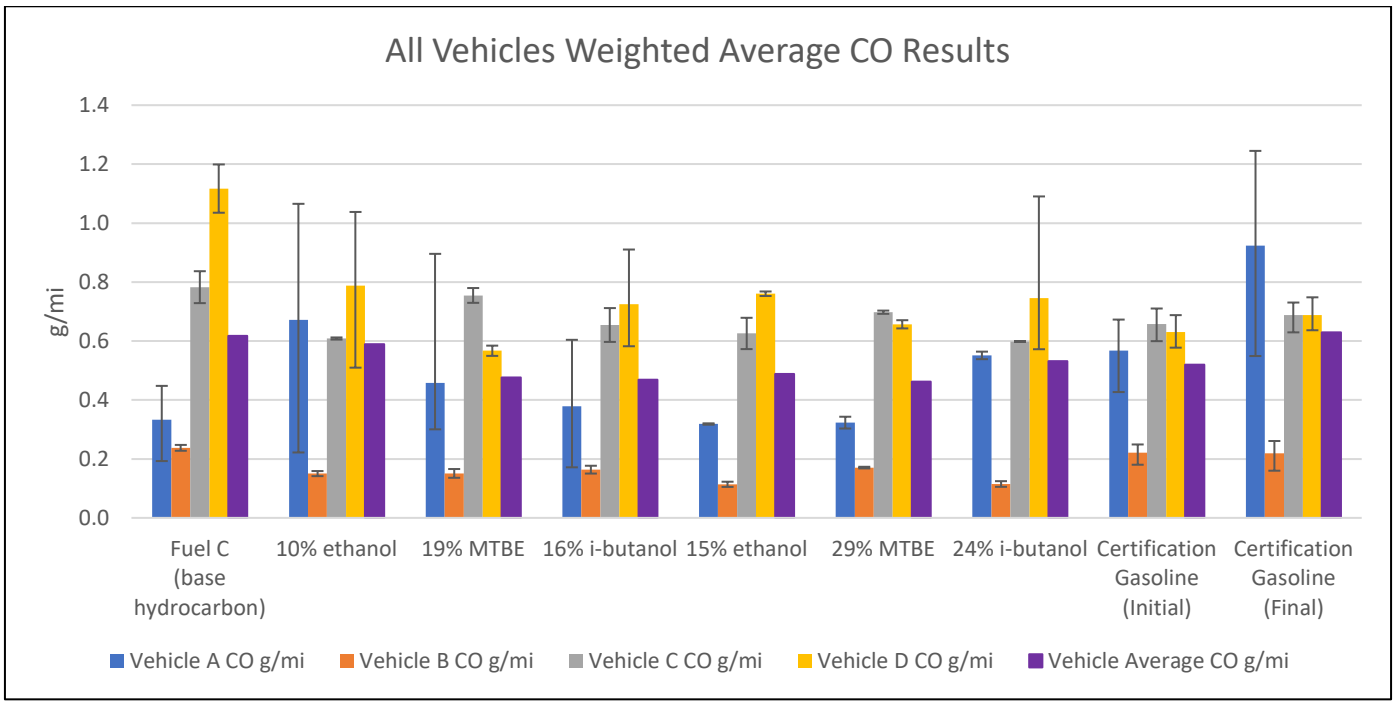

Figure 7-2 Weighted average CO emissions for each vehicle

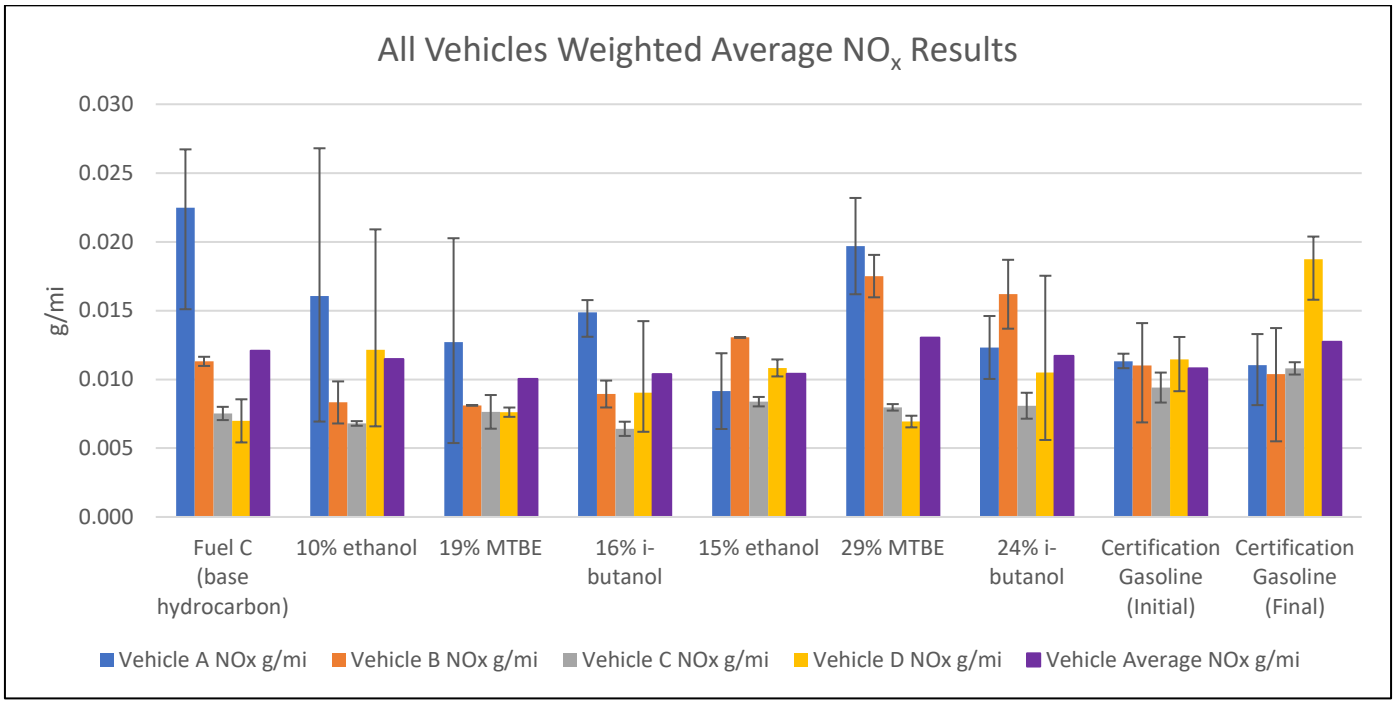

Figure 7-3 Weighted average NOx emissions for each vehicle

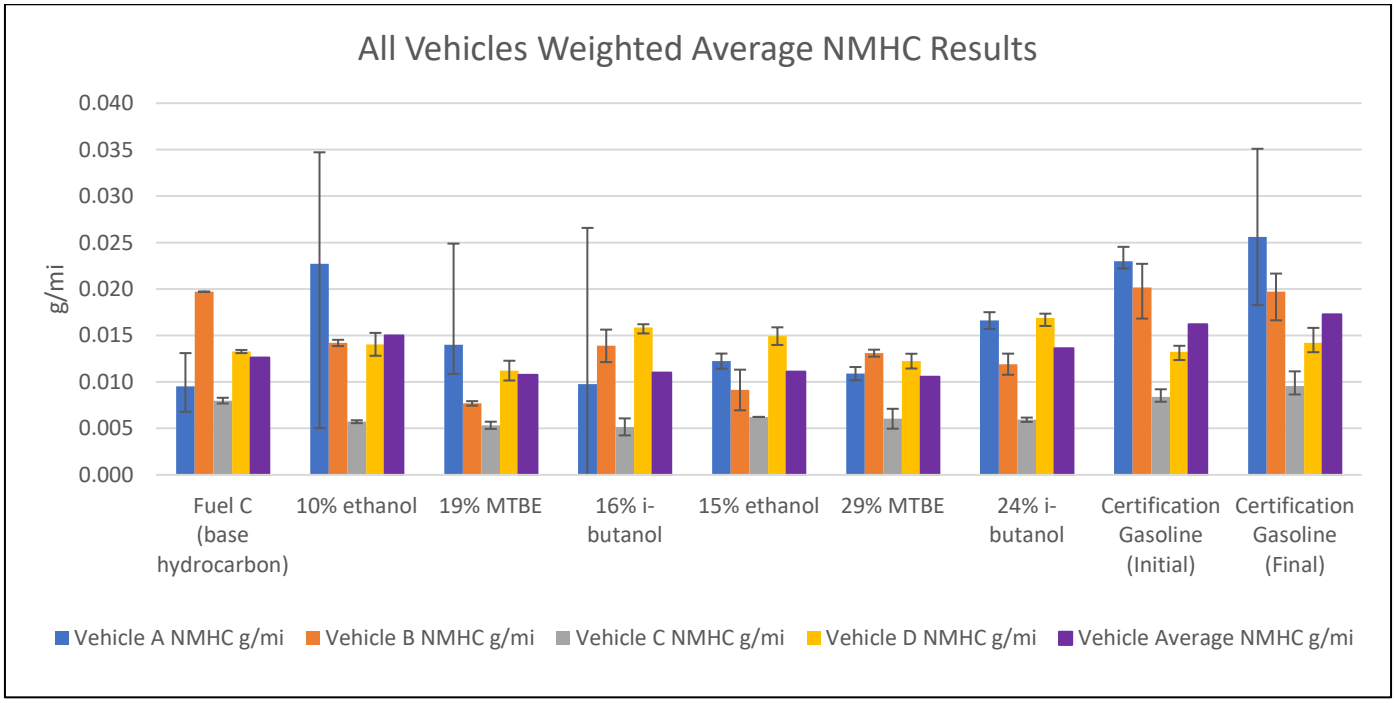

Figure 7-4 Weighted average NMHC emissions for each vehicle

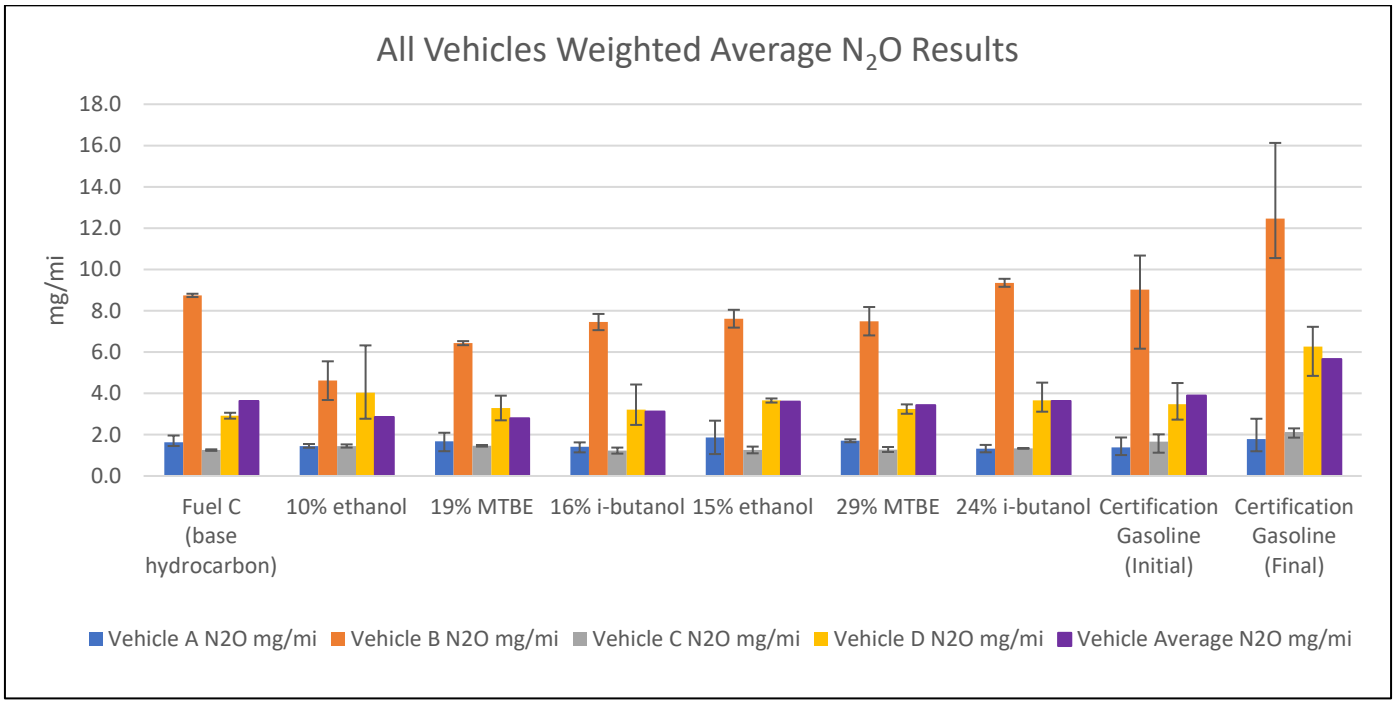

Figure 7-5 Weighted N_2O emissions for each vehicle

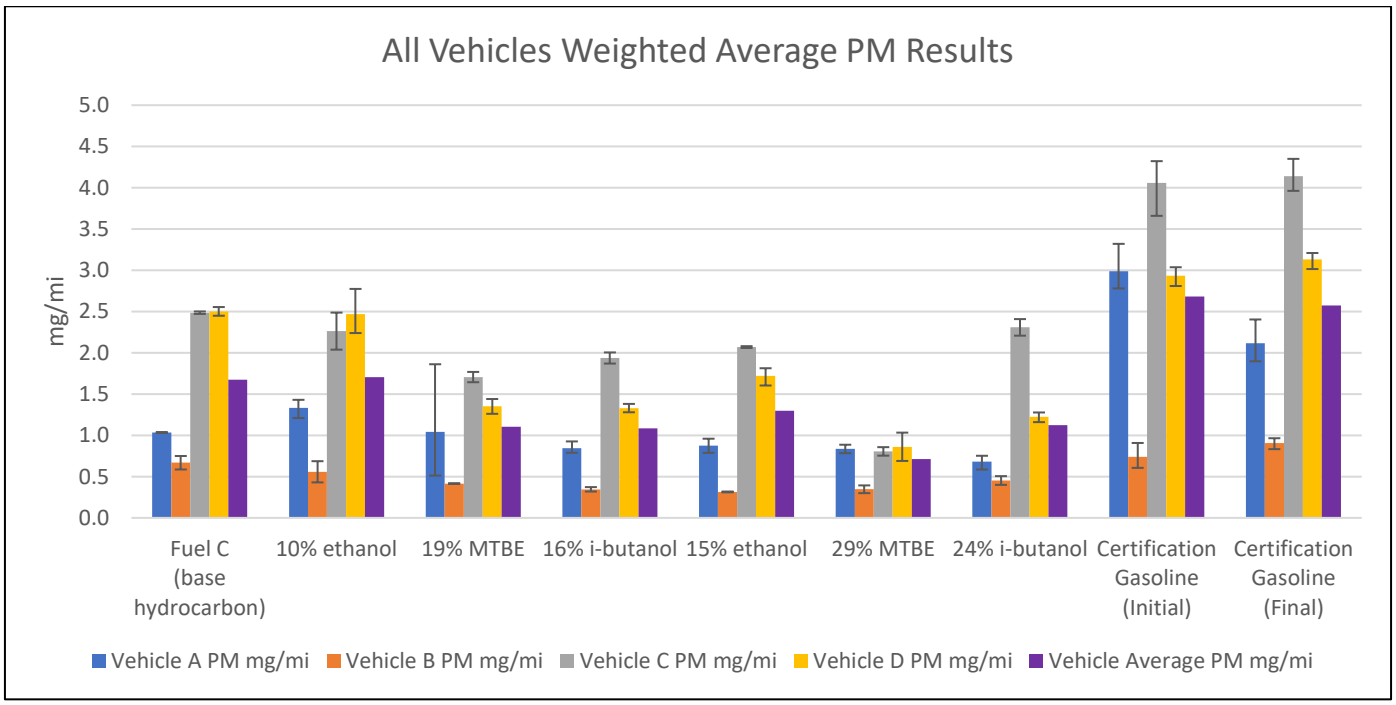

Figure 7-6 Weighted average PM emissions for each vehicle

7.2.1.NOx results for ethanol-blended fuels

Figure 7-7 shows weighted average tailpipe NOx emission over the LA92 cycle for all vehicles focusing only on the base non-oxygenated Fuel C and test fuel derivatives that were splash-blended with ethanol. Error bars represent the minimum and maximum values for a single test. Error bars are not shown for the vehicle average result shown at the far right of each category. It is important to note that this study's base non-oxygenated Fuel C was re-blended to conform to the specifications from E-94-2 and not focus on directly matching market gasoline. Due to the smaller sample size of four test vehicles for this study and that the base fuel was not a market gasoline, Figure 7-7 only shows the tailpipe emissions for the ethanol-blended test fuels next to the base non-oxygenated Fuel C. Any interpretation of these data to correlate tailpipe NOx emissions to varying amounts of ethanol using market gasoline should be avoided with respect to the on-road vehicle fleet.

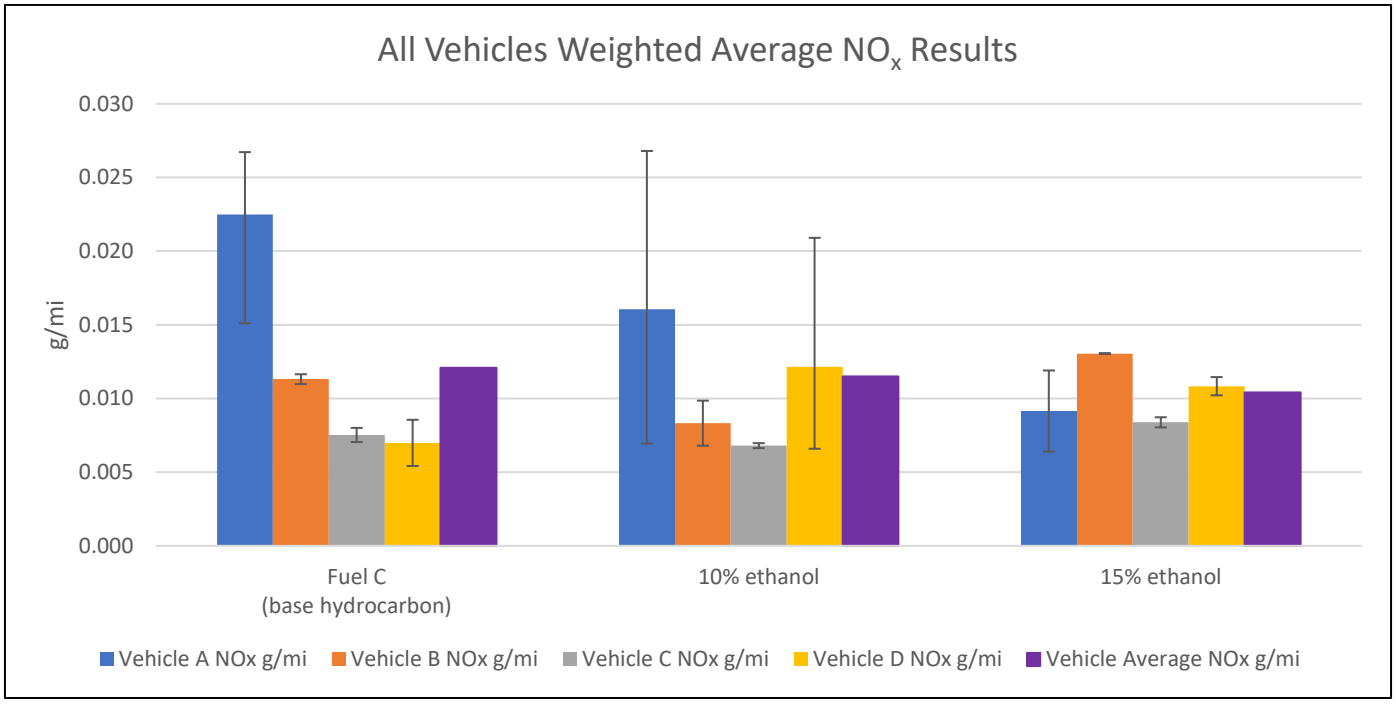

Figure 7-7 Weighted NOx emissions for each vehicle; Ethanol-blended test fuels and Fuel C

7.3.Phase 1 Average Results

Phase 1 average emission results are shown in Table 7-7 through Table 7-11. Graphical representations of Phase 1 average emissions for each vehicle are shown in Figure 7-8 through Figure 7-13. Fleet averages are also shown for emissions. Error bars represent the minimum and maximum result of an individual test. Error bars are not shown for the fleet average since the minimum and maximum results are already shown for each vehicle. Fuel categories are grouped by oxygen content. From left to right in each figure, Fuel C (non-oxygenated) on the far left, followed by the test fuels with 3.5 wt% oxygen, followed by the test fuels with 5.5 wt% oxygen, and ending with the certification gasoline categories on the far right.

Table 7-7 Vehicle A Phase 1 Average Results

Vehicle A Phase 1 Average Test Results								
Fuel	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**
-	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.218	2.304	0.162	0.177	9.4
10% ethanol	91.7	1.16	3.7	0.509	7.489	0.130	0.430	12.4
19% MTBE	92.6	1.04	3.54	0.314	4.789	0.111	0.258	11.7
16% i-butanol	90.8	1.07	3.79	0.231	2.557	0.121	0.185	6.7
15% ethanol	92.8	1.08	5.49	0.284	3.194	0.111	0.232	11.3
29% MTBE	94.4	0.92	5.37	0.243	3.400	0.134	0.195	12.3
24% i-butanol	91.7	1.09	5.63	0.380	5.482	0.130	0.314	10.9
Certification Gasoline (Initial)	92.5	1.27	0	0.131	1.986	0.052	0.110	4.0
Certification Gasoline (Final)	92.5	1.27	0	0.143	2.296	0.045	0.121	5.4

Table 7-8 Vehicle B Phase 1 Average Test Results

Vehicle B Phase 1 Average Test Results								
Fuel	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**
-	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.294	1.893	0.078	0.246	68.4
10% ethanol	91.7	1.16	3.7	0.210	1.163	0.028	0.172	34.0
19% MTBE	92.6	1.04	3.54	0.154	1.012	0.046	0.123	47.4
16% i-butanol	90.8	1.07	3.79	0.219	1.177	0.059	0.178	59.1
15% ethanol	92.8	1.08	5.49	0.130	0.444	0.054	0.101	53.5
29% MTBE	94.4	0.92	5.37	0.206	1.786	0.047	0.170	38.8
24% i-butanol	91.7	1.09	5.63	0.159	0.422	0.061	0.126	58.1
Certification Gasoline (Initial)	92.5	1.27	0	0.087	0.607	0.039	0.071	19.0
Certification Gasoline (Final)	92.5	1.27	0	0.086	0.561	0.038	0.069	22.7

Table 7-9 Vehicle C Phase 1 Average Test Results

Vehicle C Phase 1 Average Test Results								
Fuel	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**
-	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.173	6.659	0.016	0.124	14.4
10% ethanol	91.7	1.16	3.7	0.136	4.905	0.018	0.092	11.3
19% MTBE	92.6	1.04	3.54	0.143	7.262	0.021	0.094	17.6
16% i-butanol	90.8	1.07	3.79	0.141	5.680	0.017	0.090	14.3
15% ethanol	92.8	1.08	5.49	0.144	5.480	0.019	0.099	14.3
29% MTBE	94.4	0.92	5.37	0.141	7.353	0.016	0.096	13.3
24% i-butanol	91.7	1.09	5.63	0.137	4.605	0.015	0.091	13.8
Certification Gasoline (Initial)	92.5	1.27	0	0.061	2.603	0.016	0.039	4.3
Certification Gasoline (Final)	92.5	1.27	0	0.061	2.542	0.017	0.041	4.6

Table 7-10 Vehicle D Phase 1 Average Test Results

Vehicle D Phase 1 Average Test Results								
Fuel	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**
-	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.306	1.823	0.097	0.234	48.5
10% ethanol	91.7	1.16	3.7	0.323	1.638	0.160	0.256	67.6
19% MTBE	92.6	1.04	3.54	0.254	2.407	0.074	0.192	50.6
16% i-butanol	90.8	1.07	3.79	0.323	1.573	0.101	0.261	41.8
15% ethanol	92.8	1.08	5.49	0.338	2.342	0.096	0.262	54.0
29% MTBE	94.4	0.92	5.37	0.280	2.319	0.069	0.218	54.2
24% i-butanol	91.7	1.09	5.63	0.377	1.876	0.135	0.305	57.5
Certification Gasoline (Initial)	92.5	1.27	0	0.089	0.959	0.034	0.061	12.4
Certification Gasoline (Final)	92.5	1.27	0	0.101	1.049	0.048	0.064	18.3

Table 7-11 All Vehicles Phase 1 Average PM Results

All Vehicles Phase 1 Average PM Results							
Vehicle	**-**	**-**		**Vehicle A**	**Vehicle B**	**Vehicle C**	**Vehicle D**
Measurement	**AKI**	**PMI**	**Oxygen**	**PM**	**PM**	**PM**	**PM**
Units	**-**	**-**	**wt%**	**mg/mi**	**mg/mi**	**mg/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	7.3	7.3	36.1	19.3
10% ethanol	91.7	1.16	3.7	7.6	6.5	30.9	18.1
19% MTBE	92.6	1.04	3.54	5.4	2.5	25.3	10.6
16% i-butanol	90.8	1.07	3.79	5.8	4.0	26.9	11.7
15% ethanol	92.8	1.08	5.49	5.5	2.9	29.1	14.3
29% MTBE	94.4	0.92	5.37	5.1	2.7	11.1	7.8
24% i-butanol	91.7	1.09	5.63	4.0	4.6	34.1	11.9
Certification Gasoline (Initial)	92.5	1.27	0	5.5	2.3	17.9	9.9
Certification Gasoline (Final)	92.5	1.27	0	5.3	3.3	18.1	10.6

