CRC Report No. E-94-1

EVALUATION AND INVESTIGATION OF GASEOUS AND PARTICULATE EMISSIONS ON SIDI IN-USE VEHICLES WITH HIGHER ETHANOL BLEND FUELS

June 2014

COORDINATING RESEARCH COUNCIL, INC.
5755 NORTH POINT PARKWAY SUITE 265 · ALPHARETTA, GA 30022

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CRC Project E-94-1

FINAL REPORT

SwRI® Project No. 03.17589

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FOREWORD

This work was funded by the Coordinating Research Council (CRC), Inc. The Southwest Research Institute® Project Manager was Mr. Peter Morgan, Senior Research Engineer, Light Duty Vehicle Emissions. Technical staff members who contributed to this work were Mr. Peter Lobato, Engineer, Light Duty Vehicle Emissions; Kevin Whitney, Manager, Light Duty Vehicle Emissions; Dr. Imad Abdul-Khalek, Sr. Program Manager, Particle Science; Mr. Vinay Premnath, Research Engineer, Particle Science; Ms. Svitlana Kroll, Sr. Research Scientist, Emissions R&D; and Mr. Brent Shoffner, Fuels and Driveline Lubricants Research. Mr. Michael Viola from General Motors and Mr. Scott Mason from Phillips 66 served as the CRC technical contacts for this project, and Dr. Christopher J. Tennant from CRC represented the project sponsor, CRC.

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LIST OF ACRONYMNS

CAFE .....Corporate Average Fuel Economy
CARB.....California Air Resources Board
CPC.....Condensation Particle Counter
CRC.....Coordinating Research Council
CVS.....Constant Volume Sampling
DBE.....Double Bond Equivalent
DOE .....Department of Energy
DTC.....Diagnostic Trouble Code
EC .....Elemental Carbon
ECD.....Electron Capture Detector
EEPS .....Engine Exhaust Particle Sizer
EISA.....Energy Independence and Security Act
EPA.....Environmental Protection Agency
FID .....Flame Ionization Detector
GHG.....Greenhouse Gas
MON .....Motor Octane Number
MSS.....Microsoot Sensor
NA.....Naturally Aspirated
NMHC.....Non-Methane Hydrocarbon
OC.....Organic Carbon
PM.....Particulate Matter
PMI .....Particulate Mass Index
PMP.....Particulate Measurement Program
PN .....Particle Number
RON .....Research Octane Number
RVP.....Reid Vapor Pressure
SIDI.....Spark-Ignited Direct-Injection
SPNMS .....Solid Particle Number Measuring System
SPSS.....Solid Particle Sampling System
SRC.....Standard Road Cycle
SwRI .....Southwest Research Institute
THC.....Total Hydrocarbon
TOR.....Thermal/Optical Reflectance
UDC .....Unified Drive Cycle
VIN .....Vehicle Identification Number