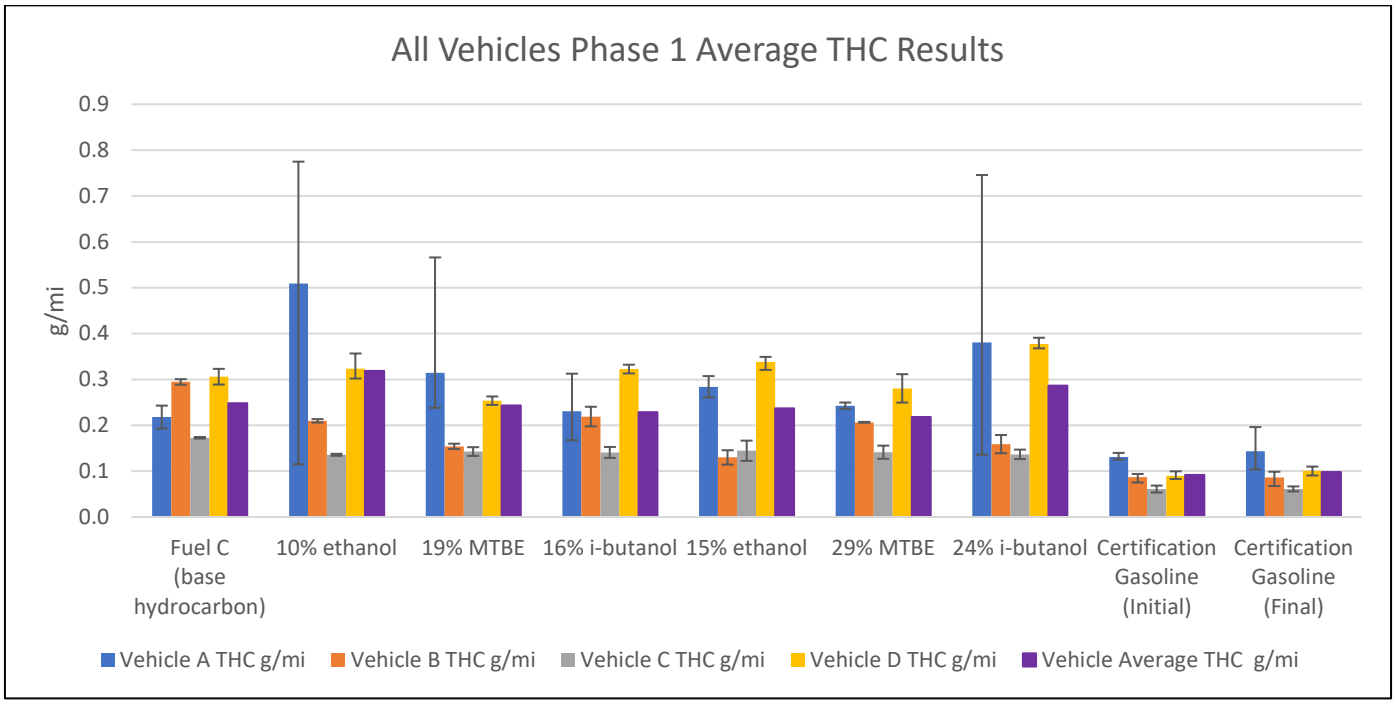

Figure 7-8 Phase 1 average THC emissions for each vehicle

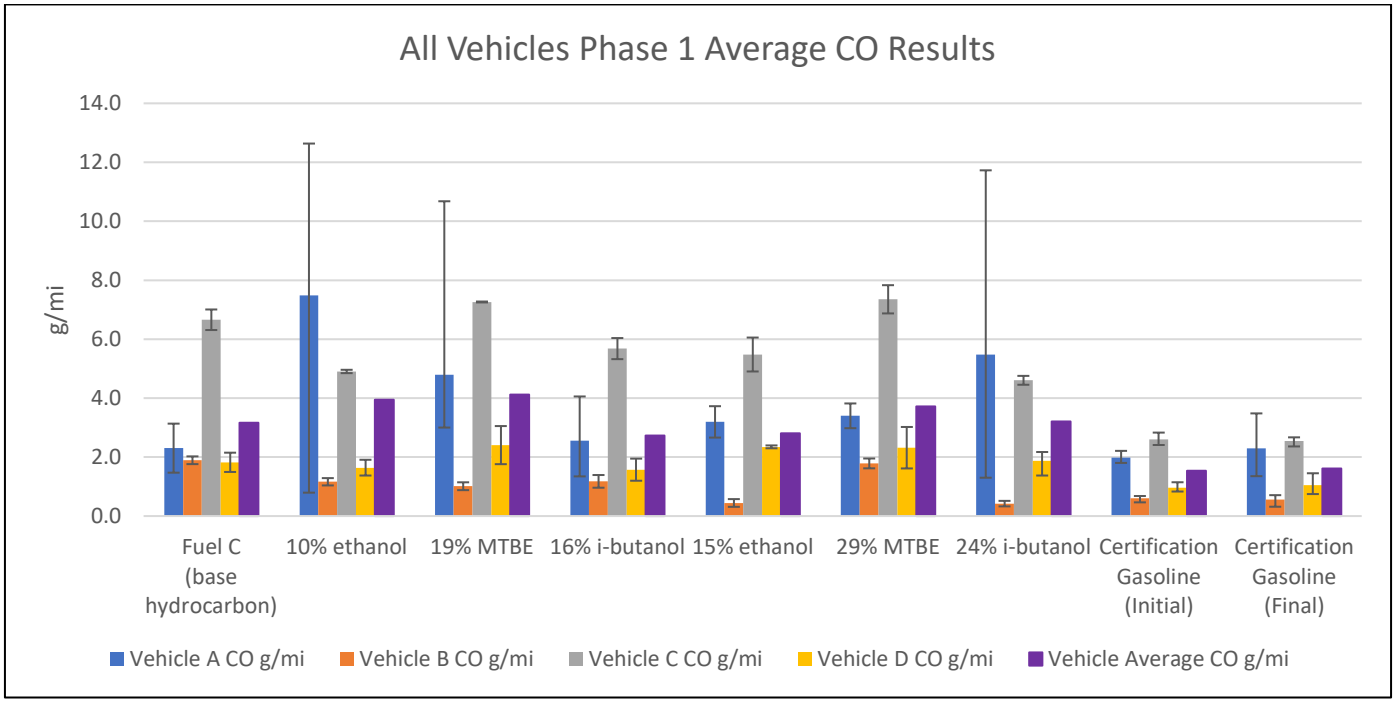

Figure 7-9 Phase 1 average CO emissions for each vehicle

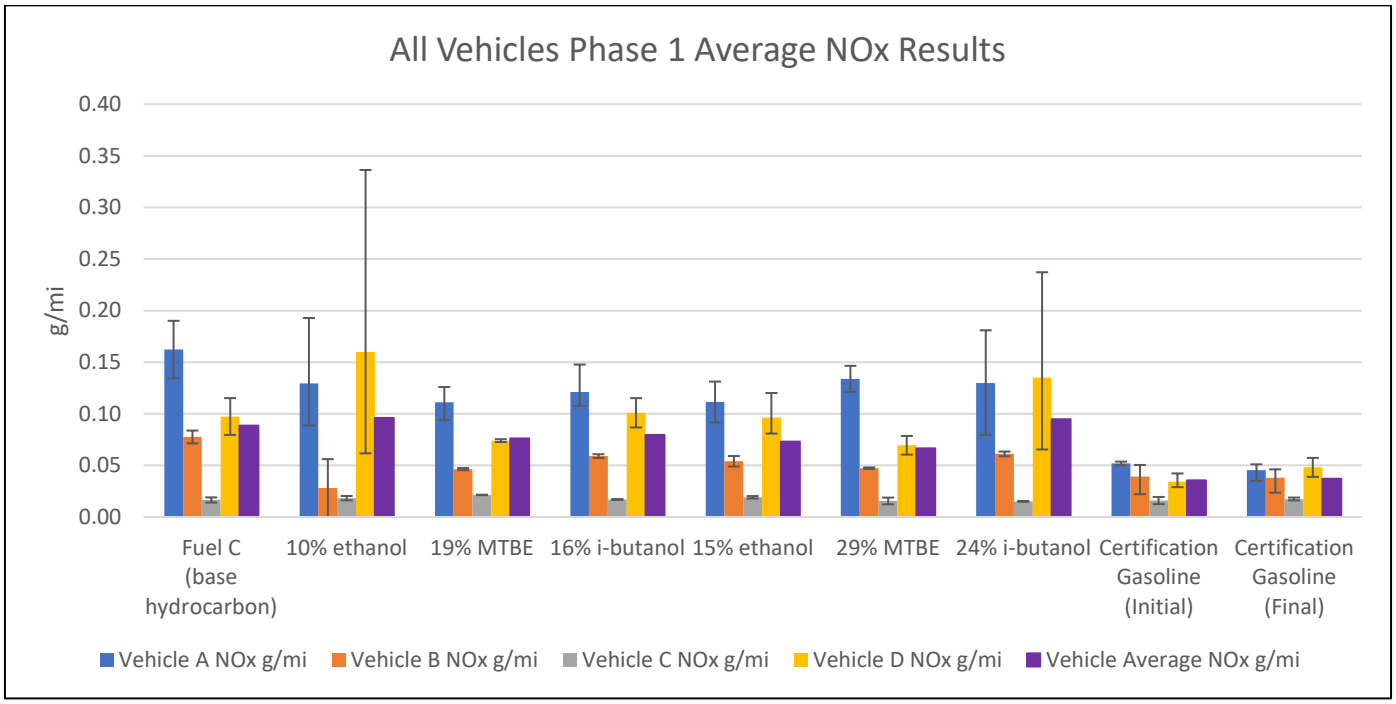

Figure 7-10 Phase 1 average NOx emissions for each vehicle

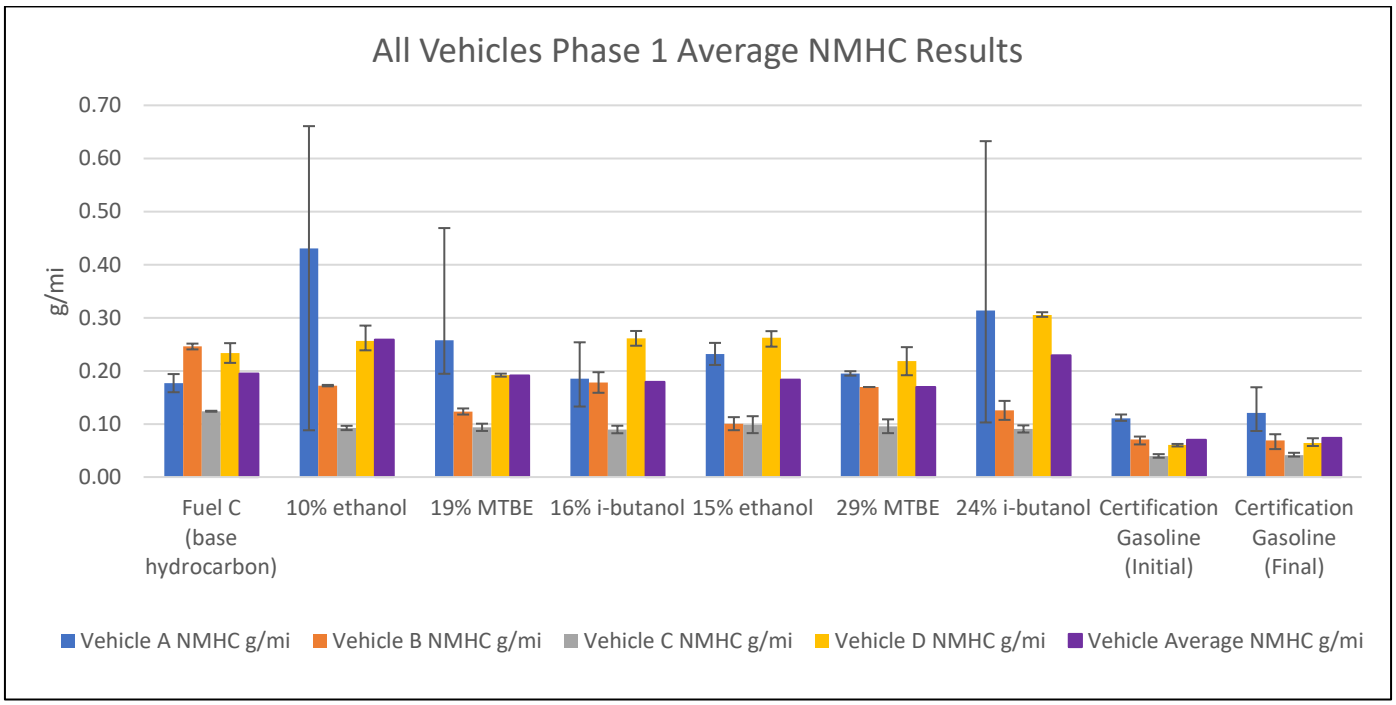

Figure 7-11 Phase 1 average NMHC emissions for each vehicle

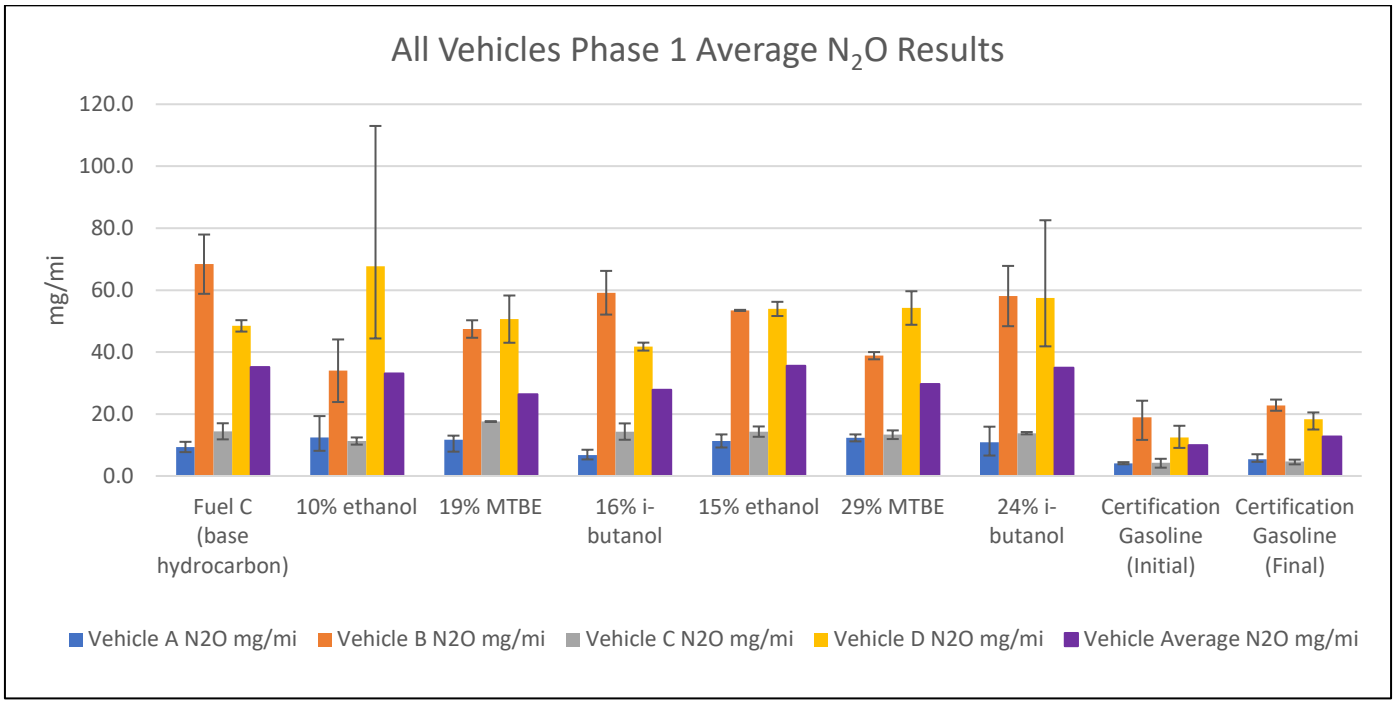

Figure 7-12 Phase 1 average N_2O emissions for each vehicle

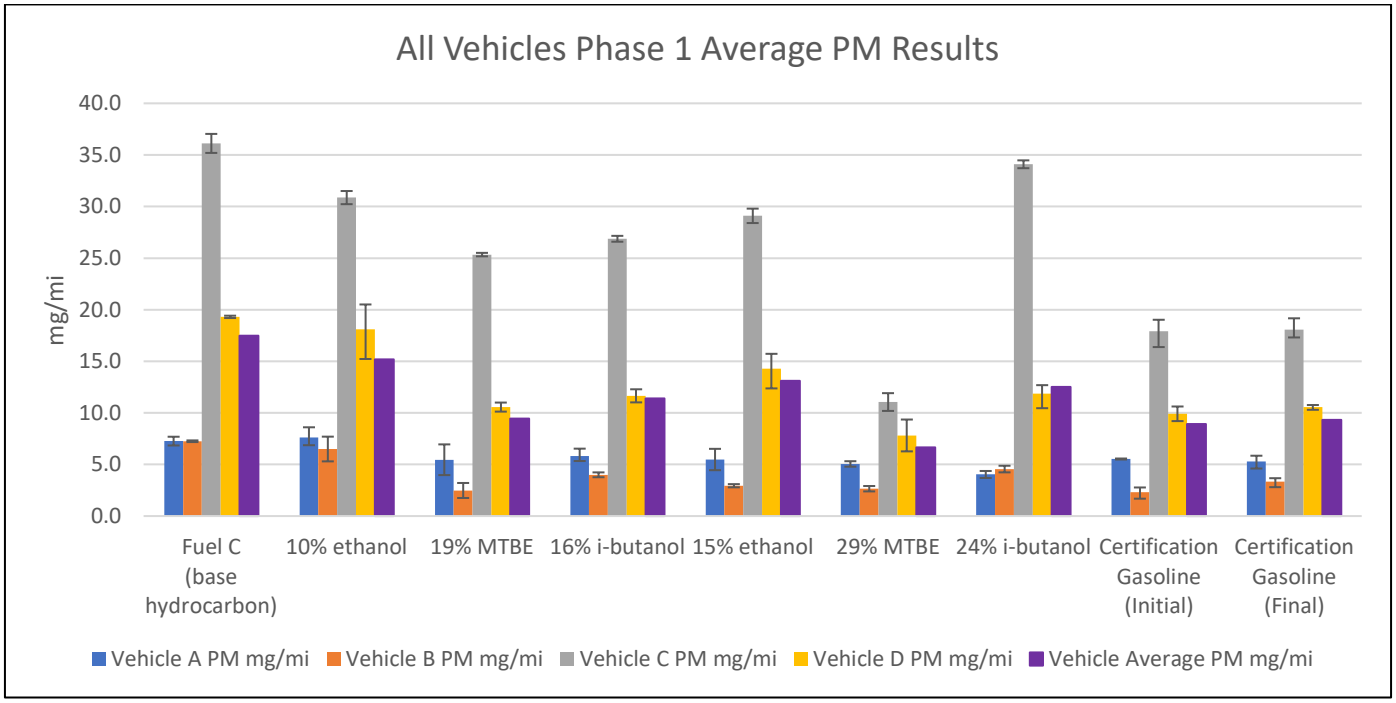

Figure 7-13 Phase 1 average PM emissions for each vehicle

7.4.Fleet Average Results

A summary of the fleet average emissions for the weighted results and phase 1 results is shown in Table 7-12 through Table 7-15. Graphical representations of the percent change in fleet average emissions for the weighted results and phase 1 results relative to Fuel C is shown in Figure 7-14 and Figure 7-15.

Large reductions in fleet average emissions are observed for all oxygenated test fuels with the exception of 10% ethanol as shown in Figure 7-14. In the case of fleet average PM emissions, 10% ethanol was the only test fuel to not decrease emissions. The remaining oxygenated test fuels were all observed to decrease fleet average PM emissions.

Phase 1 fleet average emissions of all test fuels for THC, CO, NO_x and NMHC are shown in Figure 7-15.

Table 7-12 Fleet Weighted Average Results

Fleet Weighted Average Results									
Measurement	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**	**PM**
Units	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.028	0.618	0.012	0.013	3.6	1.7
10% ethanol	91.7	1.16	3.7	0.026	0.590	0.011	0.015	2.9	1.7
19% MTBE	92.6	1.04	3.54	0.016	0.476	0.010	0.011	2.8	1.1
16% i-butanol	90.8	1.07	3.79	0.020	0.469	0.010	0.011	3.1	1.1
15% ethanol	92.8	1.08	5.49	0.024	0.489	0.010	0.011	3.6	1.3
29% MTBE	94.4	0.92	5.37	0.018	0.462	0.013	0.011	3.4	0.7
24% i-butanol	91.7	1.09	5.63	0.025	0.532	0.012	0.014	3.6	1.1
Certification Gasoline (Initial)	92.5	1.27	0	0.026	0.519	0.011	0.016	3.9	2.7
Certification Gasoline (Final)	92.5	1.27	0	0.029	0.629	0.013	0.017	5.7	2.6

Table 7-13 Fleet Phase 1 Average Results

Fleet Phase 1 Average Results									
Measurement	**AKI**	**PMI**	**Oxygen**	**THC**	**CO**	**NO_x**	**NMHC**	**N_2O**	**PM**
Units	**-**	**-**	**wt%**	**g/mi**	**g/mi**	**g/mi**	**g/mi**	**mg/mi**	**mg/mi**
Fuel C (base hydrocarbon)	88.2	1.3	0	0.248	3.170	0.088	0.195	35.2	17.5
10% ethanol	91.7	1.16	3.7	0.319	3.952	0.096	0.259	33.1	15.2
19% MTBE	92.6	1.04	3.54	0.243	4.119	0.076	0.191	26.4	9.5
16% i-butanol	90.8	1.07	3.79	0.229	2.726	0.080	0.179	27.9	11.4
15% ethanol	92.8	1.08	5.49	0.237	2.807	0.073	0.183	35.6	13.1
29% MTBE	94.4	0.92	5.37	0.218	3.715	0.067	0.170	29.7	6.6
24% i-butanol	91.7	1.09	5.63	0.286	3.213	0.095	0.229	34.9	12.5
Certification Gasoline (Initial)	92.5	1.27	0	0.092	1.539	0.035	0.070	9.9	8.9
Certification Gasoline (Final)	92.5	1.27	0	0.098	1.612	0.037	0.074	12.8	9.3

Table 7-14 Percent Change Relative to Fuel C for the Fleet Weighed Averages

Fleet Weighted Average Results Percent Change Relative to Fuel C									
Fuel C (non-oxygenated base hydrocarbon)				**Fleet Average Mass Emission**					
				THC	**CO**	**NOx**	**NMHC**	**N2O**	**PM**
				g/mi	**g/mi**	**g/mi**	**g/mi**	**mg/mi**	**mg/mi**
				0.028	0.618	0.012	0.013	3.6	1.7
Fuel Properties				**Percent Change Relative to Fuel C**					
	AKI	**PMI**	**Oxygen**	**THC**	**CO**	**NOx**	**NMHC**	**N2O**	**PM**
Units	**-**	**-**	**wt%**	**%**	**%**	**%**	**%**	**%**	**%**
Fuel C	88.2	1.3	0	-	-	-	-	-	-
10% ethanol	91.7	1.16	3.7	-8	-5	-5	19	-21	2
19% MTBE	92.6	1.04	3.54	-44	-23	-17	-15	-23	-34
16% i-butanol	90.8	1.07	3.79	-31	-24	-14	-13	-14	-35
15% ethanol	92.8	1.08	5.49	-16	-21	-14	-12	-1	-22
29% MTBE	94.4	0.92	5.37	-35	-25	8	-16	-6	-57
24% i-butanol	91.7	1.09	5.63	-13	-14	-3	8	0	-33

Table 7-15 Percent Change Relative to Fuel C for the Fleet Phase 1 Averages

Fleet Phase 1 Average Results Percent Change Relative to Fuel C									
Fuel C (non-oxygenated base hydrocarbon)				Fleet Average Mass Emission					
				THC	CO	NOx	NMHC	N2O	PM
				g/mi	g/mi	g/mi	g/mi	mg/mi	mg/mi
				0.248	3.170	0.088	0.195	35.2	17.5
Fuel Properties				Percent Change Relative to Fuel C					
Measurement	AKI	PMI	Oxygen	THC	CO	NOx	NMHC	N2O	PM
Units	-	-	wt%	%	%	%	%	%	%
Fuel C	88.2	1.3	0	-	-	-	-	-	-
10% ethanol	91.7	1.16	3.7	29	25	9	33	-6	-13
19% MTBE	92.6	1.04	3.54	-2	30	-14	-2	-25	-46
16% i-butanol	90.8	1.07	3.79	-8	-14	-10	-8	-21	-35
15% ethanol	92.8	1.08	5.49	-4	-11	-17	-6	1	-25
29% MTBE	94.4	0.92	5.37	-12	17	-25	-13	-16	-62
24% i-butanol	91.7	1.09	5.63	16	1	7	17	-1	-28

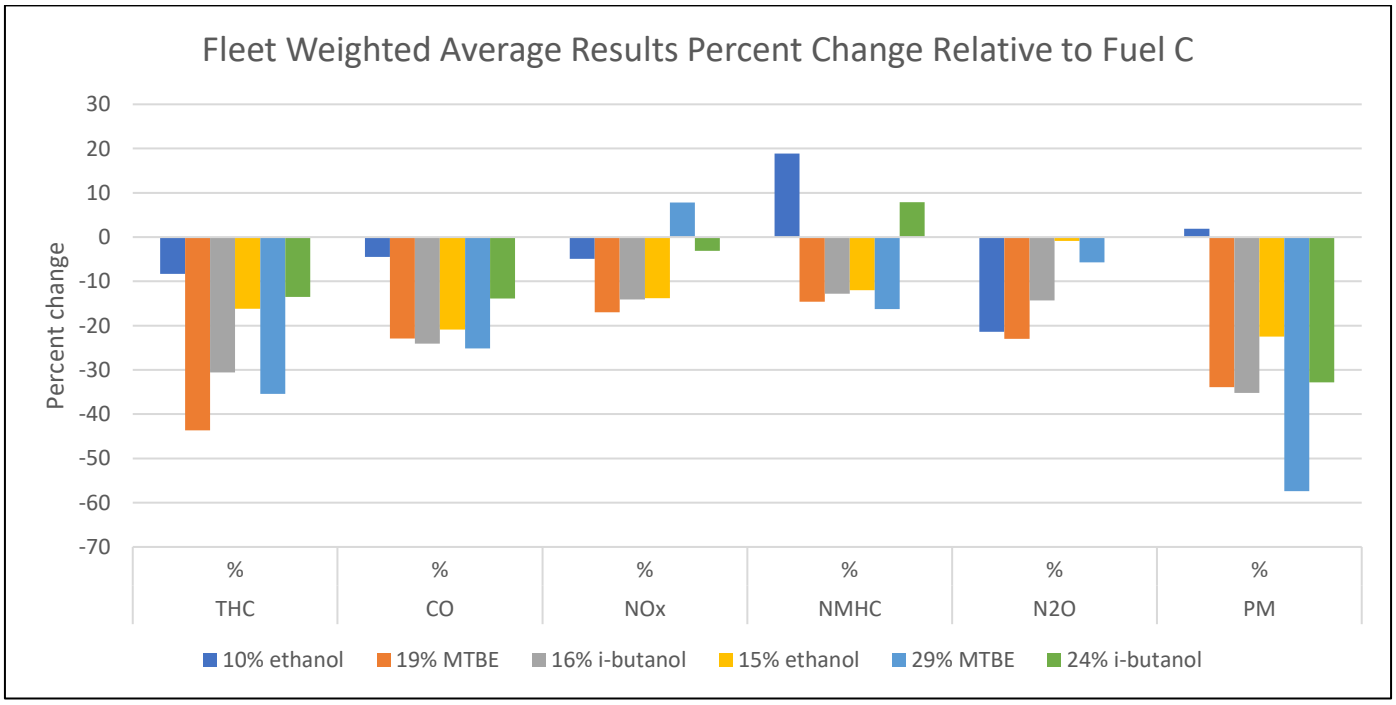

Figure 7-14 Percent Change Relative to Fuel C for the Fleet Weighted Averages

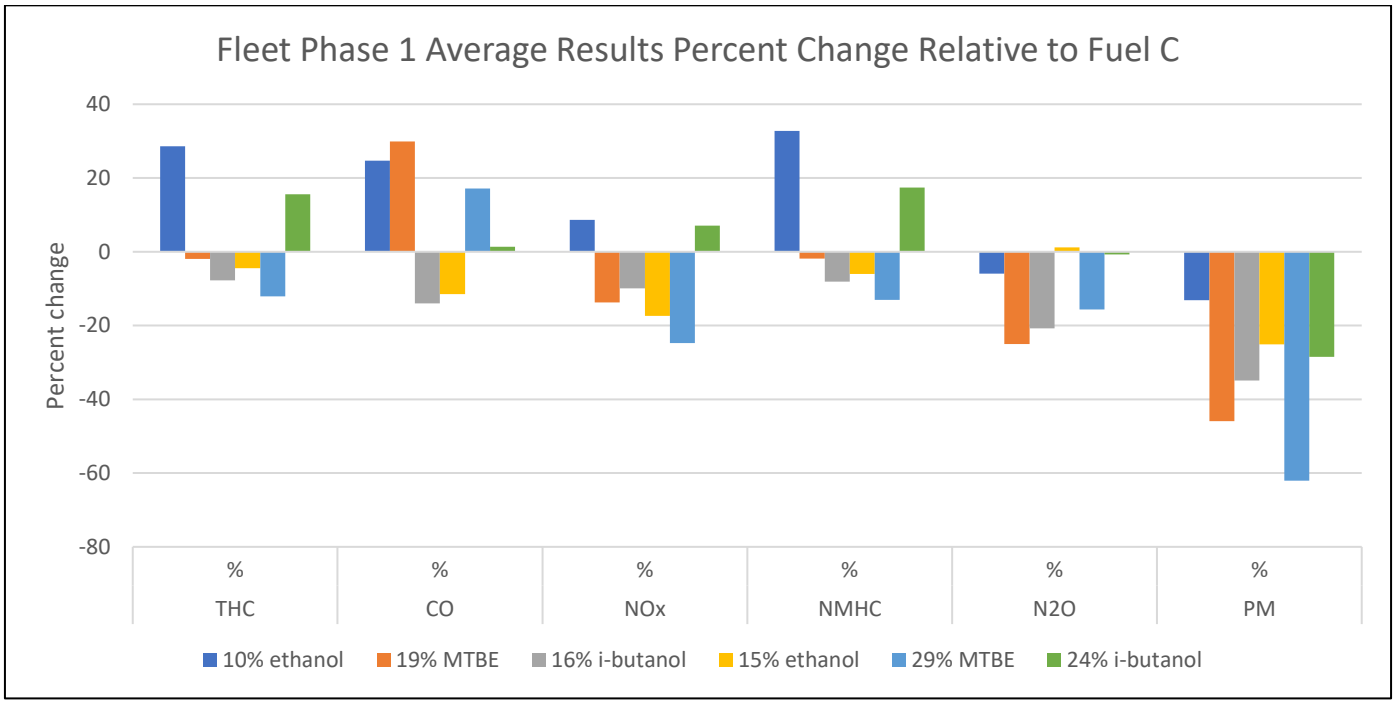

Figure 7-15 Percent Change Relative to Fuel C for the Fleet Phase 1 Averages

7.5.OBDII Total Fuel Trim and Spark Timing

The individual test averages of OBDII total fuel trim and spark-timing were plotted for each vehicle/fuel combination. These channels provide some additional insight to the adaptive strategies for each car when new fuel is introduced. For Vehicle A, there are large ranges of average total fuel trim for 19% MTBE, 10% ethanol, 16% i-butanol, and 24% i-butanol. Figure 7-16 shows the average total fuel trim for Vehicle A separated by test fuel. These test-series required a third emission test since the emission repeatability check failed the criteria. As previously mentioned in Section 7.1, Vehicle A required two separate test sequences using 19% MTBE. The second test sequence was conducted at the end of the test program in order to maintain fuel testing order that was randomly generated. For this reason, Vehicle A received more than three tests using 19% MTBE whereas all other test fuels either received two or three tests. Figure 7-17 shows the average spark-timing for Vehicle A separated by test fuel.

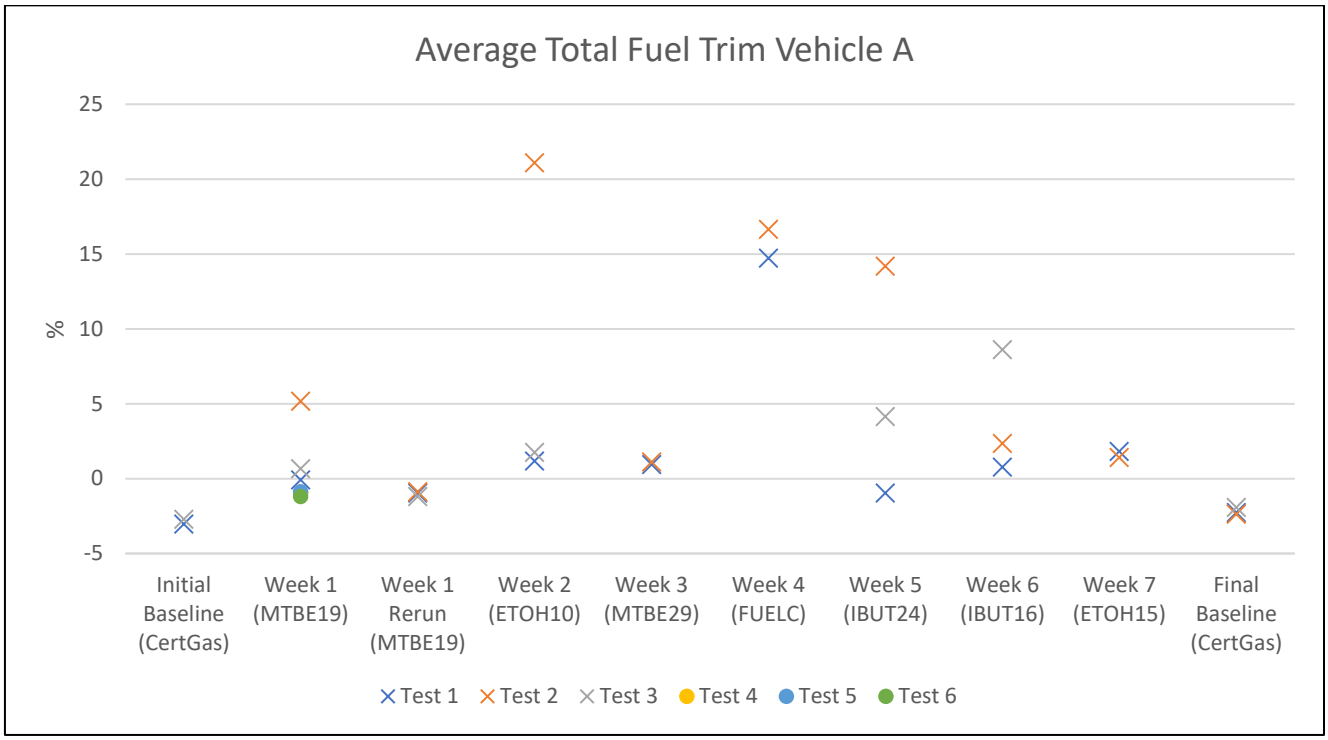

Figure 7-16 Vehicle A Average Total Fuel Trim

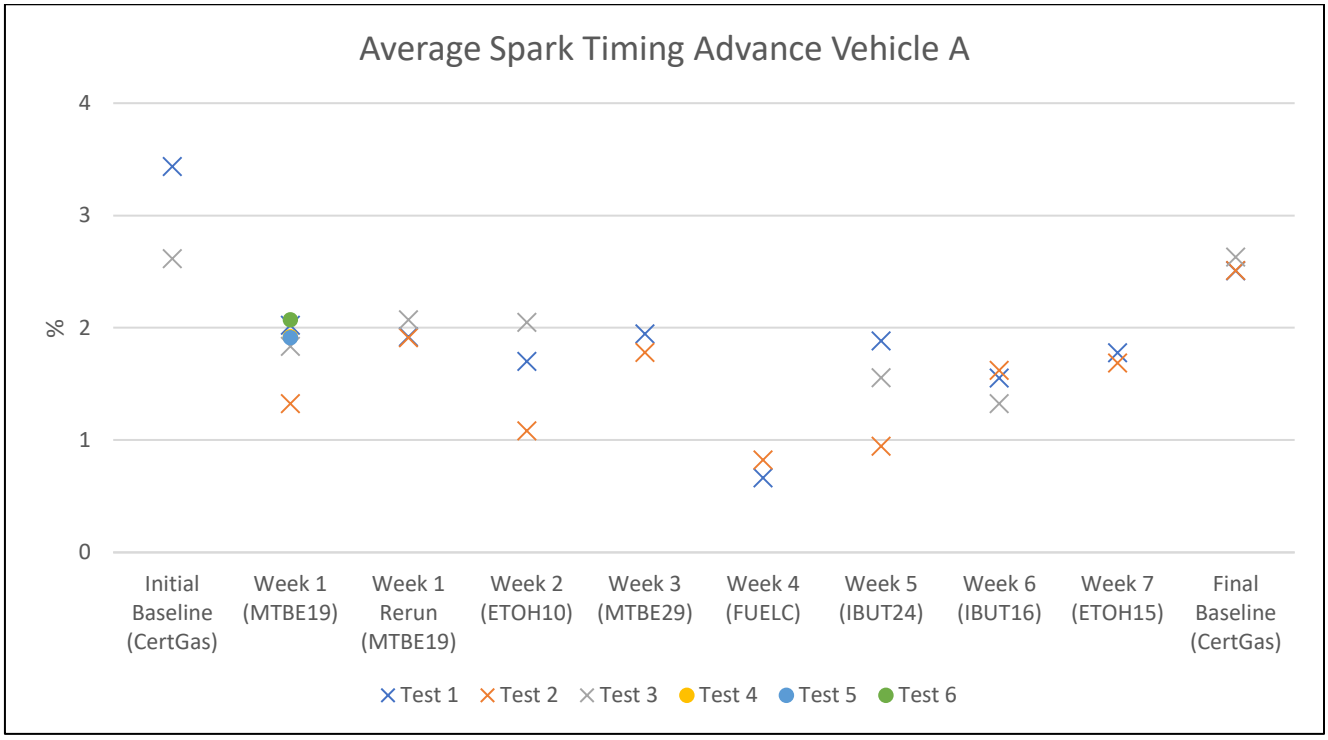

Figure 7-17 Vehicle A Average Spark-Timing

The average OBDII total fuel trim and spark-timing for Vehicle B, Vehicle C, and Vehicle C are shown in Figure 7-18 through Figure 7-23. A single average for total fuel trim and spark-timing were calculated for each test as a surrogate for overall vehicle behavior during a controlled drive trace. It should be noted that the LA92 and FTP drive cycles are long, transient events which may not be fully represented as a singular average.

Consistent averages were observed for all three vehicles in total fuel trim and spark-timing. The Vehicle C did require a third emission test for 10% ethanol, 15% ethanol, and 24% i-butanol. For these fuels, a larger range in average total fuel trim can be qualitatively observed. For all three of these vehicles, there is a well-behaved order in the average fuel trim as a function of total oxygen content. Test fuels with 0 wt% oxygen produced the smallest average fuel trim. Test fuels with nominal 5.5 wt% oxygen produced the largest average fuel trim. Test fuels with nominal 3.5 wt% oxygen produced average fuel trim results in between the other test fuels.

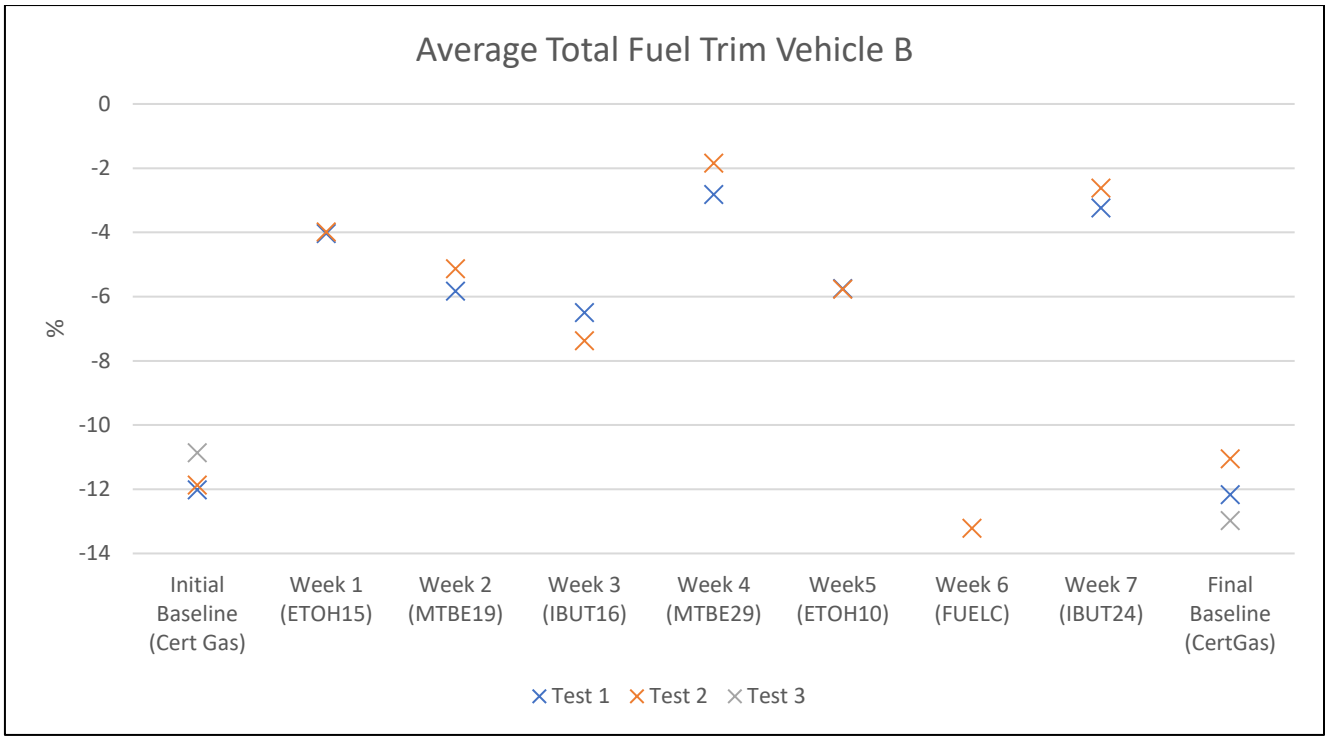

Figure 7-18 Vehicle B Average Total Fuel Trim

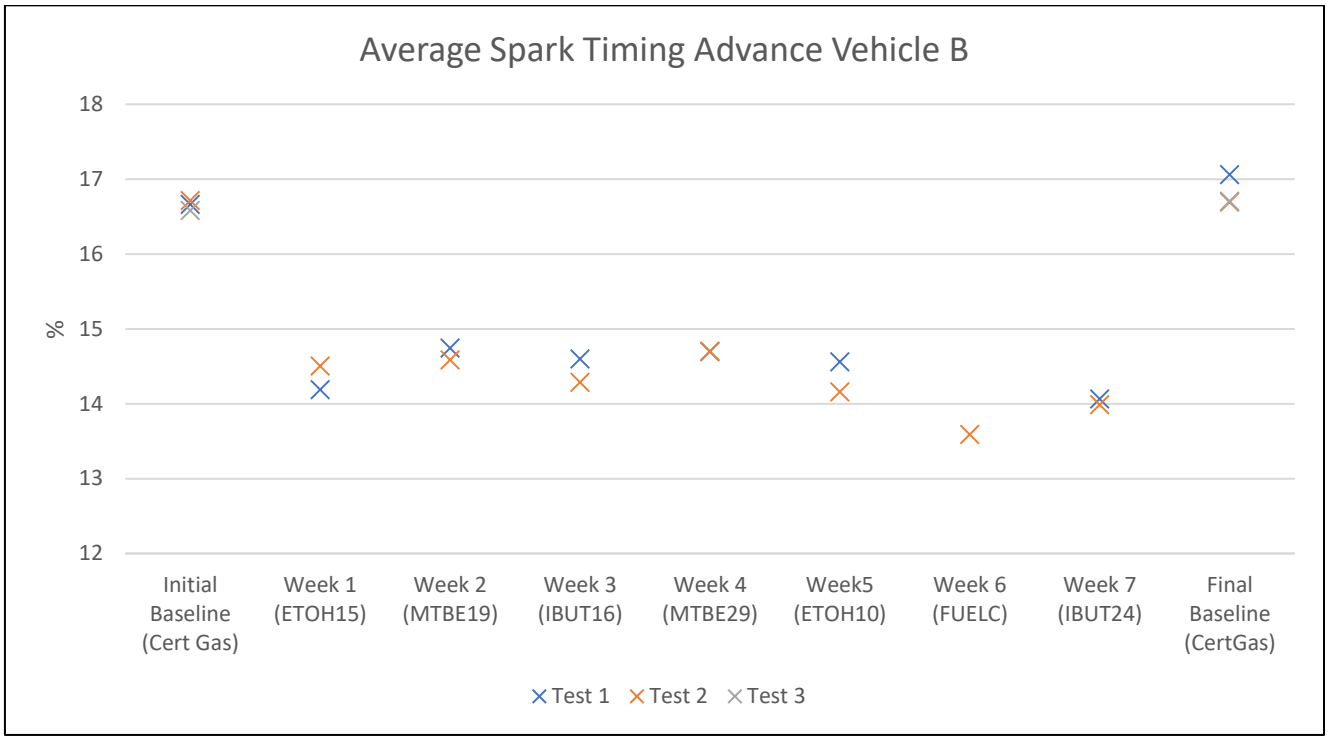

Figure 7-19 Vehicle B Average Spark-Timing

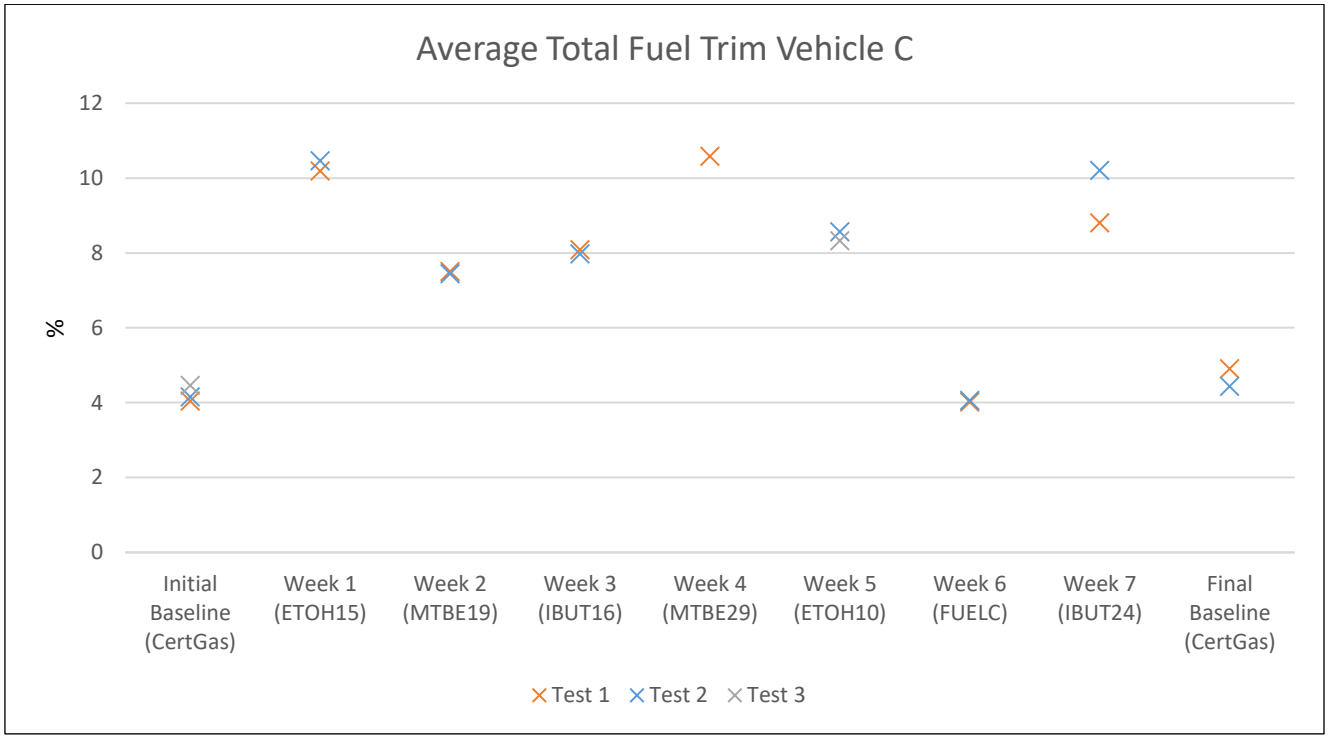

Figure 7-20 Vehicle C Average Total Fuel Trim

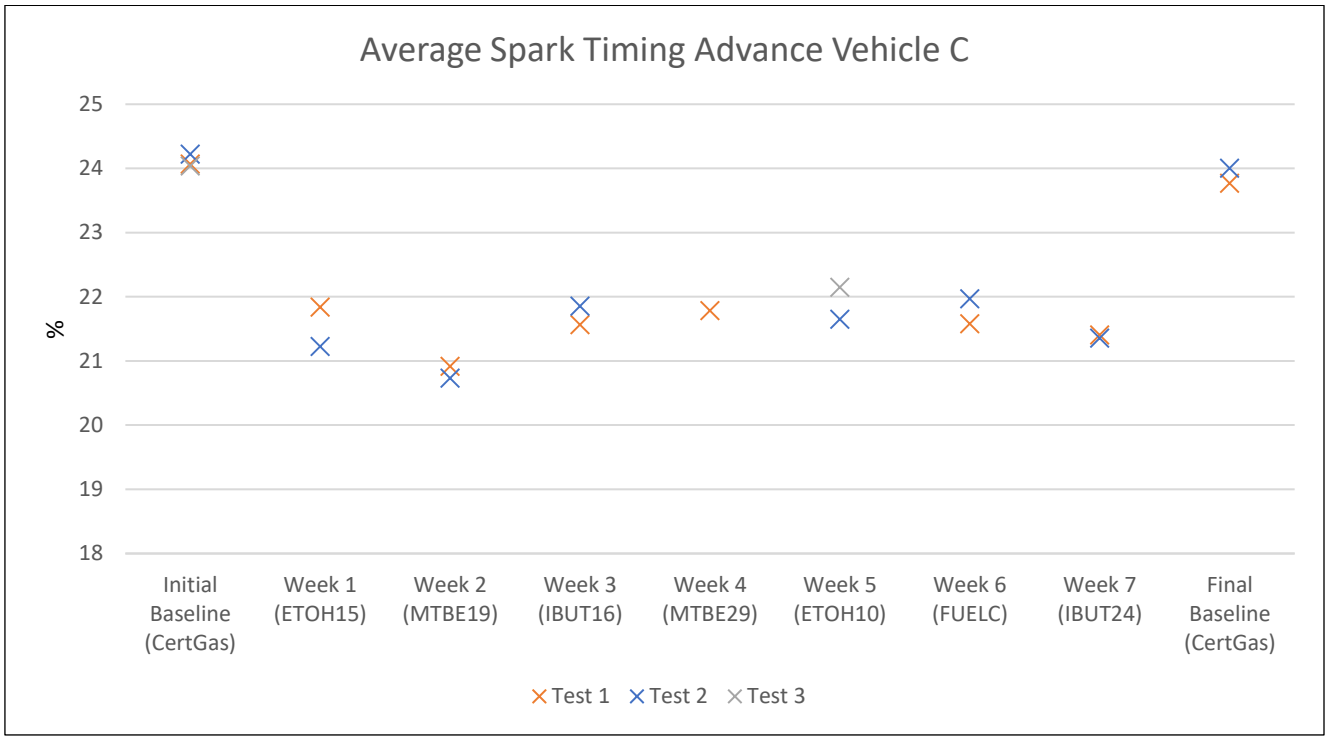

Figure 7-21 Vehicle C Average Spark-Timing

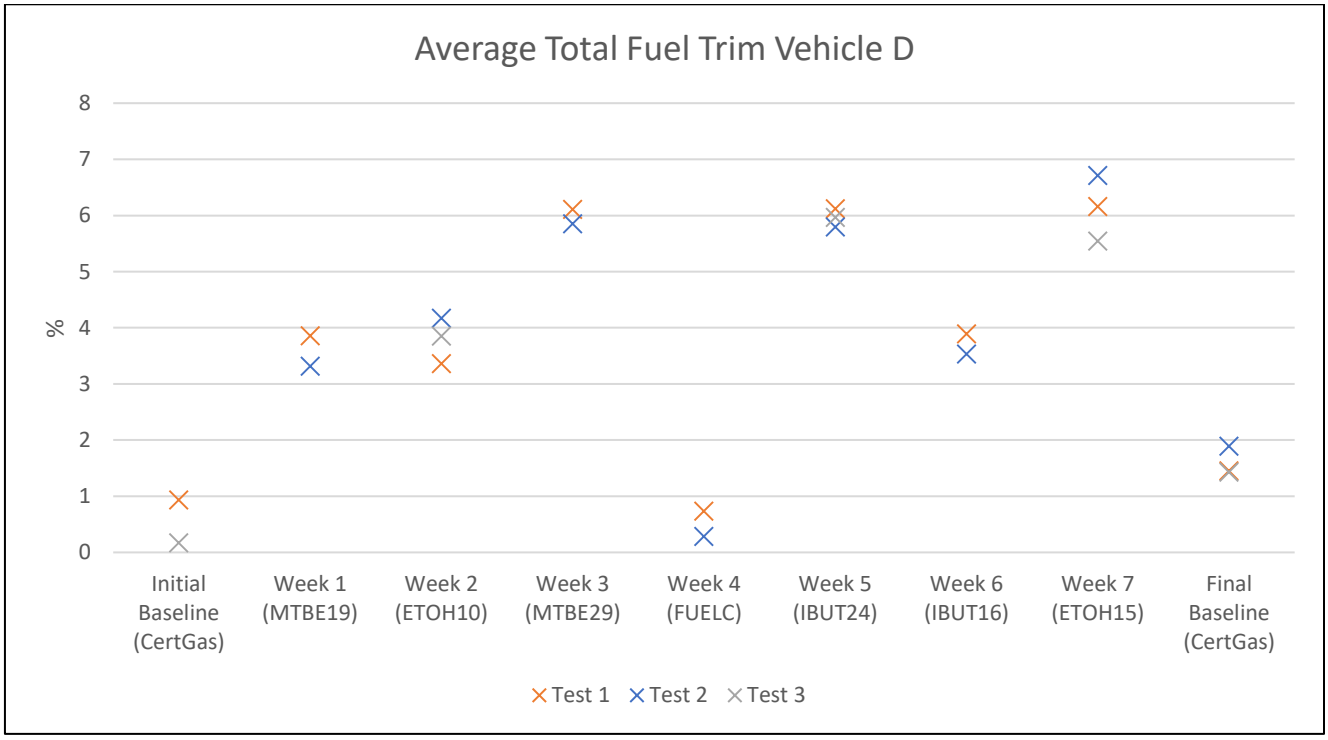

Figure 7-22 Vehicle D Average Total Fuel Trim

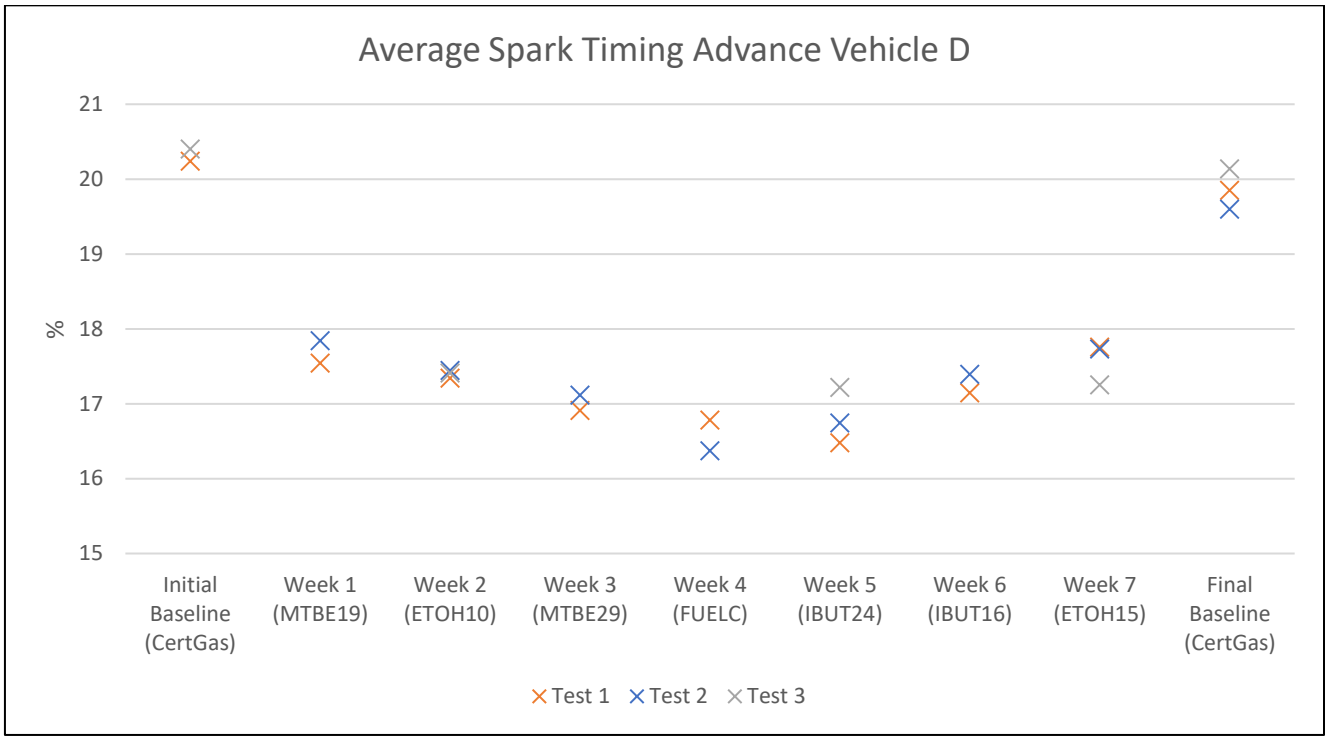

Figure 7-23 Vehicle D Average Spark-Timing

8. Statistical Analysis

8.1. Introduction

Following completion of the testing, Rincon Ranch Consulting conducted a statistical analysis under independent contract with CRC to understand the effect of the fuels on the particulate and gaseous emissions of the test fleet. The analysis developed statistical estimates of the average emissions of the four-vehicle test fleet to address two chief questions:

- How do average emissions of the test fleet respond to the two different levels of oxygen content and the three oxygenate types used in the experimental fuels?
- Which characteristics of the experimental fuels are most influential in determining the emissions?

Six different particulate and gaseous pollutants were examined: Phase 1 and weighted-average PM emissions over the LA92 cycle and the weighted-average LA92 emissions of HC, CO, NOx, and CO_2. A majority of particulate emissions are emitted in the LA92 cycle's Phase 1, which is where the effect of oxygenated fuels on PM emissions can be most easily seen. The weighted-average emissions over the LA92 cycle were evaluated for all six pollutants.

A certification fuel was used in the initial and final baseline testing of the vehicles. Seven different fuels were used in the experimental testing. Fuel C, the base fuel used in the blending of the oxygenated fuels, was re-blended for this study based on the specifications for the Fuel C in the CRC E-94-2 study of particulate emissions from SIDI vehicles. Its properties will vary somewhat from those of the previous Fuel C due to the re-blending. It is a regular

grade gasoline that would be rated low for its propensity to form PM (PMI = 1.30). Six different oxygenated fuels were created by blending varying amounts of ethanol, i-butanol, and MTBE with Fuel C to achieve two different levels for oxygen content (nominally 3.5 wt% and 5.5 wt%). As noted elsewhere, the 24% i-butanol fuel may differ from the planned splash-blending using Fuel C.

Table 8-1 summarizes the characteristics of the E-129 experimental fuels. The fuels were blended by Gage Products Company. A certificate of analysis was provided for each fuel indicating the oxygenate type and content. Subsequently, a CRC member company determined the Particulate Matter Index (PMI) values for the experimental fuels.

The formulation of the experimental fuels can be described by the variables: oxygenate type, oxygenate content, and weight percent of oxygen in the fuel. PMI is a description of a fuel in terms of its propensity to form PM when combusted in an engine. In development of the PMI[2], hydrocarbons with high double bond equivalent (DBE) values were found to be associated with increased PM emissions, as were compounds with low vapor pressures (VP). The ratio $(1 + DBE_i) / VP_i$, called the "i-term", was adopted as a measure of the propensity for an individual compound "i" to contribute to PM. The PMI value for a fuel is computed using the Honda Equation as the weighted sum of the "i-term" contributions across the hydrocarbons that are present:

$$PMI = \sum_i Wt_i * \left(\frac{1+DBE}{VP\ @\ 443K} \right) \qquad \text{(Eq. 8-1)}$$

The PMI is calculated from a detailed hydrocarbon analysis (DHA) that determines the identity and prevalence (wt%) of the hydrocarbon compounds in a fuel. For this project, a CRC member company performed a DHA using ASTM D6729-14 and ASTM D6730 test methods and calculated the PMI values for the experimental fuels.

Table 8-1 Characteristics of the E-129 Fuels

	Oxygenate Type	Oxygenate Content [a/] (vol%)	Oxygen Content [a/] (wt%)	PMI [b/]
Certification Fuel	–	0.0%	0.0%	n/a
Fuel C	–	0.0%	0.0%	1.30[c]
10% Ethanol	Ethanol	10.0%	3.7%	1.16
15% Ethanol	Ethanol	14.9%	5.5%	1.08
16% i-Butanol	i-Butanol	16.5%	3.8%	1.07
24% i-Butanol	i-Butanol	24.4%	5.6%	1.09
19% MTBE	MTBE	19.3%	3.5%	1.04
29% MTBE	MTBE	29.4%	5.3%	0.92

Notes: [a/] Reported by Gage Products Company in Certificates of Analysis.
[b/] Determined by a CRC member company using the Honda PMI equation.
[c/] Fuel was re-blended for this study to target the specifications of Fuel C in the CRC E-94-2 study. In E-94-2, the original Fuel C had a PMI of 1.40.

[2] Aikawa, K., Sakurai, T., Jetter, J., "Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions," SAE Technical Paper 2010-01-2115, 2010

The data, the methods of analysis, and the results of the emissions analysis are described below. Section 8.2 describes the methods applied in the statistical screening of the vehicle emissions data. Section 8.3 presents the statistical estimates of emissions for the test fleet. Section 8.4 examines how the PM and HC emissions of the fleet are related to selected fuel properties and characteristics. Section 8.5 presents a comparison of the results to the Phase 1 PM emissions performance of the same four vehicles in the CRC E-94-2 study. The relationships of PM emissions to the fuels are discussed. Section 8.6 summarizes the findings and conclusions of the analysis.

8.2.Statistical Screening of the Vehicle Emissions Data

Before the analysis of emissions data was conducted, the emissions data were reviewed to determine if there were changes in vehicle emission over time unrelated to fuel effects (referred to as “emissions drift”) and if there were emissions data that appeared to be statistical outliers. The procedures followed during testing are the best safeguards against these problems.

To minimize the potential for emissions drift, the test vehicles were thoroughly inspected at the start of the project and monitored throughout the program. As modern engines are designed to respond to changes in fuel characteristics, the test vehicles were pre-conditioned for emissions testing through a period of operation on each new fuel. Charts of the average fuel trim and spark timing advance were monitored during testing to gauge the degree to which the test vehicles had modified engine operation in response to the fuels. To minimize the potential for statistical outliers in the data, individual test runs were reviewed in periodic conference calls with the CRC project panel. Unexpected or potentially anomalous data were rechecked to ensure they were valid results. The statistical screening performed here is the last step in guarding against emissions drift and statistical outliers.

8.2.1.Emissions Drift

Historically, emissions drift was attributed to deterioration of the engine and emission control system that led to increased emissions as a function of age or accumulated mileage. However, with the advent of computer-controlled vehicles, changes in emissions performance may also result from changes in engine operation in response to new fuels. Baseline testing, consisting of three successive test runs using a certification fuel, was conducted at the start and the end of the test program. These baseline tests document the emissions performance of the vehicles before and after the experimental testing. Emission differences between starting and ending baselines would indicate emissions drift.

The Student’s t-Test was used to test for the presence of emission drift between the initial and final baseline tests. Figure 8-1 illustrates the nature of the t-Test using LA92 PM emissions of Vehicle A. The t-Test contrasts the difference between mean emission levels observed in the initial and final baselines to the variability observed in the six test runs performed. In this case, the Phase 1 PM emissions were observed to decrease by 0.87 mg/mi (or -34%) from the initial to final baselines. The question is whether this difference is large enough, given the observed variability in emissions, to be statistically significant. If so, the conclusion would be that emissions drift has occurred. For the example shown in the figure, the -34% reduction is statistically significant at the $p < 0.02$ level (a 1-in-50 risk of arising by chance).

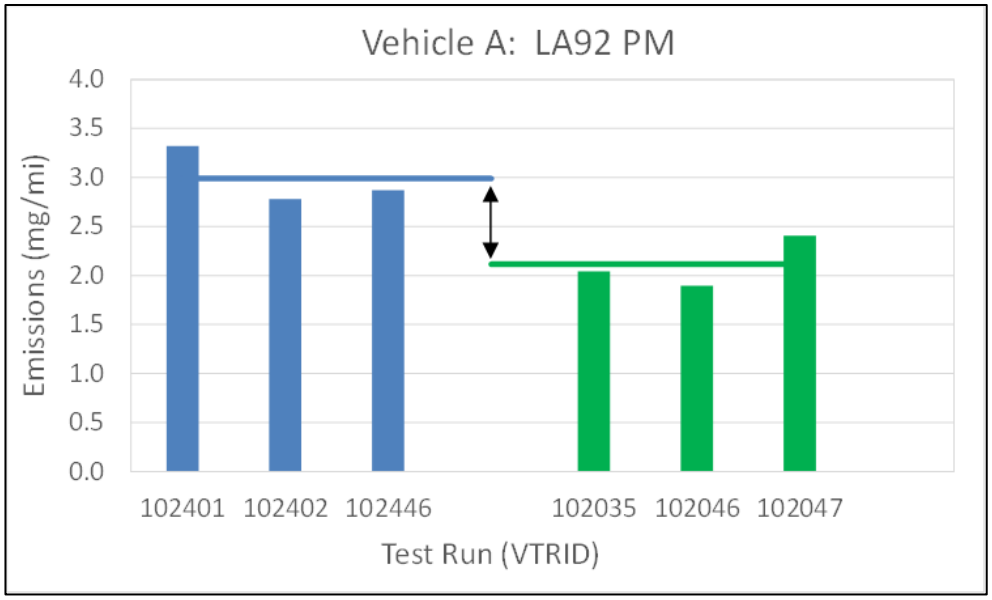

Figure 8-1 Example Application of t-Test for Baseline Emissions Drift

A conventional t-test, assuming that the emissions variance of the two baselines was equal and could be pooled, was performed for each vehicle and pollutant to determine the change in mass emissions between baselines and the statistical significance of the change. The mass emission change was then converted to a percentage of the average emission levels in the baseline testing for presentation. Table 8-2 shows that, in five of the cases, the observed emissions change was large enough to achieve at least the $p < 0.05$ level that is conventionally used for statistical significance to control the risk of a false positive[3]. Two of those cases achieve a stricter $p < 0.01$ level for significance.

The tabulated results indicate that emissions drift may have occurred in three cases (highlighted in yellow) and is likely to have occurred in two cases (highlighted in rose). These findings led to the inclusion of control variables in the emissions analysis to test for the presence of emissions drift during the experimental phase of the testing. As explained in Section 8.3.1, that evaluation found evidence of drift only for the LA92 HC emissions of Vehicle D. No drift was detected during experimental testing in the other four cases. Thus, the evidence is that emissions drift occurred between the initial and final baselines, but not during the experimental testing. This rules out a continuous form of drift and points toward discrete changes that affect only the baselines. This is possible because modern vehicles learn to optimize the engine for each new fuel; a failure to return to the fuel trim and spark timing of the initial baseline would introduce a step change in the final baseline.

[3] A false positive is an apparently significant result that is not meaningful (real) and occurs because of random variation in the data. Given that 24 statistical tests (4 vehicles x 6 pollutants) were performed to create the table and that the p=0.05 level admits a 1-in-20 chance of a false positive in each case, one would expect to have, on average, one false positive reported in the table. Therefore, a stricter p=0.01 level (1-in-100 chance of a false positive) was used to highlight the results that are least likely to be false positives.

Table 8-2 Results of t-Tests for Baseline Emissions Drift by Test Vehicle

	Vehicle A	Vehicle B	Vehicle C	Vehicle D
Phase 1 PM	-5%	+36%	+1%	+6%
LA92 PM	-34%	+20%	+2%	+7%
LA92 HC	+14%	0%	+3%	+30%
LA92 CO	+48%	-1%	+4%	+9%
LA92 NOx	-2%	-6%	+14%	+48%
LA92 CO2	+3%	-1%	+2%	+1%
Notes: Yellow highlight indicates the result is statistically significant at $0.05 > p \geq 0.01$. Rose highlight indicates the result is statistically significant at $p < 0.01$.				

Notes maintained during the testing indicated that:

- For Vehicle A, a change in PM emissions in Phases 2 and 3 of the LA92 cycle was noted in the last week of the testing and carried through into the final baseline testing. The average spark timing during the final baseline matched one of the two different values observed in the initial baseline, but two of the initial baseline values were discrepant. These differences are likely responsible for the LA92 PM emissions drift between the baselines and could be related to the observed drift in LA92 CO_2 emissions.
- For Vehicle D, the average fuel trim in the final baseline did not return to the values observed in the initial baseline. The average spark timing advance returned to the initial baseline level but showed more disparity among the three final test runs. These differences are likely to be the cause of the emissions drift observed between the baselines for LA92 HC and LA92 NOx. The fuel trim and spark timing for the testing on oxygenated fuels fell within the ranges observed for the other vehicles.
- For Vehicle C, the average fuel trim in the final baseline was somewhat higher and showed more variability than in the initial baseline, while the spark timing returned to the initial baseline levels. LA92 CO_2 emissions, a surrogate for fuel economy, increased in the final baseline (decreased fuel economy), possibly as a result of the higher fuel trim.

Thus, the cases of apparent emissions drift can be traced to the vehicles failing to return to the same average level for fuel trim and spark timing in the initial baseline after extended testing on oxygenated fuels. This highlights the importance of the pre-conditioning cycle following fuel changes for modern vehicles and of monitoring the fuel trim and spark timing during the testing as a *qualitative* tool to gauge an engine's adaption to a new fuel. In future work, it may be appropriate to extend the period of pre-conditioning before the final baseline to allow more time for the vehicles to adapt to operation on the certification fuel after lengthy testing on experimental fuels.

8.2.2.Statistical Outliers

A statistical outlier is a datum point (here, for a particular vehicle and fuel) that lies sufficiently far (high or low) from the other values in the dataset that it is an improbable outcome of the testing. Being an outlier in this sense does not automatically imply that the datum point is invalid, only that it deviates enough from other, comparable data to require additional scrutiny. Two different methods were used to screen for outliers.

In the first method, the individual test runs for each vehicle and fuel were examined to determine their mean and standard deviation. As a minimum of three data points are required to compute a proper standard deviation, this method could be applied only in cases where a 3rd or subsequent test run was conducted. Vehicle A and Vehicle D

exhibited a greater degree of emissions variability in the experimental testing and were given a 3rd or subsequent test for several fuels. No retests were needed for the other two test vehicles. As a result, the first screening method can be applied for only two of the vehicles.

To screen for outliers, the test runs for a given vehicle and fuel were scored according to the percentile of the emissions distribution they occupied. Once the mean and standard deviation were computed, the percentile of distribution was determined for each test run. If a test run were to score below the 1st percentile or beyond the 99th percentile, it would be flagged as a potential outlier. When applied to the experimental testing for Vehicle A and Vehicle D, none of the test runs were flagged as an outlier. In only one case (Vehicle A and the MTBE19 fuel) was a test run found outside the middle 80% of the data.

The percentile test has the advantage of making no assumptions about the statistical properties of the data (other than that it should follow a normal distribution), but it is not a powerful test. In all but one of the cases examined, only three test runs had been performed and the test is particularly weak. Thus, a second method based on an analysis of variance in the test run data was employed.

In the second test, the residuals from an unconstrained model of fuel effects were examined to determine if any of the test runs appeared to deviate from the norm[4]. The model allowed emissions to vary by vehicle and fuel and the vehicles to differ in their responses to fuels. Once estimated, the residuals of the test runs were pooled to determine an overall error standard deviation. Using this and the residual for each test run, a probability was computed that the observed deviation of the test run from its vehicle and fuel specific mean value could occur by chance. Test runs with low probabilities of occurrence were identified as possible outliers.

How far a datum point must deviate to be considered an outlier is subjective. Three different thresholds were used to bracket the range of reasonable choices. As Table 8-3 shows, the use of a $p < 0.01$ threshold resulted in flagging seven test runs as outliers, or about 10 percent of the 65 total test runs on experimental fuels. This choice admits a 1-in-100 chance of a false positive and, thus, a 2-in-3 chance that one of the flagged test runs will be a false positive. A $p < 0.005$ threshold is a more conservative choice and resulted in flagging only three test runs, all for Vehicle A, as potential outliers; this choice leads to only a 1-in-3 chance of a false positive. A $p < 0.001$ threshold was considered as the most conservative choice and would flag only one test run for Vehicle A; this choice leads to a 1-in-15 chance of a false positive. Given these results, one can be confident that the LA92 PM result for test run 102078 (Vehicle A/MTBE19) is an outlier. One has good reason to suspect that the LA92 HC and CO results for test run 102142 are also outliers.

Table 8-3 Count of Test Runs Flagged as Potential Outliers

Probability Threshold	Phase 1 PM	LA92 PM	LA92 HC	LA92 CO	LA92 NOx	LA92 CO_2
$p < 0.01$	0	3	2	2	0	0
$p < 0.005$	0	1 Vehicle A 19% MTBE (# 102078)	1 Vehicle A 10% Ethanol (# 102142)	1 Vehicle A 10% Ethanol (# 102142)	0	0
$p < 0.001$	0	1 Vehicle A 19% MTBE (# 102078)	0	0	0	0

[4] This method is also known as the Tukey test. For more information, see Section 5.2.2 of P. Morgan, I. Smith, V. Premnath, S. Kroll, R. Crawford, "Evaluation and Investigation of Fuel Effects on Gaseous and Particulate Emissions on SIDI In-Use Vehicles," CRC Project E-94-2, Coordinating Research Council, Inc., March 2017.

Based on the results of the second method, the test runs listed in Table 8-4 were excluded from the emissions analysis. Vehicle A demonstrated a high degree of variability on the MTBE19 fuel. Two test runs were conducted early in the test program and three more conducted in the final week. While the excess variability was for HC, CO and NOx, it is only the LA92 PM value for test run 102078 that appears to be anomalous. Notes maintained during the testing indicated that a substantial decrease in PM emissions was observed during Phase 2 and Phase 3 of the LA92 cycle in the final week and during the final baseline testing. Therefore, the LA92 PM value was excluded, but the Phase 1 PM value was retained. Test run 102142 was flagged as an outlier for the LA92 HC and CO pollutants and was excluded from the analysis for all of the gaseous pollutants as a precaution.

Table 8-4 Test Runs Excluded from the Emissions Analysis

Test Run Number	Vehicle / Fuel	Pollutants
102078	Vehicle A / 19% MTBE	LA92 PM
102142	Vehicle A / 10% Ethanol	LA92 HC, CO, NOx, CO_2

8.3.Statistical Estimates of Fleet-Average Emissions

The first objective in the analysis is to estimate the emissions of the average vehicle in the test fleet for each experimental fuel, along with the associated statistical uncertainty. Once this is done, the emission estimates by fuel can be examined to determine how emissions respond to the characteristics of the fuels, the second objective.

Following removal of the selected outliers, the dataset was reduced by averaging the emissions values across the test runs for each vehicle/fuel combination. This results in 28 data points representing the emissions for the four vehicles on each of the seven experimental fuels. When a dataset varies in the information underlying the data points, as is true here, the points are often weighted in proportion to their precision to give greater weight to points based on more information. However, recognizing that the vehicle/fuel combinations allocated additional testing were also the ones displaying greater variability, all 28 data points were given equal weight in the analysis.

8.3.1.Estimation Methodology

The analysis used multiple linear regression as the primary statistical tool to estimate the average emissions of the test fleet. In this, the test vehicles were considered to have individual, average emission levels that are constant across the different fuels tested. The fuels are considered to have individual effects that increase or decrease emissions relative to the average emission level for each vehicle. The chief outputs are the estimates of fleet-average emissions on each fuel, along with their statistical uncertainties.

The dependent variable in the regression analysis is the natural logarithm of emissions. This choice, rather than the mass emissions value itself, is commonly used because it recognizes that the variability of vehicle emissions tends to increase with the absolute level of emissions. Its use leads to a mathematical form in which the emissions response to fuels is treated as being constant in percentage terms. The model can be described as a “discrete fuel” model because dummy variables were used to represent the emissions effect of each fuel.

Equation 8-2 gives the mathematical form of the statistical model. The nomenclature assigns the subscript i as a sequential index for the four test vehicles and the subscript f as a sequential index for the seven experimental fuels. For any of the pollutants, the dependent variable $Y_{i,f}$ is the natural logarithm of emissions for vehicle i tested on fuel f.

$$Y_{i,f} = \mu + v_i + d_{f=1} + d_{f=2} + \ldots + d_{f=N-1} + \varepsilon_{i,f} \qquad \text{(Eq. 8-2)}$$

where: f = 1, …, 6 for the N=7 experimental fuels.
i = 1, …, 4 for vehicles. $v_i \sim N(0,\sigma_v)$
$\varepsilon_{i,f} \sim N(0,\sigma)$

The μ term is the overall mean emissions level for the average vehicle in the test fleet. Each vehicle is considered to have its own average emission level v_i drawn out of the population of SIDI vehicles with standard deviation σ_v. The fuel effects are represented by dummy variables d_f for the individual fuels, with one such term (the last) omitted by convention. The variable d_f takes on the value 1 for tests conducted on fuel f and the value 0 in all other cases. The error term $\varepsilon_{i,f}$ represents the unexplained variation of emissions and is treated as having mean of zero and standard deviation of σ.

Section 8.2.1 presented evidence that the emission performance of some vehicles changed between the initial and final baseline testing. Such changes might exist only between the two baselines and not involve the experimental testing or might also occur throughout the experimental testing. If such occurs during the experimental testing for one or more vehicles, the fleet-average emissions estimates for the fuels will be biased.

To test for the occurrence of emissions drift during the experimental testing, additional terms were introduced into Eq. 8-2. The change in each vehicle's odometer (ΔOdom) since its first test on an experimental fuel was used as the measure of the vehicle's progress through the testing and its exposure to emissions drift. The ΔOdom term was introduced into Eq. 8-2 for each of the vehicle/pollutants highlighted previously in Table 8-2 where the comparison of the emissions baselines indicated the presence of drift.

For Vehicle D, the ΔOdom test for drift in HC emissions achieved a p = 0.04 level of statistical significance. This term was retained as a control variable in the emissions analysis for HC because the test satisfies the conventional criterion for significance ($p < 0.05$) even if it is not strongly significant. For the other cases, the ΔOdom test demonstrated no statistical significance ($p >> 0.05$) and the term was not retained for the emissions analysis. Specifically:

- For LA92 PM and Vehicle A, $p \sim 0.43$
- For LA92 NOx and Vehicle D, $p \sim 0.53$
- For LA92 CO_2: $p \sim 0.94$ for Vehicle A and $p \sim 0.53$ for Vehicle C.

The results of these statistical tests indicate that the evidence for emissions drift between the initial and final baselines is limited primarily to the baseline testing.

A statistical model of the form of Eq. 8-2 was estimated for each dependent variable with the ΔOdom term for emissions drift included for Vehicle D for LA92 HC. The models for each pollutant were evaluated to predict the average emissions of the test fleet on each fuel along with their uncertainties. These estimates are affected by all of the uncertainties that occur in the data because of the finite sample size, including limits to our knowledge of the effect of fuels and our ability to determine the average level of emissions for each vehicle (v_i terms). Because Eq. 8-2 is for the logarithm of emissions, the estimated emission levels reflect the average logarithm of emissions, not the arithmetic average of emissions. The estimated mean log is exponentiated for presentation in the units of emissions as measured. For log-normally distributed data, such as here, the estimated fleet-average emission level

will correspond more closely to median emissions than to arithmetic average emissions. As a result, the estimates presented in this section will differ to some degree from the fleet-average emissions presented in Section 7, where the arithmetic average calculation has been employed.

The statistical models were also used to make a second set of predictions for the emissions effect of changing from Fuel C to one of the six oxygenated fuels. The calculation amounts to evaluating the model twice, once for Fuel C and again for an oxygenated fuel F. The percentage change in mass emissions is then calculated by exponentiating the result:

$$\Delta Y_{C\rightarrow F} = Y_{i,C} - Y_{i,F}$$

$$\Delta E_{C\rightarrow F} = \exp(\Delta Y_{C\rightarrow F}) - 1 \qquad \text{(Eq. 8-3)}$$

In doing so, the v_i terms in Eq. 8-2 drop out as our knowledge of the absolute emission levels is not material to estimating the relative change in emissions compared to Fuel C. The statistical significance of the differences based on the usual t-Test is determined by the statistical package as an output of the model estimation itself. While both sets of emission estimates are presented below, the percentage changes relative to Fuel C are the best estimates of the emissions effects of the oxygenated fuels.

The results tabulated in later subsections include an estimate of the probability that emissions of the oxygenated fuels are reduced below the level of Fuel C. This probability is computed as 1 – p where p is the statistical significance of the result. When the reported probability is 0.95 or higher, it is likely that emissions are decreased compared to Fuel C; it is very likely that emissions are decreased when the reported probability is 0.99 or higher. In addition to the tabulated probabilities, a useful visual (but approximate) test for significance is that two statistical estimates are statistically different from each other at the p = 0.05 level if their 1σ error bars do not overlap.

Where statistical confidence is described qualitatively, the term “confident” means that the observed differences achieve the $0.05 < p \leq 0.01$ level of significance, which admits up to a 1-in-20 chance that the result is a false positive. The term “highly confident” means that the observed differences achieve the $p < 0.01$ level of significance, which admits no more than a 1-in-100 chance of a false positive.

It should be remembered that the E-129 dataset is relatively small (28 data points) and the test fleet contains only four vehicles. Thus, the failure of a result to achieve an accepted level of statistical significance (lack of evidence) is not necessarily an indication that the effect is not present (evidence of absence). When such a result is seen repeatedly in the data, it is reasonable to surmise that an effect *could* be present, although additional testing would be needed to demonstrate that.

8.3.2.Particulate and Gaseous Emissions of the Test Fleet

This section presents the primary outputs of the statistical analysis, which are the estimated average emissions of the test fleet on each of the experimental fuels. The emissions effect of fuels is given in both mass emission terms (mg/mi or g/mi) and as percentage changes from Fuel C. Statistical uncertainties are given for both metrics as the ±1σ ranges. In addition to tabulating the emissions estimates, the discussion presents the results graphically.

Six pollutants are considered. For three pollutants – Phase 1 PM, LA92 PM, and LA92 HC – the relationship of the fuels to emissions is complex and is given further consideration in a subsequent section. For the remaining gaseous pollutants – LA92 CO, LA92 NOx, and LA92 CO_2 – this section identifies the fuel characteristics that influence emissions.

Phase 1 PM Emissions

Table 8-5 summarizes the estimated Phase 1 PM emissions of the test fleet for each of the experimental fuels; Figure 8-2 displays them graphically. In these, and similar figures, the error bars show the ±1σ uncertainty range in the estimated fleet-average emissions. This usage differs from earlier sections of this report, where the error bars represent the range of the test run data. The figure uses colors to distinguish Fuel C and the different oxygenate types (charcoal for Fuel C, green for ethanol, orange for i-butanol, blue for MTBE) and shades of the colors to distinguish the two oxygen content levels (lighter shade for 3.5 wt% and darker shade for 5.5 wt%), with a pattern of horizontal lines within the bars for the 3.5 wt% fuels.

Table 8-5 Estimated Phase 1 PM Emissions of the Test Fleet

Fuel	Mass Emissions		Emissions Change from Fuel C		
	Estimated Emissions (mg/mi)	±1σ Range (mg/mi)	Emissions Change (%)	±1σ Range (%)	Probability Emissions Decrease
Fuel C	13.85	(12.41 to 15.45)	0%	—	—
10% Ethanol	12.90	(11.56 to 14.40)	-7%	(-20% to +9%)	0.35
15% Ethanol	9.04	(8.09 to 10.12)	-35%	(-44% to -23%)	0.98
16% i-Butanol	9.24	(8.43 to 10.13)	-33%	(-41% to -24%)	>0.99
24% i-Butanol	9.30	(8.36 to 10.34)	-33%	(-42% to -22%)	0.99
19% MTBE	7.75	(6.79 to 8.83)	-44%	(-54% to -33%)	0.98
29% MTBE	5.83	(5.23 to 6.51)	-58%	(-64% to -51%)	>0.99

As seen most easily in the figure, each of the oxygenated test fuels reduces the Phase 1 PM emissions of the test fleet below the level of Fuel C as is evident for all oxygenate types and at both levels of oxygen content. In comparison to emissions on Fuel C, the Phase 1 PM emissions of the test fleet are reduced by -7% on the 10% ethanol fuel, by -33% to -35% on the 15% ethanol and the two i-butanol fuels, and by -44% and -58% on the two MTBE fuels. As seen in Table 8-5 and Figure 8-2, the Phase 1 PM error bars for Fuel C and the 10% ethanol fuel overlap with each other. The formal t-Test for statistical significance agrees that emissions on the 10% ethanol fuel are not reduced by enough for the change from Fuel C to be statistically significant. However, the changes for the other oxygenated fuels are large enough that one can be confident or highly confident that emissions are reduced.

The relationship of emissions to oxygen content and oxygenate type is not clear from these results. The 10% ethanol fuel yields the smallest emissions change, while the 29% MTBE fuel yields the largest. In between, 15% ethanol, both i-butanol fuels, and the 19% MTBE fuel all lead to comparable levels of Phase 1 PM emissions. A later section will demonstrate that the amount of oxygenate used to blend the fuels is the primary (but not sole) determinant of PM emissions.

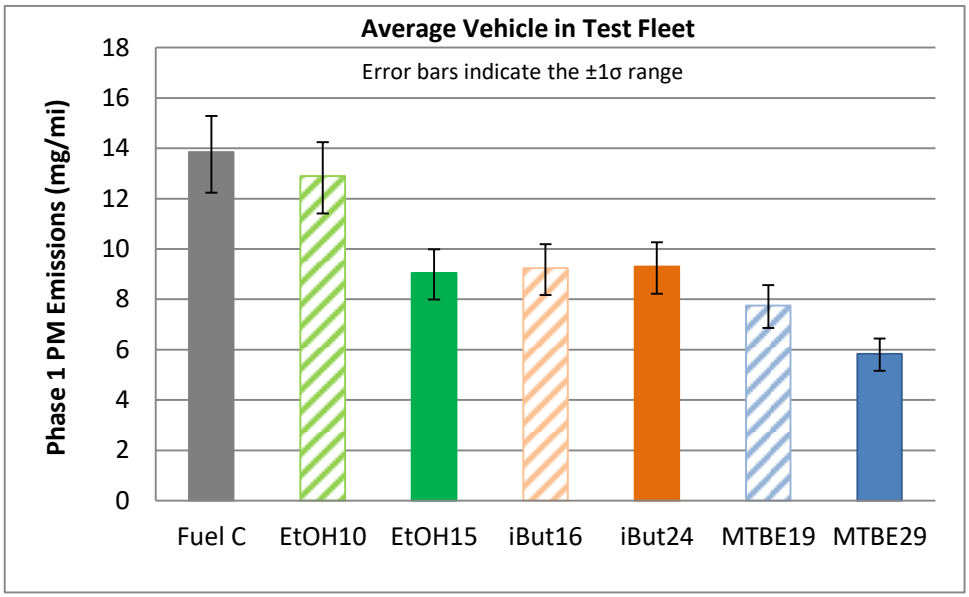

Figure 8-2 Estimated Phase 1 PM Emissions by Fuel

LA92 PM Emissions

Table 8-6 summarizes the estimated LA92 PM emissions of the test fleet for each of the experimental fuels, which are displayed graphically in Figure 8-3. The estimated PM emissions of the test fleet are much lower for the entire LA92 cycle than in Phase 1 where the majority of PM is formed. Nevertheless, the percentage reductions from Fuel C are very similar to those seen in Phase 1.

Table 8-6 Estimated LA92 PM Emissions of the Test Fleet

Fuel	Mass Emissions		Emissions Change from Fuel C		
	Estimated Emissions (mg/mi)	±1σ Range (mg/mi)	Emissions Change (%)	±1σ Range (%)	Probability Emissions Decrease
Fuel C	1.44	(1.305 to 1.60)	0%	—	—
10% Ethanol	1.43	(1.28 to 1.59)	-1%	(-15% to 15%)	0.05
15% Ethanol	0.99	(0.90 to 1.10)	-31%	(-40% to -20%)	0.99
16% i-Butanol	0.93	(0.83 to 1.04)	-35%	(-45% to -24%)	0.98
24% i-Butanol	0.97	(0.87 to 1.08)	-33%	(-43% to -22%)	0.98
19% MTBE	0.97	(0.87 to 1.07)	-33%	(-42% to -22%)	0.98
29% MTBE	0.67	(0.60 to 0.74)	-54%	(-60% to -46%)	>0.99

As before, the emissions change for the 10% ethanol fuel is small and not statistically significant. However, the other emission changes are large enough that one can be confident or highly confident that emissions are reduced compared to Fuel C.

For the 10% ethanol fuel, LA92 PM emissions are reduced by -3% (versus -7% for Phase 1 PM) and are not statistically different from Fuel C. The largest emissions reduction is again for the MTBE29 fuel (-54% here versus -58% for Phase 1 PM). The four intermediate fuels are similar in terms of the percentage reductions from Fuel C (-29% to -34% here versus -33% to -44% for Phase 1 PM). Allowing for the uncertainties in the estimates, the pattern of LA92 PM emissions by fuel is the same as for Phase 1 PM. Thus, the effect of the fuels on PM emissions appears to carry forward consistently through all phases of the LA92 cycle on a percentage basis.