EXECUTIVE SUMMARY

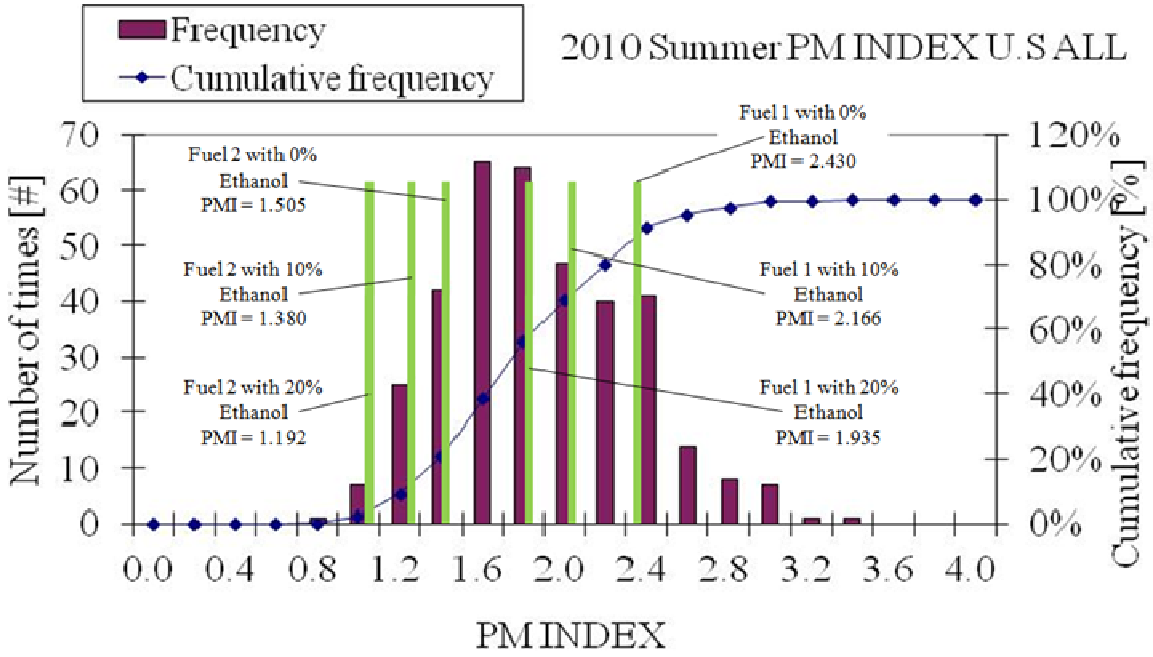
The recently adopted Corporate Average Fuel Economy (CAFE) and Greenhouse Gas (GHG) emissions standards for model year 2017-2025 light-duty vehicles are significantly more stringent than those applicable to current production. This has influenced manufacturers to develop new engine technologies, such as spark ignited direct injection (SIDI) gasoline engines, to improve fuel economy. Currently many manufacturers are producing both naturally aspirated (NA) and turbo-charged SIDI engines in light-duty vehicles and are meeting both gaseous and particulate matter (PM) emissions standards with E0 certification fuel. Europe is implementing, for the first time, a particulate number (PN) standard starting with EURO VI emissions regulations. There is an interest to investigate the impacts of various fuel parameters on in-use vehicles with SIDI engines in terms of gaseous (regulated and unregulated), PM and PN emissions.

The 2007 Energy Independence and Security Act (EISA) mandates the growth of significant volumes of renewable fuels in the U.S. transportation sector, possibly resulting in large volumes of mid-level ethanol blends (such as 15% or 20% ethanol) throughout the U.S. fuel supply in the future. Given the octane number properties of ethanol, there is interest in understanding how increasing the ethanol content and octane number rating of a gasoline fuel affects a vehicle's engine efficiency, fuel economy and ability to meet greenhouse gas, particulate mass and particle number emissions standards.

This project, Coordinating Research Council (CRC) E-94-1, was conducted by Southwest Research Institute (SwRI) in order to investigate variations in regulated gaseous, greenhouse gas, PM and PN emissions from vehicles equipped with SIDI engines over a range of fuel properties. The intention of this investigation was to be used as a pilot study to guide future work.

Two ethanol-free gasoline fuels were selected with Particulate Mass Indices (PMI) which span a wide range of those calculated based on recent surveys of the U.S. fuel supply, as seen in Figure ES-1. These two fuels were splash blended with ethanol to produce fuels with ethanol concentrations of 0, 10% and 20%, (E0, E10, and E20, respectively), yielding six fuels total. The PM Indices for the ethanol blends made with the high PMI fuel (Fuel 1) ranged from 2.430 (E0) to 1.935 (E20), while those for the ethanol blends made with the low PMI fuel (Fuel 2) ranged from 1.505 (E0) to 1.192 (E20).

The test fleet included three modern vehicles equipped with SIDI engines and were deemed representative of the spectrum of models commonly available in the U.S. based on weight class and engine configuration. Table ES-1 shows an overview of the three vehicles used in this program. These vehicles are referred to as Vehicles A, B and C in the report.



Note: Unpublished data; Used with permission from Honda R&D

FIGURE ES-1. HISTOGRAM OF FUEL PMI IN UNITED STATES

TABLE ES-1. VEHICLES USED THROUGHOUT PROGRAM

Vehicle	2012 Volkswagen Jetta GLI	2013 Ford F150	2011 Chevrolet Equinox
Engine Type	2.0L Turbocharged I4	3.5L Turbocharged V6	2.4L Naturally Aspirated I4
Certification Group	EPA Tier 2 Bin 5; California: ULEV II	EPA Tier 2 Bin 5; California: not for sale	EPA Tier 2 Bin 4; California: ULEV qualified