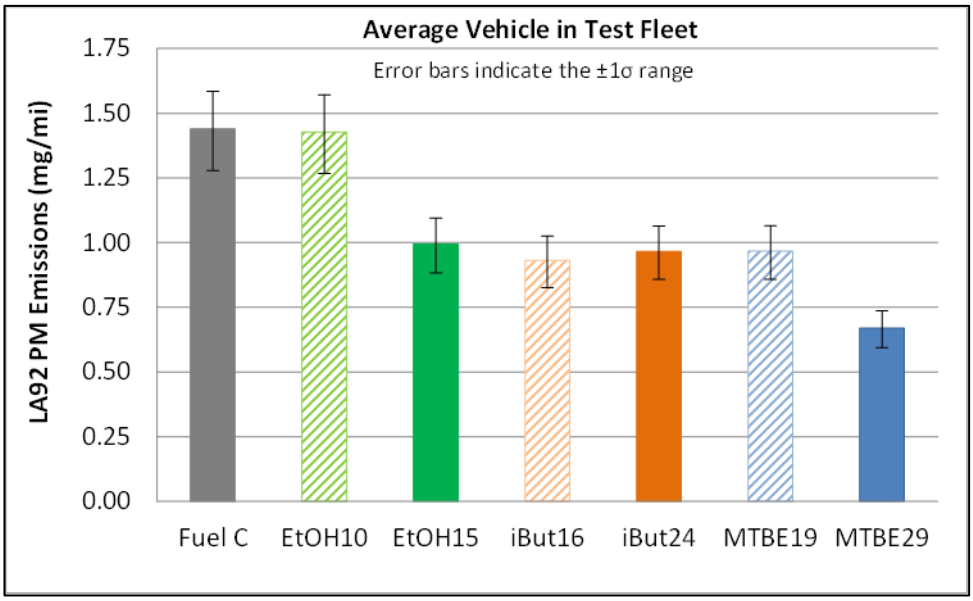

Figure 8-3 Estimated LA92 PM Emissions by Fuel

LA92 HC Emissions

Table 8-7 summarizes the estimated LA92 HC emissions of the test fleet for each of the experimental fuels, which are displayed graphically in Figure 8-4. The emissions data indicate that LA92 HC emissions respond to the fuels in a manner that is similar to Phase 1 and LA92 PM emissions but with some differences and greater variability among the fuels.

The similarities to LA92 PM emissions are as follows. The LA92 HC emissions of the 10% ethanol fuel are not statistically different from emissions on Fuel C and that HC emissions of the other fuels (15% ethanol through 29% MTBE) are reduced from Fuel C by enough to approach or achieve statistical significance in 4 of the 5 cases. The dissimilarities to LA92 PM emissions are that the three middle fuels (15% ethanol through 24% i-butanol) have numerically smaller HC emission reductions (-11% to -22% here versus -29% to -34% for LA92 PM) and that the MTBE29 fuel does not have the largest HC emissions reduction (the 19% MTBE fuel does).

While HC is a gaseous pollutant, it consists of incompletely burned hydrocarbons, which also make up a substantial portion of the solid-phase PM. Some of the same factors that influence PM formation appear to influence gaseous HC formation as well, leading to the generally similar pattern of emissions by fuel. However, other factors are involved in HC formation and may not respond to the oxygenated fuels, leading to the generally smaller emissions reductions observed for HC.

Table 8-7 Estimated LA92 HC Emissions of the Test Fleet

Fuel	Mass Emissions		Emissions Change from Fuel C		
	Estimated Emissions (mg/mi)	±1σ Range (mg/mi)	Emissions Change (%)	±1σ Range (%)	Probability Emissions Decrease
Fuel C	0.021	(0.018 to 0.024)	0%	—	—
10% Ethanol	0.023	(0.020 to 0.026)	+11%	(-7% to 32%)	0.44
15% Ethanol	0.015	(0.013 to 0.018)	-26%	(-38% to -12%)	0.90
16% i-Butanol	0.015	(0.014 to 0.017)	-26%	(-37% to -13%)	0.94
24% i-Butanol	0.018	(0.016 to 0.020)	-13%	(-25% to +1%)	0.90
19% MTBE	0.014	(0.012 to 0.017)	-30%	(-44% to -14%)	0.58
29% MTBE	0.016	(0.014 to 0.018)	-23%	(-35% to -9%)	0.86

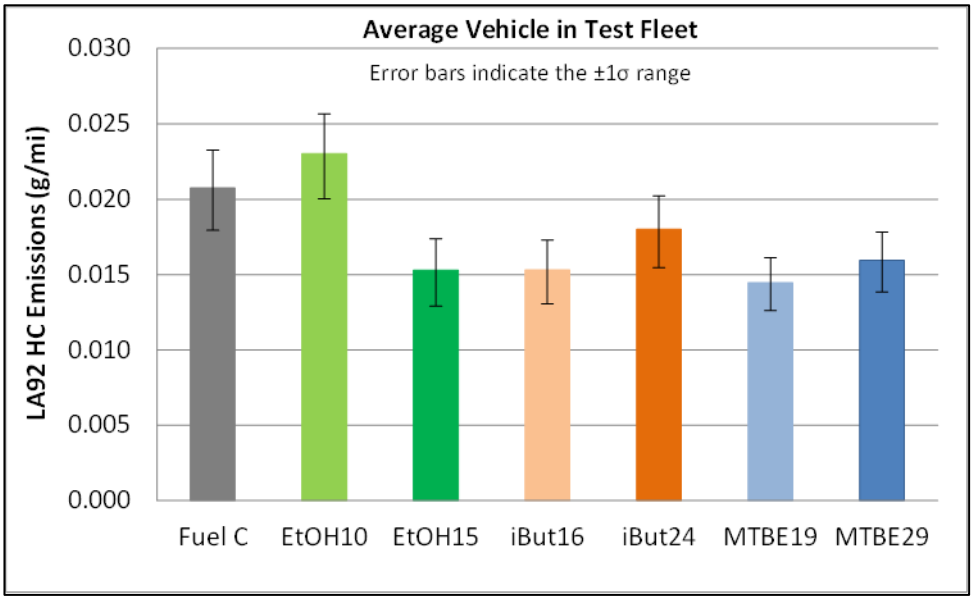

Figure 8-4 Estimated LA92 HC Emissions by Fuel

LA92 CO Emissions

Table 8-8 summarizes the estimated LA92 CO emissions of the test fleet for each of the experimental fuels, which are displayed graphically in Figure 8-5. Here, the figure plots the percentage emissions reductions from Fuel C against oxygen content, which explains the overall variation of LA92 CO emissions with fuels. A trend line (black), constrained to pass through 0% change at Fuel C, is plotted to indicate the linear relationship of CO emissions to oxygen content. When needed, formal statistical tests were performed to determine whether the differences of individual fuels from the trend line were statistically significant.

For the three fuels at 3.5 wt% oxygen content, LA92 CO emissions are estimated to average 0.44 g/mi (or -13% below Fuel C), while at 5.5 wt% oxygen content CO emissions are estimated to average 0.39 g/mi (or -24% below Fuel C). Compared to Fuel C, the emission reductions are not large enough to achieve true statistical significance, although the 24% i-butanol fuel comes very close.

As seen in the figure, the individual fuels overlap the trend line with oxygen content, except for the 10% ethanol fuel which lies above the trend line (although not by enough for the offset to be statistically significant). Fuel oxygen content is the factor influencing LA92 CO emissions. The slope of the trend line estimates that LA92 CO emissions decrease by 5% for each 1.0 wt% increase in oxygen content.

Table 8-8 Estimated LA92 CO Emissions of the Test Fleet

Fuel	Mass Emissions		Emissions Change from Fuel C		
	Estimated Emissions (mg/mi)	±1σ Range (mg/mi)	Emissions Change (%)	±1σ Range (%)	Probability Emissions Decrease
Fuel C	0.51	(0.45 to 0.58)	0%	—	—
10% Ethanol	0.50	(0.44 to 0.57)	- 2%	(-18% to 18%)	0.07
15% Ethanol	0.36	(0.31 to 0.42)	-29%	(-43% to -13%)	0.75
16% i-Butanol	0.41	(0.36 to 0.47)	-19%	(-33% to -3%)	0.74
24% i-Butanol	0.41	(0.37 to 0.46)	-20%	(-32% to -6%)	0.93
19% MTBE	0.42	(0.37 to 0.47)	-19%	(-32% to -3%)	0.77
29% MTBE	0.40	(0.35 to 0.45)	-22%	(-35% to -7%)	0.82

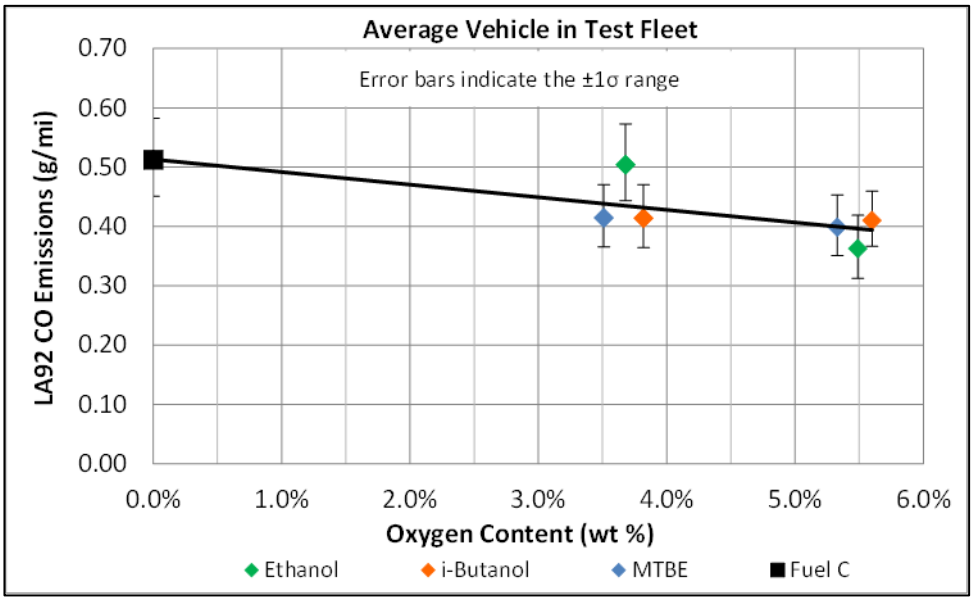

Figure 8-5 Estimated LA92 CO Emissions versus Oxygen Content

LA92 NOx Emissions

Table 8-9 summarizes the estimated LA92 NOx emissions of the test fleet for each of the experimental fuels, which are displayed graphically in Figure 8-6. As for CO, the figure plots the percentage emissions reductions from Fuel C versus oxygen content, coloring the data points to indicate the oxygenate type.

For the experimental fuels, there is no relationship between LA92 NOx emissions and oxygen content or oxygenate type (see the black trend line plotted in the figure). Instead, NOx emissions are reduced by a small (and not statistically significant) amount compared to Fuel C for the three fuels at 3.5 wt% oxygen, while NOx emissions are essentially unchanged from Fuel C for the three fuels at 5.5 wt% oxygen. As the differences from Fuel C are not statistically significant, one should conclude that the oxygen content of the oxygenated six fuels has no detectable effect on the LA92 NOx emissions of the test fleet.

Table 8-9 Estimated LA92 NOx Emissions of the Test Fleet

Fuel	Mass Emissions		Emissions Change from Fuel C		
	Estimated Emissions (mg/mi)	±1σ Range (mg/mi)	Emissions Change (%)	±1σ Range (%)	Probability Emissions Decrease
Fuel C	0.0108	(0.0094 to 0.0123)	0%	—	—
10% Ethanol	0.0093	(0.0081 to 0.0106)	-14%	(-29% to +4%)	0.56
15% Ethanol	0.0102	(0.0090 to 0.0115)	-5%	(-20% to +13%)	0.52
16% i-Butanol	0.0094	(0.0083 to 0.0106)	-13%	(-27% to +4%)	0.70
24% i-Butanol	0.0114	(0.0101 to 0.0129)	6%	(-10% to +26%)	0.22
19% MTBE	0.0088	(0.0074 to 0.0104)	-18%	(-36% to +4%)	0.24
29% MTBE	0.0117	(0.0103 to 0.0134)	9%	(-10% to +32%)	0.35

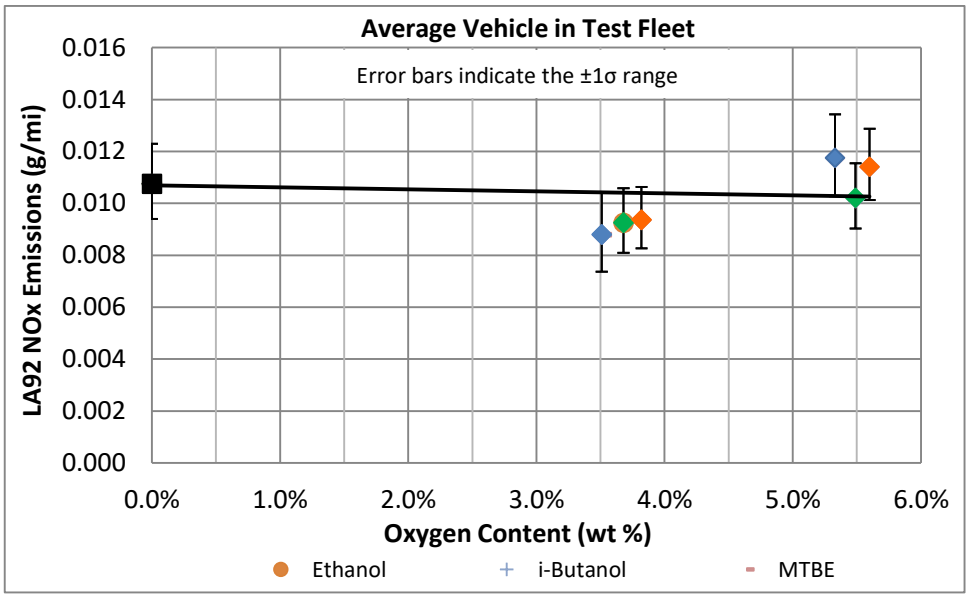

Figure 8-6 Estimated LA92 NOx Emissions versus Oxygen Content

LA92 CO_2 Emissions

Table 8-10 summarizes the estimated LA92 CO_2 emissions of the test fleet for each of the experimental fuels, which are displayed graphically in Figure 8-7. Here, the figure plots the percentage emissions reductions from Fuel C versus the volumetric amount of oxygenate used in blending each fuel.

Oxygenate use (vol%), rather than the oxygen content (wt%), is the fuel characteristic that influences LA92 CO_2 emissions as all of the emission changes from Fuel C are highly significant statistically. The three oxygenates all have lower carbon intensities (carbon mass per unit of energy content) than Fuel C. Blending the oxygenates with Fuel C reduces the carbon intensity of the oxygenated fuel with the result that LA92 CO_2 emissions are reduced in proportion to the oxygenate amount that is used (see black trend line in the figure). Neither oxygen content or oxygenate type directly influence CO_2 emissions, only the amount of an oxygenate that must be blended to reach a given oxygen content.

Table 8-10 Estimated LA92 CO_2 Emissions of the Test Fleet

Fuel	Mass Emissions		Emissions Change from Fuel C		
	Estimated Emissions (g/mi)	±1σ Range (g/mi)	Emissions Change (%)	±1σ Range (%)	Probability Emissions Decrease
Fuel C	345.8	(344.4 to 347.3)	0.0%	—	—
10% Ethanol	340.8	(339.5 to 342.2)	-1.4%	(-2.0% to -0.9%)	0.99
15% Ethanol	338.1	(336.8 to 339.3)	-2.2%	(-2.8% to -1.7%)	>0.99
16% i-Butanol	339.2	(338.0 to 340.4)	-1.9%	(-2.4% to -1.4%)	>0.99
24% i-Butanol	336.5	(335.3 to 337.7)	-2.7%	(-3.2% to -2.2%)	>0.99
19% MTBE	336.5	(335.0 to 337.9)	-2.7%	(-3.2% to -2.2%)	>0.99
29% MTBE	335.3	(334.0 to 336.6)	-3.0%	(-3.5% to -2.5%)	>0.99

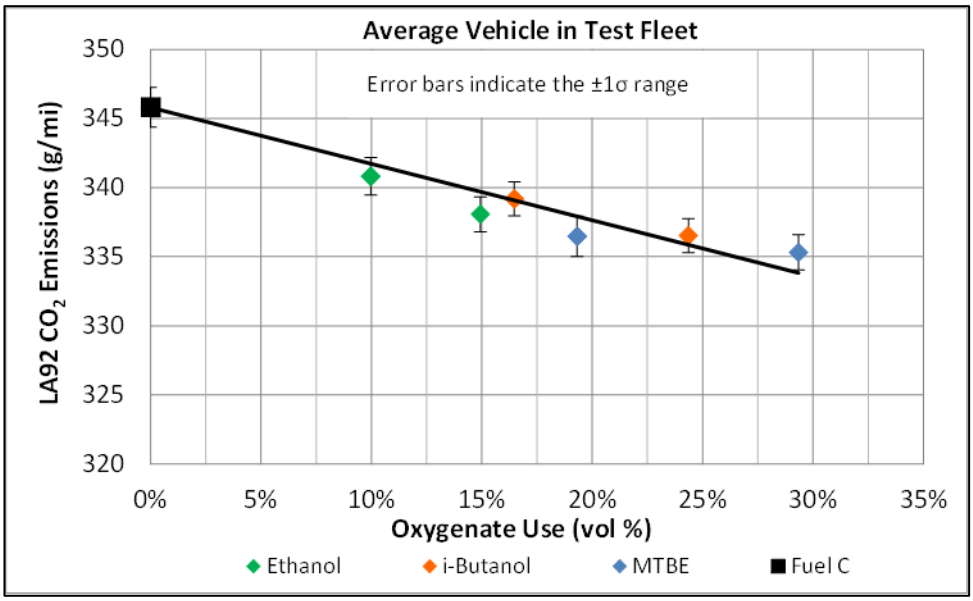

Figure 8-7 Estimated LA92 CO_2 Emissions versus Oxygenate Use

8.4.Trends in PM and HC Emissions with Fuel Characteristics

This section examines in more detail the relationships between PM and HC emissions of the test fleet and the characteristics of the experimental fuels. Four fuel variables are considered:

- Oxygen content (wt%) of the fuels
- Oxygenate type (ethanol, i-butanol, and MTBE)
- Oxygenate used (vol%) in blending
- PMI

The first two variables are the design variables of the experiment in which two different levels for oxygen content (3.5 wt% and 5.5 wt%) were achieved using each of three oxygenates. Because the oxygenates differ in the amount of oxygen they carry, different volumes of oxygenate were needed to achieve the two oxygen content levels. The amount of oxygenate used is the volumetric percent of oxygenate present in the fuel.

The PMI is an index of a fuel's propensity to contribute to PM emissions and is determined from detailed information regarding the chemical composition of the fuel, both hydrocarbons and oxygenated compounds. The index considers the weight percent of each constituent and its individual propensity to contribute to PM. The PMI values of the experimental fuels are influenced by the hydrocarbon composition of Fuel C, the amount of oxygenate used in blending, and two characteristics of the oxygenate type (DBE and vapor pressure).

The variables are explored for Phase 1 PM, which is where the effect of fuels on PM emissions is most clearly seen. Final results are shown for LA92 PM and HC emissions. For reference, Table 8-11 summarizes the chief characteristics of Fuel C and the three oxygenates used in blending.

Table 8-11 Characteristics of Fuel C and the Oxygenates

Component	PMI or i-term	Oxygen Content (wt%)	Carbon Content (wt%)	Carbon Intensity (gm C per 1,000 kJ)	Net Heat of Combustion (kJ/kg)
Fuel C	1.26	0%	86%	19.8	43,350 [a/]
Ethanol	0.0044	35%	52%	19.4	26,952
i-Butanol	0.011	22%	65%	18.9	34,366
MTBE	0.0070	18%	68%	19.4	35,108
[a/] As reported in the Certificate of Analysis.					

8.4.1.Phase 1 PM Emissions

Figure 8-8 plots the percentage reductions of Phase 1 PM emissions from Fuel C against the oxygen content of the oxygenated fuels. For each oxygenate type, Phase 1 PM emissions are reduced in response to increasing oxygen content. However, the rate of change varies with the oxygenate type that is used. The ethanol fuels have the shallowest slope, followed by the i-butanol fuels with an intermediate slope and the MTBE fuels with the steepest slope.

The ranking of the slopes from shallow to steep matches the ranking of the oxygenates based on oxygen content. Ethanol has the highest oxygen content (35 wt%) and smaller volumes of it are needed to reach the two design levels for oxygen content. i-Butanol has an intermediate oxygen content (22%) and larger volumes are needed to reach the two oxygen content levels. MTBE has the lowest oxygen content (18%) and still larger volumes are needed to reach the two levels. Thus, the use of larger volumes of oxygenate to achieve a given level for oxygen content is associated with greater reductions in the Phase 1 PM emissions of the fuels.

Figure 8-9 demonstrates that the volumetric amount of oxygenate used in blending is the primary factor influencing the reduction of Phase 1 PM emissions. The 10% ethanol fuel has the smallest emissions reduction compared to Fuel C. The 29% MTBE fuel has the largest PM emissions reduction. The other oxygenated fuels, with intermediate volumes of the oxygenates, have intermediate emissions reductions. The individual fuel data points follow the overall trend line with error bars that overlap the trend line in all but one case. The 10% ethanol and 24% i-butanol fuels stand above the trend line but not by enough that the offset is statistically significant.

All of the oxygenates are saturated compounds (DBE=0) that have low potential to form PM when combusted. The dilution of the gasoline hydrocarbons with oxygenated compounds of low PM potential is the *primary* determinant of the reduction in Phase 1 PM emissions. However, this may not be the entire story as the individual fuels vary around the trend line; other characteristics of the oxygenates may influence PM emissions as a *secondary* determinant for some fuels.

The three oxygenates make only very small contributions to the PMI in comparison to Fuel C's PMI of 1.30. Ethanol has the lowest "i-term" (0.004) because of its very high vapor pressure, while i-butanol and MTBE have values that are not much larger (0.011 and 0.007, respectively). When used in blending, the oxygenates reduce the PMI compared to Fuel C to nearly the same extent they dilute the gasoline hydrocarbons.

Figure 8-10 demonstrates this by plotting the Phase 1 PM emission reductions from Fuel C against the PMI of the experimental fuels. The overall trend line mirrors the trend in Figure 8-9 but with *increased* oxygenate use now corresponding to *decreased* PMI. The individual data points follow the trend line, but the 10% ethanol fuel stands above the PMI trend line, although not by a statistically significant amount. All but one of the fuels (10% ethanol) overlap the trend line within their ±1σ error bars, with some fuels above and below the trend lines.

Both the oxygenate use and the PMI are good indicators of Phase 1 PM emissions for these fuels. The PMI trend line (R^2 = 0.896) is a better fit to the data compared to oxygenate use (R^2 = 0.828) and will be preferred over oxygenate use because the PMI incorporates information about the PM contributions of both the base gasoline hydrocarbons and the oxygenates through the "i-term". Nevertheless, the dilution of gasoline hydrocarbons is the primary determinant of PM emissions, whether measured by oxygenate use or by PMI.

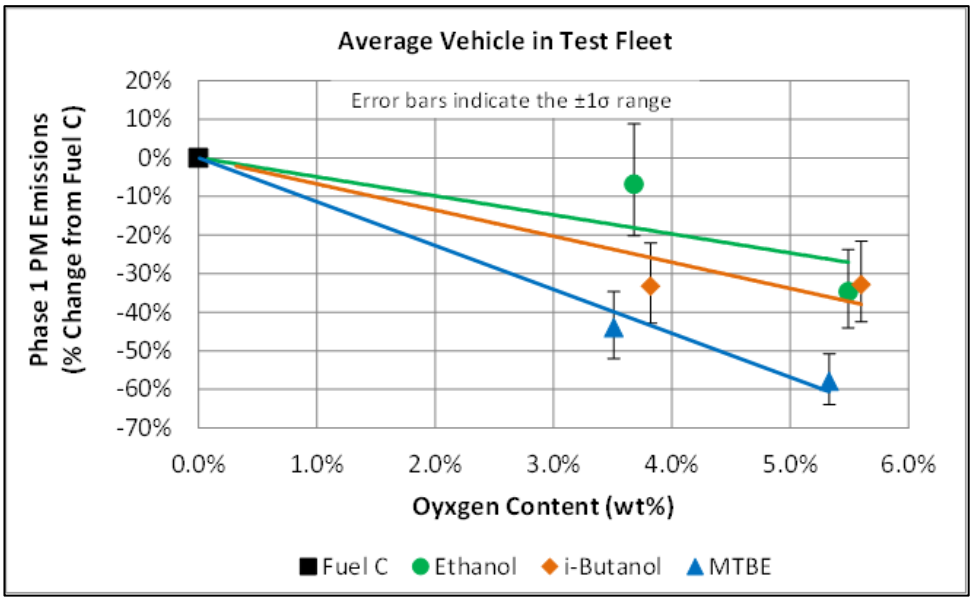

Figure 8-8 Estimated Phase 1 PM Emissions versus Oxygen Content

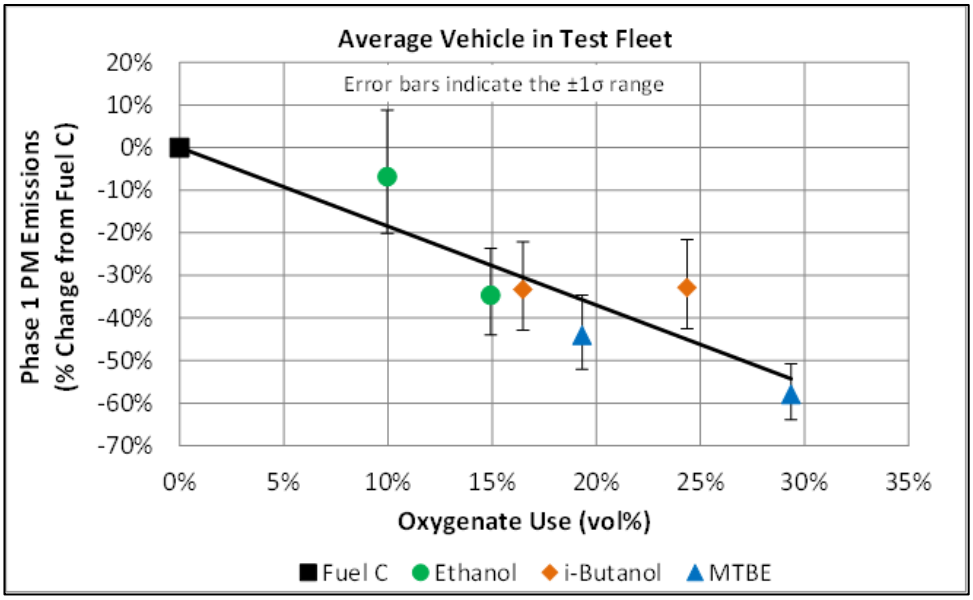

Figure 8-9 Estimated Phase 1 PM Emissions versus Oxygenate Use

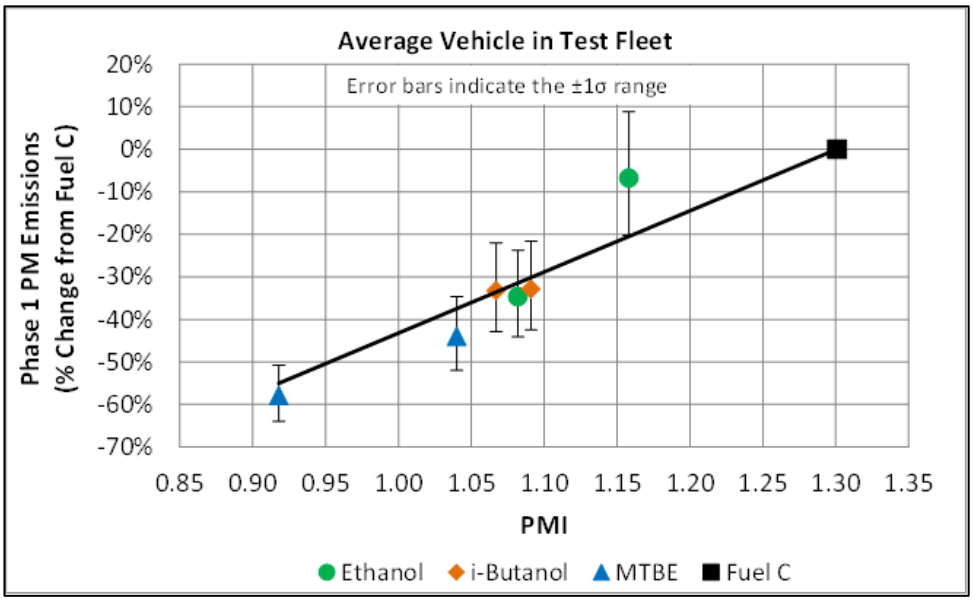

Figure 8-10 Estimated Phase 1 PM Emissions versus PMI

8.4.2.LA92 PM and HC Emissions

LA92 PM and LA92 HC emissions are the other two pollutants where the relationship to fuel oxygen content and oxygenate type is complex. The emission changes for both are found to be related to the reduction in PMI due to the addition of oxygenates.

Figure 8-11 plots the percentage changes in LA92 PM emissions from Fuel C against the PMI. The LA92 PM emission levels are much lower in g/mi terms than for Phase 1 PM. However, the magnitude of the emissions changes, their trend with PMI, and the patterns among the fuels are nearly identical to that seen in Phase 1. All but

one of the individual data points overlap the trend line within their error bars, but fuel 10% ethanol stands above the line. None of the offsets from the trend line is statistically significant. The similarity to Phase 1 should not be a surprise, as the mechanism of PM formation is the same throughout the LA92 cycle and the majority of the total PM is emitted in Phase 1.

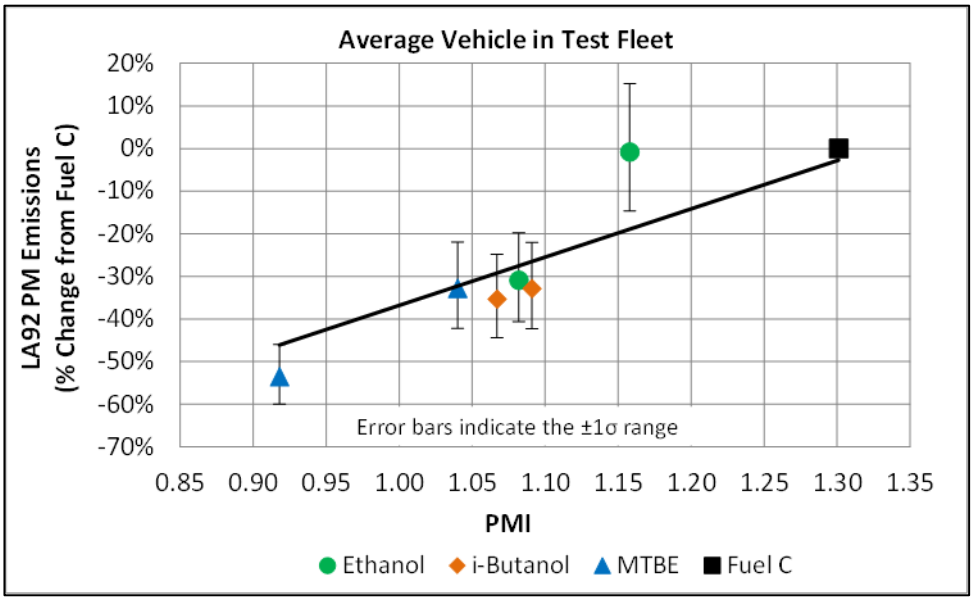

Figure 8-11 Estimated LA92 PM Emissions versus PMI

LA92 HC emissions also display a complex relationship to fuel oxygen content and oxygenate type. Figure 8-12 plots the percentage change in LA92 HC emissions from Fuel C against the PMI. The pattern of emissions reductions by fuel is very similar to that for LA92 PM, but the emission changes are generally smaller in percentage terms and there is more scatter around the overall trend line. The 10% ethanol and 24% i-butanol fuels stand above the line again, but only the 10% ethanol fuel is far enough above that its error bars do not overlap. Again, none of the differences from the trend line is statistically significant. Although HC is a gaseous pollutant, it responds to the oxygenated fuels in much the same way as PM.

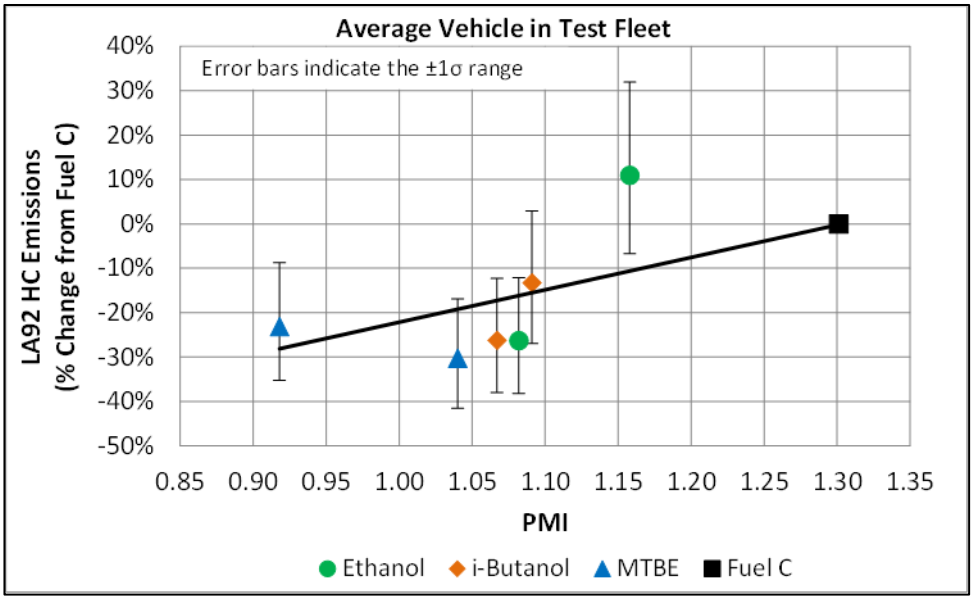

Figure 8-12 Estimated LA92 HC Emissions versus PMI

8.5.Discussion of the Phase 1 PM Results

8.5.1.Comparison of Phase 1 PM Results to CRC E-94-2

The four vehicles tested in this project also participated in the CRC E-94-2 project, where four E0 and four E10 gasolines were tested according to an experiment design that involved the PMI level (low, high), octane number (AKI 87 and 94), and ethanol content (0 and 10 vol%). The E10 fuels were match-blended to correspond to the PMI and octane number values of the E0 fuels. The PMIs of the resulting fuels ranged from approximately 1.25 to 2.65. The E-129 project was undertaken to extend the E-94-2 study to higher levels of oxygenation and to other oxygenate types.

To permit a comparison of the two studies, the Phase 1 PM emissions data of the four test vehicles were extracted from the E-94-2 dataset and combined with the results of this study. In Figure 8-13, the seven experimental fuels in this study are plotted on the left, while the eight E0 and E10 fuels from E-94-2 are plotted on the right[5]. The measured emission levels of the four test vehicles have changed somewhat since their participation in the E-94-2 study, which creates the vertical gap at Fuel C. In particular, re-blended Fuel C had a slightly higher PMI than before, and a new road load model was developed for the E-129 testing, both of which introduce differences compared to E-94-2. Except for the gap, the E-129 fuels continue the trend of PM emissions with PMI that was seen before.

In the E-94-2 study, ethanol at the E10 level was found to increase Phase 1 PM emissions above the emissions level of E0 fuels having the same PMI. The emissions increase was represented by a constant percent that, when plotted in the space of mass emissions, results in a mg/mi emissions offset that narrowed as the PMI value and PM emissions decrease. The narrowing of the emissions offset for ethanol fuels at lower PMI levels has been seen in

[5] In the figure, the PMI value for E-94-2 Fuel H has been corrected from that published to reflect the re-analysis of the retained sample at the start of the E-94-3 program.

other studies[6] and the emissions impact of ethanol is more prominent when blended into test fuels with higher values, typically greater than 1.00. The increase in Phase 1 PM emissions associated with ethanol at the E10 level was large enough to be highly significant statistically for the E-94-2 fuels.

If one adjusts the Phase 1 PM emissions of the E-129 fuels upward in the figure to place its Fuel C on the E0 trend line of the prior study, the fuels in the E-129 dataset create a nearly perfect extension of the emissions trend line to lower PMI values. The 10% ethanol fuel lies somewhat above the extended E0 trend line, but by only a small (and statistically not significant) amount. Its small vertical offset is consistent with a continued narrowing of the ethanol effect at lower PMI values. The continuity with the E-94-2 trend is unexpected, however, as the E-129 trend line is for oxygenated fuels, while the E-94-2 trend line is for E0 fuels alone. Except for the 10% ethanol fuel, the oxygenated fuels tested in this study do not display an offset to higher PM emissions when compared to E0 fuels of equal PMI, as was seen for the E10 fuels in the E-94-2 study.

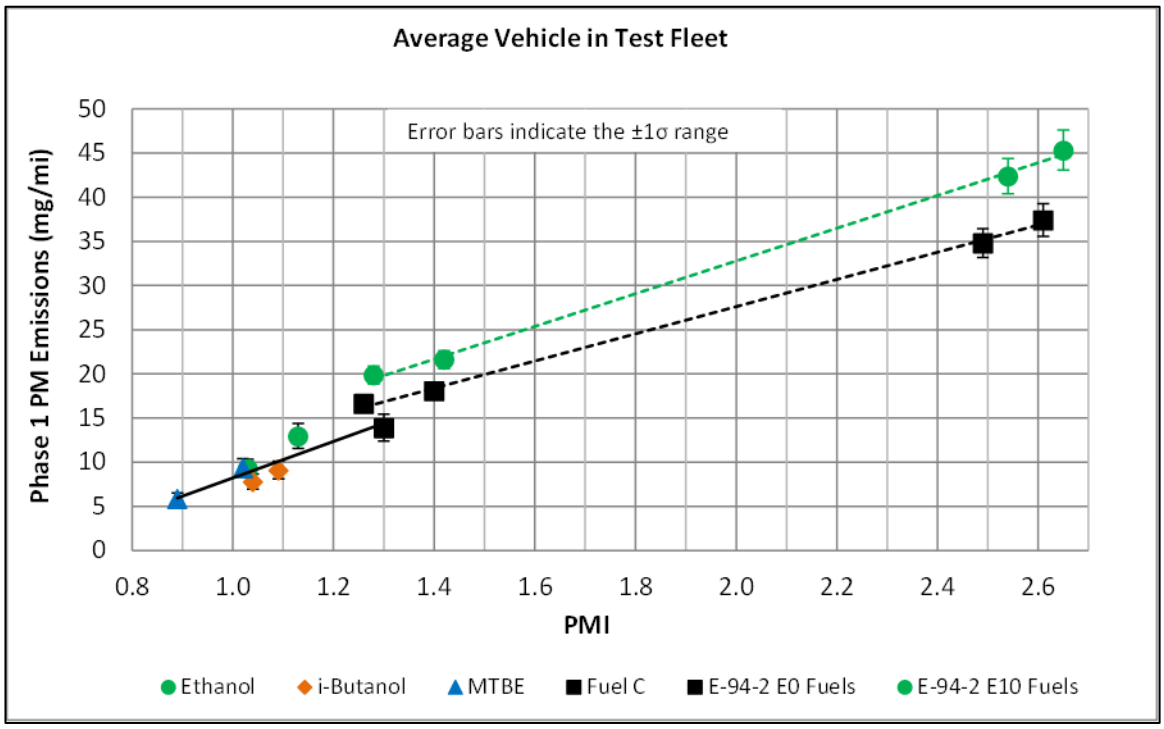

Figure 8-13 Comparison of Estimated Phase 1 PM Trends to the CRC E-94-2 Study

The 15% ethanol fuel and the fuels blended with i-butanol or MTBE lie at appreciably lower PMI values than were considered in E-94-2 and do not demonstrate any clear-cut pattern in their offsets with respect to the overall trend line. In fact, the 15% ethanol fuel is on the overall trend line and appears to suggest that the ethanol effect is not present at the E15 level. Why this should be – that the E10 offset does not extend to the 15% ethanol fuel and no offset is seen for the other oxygenates – is not understood. This could be related to the fact that the oxygenated fuels in E-129 lie at lower PMI values where PM emissions are smaller and it is harder to resolve emission differences due to ethanol or another oxygenate. It could also be related to the size of the test fleet (4 vehicles), which may not be large enough to permit the data to detect such emissions differences. These may not provide a

[6] See Butler, A., Sobotowski, R., Hoffman, G., and Machiele, P., "Influence of Fuel PM Index and Ethanol Content on Particulate Emissions from Light-Duty Gasoline Vehicles," SAE Technical Paper 2015-01-1072, 2015 as one example.

complete explanation, however. Section 8.5.3 presents a high-level review of the differences in distillation properties for the three oxygenates in this study. These differences may also contribute to some of the emissions discrepancies of the 15% ethanol and 24% i-butanol fuels.

8.5.2.Discussion

The E-129 testing demonstrates that the relationship between PM emissions and PMI extends to lower PMI levels than were examined in the E-94-2 study and to higher levels of oxygenation, using three different oxygenates. The dilution of gasoline hydrocarbons with oxygenates having low PM potential is the *primary* factor responsible for reducing Phase 1 and LA92 PM emissions. The PMI values of the fuels are the best indicator of emissions. In large part, this is because the oxygenates make very small contributions to the PMI calculation. Thus, adding oxygenates to an E0 fuel "dilutes" its PMI value nearly in proportion to the volumetric dilution of the gasoline hydrocarbons.

In this, the 10% ethanol fuel is found to lie above the overall trend line for Phase 1 PM, LA92 PM, and LA92 HC emissions. While the offset does not reach statistical significance, it is consistent across three pollutants and consistent with a narrowing of the larger and statistically significant ethanol effect seen in E-94-2. Thus, the failure of the effect of 10% ethanol to reach significance in the E-129 data could be the result of the small sample of test vehicles rather than evidence of its absence. With other oxygenates and at higher oxygenation levels, PM emissions of the E-129 fuels follow a trend line of decreasing PM emissions with decreasing PMI that is continuous with, and without offset from, the trend of E0 fuels in E-94-2.

The latter finding is unexpected. The presence of ethanol at the E10 level appears to increase PM emissions above the trend line with PMI. Yet, the 15% ethanol fuel lies on the PMI trend line as do the i-butanol and MTBE fuels. It is not understood why the fuels with ethanol at the E10 level demonstrate increased PM emissions when compared to E0 fuels of equal PMI value. Nor is it understood why the 15% ethanol and the i-butanol and MTBE fuels in this study also follow the E0 trend.

Past studies have offered some hypotheses for the E10 effect. One study[7] found that there was a reinforcing interaction of ethanol on PM emissions at the E10-E20 level in 10 of 15 port fuel-injected vehicles tested. It went on to say that the finding was consistent with statements in previous studies "associating ethanol's higher heat of vaporization with a cooling effect that has the potential to hinder fuel evaporation and lead to increased PM emissions." A second study[8] explored heat of vaporization (HoV) and net heating value (NHV) as variables that might improve the predictive performance of PM indices for emissions at oxygenation levels up to 100%.

The emissions trends in the E-129 data are inconsistent with the HoV hypothesis. If 10% ethanol exerts a cooling effect that leads to increased PM emissions, then one would expect 15% ethanol to lead to an even larger emissions effect. Instead, the 15% ethanol fuel in this study does not demonstrate increased PM emissions in comparison to what would be expected from its PMI. The HoV hypothesis should also apply to the other oxygenates, although their HoV values are smaller than that of ethanol. MTBE's HoV is similar to the gasoline hydrocarbons that it replaces and might not lead to an emissions effects. The i-butanol HoV lies between that of MTBE and ethanol and should lead to some cooling and an emissions increase if the HoV hypothesis is correct. Yet, no such emissions increase is seen in the data. The E-129 data highlight an unanswered question on ethanol's emissions effect but, by themselves, do not refute the HoV hypothesis because only 4 vehicles were tested in the program.

[7] See Butler 2015. SAE Technical Paper 2015-01-1072, 2015.

[8] Barrientos, E., Anderson, J., Mariq, M., Boehman, A., "Particulate Matter Indices using Fuel Smoke Point for Vehicle Emissions with Gasoline, Ethanol Blends, and Butanol Blends", Combustion and Flame 167, 2016.

The NHV hypothesis was considered for this study by computing an NHV-adjusted PMI for each E-129 fuel. The measured NHV for Fuel C was used to calculate the NHVs of the oxygenated fuels based on the information found in Table 8-11. Fuel C had an NHV of 43,350 kJ/kg and the oxygenated fuels range from about 40,800 to 41,800 kJ/kg. Because the oxygenated fuels have lower NHVs than Fuel C, more must be combusted over the LA92 cycle, thereby raising their contributions to PM compared to the PMI. To account for this, a NHV-adjusted PMI value was defined that increases the PMI by the ratio 43,350/NHV.

Figure 8-14 replots the Phase 1 PM emissions against the NHV-adjusted PMI. Use of the NHV-adjusted PMI has, at best, a subtle effect on the relationship of PM emissions to PMI (compare to Figure 8-10). The 10% ethanol fuel now overlaps the trend line within its error bars and the i-butanol and MTBE fuels all straddle the trend line. This demonstration suggests that the NHV hypothesis *may* have merit, but it does not make a large difference.

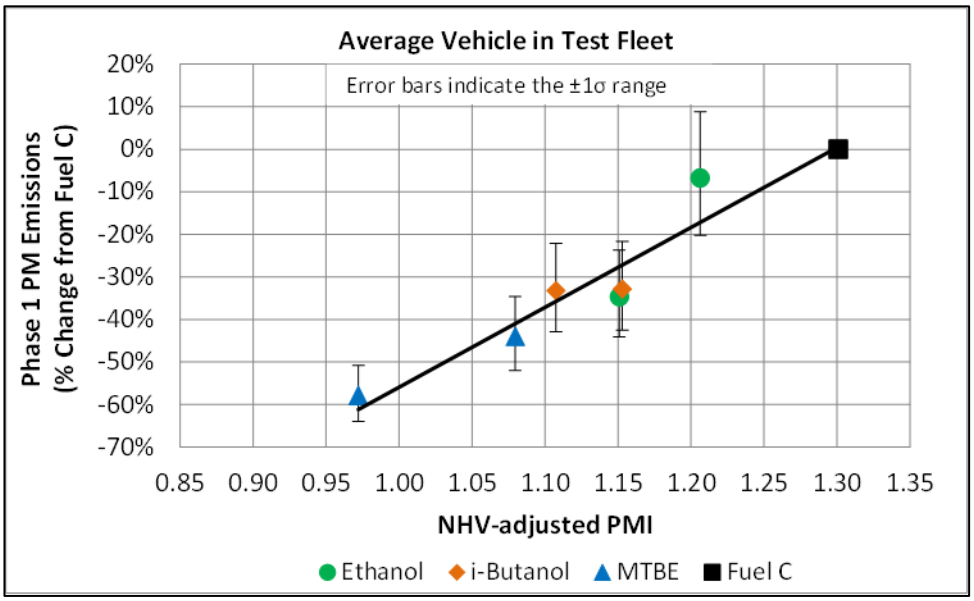

Figure 8-14 Trend of Estimated Phase 1 PM Emissions with NHV-adjusted PMI

Modern engines are designed to adjust their operation in response to the impacts that fuel characteristics have on combustion. As result, the way in which an engine operates can change in response to oxygen content, the type of oxygenate present in the fuel, the fuel octane number and other factors. Obviously, changes in engine operation in response to fuel characteristics have the potential to influence fuel economy and emissions. Currently, most MY2017 and later vehicles are certified to meet emissions standards using E10 gasoline both federally and for California. In addition, most new vehicles are now approved by the manufacturer to operate on E15 gasoline.

The same is not true for the MY2012-2013 vehicles used in this project, which were certified for emissions on E0 gasoline and, in California, on gasoline with 2 wt% oxygen from MTBE. In early 2011, EPA granted a waiver for the use of E15 gasoline in MY 2001 and later vehicles on the basis that no adverse emissions impacts were expected. However, we know of no manufacturers who had approved E15 for use in their new vehicles at the time the four test vehicles were manufactured except for “fuel flexible” vehicles. In order for MY2012-13 vehicles to have acceptable operation on E0 to E10 fuels in consumer hands, the emissions and fuel control systems necessarily were designed and calibrated with sufficient range to allow for operation on E10 fuels, but it is unlikely that the design and calibration of the test vehicles extended to the E15 level. Nevertheless, the fuel and emission control calibrations of the test vehicles had a sufficient range of authority to adapt to the more-highly oxygenated fuels without an observed increase in emissions.

If it is true that the test vehicles were not designed and calibrated for operation on E15 fuels or for oxygenates other than ethanol, then the vehicles were operated outside their design range on such fuels. In this case, the vehicles may not be able to optimize emissions and fuel control for the fuels having 5.5 wt% oxygen as fully as is possible on E10. Thus, emissions comparisons between E0-E10 fuels versus E15 and other fuels may be difficult to make. Further consideration of this issue with vehicles designed to operate on E15 is needed to fully understand the emissions trends observed in the E-129 data.

8.5.3. Distillation Properties of Oxygenated Test Fuels for Ethanol, i-Butanol, and MTBE

This report presents emissions results from gasoline blends using different oxygenated compounds. These oxygenates have different distillation properties when splash blended which may provide insight for future work to explain differences in emission changes with respect to each oxygenate. This section provides a high-level discussion of several literature references that discuss in detail test design, distillation curves, fuel-blending processes, engine design, technologies and calibrations for emission testing programs using oxygenated fuel blends.

There are extensive literature references concerning the volatility properties of gasoline test fuel. In particular, much attention has been focused on the distillation curves (temperatures at which a certain percentage of volatiles have evaporated), how these curves are influenced by the blending process (match versus splash), and chemical compositions. Match blending is useful when trying to target specific fuel properties that are important precursors to the formation of PM or other criteria emissions (T10, T50, T90, aromatics, Vapor Pressure or VP, etc…). However, match blending requires changing several parameters simultaneously and rarely captures the full range of impacts on all of the properties of a finished fuel that result from splash-blending. Further, some match blending programs have resulted in unusual fuels unrepresentative of the market. Several studies have presented data over the last 10 years with gasoline-ethanol test fuels formulated using both match blending and splash blending techniques which have generated subsequent debates over emissions results and conclusions concerning the impact of ethanol on PM formation in engine exhaust. A general consensus is that the mechanism for engine exhaust PM formation is complex and it is very difficult to design a single test program that will fully provide a clear “cause and effect” explanation for every scenario (real-world or modeling). The mechanism is further complicated by the non-linear blending effect of an azeotropic oxygenate such as ethanol on the distillation curve of the finished gasoline-ethanol fuel.

Clark et al[9] reviewed the varying design approaches and their impacts on several major test programs which presented emission results from varying amounts of ethanol blends and blending techniques. Anderson et al[10] described *Issues with T50 and T90 as Match Criteria for Ethanol-Gasoline Blends*. Butler et al[11] responded to Anderson et al and examined a broader scope with a large number of fuels and goes on to show evidence of multiple vehicles that are insensitive to varying gasoline-ethanol blends which adds yet another layer of complexity when engine design, technologies and calibrations are taken into account. Darlington et al[12] argued that in some

[9] Clark, N., Klein, T., Higgins, T., and McKain, D.L., “Emissions from Low- and Mid-Level Blends of Anhydrous Ethanol in Gasoline,” SAE Technical Paper 2019-01-0997, 2019, doi:10.4271/2019-01-0997.

[10] Anderson, J., Wallington, T., Stein, R., and Studzinski, W., "Issues with T50 and T90 as Match Criteria for Ethanol-Gasoline Blends," *SAE Int. J. Fuels Lubr.* 7(3):2014, doi:10.4271/2014-01-9080.

[11] Butler, A., Sobotowski, R., Hoffman, G., and Machiele, P., "Influence of Fuel PM Index and Ethanol Content on Particulate Emissions from Light-Duty Gasoline Vehicles," SAE Technical Paper 2015-01-1072, 2015, doi:10.4271/2015-01-1072.

[12] Darlington, T., Kahlbaum, D., Van Hulzen, S., and Furey, R., "Analysis of EPAct Emission Data Using T70 as an Additional Predictor of PM Emissions from Tier 2 Gasoline Vehicles," SAE Technical Paper 2016-01-0996, 2016, doi:10.4271/2016-01-0996.

cases T70 is an important predictor for PM emissions in addition to T50, T90, and VP. T70 becomes relevant to this study in the case of i-butanol and MTBE.

Distillation curves were acquired from the literature for gasoline-blends with varying volumetric additions of ethanol, i-butanol and MTBE because the full distillation properties had not been analyzed at the time of this report for the oxygenated test fuels used in this study. The literature values presented in this section illustrate the dilution behavior of the distillation curve for each oxygenate in equivalent or similar volume concentrations to those used in this study.

Andersen et al[13] presents distillation curves for several oxygenates splash blended into the same base hydrocarbon, EEE (Tier 2) emissions test gasoline. The distillation curves for the base fuel (EEE) and blends with 10% ethanol, 15% ethanol, 10% i-butanol and 20% i-butanol are shown in Figure 8-15 but Anderson did plot fuel blends up 85% by volume for both ethanol and i-butanol. It is important to point out that the base fuel in the example (EEE) is different than Fuel C, the base hydrocarbon used for this study. The non-linear behavior of ethanol is clearly shown by the 'near-azeotropic' characteristic at the T40 and T50 points where the slope drastically steepens. The non-linear behavior for E15 is pushed farther to the right in the plot relative to E10 and in this example lowers the T50 value from 98.8 C to 75.5 C. One theory regarding ethanol's potential to increase PM emissions is based around its high heat of vaporization (HoV). The high HoV encourages a cooling effect and thereby reduces fuel vaporization. If the PM emissions increases observed in this study for E10 are in part due to its HoV then the E15 blend might show a similar result. This was not observed. Due to the non-linear properties of ethanol, the HoV increase for low and mid-ethanol gasoline blends is very low. According to Anderson et al[10], E20 only has a 20% greater HoV compared to E10. In this study, the HoV increase for E15 would be expected to be lower than 20% yet there could be a substantial reduction in T50 which might explain the larger reduction in PM emissions.

In contrast, the behavior of 20% i-butanol is shown to influence both the light-end (T5-T40) and the heavy-end (T60-T90) in opposite directions relative to 10% i-butanol yet T50 remains unchanged. In this example, 20% i-butanol increases T5-T40 and decreases T60-T90 relative to 10% i-butanol. Andersen et al[13] showed that even higher concentrations of i-butanol continue to increase the lower end of the distillation curve and continue to decrease the upper end of the distillation curve. A better understanding is necessary of the distillation curves of the gasoline-oxygenate blends used in this study by investigating the influence these distillation curves have on the formation of PM and the associated PMI calculation.

[13] Andersen, V.F., Anderson, J.E., Mueller, S.A., Nielsen, O.J., Wallington, T.J., "Distillation Curves for Alcohol-Gasoline Blends," Energy & Fuels **2010** 24 (4), 2683-2691, DOI: 10.1021/ef9014795

[10] Anderson, J., Wallington, T., Stein, R., and Studzinski, W., "Issues with T50 and T90 as Match Criteria for Ethanol-Gasoline Blends," *SAE Int. J. Fuels Lubr.* 7(3):2014, doi:10.4271/2014-01-9080.

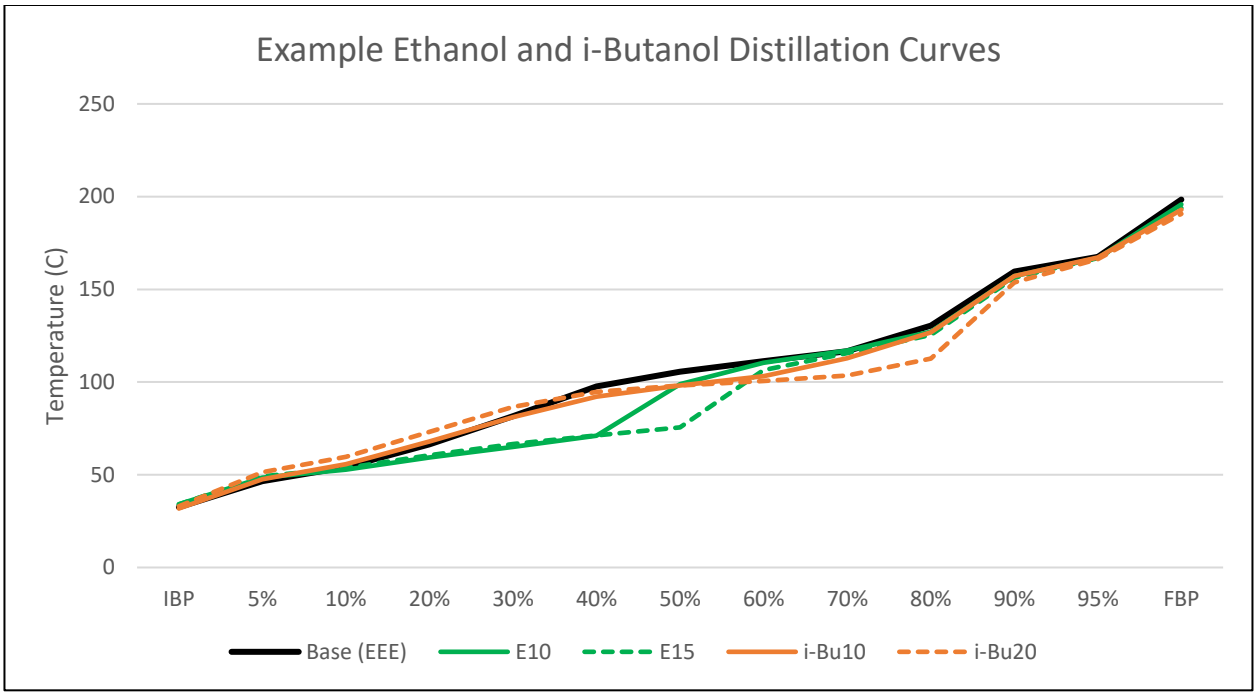

Figure 8-15 Example Distillation curves for varying amounts of ethanol and i-butanol into the same base hydrocarbon (EEE, test gasoline). IBP=initial boiling point. FBP=final boiling point.

There are dramatic differences between ethanol and i-butanol in how their respective distillation curves are influenced (magnitude and location) by the addition of higher volume concentrations into the same base hydrocarbon. These differences may further complicate the mechanism of PM formation.

Figure 8-16 shows the distillation curves for varying amounts of MTBE presented by Viljanen et al[14]. In this figure, the base fuel was 7% MTBE by volume and the other two fuels were created by splash blending higher concentrations of MTBE (16% and 25%) into the base fuel. There is a small increase at T5 as a result of increasing the MTBE concentration in this example, but the main differences are smooth reductions of T40-T90. The largest of these reductions are T60 and T70.

[14] Viljanen, J., Kokko, J., and Lundberg, M., "Effects of MTBE on Gasoline Engine Cold Weather Operation," SAE Technical Paper 890052, 1989, https://doi.org/10.4271/890052.

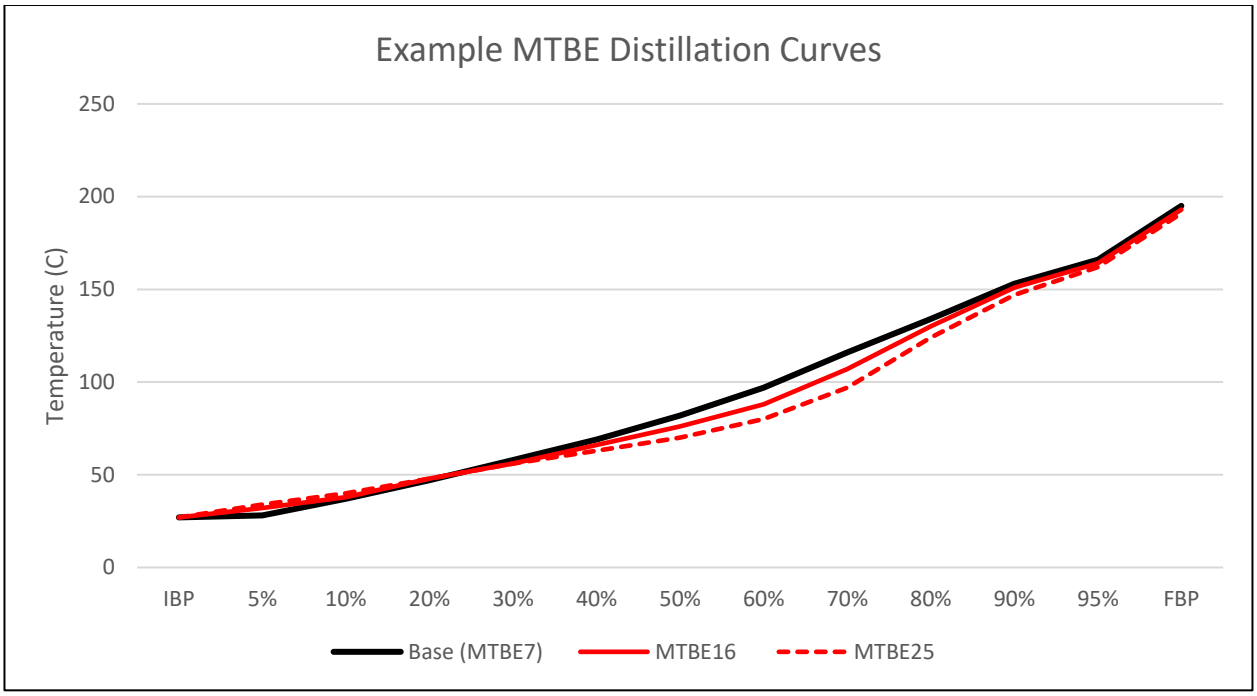

Figure 8-16 Example distillation curves for varying amounts of MBTE splash blended into the same base fuel (MTBE). IBP=initial boiling point. FBP=final boiling point.

MTBE and i-butanol are similar in their effect of reducing T60-T80. i-Butanol is different from ethanol and MTBE in that it increases T5-T40 to a greater extent. Ethanol is distinct from the other two due to its strong, non-linear 'near-azeotropic' behavior in the mid-range part of the curve. This 'near-azeotropic' point is dependent on the level of ethanol concentration and can greatly shift the distillation curve with small incremental amounts of added ethanol. These characteristics are unique for each oxygenate when splash blended into a base fuel.

These differences between the distillation curves for the three gasoline-oxygenate fuel blends are one important consideration when interpreting the emissions results in this study. The experimental design involved two levels of oxygen content for each of the three oxygenates. The observed emission changes were analyzed to determine whether they depended on oxygen content including how the PMI values of the fuels affect PM emissions. The distillation curves of the gasoline-oxygenate experimental fuel blends have not been determined by laboratory analysis and any differences between them were not known at the time this report was written. The influence on PM emissions that may arise from the differences in distillation properties, if present, will contribute to the emission differences that are observed among the oxygenates and between the oxygenates two different concentration levels. In this study, these emission differences prove to be relatively small and are difficult to resolve given the small test fleet and the uncertainties in each emissions estimate. Thus, the emissions influence of the oxygenates' differential effects on distillation properties, if present, will not be revealed in the analysis that is presented here.

8.6.Summary of Fuel Effects on Emissions

Table 8-12 summarizes how the emissions of the test fleet are related to characteristics of the oxygenated fuels. Phase 1 PM and LA92 PM emissions are reduced in all of the oxygenated fuels (except for the 10% ethanol fuel), because the blending of oxygenates dilutes the gasoline hydrocarbons of Fuel C with compounds that have low

potential to contribute to PM. For the 10% ethanol, the observed reduction compared to Fuel C is not statistically-significant, while the reductions for the other oxygenated fuels are. The 10% ethanol fuel also deviates from the emissions trend line with PMI, but the differences observed here is not statistically significant.

For the gaseous pollutants, LA92 HC emissions respond to fuels in much the same way as PM, but the emissions reductions are smaller on a percentage basis and there is more scatter around the trend line. LA92 CO emissions are reduced in proportion to the oxygen content of the fuels, while LA92 NOx emissions are unchanged. LA92 CO_2 emissions are reduced in proportion to the volumetric use of oxygenates, because the three oxygenated compounds contain less carbon per kJ of energy than typical E0 gasoline.

Table 8-12 Relationship of Emission Changes to Characteristics of the Oxygenated Fuels

Phase 1 PM	The 10 vol% ethanol fuel does not significantly reduce emissions below Fuel C and appears to lead to higher emissions than expected from its PMI. The other oxygenated fuels significantly reduce PM emissions in response to the dilution of gasoline hydrocarbons by the addition of oxygenated molecules.
LA92 PM	
LA92 HC	Emissions respond much like PM
LA92 CO	Emissions are reduced in proportion to the oxygen content (wt%) of the fuels.
LA92 NOx	Emissions are unchanged by the oxygenated fuels.
LA92 CO_2	Emissions are reduced in proportion to the volumetric use of oxygenate.

With respect to PM emissions specifically, the findings of this study are:

- With the exception of the 10% ethanol fuel, the oxygenated fuels significantly reduce Phase 1 and LA92 PM emissions of the test fleet in comparison to Fuel C. The 10% ethanol fuel is observed to reduce Phase 1 PM, but the emissions change from Fuel C is not statistically significant, unlike the other oxygenated fuels.
- The dilution of gasoline hydrocarbons with oxygenated compounds of low PM potential is the *primary* reason that oxygenated fuels reduce PM emissions for the three oxygenates considered. This effect is well-represented by the PMI index,
- The 10% ethanol fuel deviates from the trend lines with PMI for several of the pollutants. While none of the observed differences reached the level of statistical significance, the consistency across pollutants suggests the possibility that some properties or characteristics of E10 fuels may exert a *secondary* influence on PM emissions.

When the emissions trends in this study are compared to those of CRC E-94-2, the E-129 fuels extend the trend of decreasing PM emissions with decreasing PMI. In the prior study, ethanol at the E10 level was found to increase Phase 1 PM emissions above the level of E0 fuels having the same PMI. In this study, the 10% ethanol fuel lies a small distance above the extended E0 trend line, consistent with a continued narrowing of the E10 emissions effect as one moves toward lower PMI values. The continuity with the prior E-94-2 trend carries a surprise, however, as the data points for the 15% ethanol fuel and fuels oxygenated with i-butanol and MTBE lie on the E-94-2 trend line defined by the E0 fuels alone. Thus, the other oxygenated fuels do not show the same tendency as E10 to increase Phase 1 PM emissions above the level of E0 fuels having the same PMI.

It is not understood why the fuels oxygenated with ethanol at the E10 level increases PM emissions when compared to E0 fuels of equal PMI value. Nor is it understood why the E15 and the i-butanol and MTBE fuels follow the E0 trend line with PMI from the E-94-2 study. Past studies have suggested that the E10 emissions effect might be related to ethanol's high HoV and to differences in the NHV between E0 and oxygenated fuels. If so, one would expect an E15 fuel to show higher PM emissions than an E10 fuel, while the opposite was seen in the emissions testing conducted here. If the performance of the test vehicles on E10 and E15 can be fairly compared, the E-129 emissions data are inconsistent with prior hypotheses regarding the effect of ethanol on emissions.

There is need to recognize that the ability of modern engines to adjust their operation based on characteristics of the fuels has the potential to influence fuel economy and emissions. If the E-129 test vehicles were operated outside their design range in this project, the vehicles may not have optimized emissions and fuels control as fully as the optimization that was possible on E10. Thus, emissions comparisons between E0—E10 fuels versus E15 and the other fuels may be difficult to make. Further consideration of this issue using vehicles approved for operation on E15 is needed to fully understand the emissions trends observed in the E-129 data.

8.7.Summary and Recommendations

Summary of the Testing

This study evaluated the tailpipe emissions of four motor vehicles with varying engine technologies, engine-size and charge-air. All four vehicles were equipped with spark-ignited direct-injected gasoline engines, were from model years 2012 or 2013, and were from a variety of automotive manufacturers. Tailpipe emissions were collected for each vehicle using the LA92 Unified Cycle.

Eight total fuels were used for testing during this project. One base hydrocarbon fuel was selected from the CRC E-94-2 study and used to create six additional test fuels by splash blending different oxygenates. The splash-blended oxygenated test fuels were 10% ethanol, 19% MTBE, 16% i-butanol, 15% ethanol, 29% MTBE and 24% i-butanol. Each oxygenated test fuel targeted a total oxygen content of either 3.5% or 5.5% depending on the total chemical concentration. The eighth fuel used was a non-oxygenated (Tier 2) certification gasoline compliant with the fuel specifications described in 40 CFR Part 86 for the Federal Test Procedure and was used in baseline testing at the beginning and end of the study to monitor any change in vehicle performance.

In the final baseline testing, some of the vehicles failed to return to the initial baseline values for fuel trim and spark timing following the extended testing on oxygenated fuels. This highlights the importance of the pre-conditioning cycle following fuel changes and of monitoring the fuel trim and spark timing during the testing as a *qualitative* tool to gauge an engine's adaption to a new fuel. In future work, it may be appropriate to extend the period of pre-conditioning before the final baseline to allow more time for the vehicles to "re-learn" the certification fuel.

Summary of Fuel Effects on Emissions

The dilution of gasoline hydrocarbons with oxygenated compounds was found to be the primary influence on emissions of the test fleet and is well-measured by the PMI index. The addition of oxygen molecules to the fuels reduces Phase 1 PM and LA92 PM emissions compared to Fuel C because the oxygenated compounds have low (nearly zero) potential to contribute to the PMI. The 10% ethanol fuel reduces PM emissions compared to Fuel C, but not by a statistically-significant amount. The other oxygenated fuels significantly reduce PM emissions.

LA92 HC emissions responded to the fuels in much the same way as PM, but to a lesser extent and with more variability. LA92 CO emissions were reduced in proportion to the oxygen content carried by the fuels, while LA92 NOx emissions were unchanged overall. LA92 CO_2 emissions were reduced in proportion to oxygenate use because the oxygenated compounds are less carbon intensive per kJ than Fuel C.

Surrounding these primary trends are two different fuel effects that are not understood at present, specifically:

- Why fuels oxygenated with ethanol at the E10 level demonstrate increased PM emissions in comparison to E0 fuels of equal PMI value, while at the E15 level, PM emissions were significantly decreased.
- Why the 15% ethanol and the i-butanol and MTBE fuels generally follow the PMI trend line established for E0 fuels in the prior CRC E-94-2 study, rather than being offset above it like the E10 fuels.

Research on fuels and PM emissions should be continued in the effort to resolve these unanswered questions. The most pressing need is to formulate a set of well-defined hypotheses for how other variables might explain the unresolved fuel effects. The variables include the design of emission and fuel control systems and their calibrations for operation on both 10% ethanol and other oxygenated fuels. The characteristics of the oxygenates should also be considered (i.e. distillation curves). Further emissions testing and analysis could be performed to test the hypotheses. In particular, testing of MY2017-2018 and newer vehicles could shed additional light on PM emissions from fuels up to the E15 level.

9. Appendix

9.1.Vehicle Coastdown History

Four consecutive coastdowns from 70-30 mph were performed every test week during the Fuel Change Procedure. The third and fourth consecutive coastdowns were required to be within 0.5 seconds of each other and were also required to be within ±7% of the coastdown running average for the whole program. Figure 9-1 through Figure 9-4 shows the coastdown history for all vehicles. The third and fourth coastdowns are represented as circles. The 7% boundary conditions are represented as red lines.

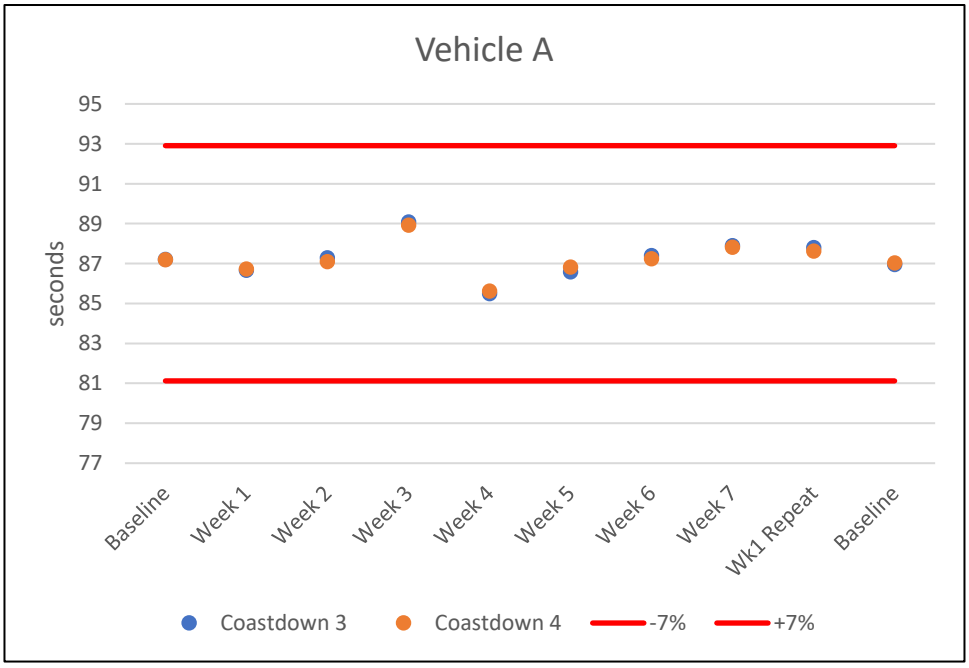

Figure 9-1 Vehicle A Coastdown History

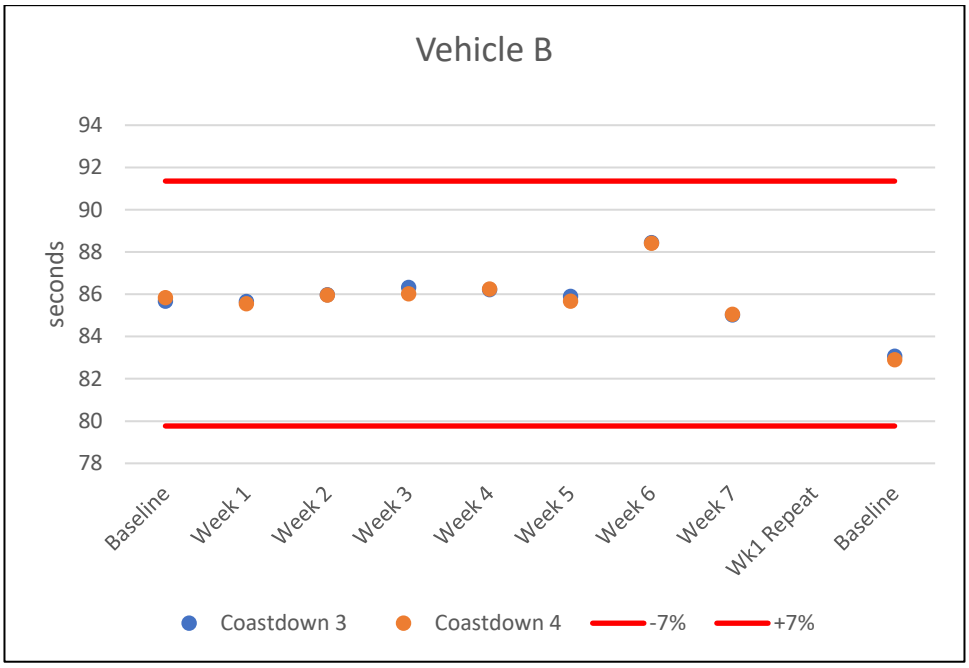

Figure 9-2 Vehicle B Coastdown History

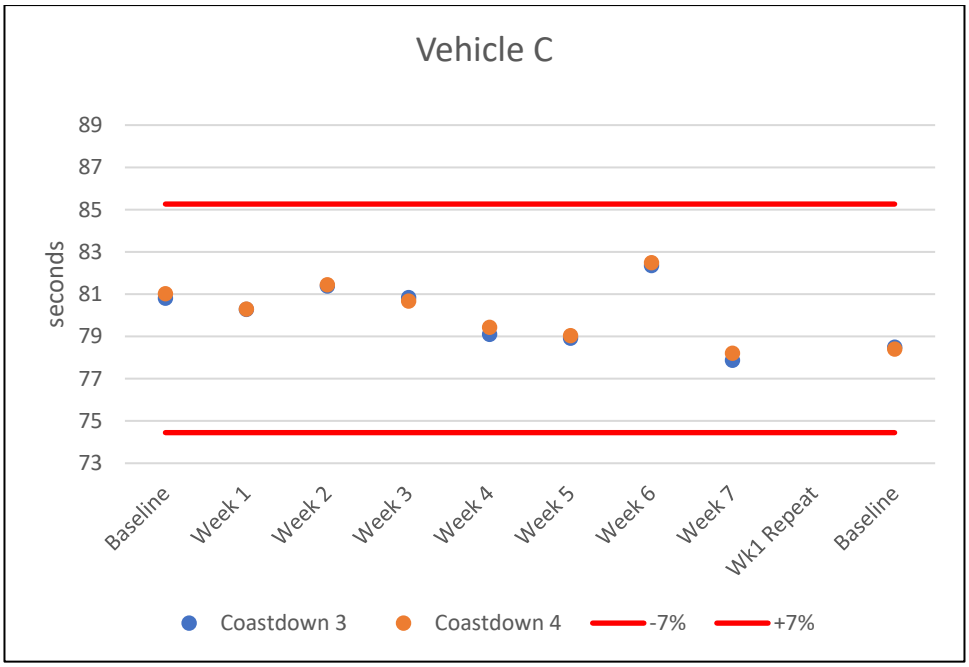

Figure 9-3 Vehicle C Coastdown History

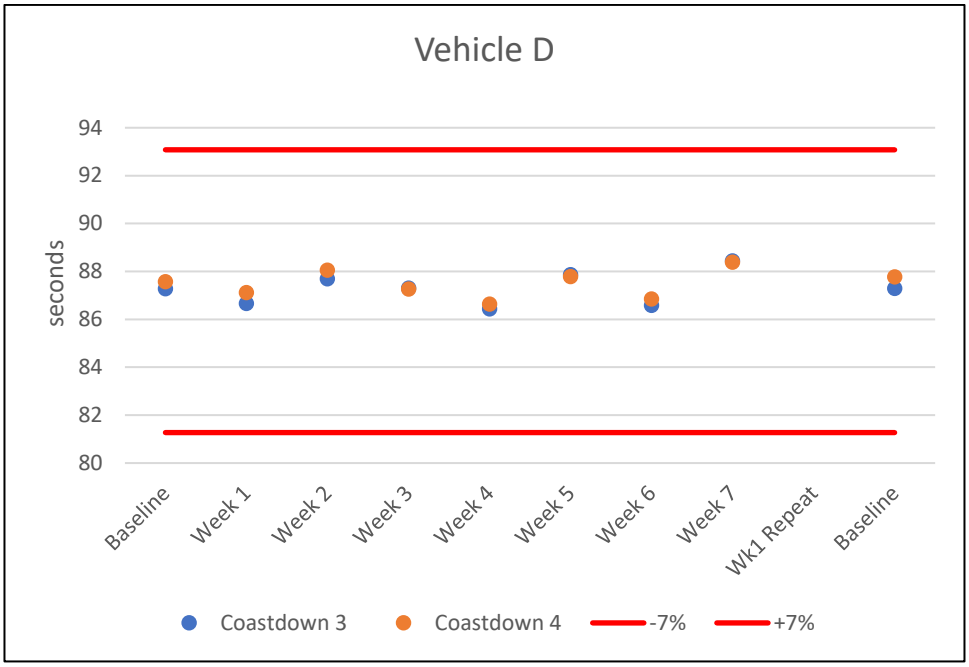

Figure 9-4 Vehicle D Coastdown History

9.2.Test Fuel Certificate of Analysis

Figure 9-5 through Figure 9-12 show the Certificate of Analysis for each test fuel in this program.