These three vehicles were tested twice with each of the six splash-blended fuels over the LA92 drive cycle. During this drive cycle, NMHC, CO, NO_X, N_2O, elemental carbon, organic carbon, particulate mass, soot mass, particle size and fuel economy were determined. Since testing was limited, no statistical analysis was performed. Fuel blends were based on gasolines that span a wide range of PMI in the marketplace, with splash-blended addition of ethanol, to observe the effects; however because other fuel properties were not matched between blends, the effects cannot be attributed to PMI or any other property. More data are needed to draw conclusions about the emissions effects of a fuel's PMI, however a summary of observations from this study are as follows:

- Particulate emissions and some of the gaseous emissions changed to varying degrees on the vehicles when tested on the same E0 fuel at the beginning and end of the test sequence. An example of this shift is shown in Figure ES-2 for the measured soot mass emissions. Because Vehicle A showed a shift in long-term fuel trim (Figure ES-3), a possible explanation is that the vehicle conditioning procedure was not sufficient.

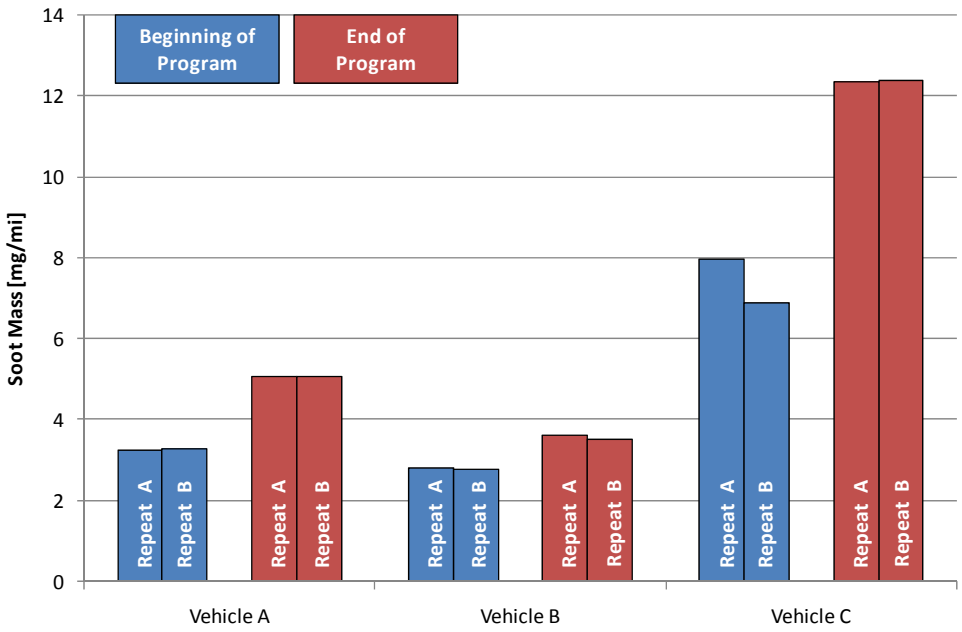


FIGURE ES-2. SHIFT IN SOOT MASS EMISSIONS BETWEEN BEGINNING AND END OF PROGRAM: FUEL 1, 0% ETHANOL

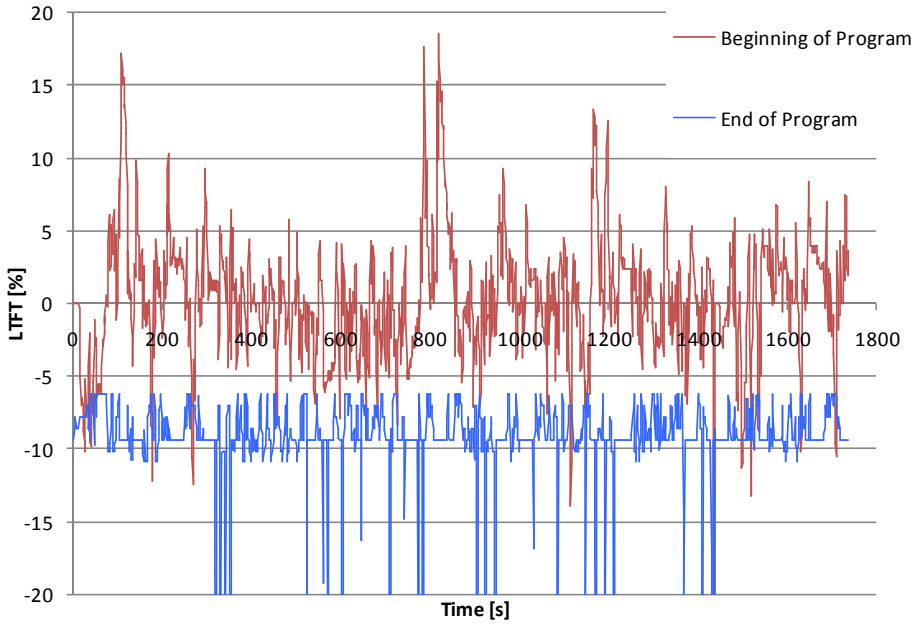


FIGURE ES-3. SHIFT IN LONG-TERM FUEL TRIM – VEHICLE A