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 12/15/17 at 1:56 PM

Customer: C00100 / CRC, Inc.

Sales Order # : 93415 Customer PO # : 790 Shipped Qty : 150

Packaged Product: 40580-55F
US EPA Cert Fuel 96 RON

Property	Test Method	UOM	Specification	Value
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7412
API GRAVITY @ 60 F	ASTM D4052		REPORT	59.4
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	75.0 - 95.0(23.9 - 35.0)	87.8(31.0)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	120.0 - 135.0(48.9 - 57.2)	123.7(50.9)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	200.0 - 230.0(93.3 - 110.0)	218.8(103.8)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	300.0 - 325.0(148.9 - 162.8)	321.0(160.6)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	415.0(212.8), MAX	363.9(184.4)
RVP @ 100 F	ASTM D5191	PSI (KPA)	8.70 - 9.20(59.94 - 63.39)	8.74(60.22)
RESEARCH OCTANE NUMBER	ASTM D2699	RON	96.0 - 98.5	96.7
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	88.3
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	92.5
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	7.5, MIN	8.4
AROMATIC CONTENT	ASTM D1319	VOL.%	35.0, MAX	29.1
OLEFIN CONTENT	ASTM D1319	VOL.%	10.0, MAX	0.5
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	76.1
SULFUR CONTENT	ASTM D5453	PPM	25.0 - 35.0	27.0
LEAD CONTENT	ASTM D3237	G/GAL	0.05, MAX.	0
PHOSPHOROUS CONTENT	ASTM D3231	G/GAL	0.005, MAX.	0
CARBON CONTENT	ASTM D5291	WT.%	REPORT	86.40
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	13.61
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	6.350
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	1.877
NET HEAT OF COMBUSTION	ASTM D240	BTU/LB (MJ/KG)	REPORT	18765.9(43.7)
CARBON DENSITY	CALCULATED		2401 - 2441	2404
OXYGENATES	ASTM D4815	VOL.%	NONE	NONE

Lot # 11747000 Made 12/11/17
In sealed unopened containers this product is good until 12/11/19

Approved By: Robert Pietz III

Figure 9-5 Certification Gasoline Certificate of Analysis

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 05/17/18 at 11:33 AM

Customer PO # :

Packaged Product: 41803-55F
CRC E-94-2 Fuel C

Property	Test Method	UOM	Specification	Value
RESEARCH OCTANE NUMBER	ASTM D2699	RON	90.5 - 91.5	91.5
MOTOR OCTANE NUMBER	ASTM D2700	MON	REPORT	84.4
OCTANE RATING	GAGE-CALCULATED	R+M/2	REPORT	88.0
OCTANE SENSITIVITY	GAGE-CALCULATED	R-M	REPORT	7.1
AROMATIC CONTENT	ASTM D1319	VOL.%	23.0 - 27.0	24.5
PMI HONDA EQ	PMI Calc Tool		1.40, MAX	1.26
RVP @ 100 F	ASTM D5191	PSI (KPA)	6.50 - 7.50(44.79 - 51.68)	7.35(50.64)
ETHANOL CONTENT	ASTM D4815mod	VOL%	REPORT	0.00
SULFUR CONTENT	ASTM D5453	PPM	8.0 - 12.0	8.8
C6 AROMATICS (BENZENE)	ASTM D6729	VOL%	0.4 - 0.8	0.4
OLEFIN CONTENT	ASTM D1319	VOL.%	4.0 - 6.0	4.9
DISTILLATION, IBP	ASTM D86	DEG F (DEG C)	REPORT	88.5(31.4)
DISTILLATION, 5%	ASTM D86	DEG F (DEG C)	REPORT	123.7(50.9)
DISTILLATION, 10%	ASTM D86	DEG F (DEG C)	REPORT	140.8(60.4)
DISTILLATION, 20%	ASTM D86	DEG F (DEG C)	REPORT	165.6(74.2)
DISTILLATION, 30%	ASTM D86	DEG F (DEG C)	REPORT	188.0(86.7)
DISTILLATION, 40%	ASTM D86	DEG F (DEG C)	REPORT	206.9(97.2)
DISTILLATION, 50%	ASTM D86	DEG F (DEG C)	170.0 - 250.0(76.7 - 121.1)	222.0(105.6)
DISTILLATION, 60%	ASTM D86	DEG F (DEG C)	REPORT	235.0(112.8)
DISTILLATION, 70%	ASTM D86	DEG F (DEG C)	REPORT	247.8(119.9)
DISTILLATION, 80%	ASTM D86	DEG F (DEG C)	REPORT	264.7(129.3)
DISTILLATION, 90%	ASTM D86	DEG F (DEG C)	280.0 - 320.0(137.8 - 160.0)	296.5(146.9)
DISTILLATION, 95%	ASTM D86	DEG F (DEG C)	REPORT	330.1(165.6)
DISTILLATION, DRY POINT	ASTM D86	DEG F (DEG C)	360.0 - 400.0(182.2 - 204.4)	379.8(193.2)
RECOVERY	ASTM D86	VOL.%	REPORT	97.8
RESIDUE	ASTM D86	VOL.%	2.0, MAX	1.0
LOSS	ASTM D86	VOL.%	REPORT	1.2
DI CORRECTED	ASTM D4814	DRIVE. INDEX	1250, MAX	1174
C10+ AROMATICS	ASTM D6729	VOL%	4.0, MAX	3.0
EXISTENT GUM (WASHED)	ASTM D381	MG/100ML	REPORT	0.0
UNWASHED GUM	ASTM D381	MG/100ML	REPORT	14.60
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7382
DENSITY @ 60.0 F	ASTM D4052	G/ML	REPORT	0.737
API GRAVITY @ 60 F	ASTM D4052		REPORT	60.20
SATURATE CONTENT	ASTM D1319	VOL.%	REPORT	70.6
CARBON CONTENT	ASTM D5291	WT.%	REPORT	85.93
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	14.07
OXYGEN CONTENT	ASTM D4815	WT.%	REPORT	0.00
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	1.951
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	6.107
O/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	0.000
NET HEAT OF COMBUSTION	ASTM D240	MJ/KG (BTU/LB)	REPORT	43.35(18637.15)
SULFUR CONTENT	ASTM D5453	PPM	0.0 - 10.0	8.5

Lot # 11744700 Made 01/05/18
In sealed unopened containers this product is good until 01/05/20

Approved By: Robert Pettitt

Figure 9-6 Fuel C Certificate of Analysis

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 05/17/18 at 11:40 AM

Customer PO # :

Packaged Product: 42356-55F
CRC E-129 BASE E10

Property	Test Method	UOM	Specification	Value
ETHANOL CONTENT	ASTM D4815	VOL.%	9.50 - 10.50	9.97
CRC E-94-2 FUEL C	GAGE-CALCULATED	VOL%	89.50 - 90.50	90.03
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7427
CARBON CONTENT	ASTM D5291	WT.%	REPORT	82.24
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	14.07
OXYGEN CONTENT	ASTM D4815	WT.%	REPORT	3.70
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	2.038
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	5.846
O/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	0.034
NET HEAT OF COMBUSTION	ASTM D240	MJ/KG (BTU/LB)	REPORT	41.65(17906.28)
SULFUR CONTENT	ASTM D5453	PPM	10.0, MAX	8.0

Lot # 11745000 **Made** 01/15/18

In sealed unopened containers this product is good until 01/15/20

Approved By: Robert Petzold

Figure 9-7 10% Ethanol Blend Certificate of Analysis

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 05/17/18 at 11:55 AM

Customer PO # :

Packaged Product: 42361-55F
CRC E-129 BASE, 19 MTBE

Property	Test Method	UOM	Specification	Value
MTBE CONTENT	ASTM D4815mod	VOL.%	18.50 - 19.50	19.32
CRC E-94-2 FUEL C	GAGE-CALCULATED	VOL%	80.50 - 81.50	80.68
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7395
CARBON CONTENT	ASTM D5291	WT.%	REPORT	82.37
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	14.10
OXYGEN CONTENT	ASTM D4815	WT.%	REPORT	3.54
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	2.040
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	5.843
O/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	0.032
NET HEAT OF COMBUSTION	ASTM D240	MJ/KG (BTU/LB)	REPORT	41.70(17927.77)
SULFUR CONTENT	ASTM D5453	PPM	10.0, MAX	8.0

Lot # 11746200 **Made** 01/14/18

In sealed unopened containers this product is good until 01/14/20

Approved By: Robert Pietzsch

Figure 9-8 19% MTBE Blend Certificate of Analysis

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

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Date: 05/17/18 at 11:50 AM

Customer PO # :

Packaged Product: 42359-55F
CRC E-129 BASE, 16 Isobutanol

Property	Test Method	UOM	Specification	Value
ISOBUTANOL CONTENT	GAGE-GC2	VOL%	15.50 - 16.50	16.31
CRC E-94-2 FUEL C	GAGE-CALCULATED	VOL%	83.50 - 84.50	83.69
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7480
CARBON CONTENT	ASTM D5291	WT.%	REPORT	82.15
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	14.05
OXYGEN CONTENT	ASTM D4815	WT.%	REPORT	3.79
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	2.038
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	5.846
O/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	0.035
NET HEAT OF COMBUSTION	ASTM D240	MJ/KG (BTU/LB)	REPORT	41.41(17803.10)
SULFUR CONTENT	ASTM D5453	PPM	10.0, MAX	7.8

Lot # 11745600 **Made** 01/15/18
In sealed unopened containers this product is good until 01/15/20

Approved By: Robert Petzold

Figure 9-9 16% i-Butanol Blend Certificate of Analysis

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

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Customer PO # :

Packaged Product: 42357-55F
CRC E-129 BASE E15

Property	Test Method	UOM	Specification	Value
ETHANOL CONTENT	ASTM D4815	VOL.%	14.50 - 15.50	14.85
CRC E-94-2 FUEL C	GAGE-CALCULATED	VOL%	84.50 - 85.50	85.15
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7452
CARBON CONTENT	ASTM D5291	WT.%	REPORT	80.53
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	13.98
OXYGEN CONTENT	ASTM D4815	WT.%	REPORT	5.49
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	2.069
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	5.759
O/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	0.051
NET HEAT OF COMBUSTION	ASTM D240	MJ/KG (BTU/LB)	REPORT	40.78 (17532.24)
SULFUR CONTENT	ASTM D5453	PPM	10.0, MAX	8.1

Lot # 11745300 **Made** 01/15/18

In sealed unopened containers this product is good until 01/15/20

Approved By: Robert Pitzitt

Figure 9-10 15% Ethanol Blend Certificate of Analysis

GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

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Date: 05/17/18 at 11:58 AM

Customer PO # :

Packaged Product: 42362-55F
CRC E-129 BASE, 29 MTBE

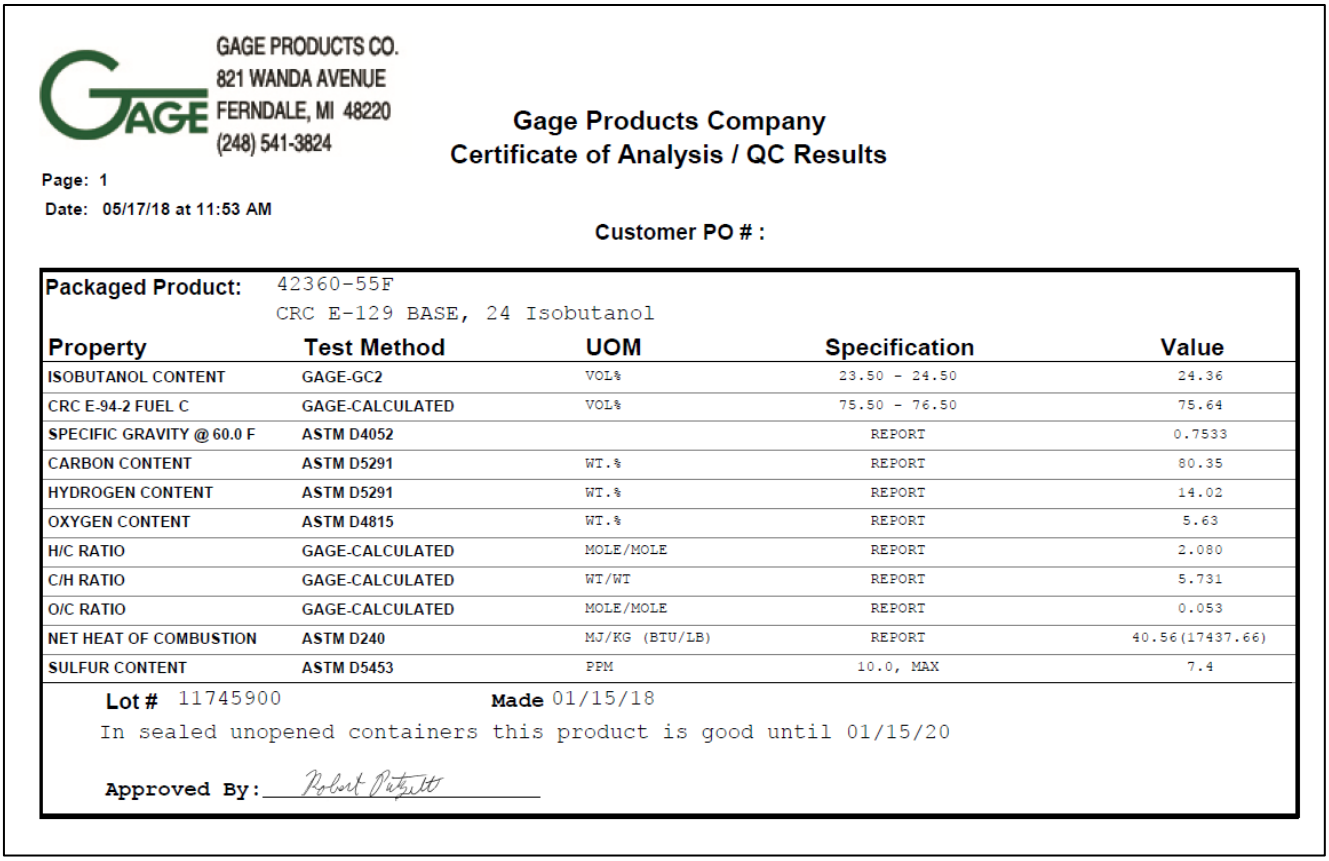
Property	Test Method	UOM	Specification	Value
MTBE CONTENT	ASTM D4815mod	VOL.%	28.50 - 29.50	29.35
CRC E-94-2 FUEL C	GAGE-CALCULATED	VOL%	70.50 - 71.50	70.65
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7402
CARBON CONTENT	ASTM D5291	WT.%	REPORT	80.60
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	14.04
OXYGEN CONTENT	ASTM D4815	WT.%	REPORT	5.37
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	2.075
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	5.743
O/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	0.050
NET HEAT OF COMBUSTION	ASTM D240	MJ/KG (BTU/LB)	REPORT	41.35(17777.30)
SULFUR CONTENT	ASTM D5453	PPM	10.0, MAX	7.4

Lot # 11746500 **Made** 01/14/18

In sealed unopened containers this product is good until 01/14/20

Approved By: Robert Butzlaff

Figure 9-11 29% MTBE Blend Certificate of Analysis



GAGE PRODUCTS CO.
821 WANDA AVENUE
FERNDALE, MI 48220
(248) 541-3824

Gage Products Company
Certificate of Analysis / QC Results

Page: 1
Date: 05/17/18 at 11:53 AM

Customer PO # :

Packaged Product: 42360-55F
CRC E-129 BASE, 24 Isobutanol

Property	Test Method	UOM	Specification	Value
ISOBUTANOL CONTENT	GAGE-GC2	VOL%	23.50 - 24.50	24.36
CRC E-94-2 FUEL C	GAGE-CALCULATED	VOL%	75.50 - 76.50	75.64
SPECIFIC GRAVITY @ 60.0 F	ASTM D4052		REPORT	0.7533
CARBON CONTENT	ASTM D5291	WT.%	REPORT	80.35
HYDROGEN CONTENT	ASTM D5291	WT.%	REPORT	14.02
OXYGEN CONTENT	ASTM D4815	WT.%	REPORT	5.63
H/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	2.080
C/H RATIO	GAGE-CALCULATED	WT/WT	REPORT	5.731
O/C RATIO	GAGE-CALCULATED	MOLE/MOLE	REPORT	0.053
NET HEAT OF COMBUSTION	ASTM D240	MJ/KG (BTU/LB)	REPORT	40.56(17437.66)
SULFUR CONTENT	ASTM D5453	PPM	10.0, MAX	7.4

Lot # 11745900 **Made** 01/15/18
In sealed unopened containers this product is good until 01/15/20

Approved By: Robert Petzold

Figure 9-12 24% i-Butanol Blend Certificate of Analysis

9.3.Phase-Specific Emissions

The phase-specific emissions for each vehicle are shown in Figure 9-13 through Figure 9-76. Both the Baseline Emissions and Iterative Emissions are included. For every figure, there are four categories; Phase 1, Phase 2, Phase 3, and Weighted. Each colored bar represents the average result for that category. The error bars represent the minimum and maximum result for the number of tests that created the categorical average. Phase 1 averages/error bars are linked to the left most vertical axis. Phase 2, 3 and Weighted averages/error bars are linked to the right most vertical axis. Each colored bar represents an individual test fuel. The order of the color bars also represents the sequential test order in which the fuels were tested. For the Baseline Emissions figures, the same fuel was used but the different colored bars represent the initial and final testing sequences described in this report. The green colored bars represent the initial Baseline Emissions and the purple colored bars represent the final Baseline Emissions.

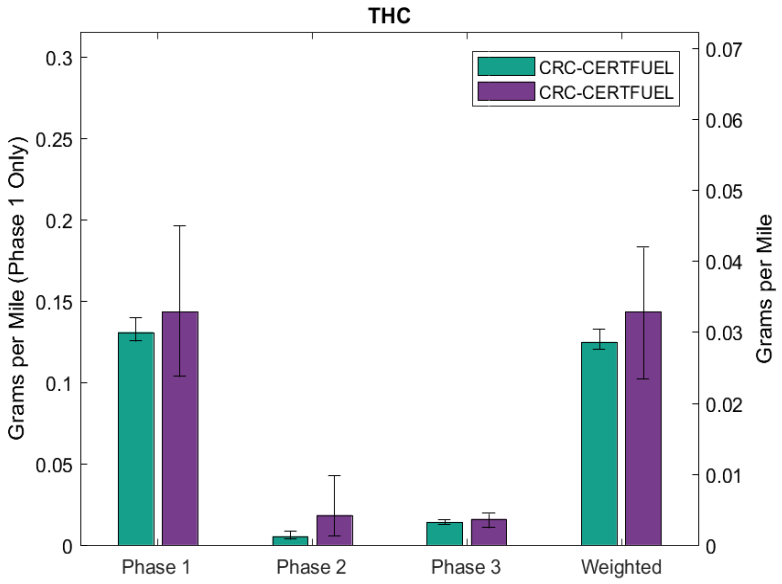


Figure 9-13 Vehicle A Baseline THC Emissions

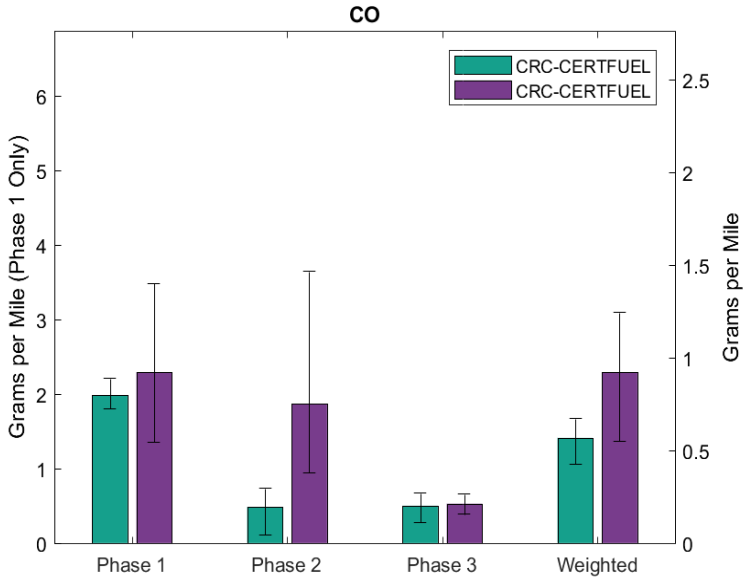


Figure 9-14 Vehicle A Baseline CO Emissions

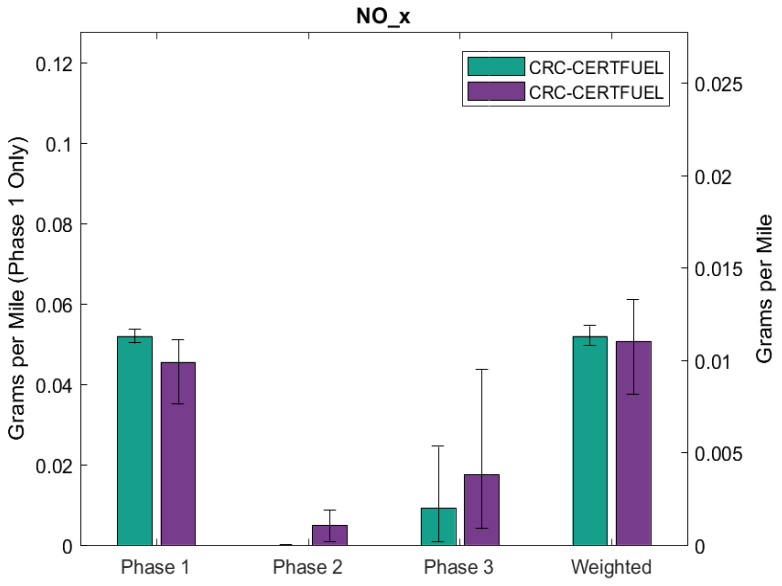


Figure 9-15 Vehicle A Baseline NO_x Emissions

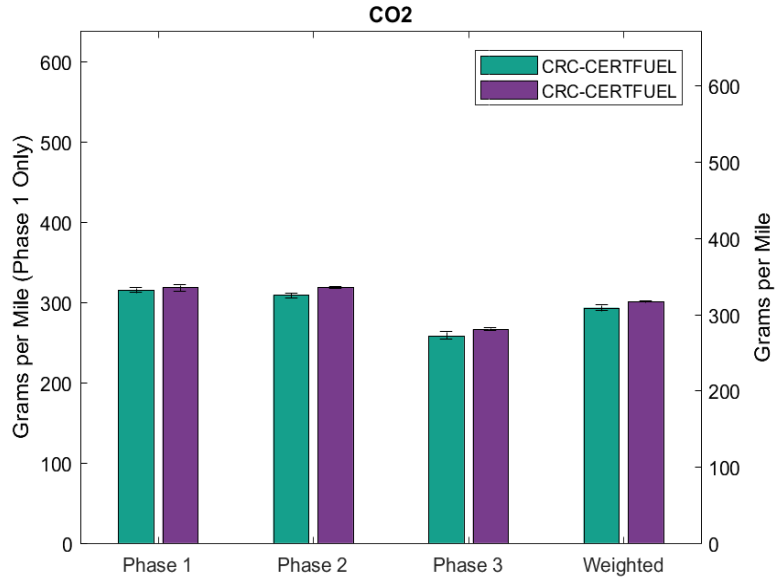


Figure 9-16 Vehicle A Baseline CO_2 Emissions

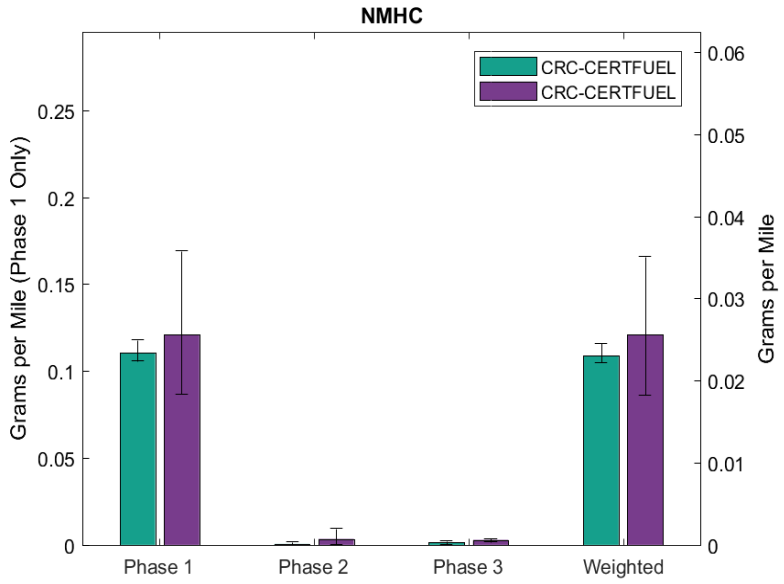


Figure 9-17 Vehicle A Baseline NMHC Emissions

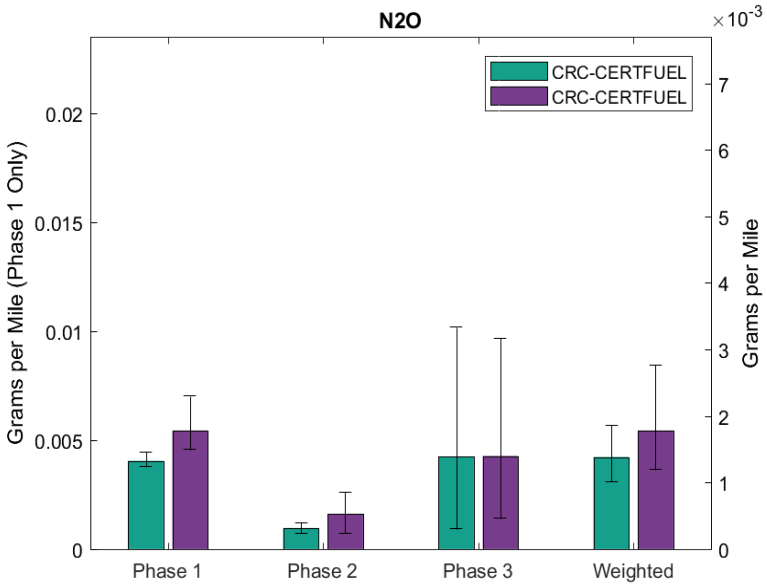


Figure 9-18 Vehicle A Baseline N_2O Emissions

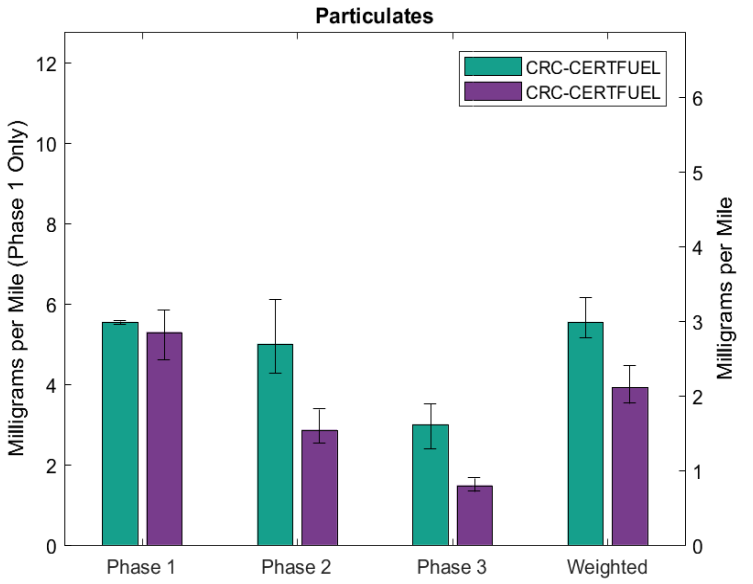


Figure 9-19 Vehicle A Baseline Particulate Matter Emissions

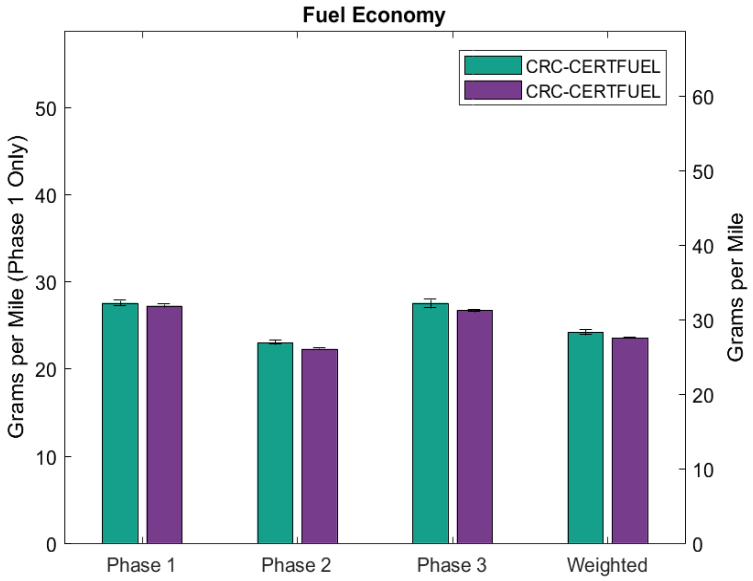


Figure 9-20 Vehicle A Baseline Fuel Economy

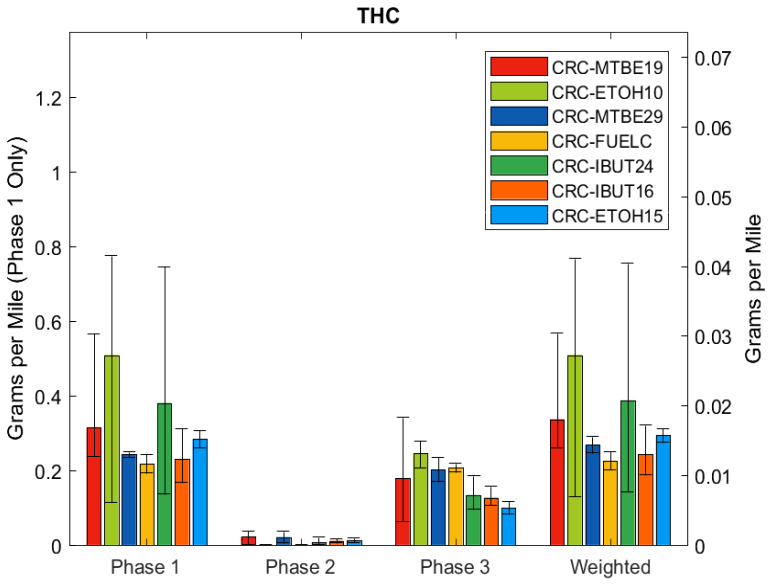


Figure 9-21 Vehicle A Iterative THC Emissions

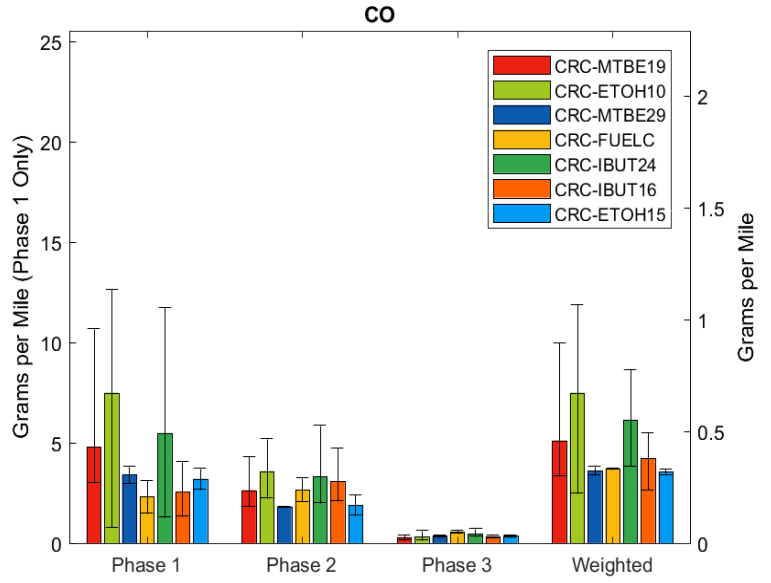


Figure 9-22 Vehicle A Iterative CO Emissions

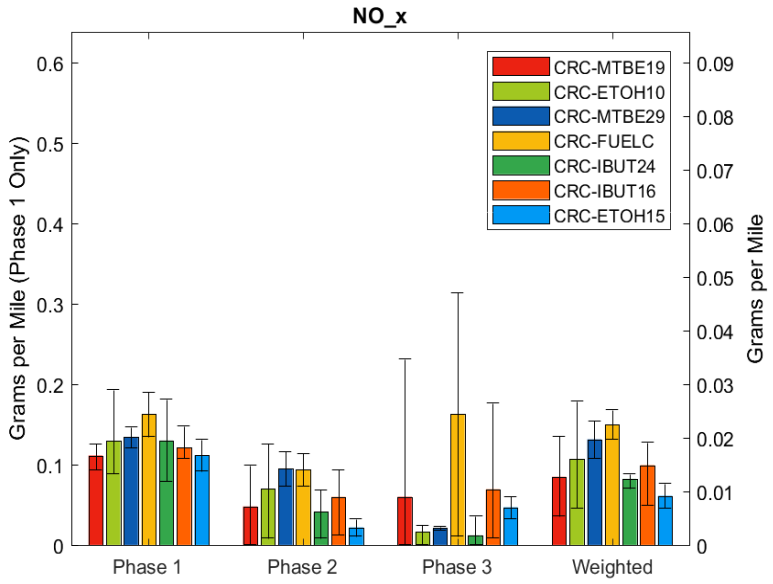


Figure 9-23 Vehicle A Iterative NO_x Emissions

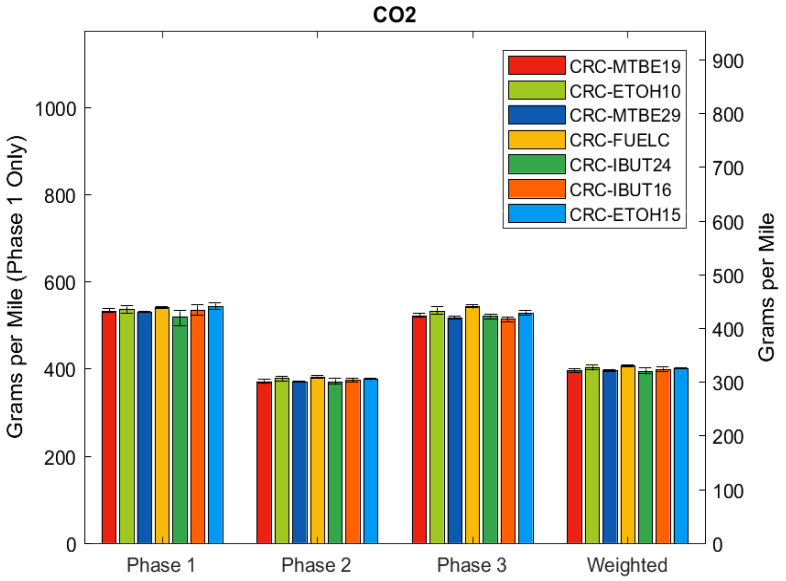


Figure 9-24 Vehicle A Iterative CO_2 Emissions

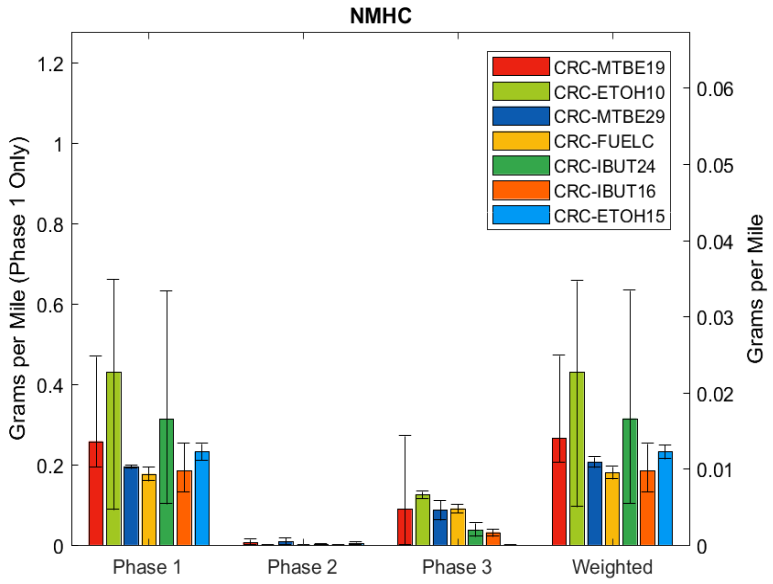


Figure 9-25 Vehicle A Iterative NMHC Emissions

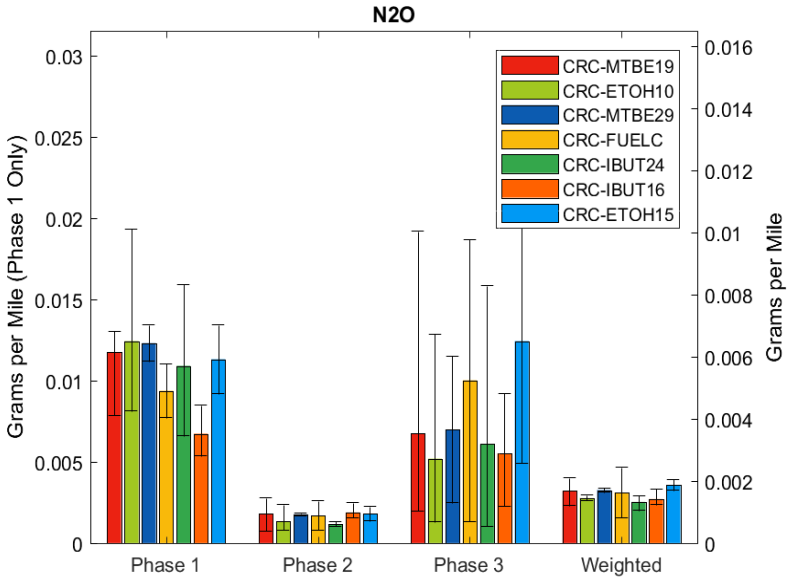


Figure 9-26 Vehicle A Iterative N_2O Emissions

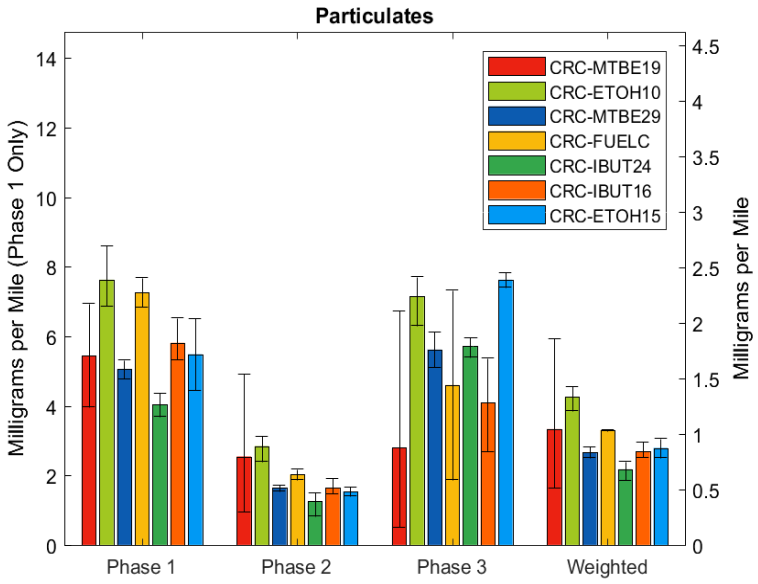


Figure 9-27 Vehicle A Iterative Particulate Matter Emissions

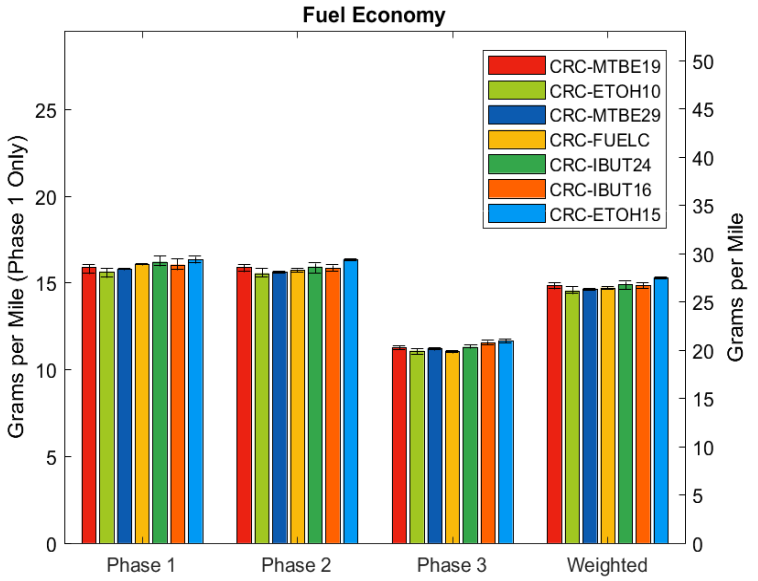


Figure 9-28 Vehicle A Iterative Fuel Economy

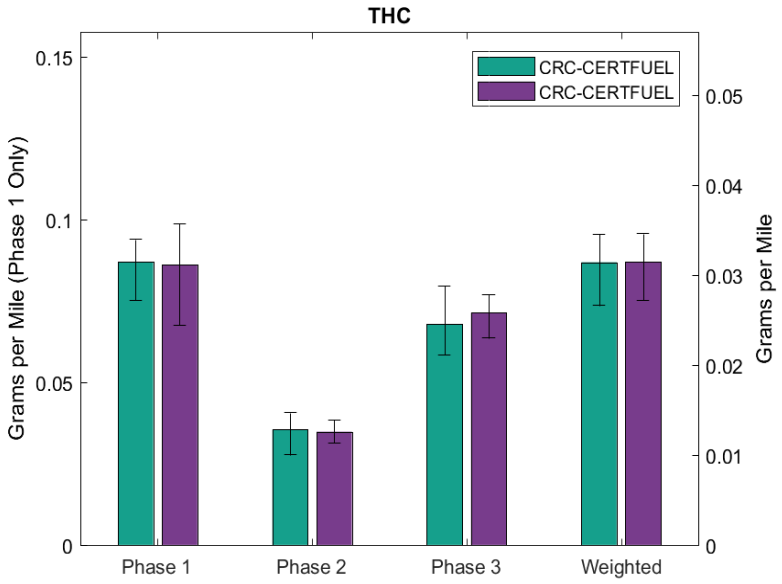


Figure 9-29 Vehicle B Baseline THC Emissions

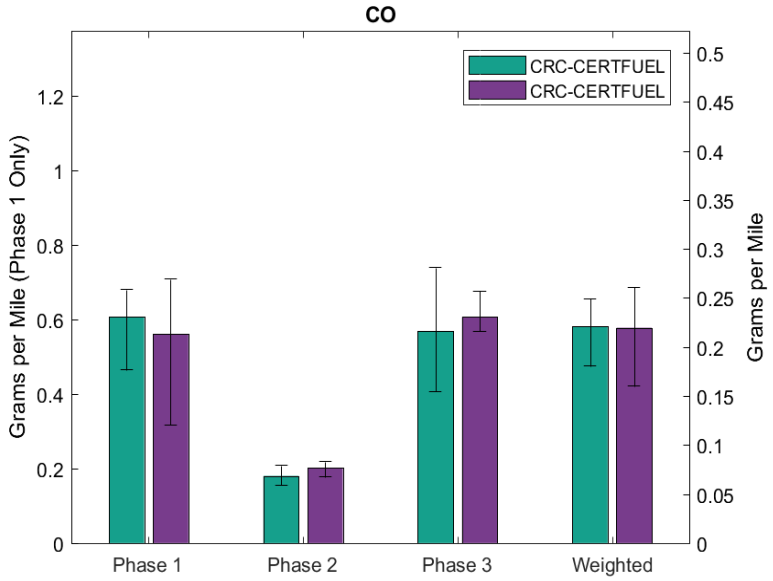


Figure 9-30 Vehicle B Baseline CO Emissions

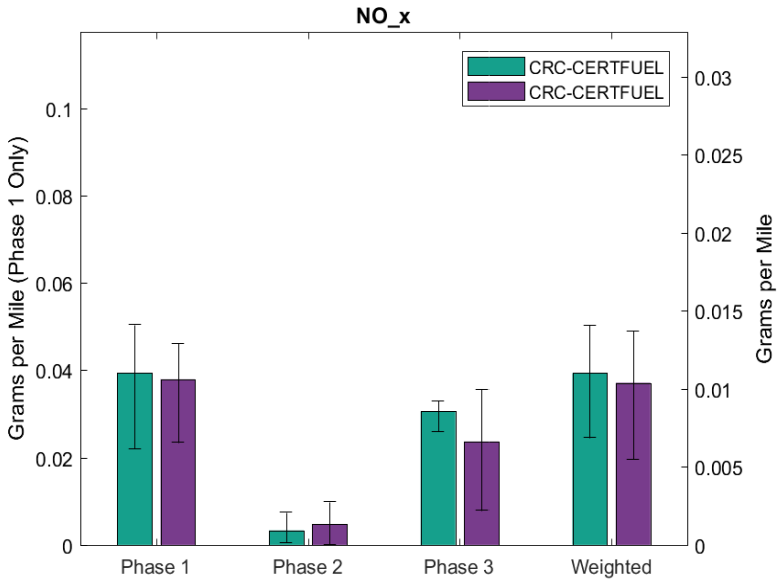


Figure 9-31 Vehicle B Baseline NO_x Emissions

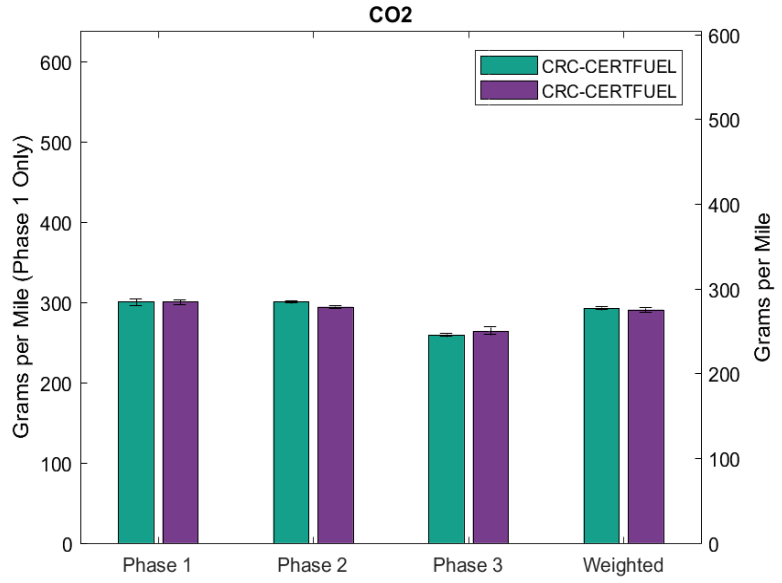


Figure 9-32 Vehicle B Baseline CO_2 Emissions

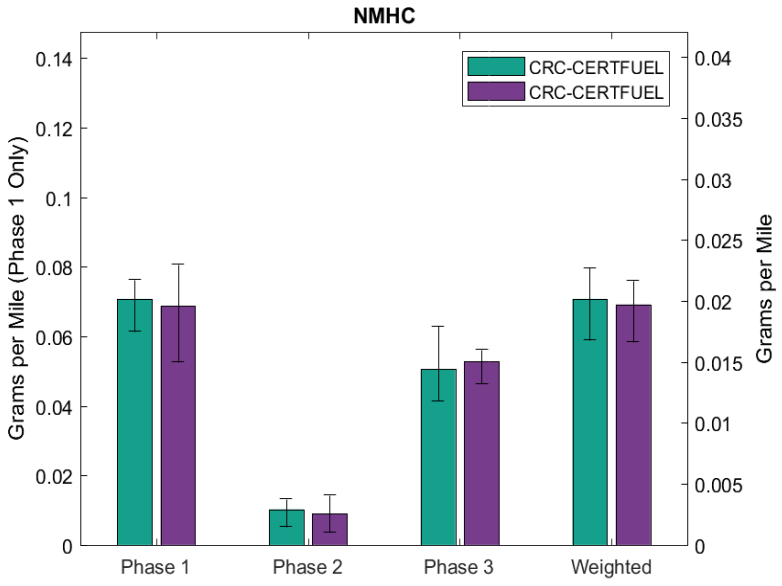


Figure 9-33 Vehicle B Baseline NMHC Emissions

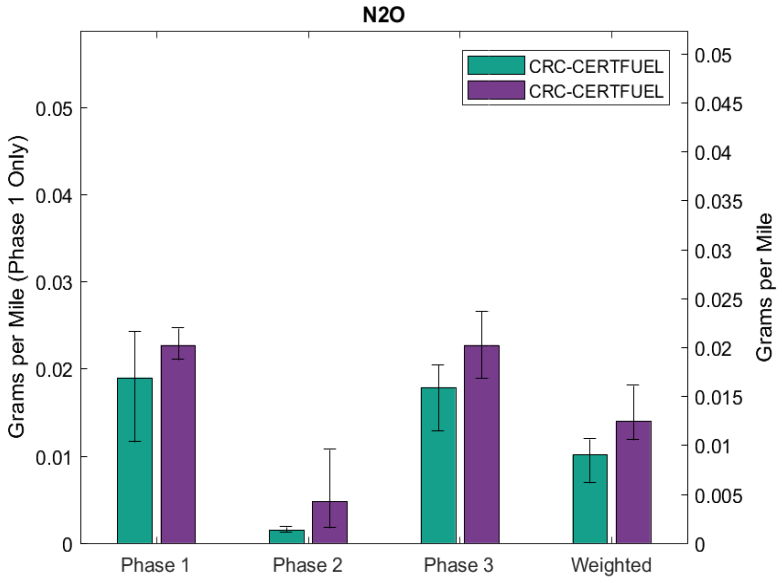


Figure 9-34 Vehicle B Baseline N_2O Emissions

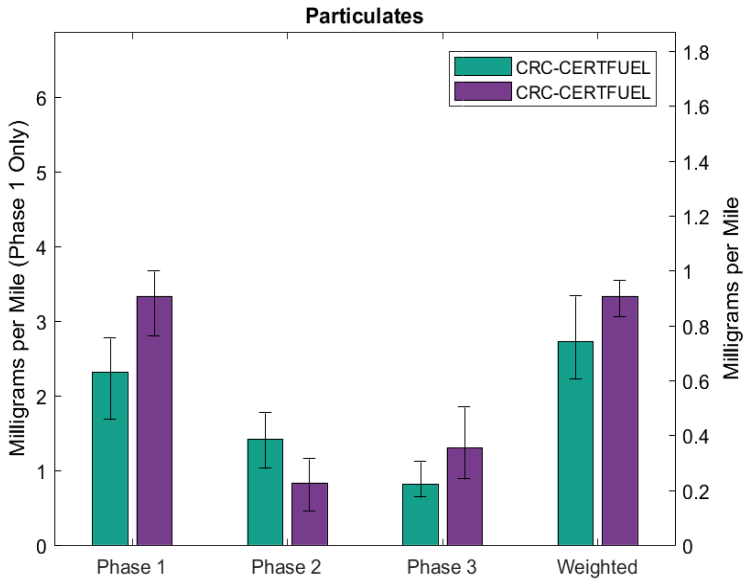


Figure 9-35 Vehicle B Baseline Particulate Emissions

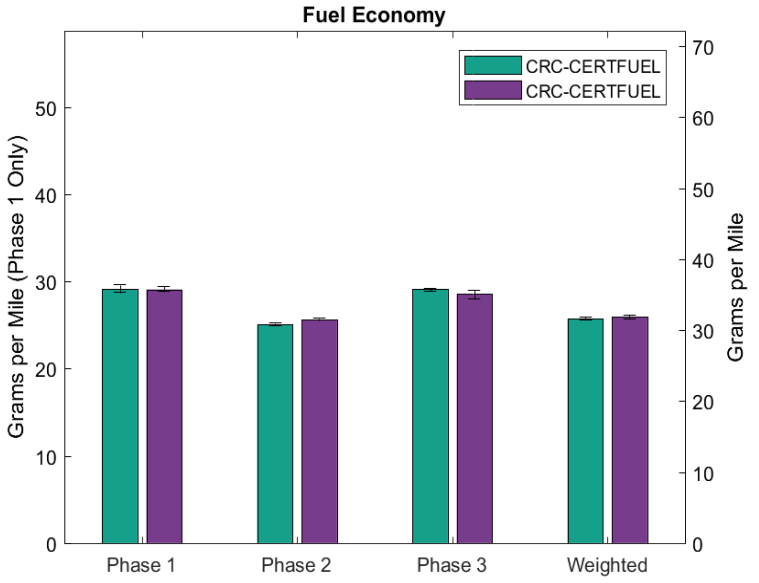


Figure 9-36 Vehicle B Baseline Fuel Economy

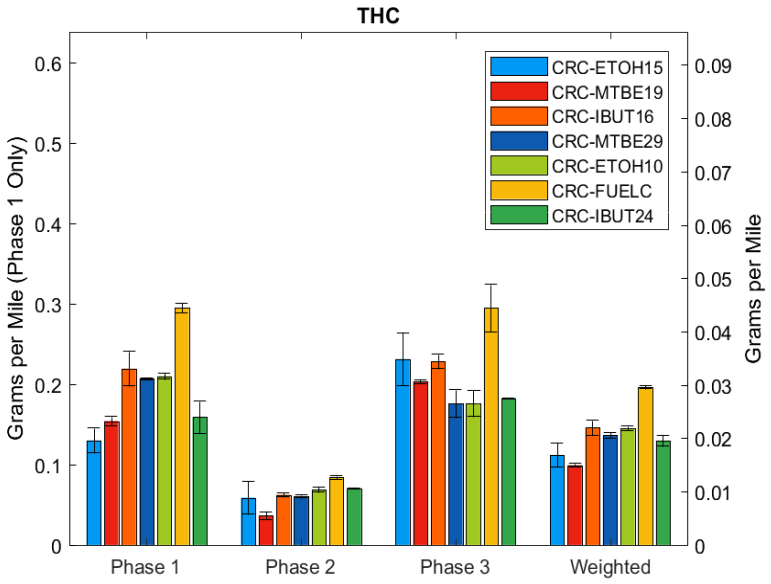


Figure 9-37 Vehicle B Iterative THC Emissions

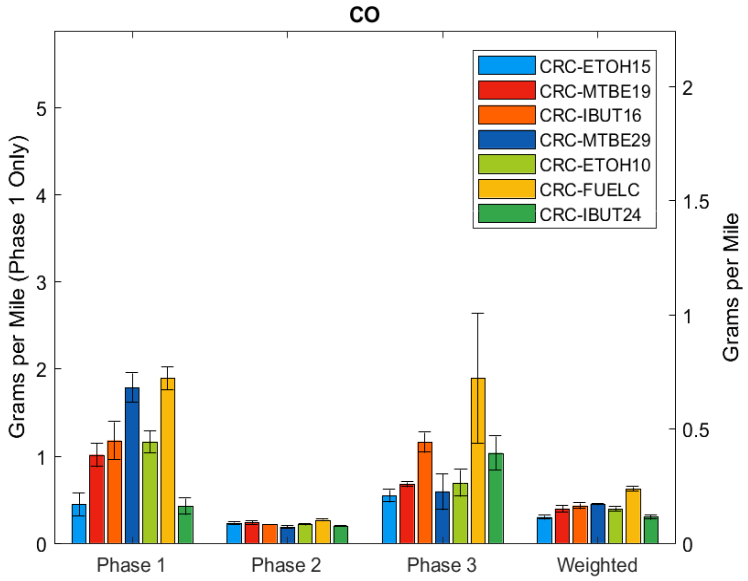


Figure 9-38 Vehicle B Iterative CO Emissions

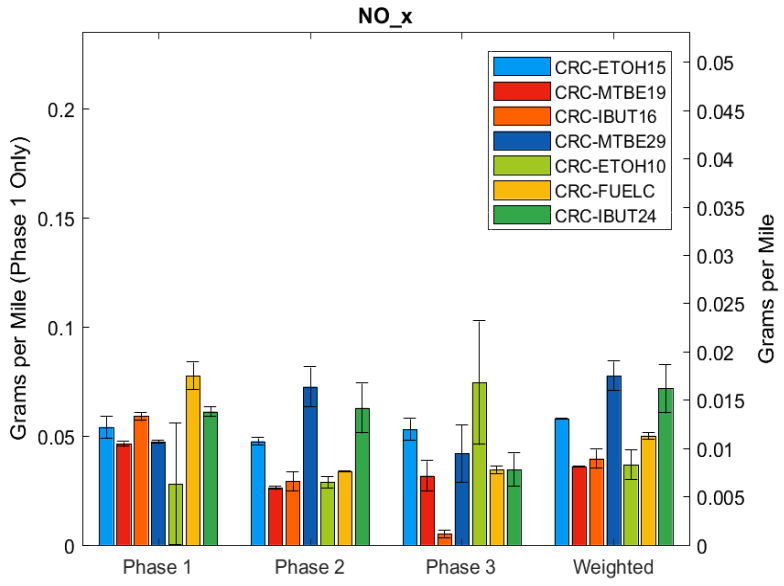


Figure 9-39 Vehicle B Iterative NO_x Emissions

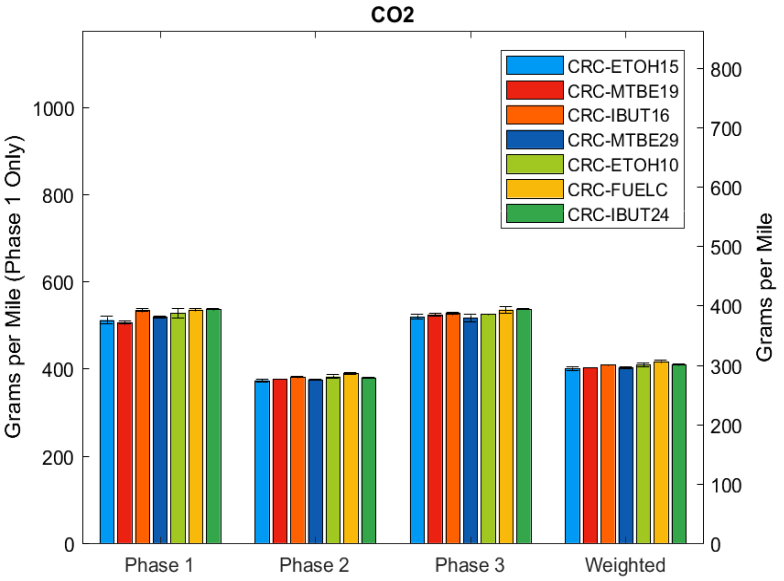


Figure 9-40 Vehicle B Iterative CO_2 Emissions

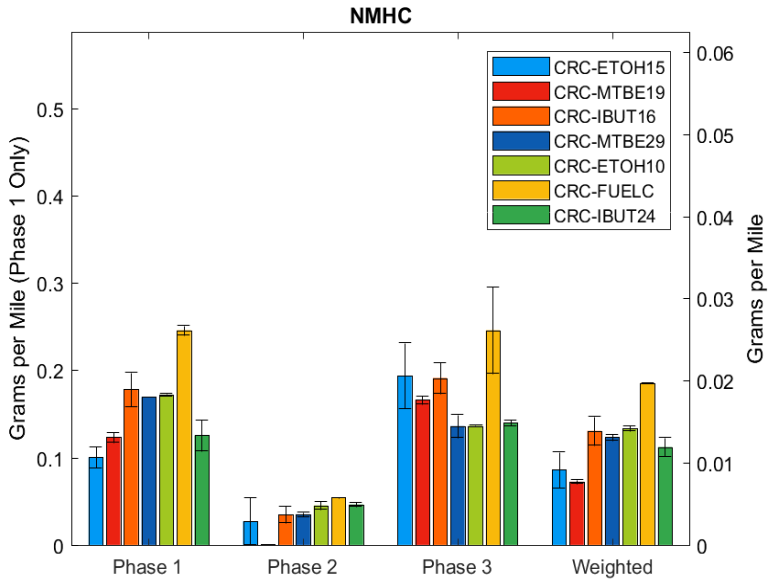


Figure 9-41 Vehicle B Iterative NMHC Emissions

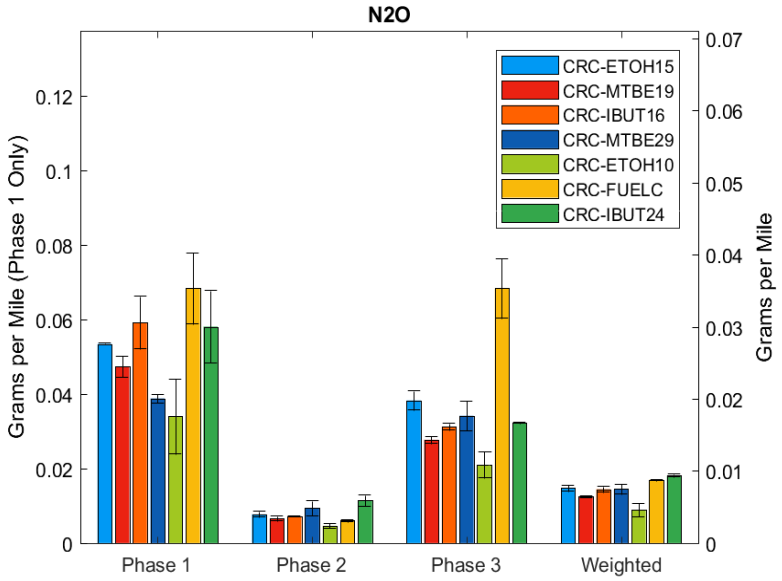


Figure 9-42 Vehicle B Iterative N_2O Emissions

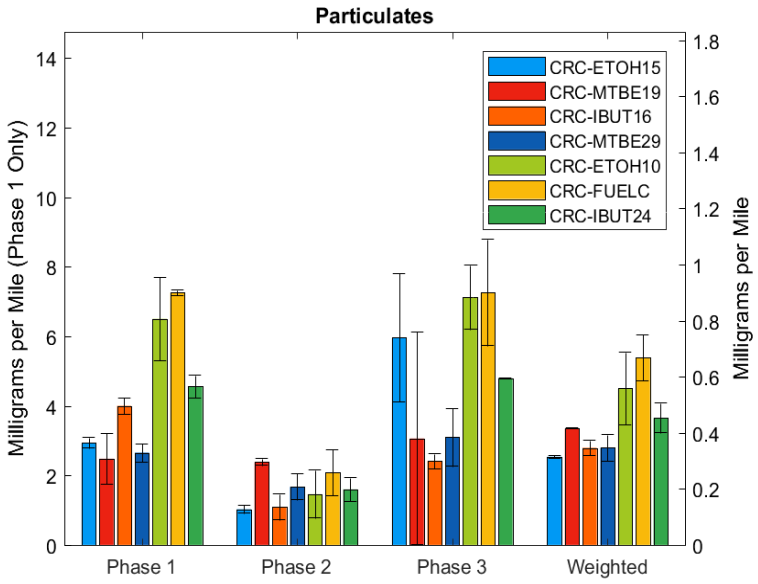


Figure 9-43 Vehicle B Iterative Particulate Matter Emissions

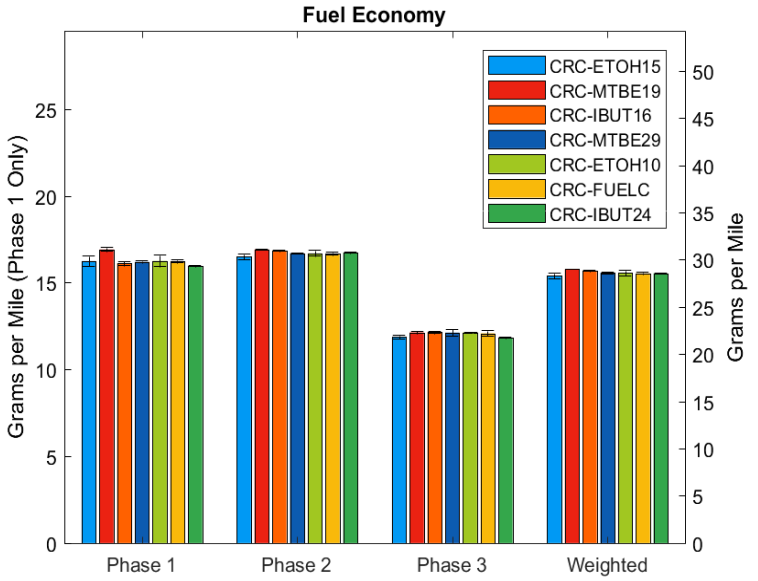


Figure 9-44 Vehicle B Iterative Fuel Economy

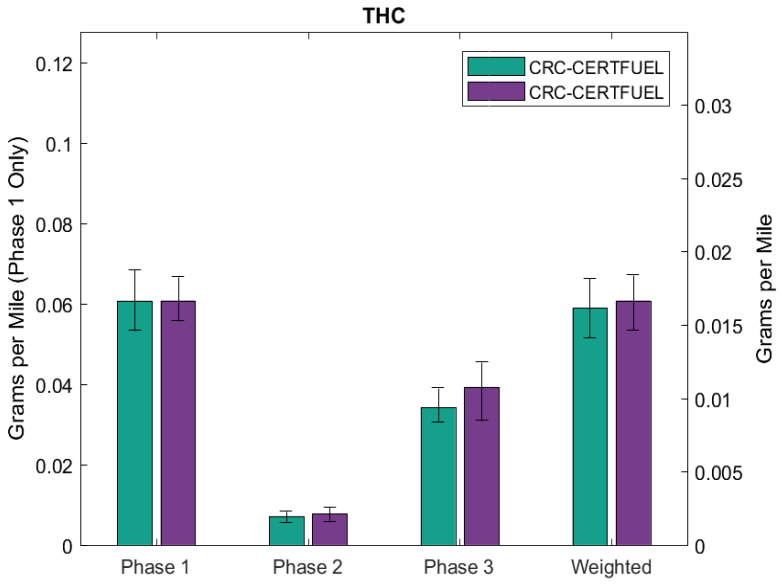


Figure 9-45 Vehicle C Baseline THC Emissions

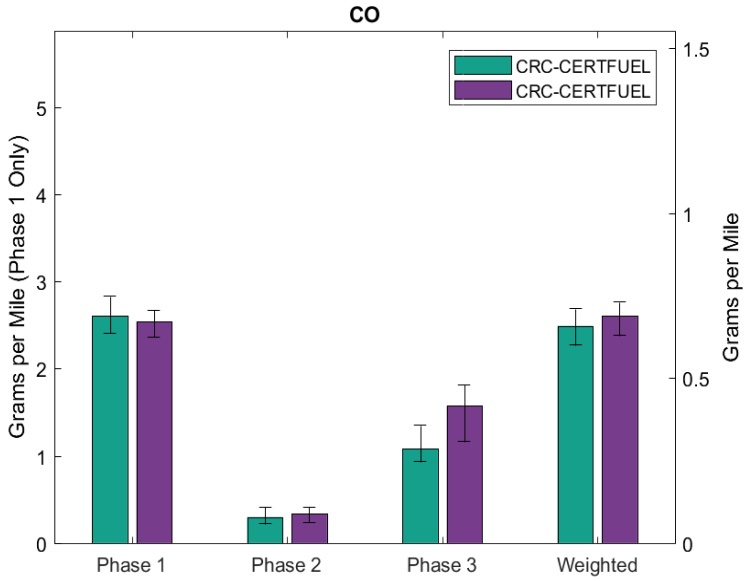


Figure 9-46 Vehicle C Baseline CO Emissions

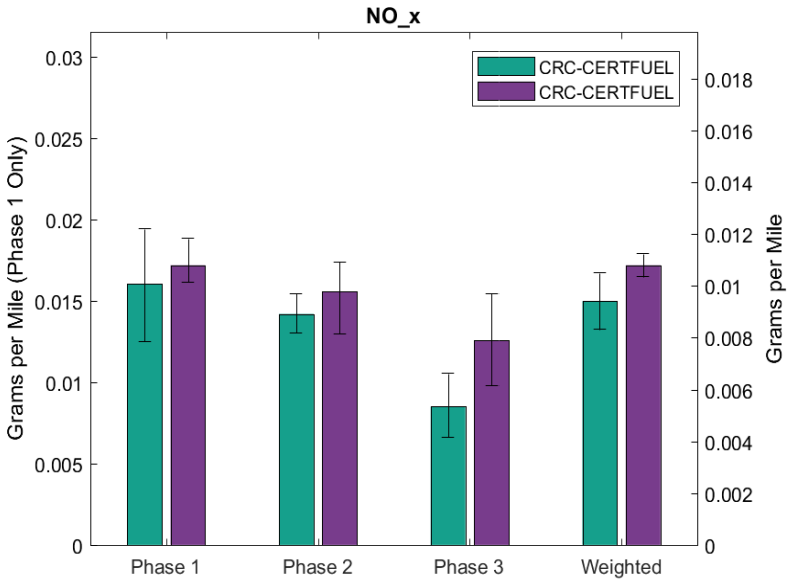


Figure 9-47 Vehicle C Baseline NO_x Emissions

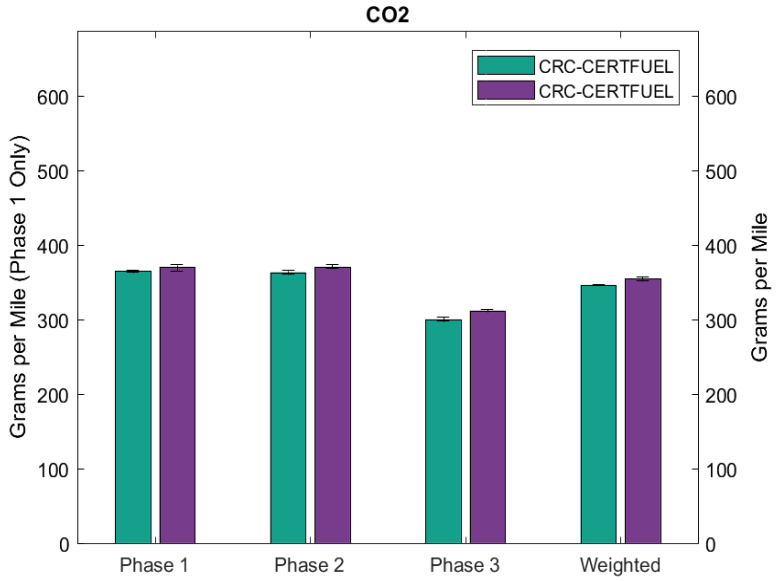


Figure 9-48 Vehicle C Baseline CO_2 Emissions

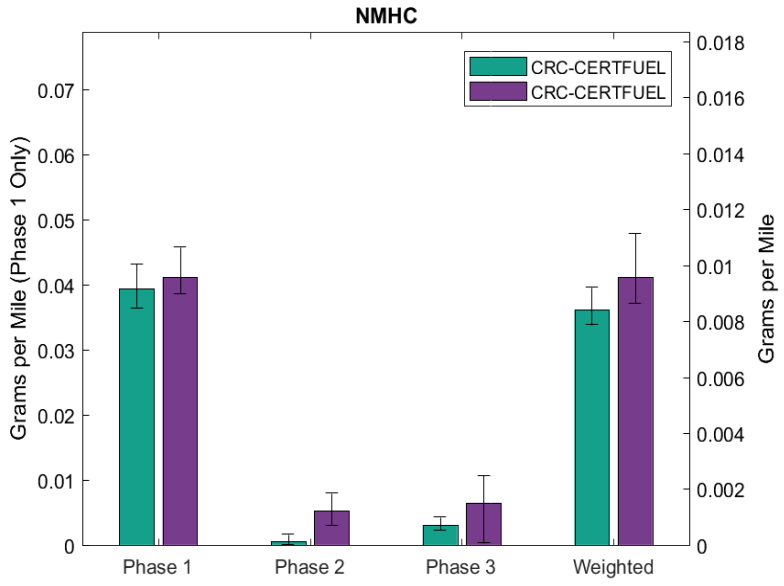


Figure 9-49 Vehicle C Baseline NMHC Emissions

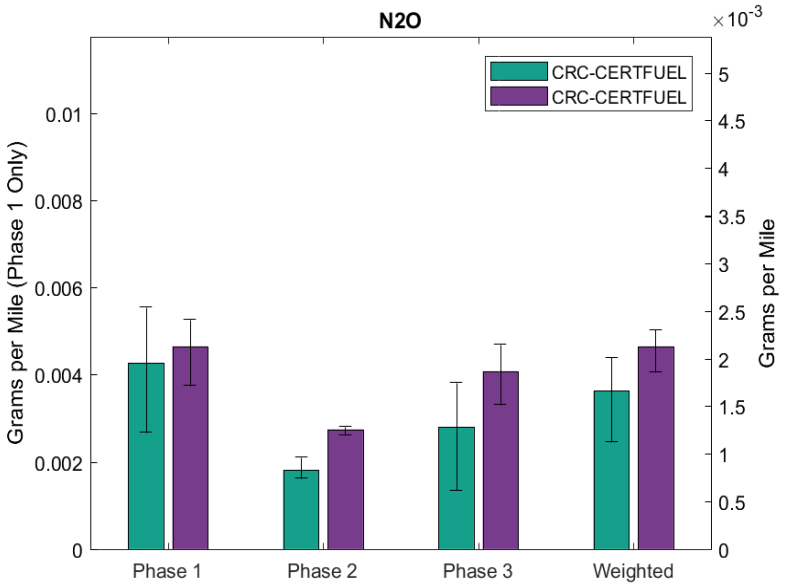


Figure 9-50 Vehicle C Baseline N_2O Emissions

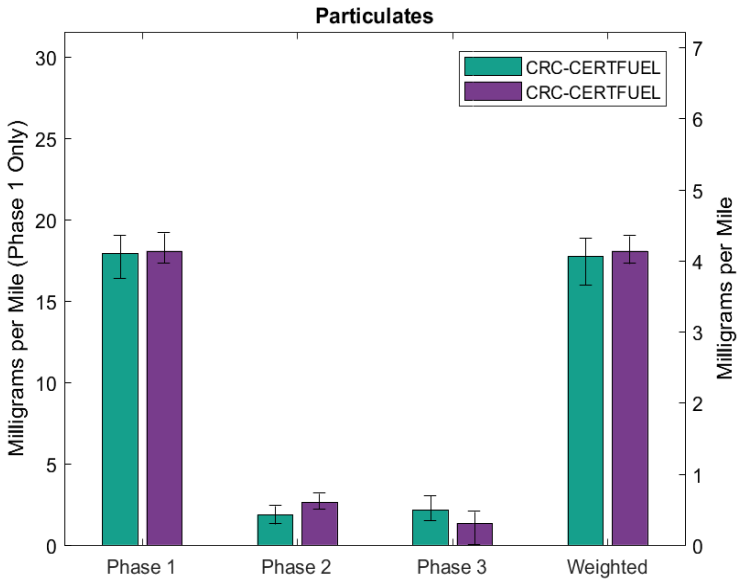


Figure 9-51 Vehicle C Baseline Particulate Matter Emissions

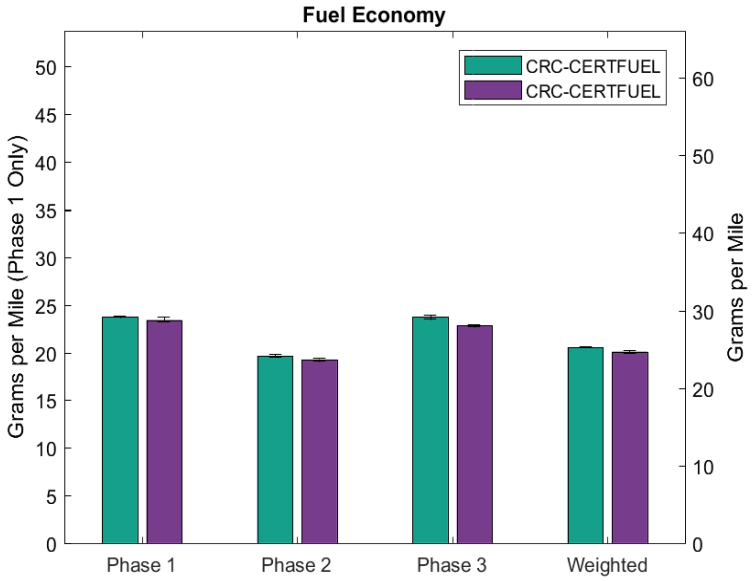


Figure 9-52 Vehicle C Baseline Fuel Economy

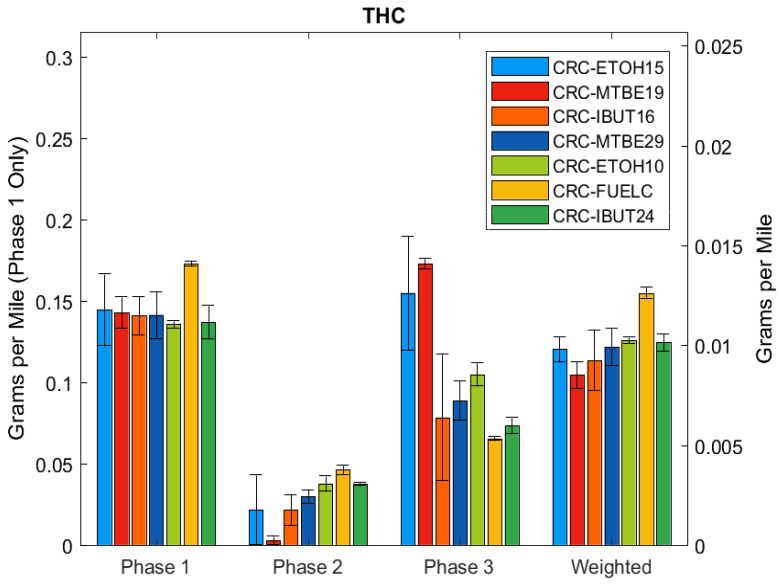


Figure 9-53 Vehicle C Iterative THC Emissions

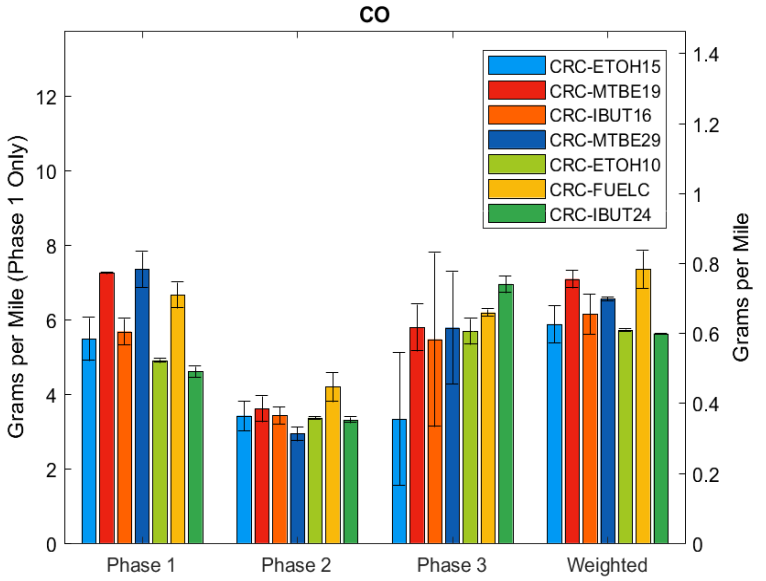


Figure 9-54 Vehicle C Iterative CO Emissions

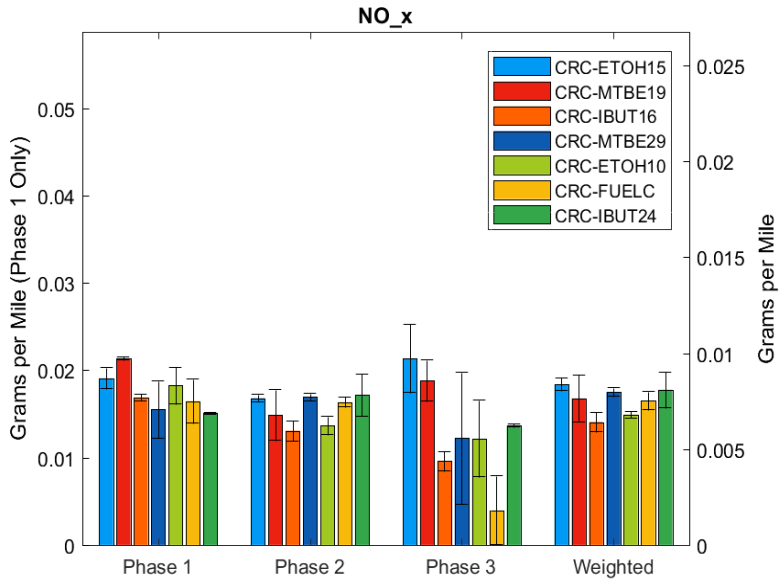


Figure 9-55 Vehicle C Iterative NO_x Emissions

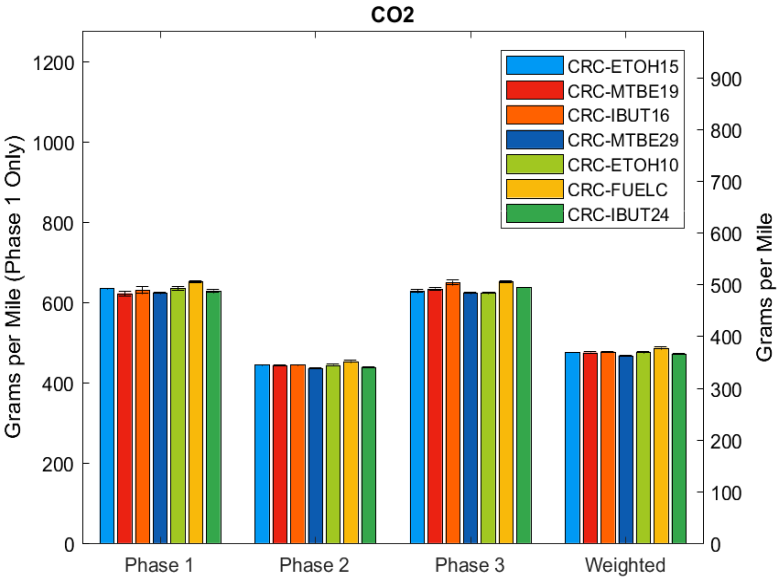


Figure 9-56 Vehicle C Iterative CO_2 Emissions

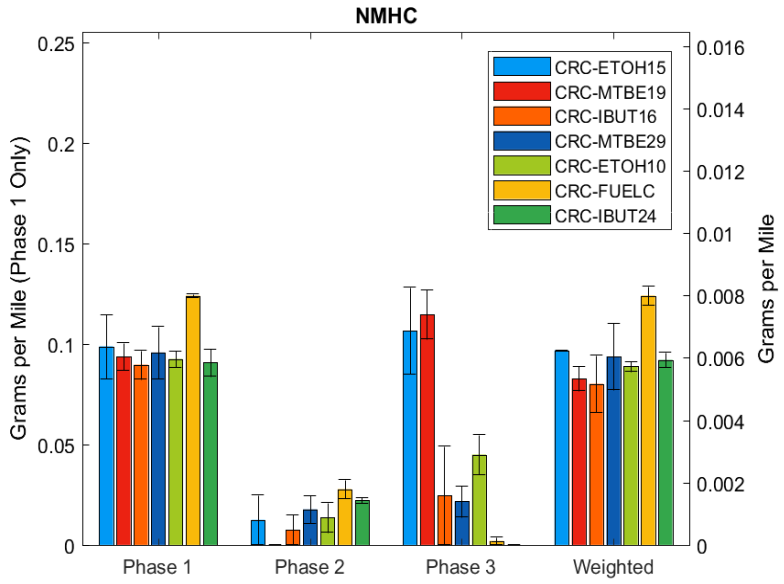


Figure 9-57 Vehicle C Iterative NMHC Emissions

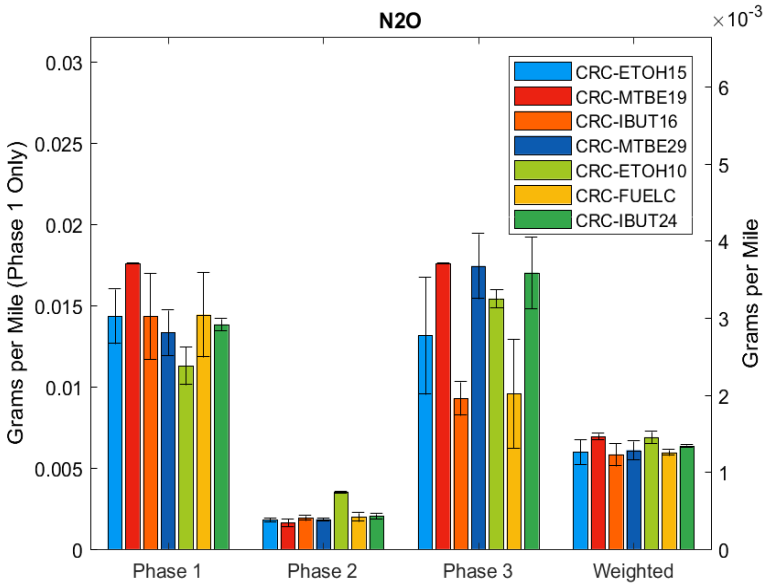


Figure 9-58 Vehicle C Iterative N_2O Emissions

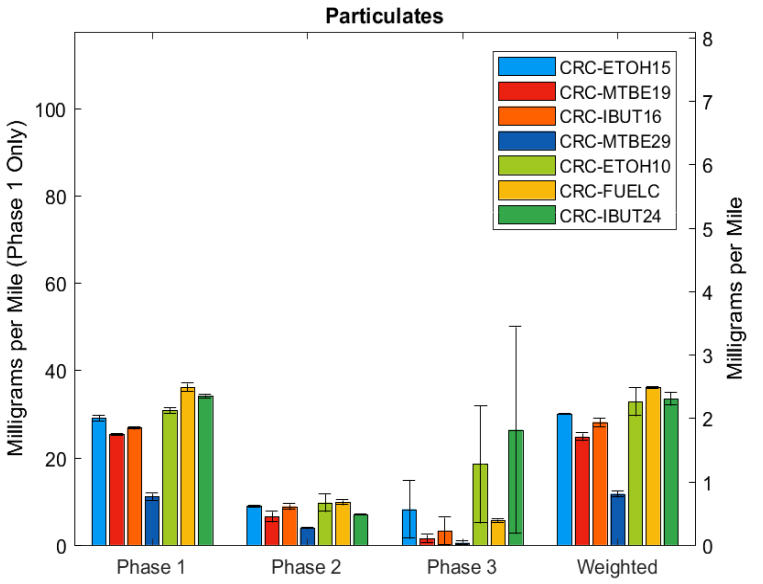


Figure 9-59 Vehicle C Iterative Particulate Matter Emissions

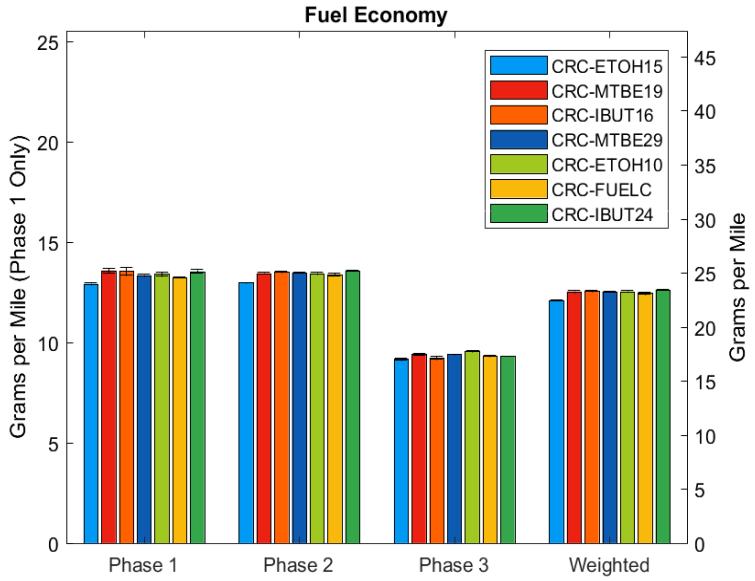


Figure 9-60 Vehicle C Iterative Fuel Economy

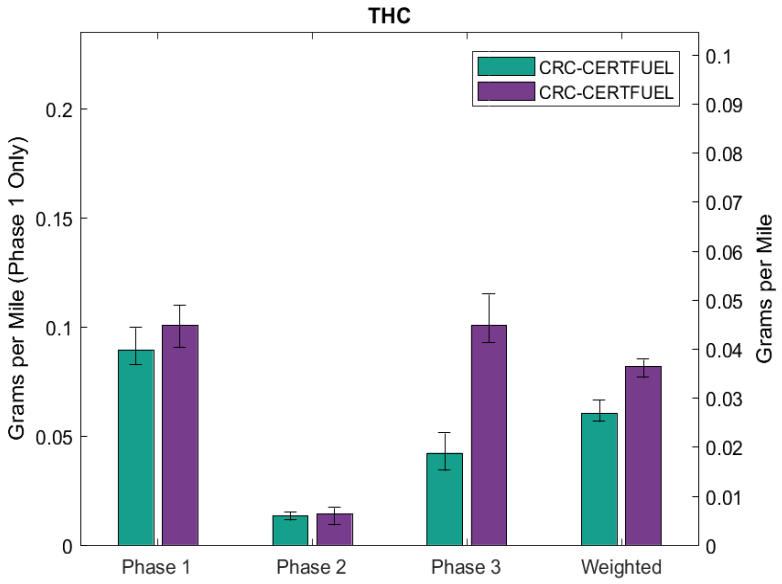


Figure 9-61 Vehicle D Baseline THC Emissions

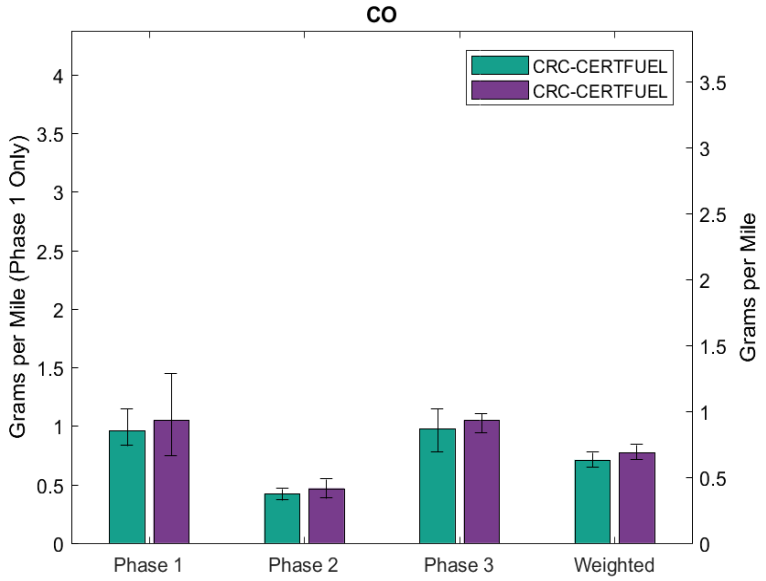


Figure 9-62 Vehicle D Baseline CO Emissions

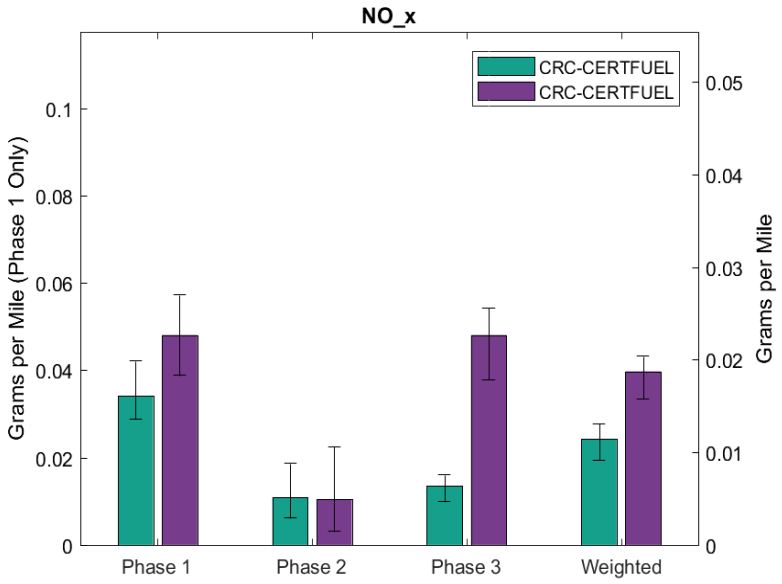


Figure 9-63 Vehicle D Baseline NO_x Emissions

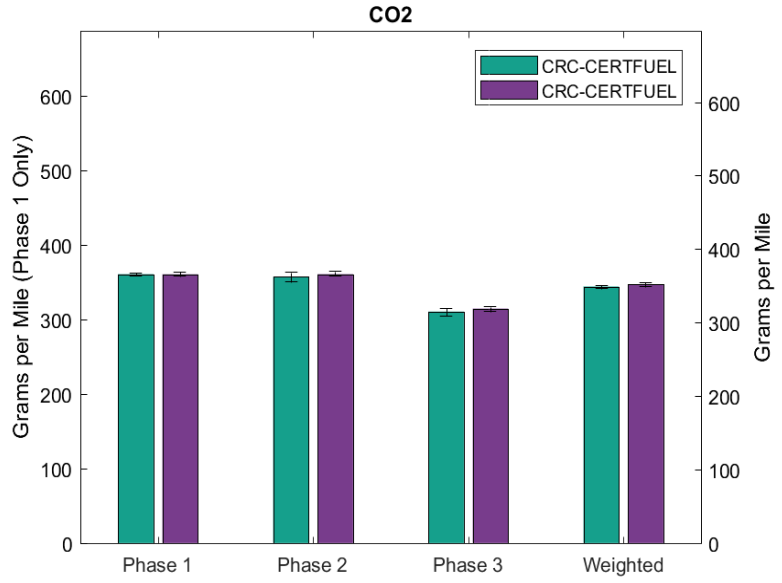


Figure 9-64 Vehicle D Baseline CO_2 Emissions

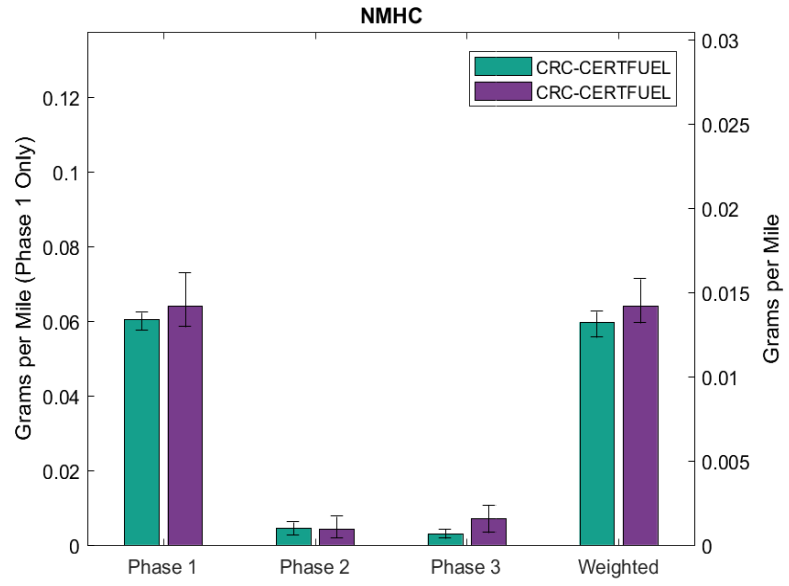


Figure 9-65 Vehicle D Baseline NMHC Emissions

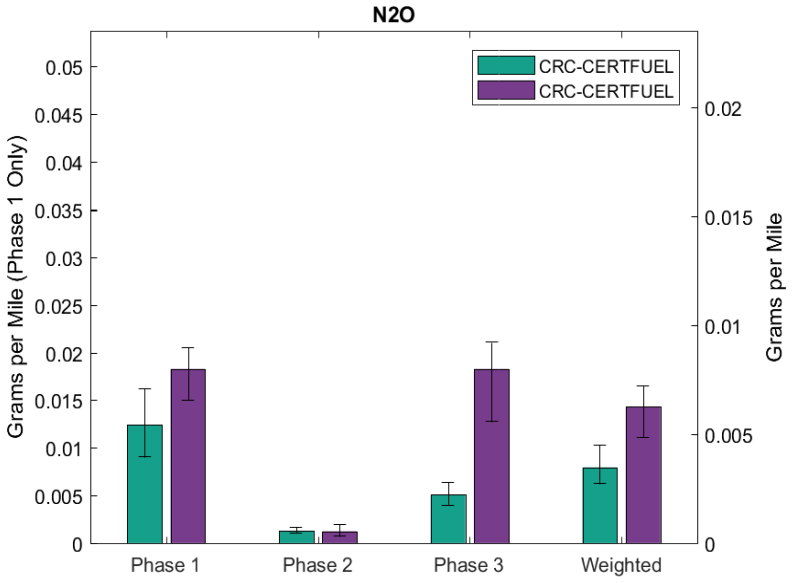


Figure 9-66 Vehicle D Baseline N_2O Emissions

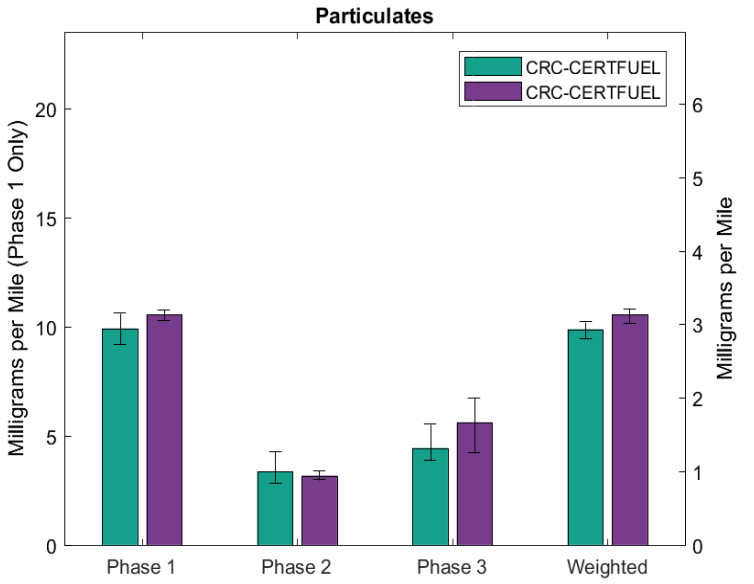


Figure 9-67 Vehicle D Baseline Particulate Matter Emissions

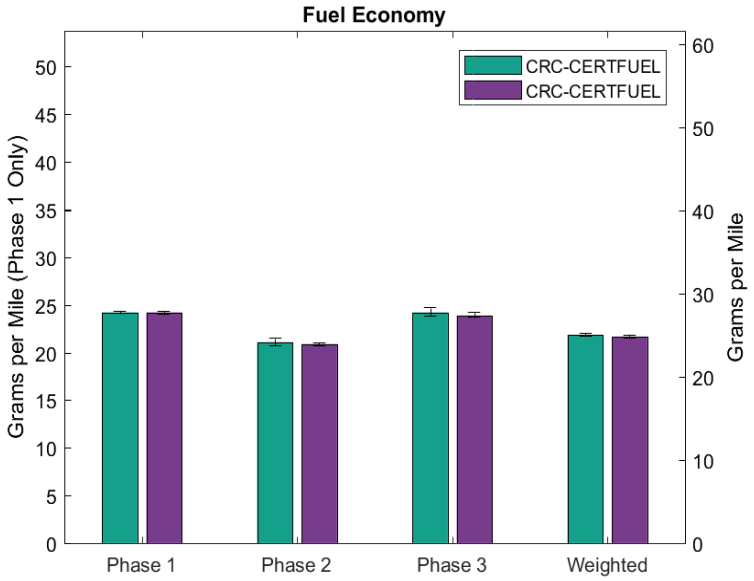


Figure 9-68 Vehicle D Baseline Fuel Economy

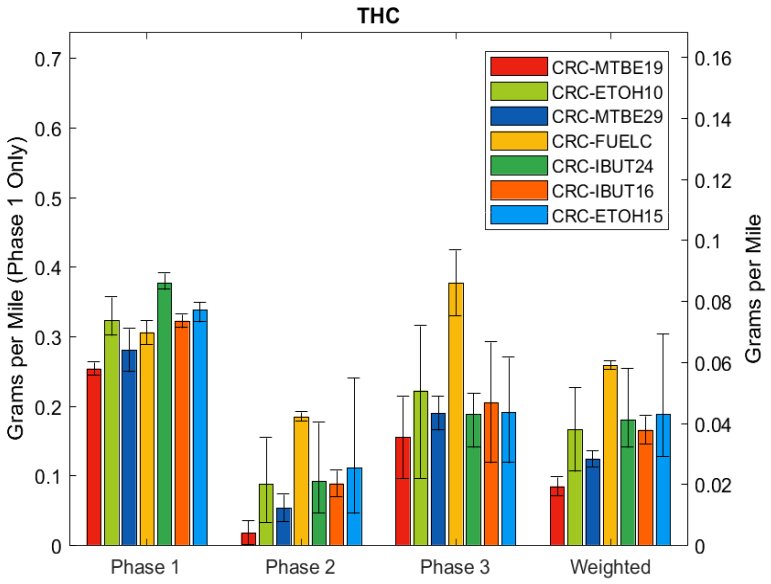


Figure 9-69 Vehicle D Iterative THC Emissions

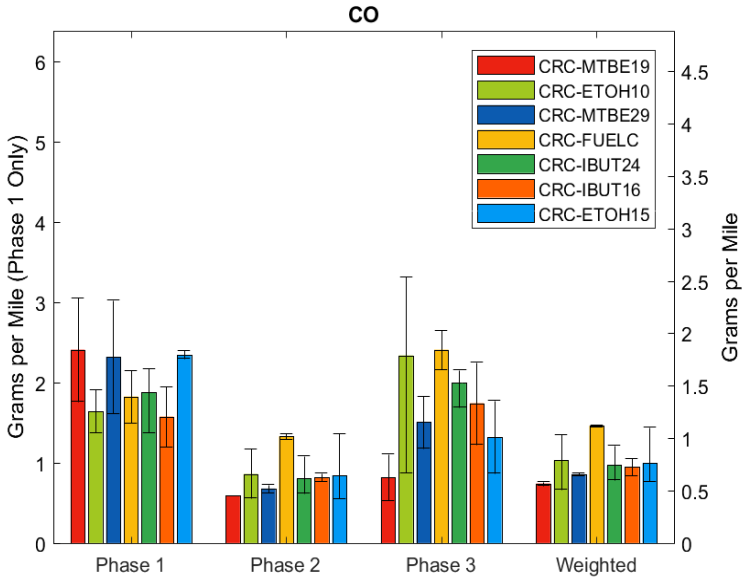


Figure 9-70 Vehicle D Iterative CO Emissions

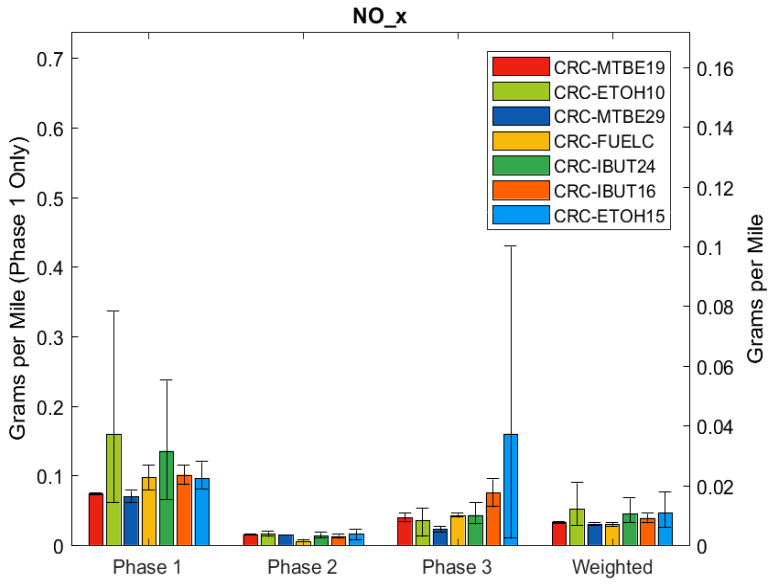


Figure 9-71 Vehicle D Iterative NO_x Emissions

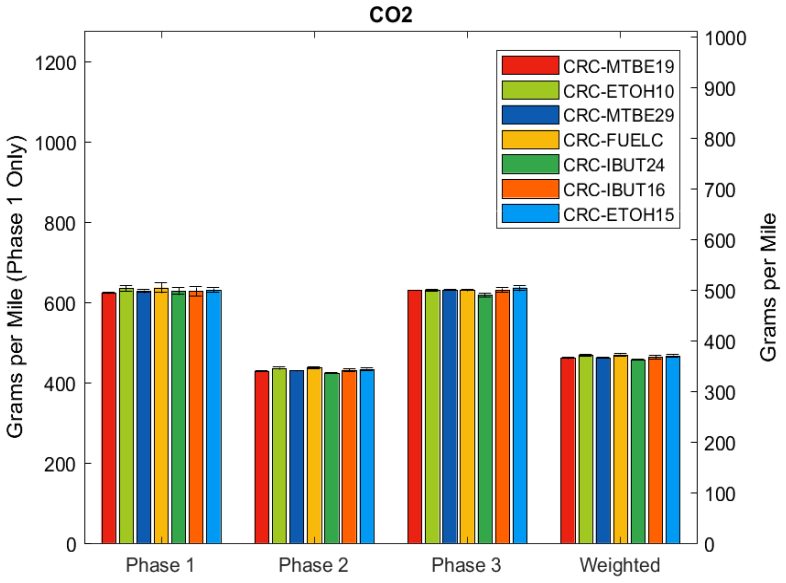


Figure 9-72 Vehicle D Iterative CO_2 Emissions

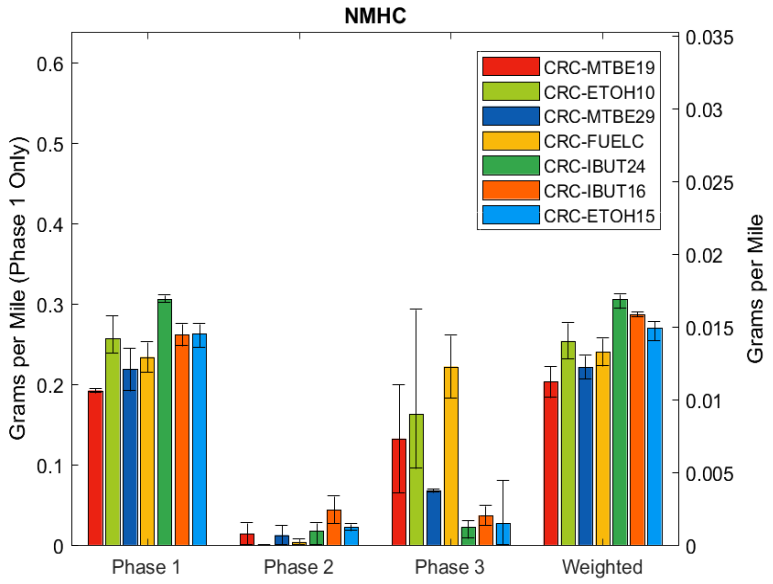


Figure 9-73 Vehicle D Iterative NMHC Emissions

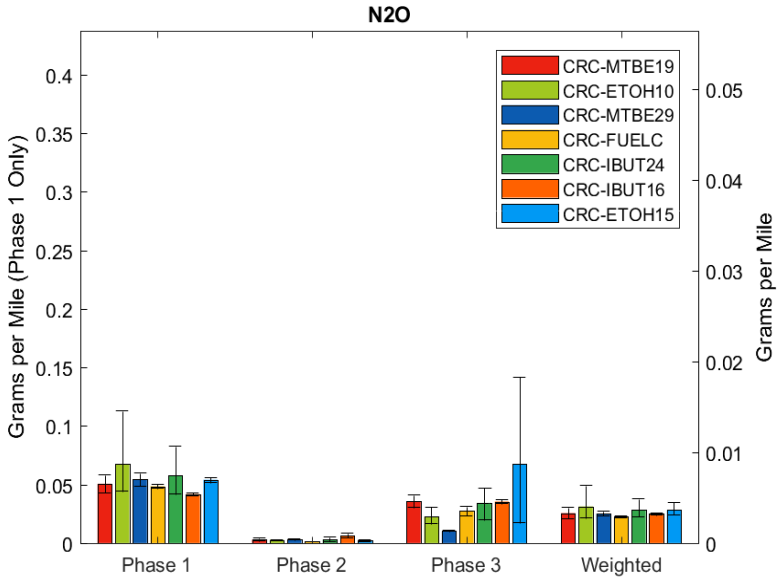


Figure 9-74 Vehicle D Iterative N_2O Emissions

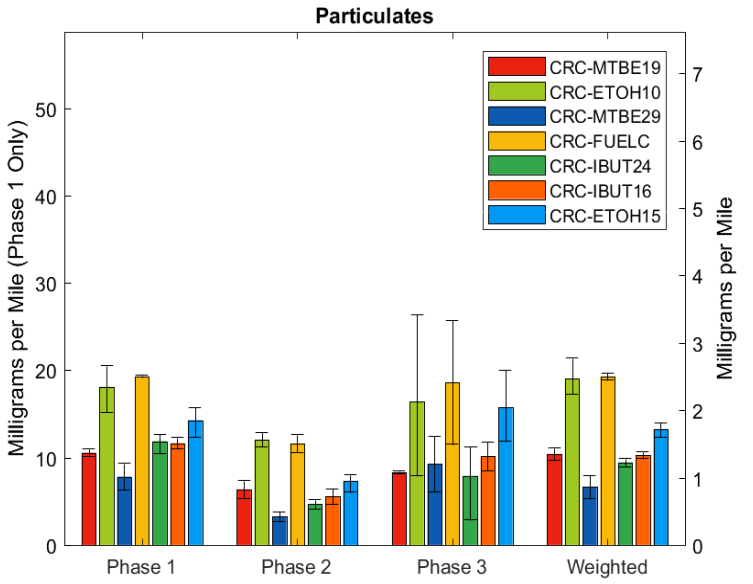


Figure 9-75 Vehicle D Iterative Particulate Matter Emissions

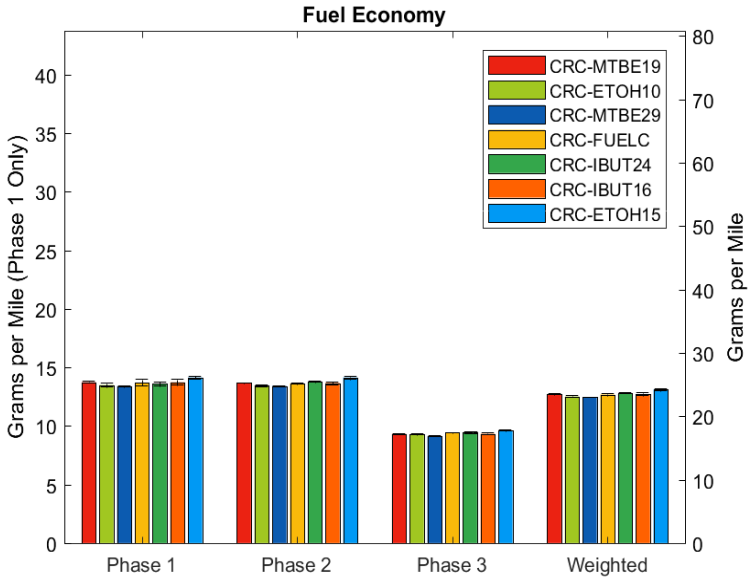


Figure 9-76 Vehicle D Iterative Fuel Economy

9.4.Filter Weight Gains

The individual net, weight-gains are shown in Table 9-1 through Table 9-4 for all vehicles. The values represent the difference between the buoyancy corrected pre-weight and post-weight.

Table 9-1 Vehicle A Filter Weight Gain

Vehicle A PM filter loading	Phase 1	Phase 2	Phase 3
	µg	µg	µg
Baseline 1	174.7	119.5	58.1
Baseline 2	175.6	88.5	49
Baseline 3	181.3	80.8	61.7
Wk1 1	72.8	100.6	12.7
Wk1 2	69.6	108.8	20.1
Wk1 3	74.7	121.2	23
Wk2 1	91.4	73.2	25.1
Wk2 2	73	76.4	21.2
Wk2 3	78.7	58.9	26.1
Wk3 1	57.6	42.7	20.7
Wk3 2	51.1	37.8	17.3
Wk3 3	-	-	-
Wk4 1	82.9	53.6	6.4
Wk4 2	72.9	46	24.8
Wk4 3	-	-	-
Wk5 1	47.4	20.5	20.5
Wk5 2	40.3	35.8	18.5
Wk5 3	44.5	37.3	19.9
Wk6 1	71.2	47.4	9.2
Wk6 2	58	37.5	14.6
Wk6 3	59.3	36.3	18.2
Wk7 1	70.2	41.1	24.9
Wk7 2	47.6	34.4	26.4
Wk7 3	-	-	-
Rerun Wk1 1	53.4	29.3	5.6
Rerun Wk1 2	49.1	23.6	1.7
Rerun Wk1 3	43	38.4	4.4
Baseline 1	175.9	48	25.3
Baseline 2	149.5	50.4	23.5
Baseline 3	190	63.9	29.2

Table 9-2 Vehicle B Filter Weight Gain

Vehicle B PM filter loading	Phase 1	Phase 2	Phase 3
	µg	µg	µg
Baseline 1	83.8	12.1	6.5
Baseline 2	90.1	16.8	9.9
Baseline 3	54.8	13.8	6.1
Wk1 1	29.7	8.8	10.4
Wk1 2	32.9	11.2	5.5
Wk1 3	-	-	-
Wk2 1	18.8	24.1	8.1
Wk2 2	33.5	21.6	0
Wk2 3	-	-	-
Wk3 1	40.2	14.1	2.9
Wk3 2	45.2	6.9	3.5
Wk3 3	-	-	-
Wk4 1	26.2	12.7	5.3
Wk4 2	31.5	20.2	3.1
Wk4 3	-	-	-
Wk5 1	58.4	7.6	11
Wk5 2	82.4	20.8	8.2
Wk5 3	-	-	-
Wk6 1	78.1	13.8	7.6
Wk6 2	77.6	26.7	11.7
Wk6 3	-	-	-
Wk7 1	52.8	18.9	6.4
Wk7 2	46	12.3	6.4
Wk7 3	-	-	-
Baseline 1	119.3	4.3	16.3
Baseline 2	114.5	8.4	7.8
Baseline 3	91.2	11	10.4

Table 9-3 Vehicle C Filter Weight Gain

Vehicle C PM filter loading	Phase 1	Phase 2	Phase 3
	µg	µg	µg
Baseline 1	589.8	17.1	16.6
Baseline 2	613.7	19.3	11.3
Baseline 3	528.8	10.6	14.4
Wk1 1	299.6	49.1	10.9
Wk1 2	313.5	46.8	1.1
Wk1 3	-	-	-
Wk2 1	269.3	28.3	0.4
Wk2 2	258	40	1.7
Wk2 3	-	-	-
Wk3 1	288.6	51.3	4.7
Wk3 2	282	43.9	0
Wk3 3	-	-	-
Wk4 1	127	21.4	0.8
Wk4 2	110.2	20.2	0
Wk4 3	-	-	-
Wk5 1	338.6	63.9	24.1
Wk5 2	314.8	41	3.8
Wk5 3	-	-	-
Wk6 1	370.8	55.2	4.4
Wk6 2	393.3	49.5	3.8
Wk6 3	-	-	-
Wk7 1	360.4	37.2	37.2
Wk7 2	362.7	38.1	2
Wk7 3	-	-	-
Baseline 1	616.7	17.8	14.4
Baseline 2	570.9	19.6	0.2
Baseline 3	557.1	25.4	15.5

Table 9-4 Vehicle D Filter Weight Gain

Vehicle D PM filter loading	Phase 1	Phase 2	Phase 3
	µg	µg	µg
Baseline 1	349.3	29.4	41.4
Baseline 2	296.7	29.3	51.4
Baseline 3	323	44.7	37.9
Wk1 1	118.9	54.6	11.9
Wk1 2	109.6	74.8	11.3
Wk1 3	-	-	-
Wk2 1	199.7	114.1	20.8
Wk2 2	219	129.4	36.8
Wk2 3	164.9	122.4	11
Wk3 1	101.6	39	17.4
Wk3 2	67.6	27.6	8.6
Wk3 3	-	-	-
Wk4 1	209.6	108.3	35.9
Wk4 2	208.7	128	16.1
Wk4 3	-	-	-
Wk5 1	134.7	48.5	13.5
Wk5 2	113.8	52.9	16
Wk5 3	139	42.2	4.1
Wk6 1	134	47.9	16.7
Wk6 2	118.2	65.2	12
Wk6 3	-	-	-
Wk7 1	133.9	81.4	28.2
Wk7 2	159.9	61.1	21.5
Wk7 3	168.4	79.3	16.6
Baseline 1	350	32.7	41.4
Baseline 2	335	35.6	65.5
Baseline 3	350.8	31.2	57