- Table ES-2 shows the percent change in PM, Soot, THC, CO and NO_X emissions of the three vehicles from the beginning to the end of the program. Two consecutive emission tests (*data range*, see Figure ES-4) were run at the beginning of the program, and two emissions tests were run at the end of the program, on the same E0 fuel. The values in Table ES-2 are the percent change in the average of two consecutive tests. It is important to note that the percent changes listed do not show overlapping data ranges. Those that do are listed as "data ranges overlap" since pre- and post-test emissions were comparable.

Additionally, repeatability criteria are not computed the same way as percent change. The difference between the two values is described in Figure ES-4. The percent change describes the change between the beginning and end of the project, while repeatability shows how two consecutive emissions tests compare to each other.

TABLE ES-2. CHANGE IN EMISSIONS: BEGINNING VERSUS END OF PROJECT

	Percent Change			Repeatability Criteria
	Vehicle A	Vehicle B	Vehicle C	
PM	+20%	data ranges overlap	+51%	n/a
Soot	+55%	+28%	+66%	n/a
THC	data ranges overlap	+61%	+30%	30%
CO	data ranges overlap	+21.7%	-13.2%	50%
NOx	+20.8%	-52.6%	data ranges overlap	50%

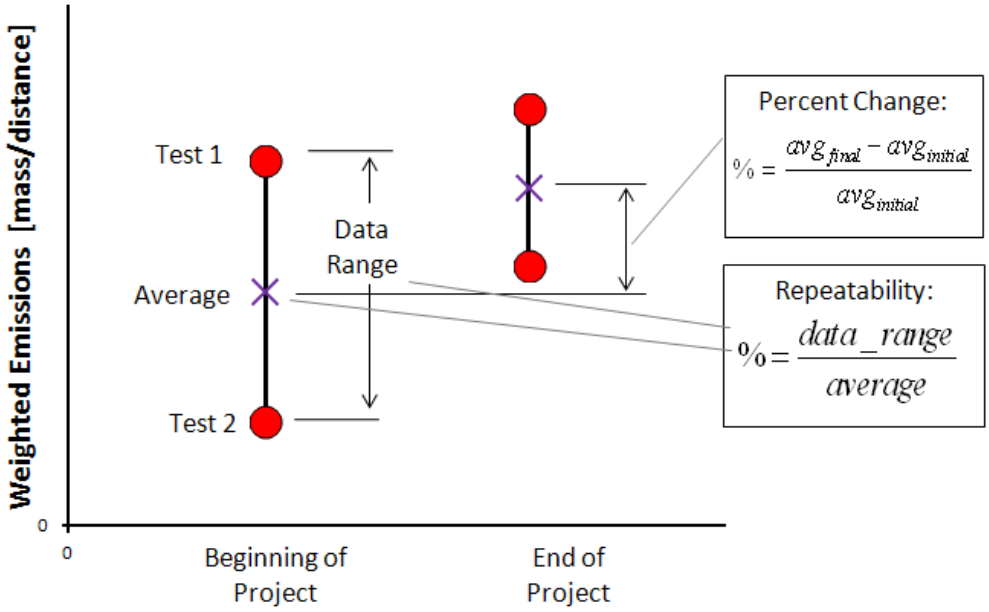


FIGURE ES-4. DETERMINING TEST REPEATABILITY AND PERCENT CHANGE

- There appeared to be no change in fuel economy between Fuel 1 and Fuel 2. As expected, increased ethanol addition was consistent with decreased fuel economy.

- Particle emissions did not always decrease with increasing ethanol addition.

- Soot mass emissions correlated closely with PM mass emissions. Additionally, PM emissions consisted primarily of Elemental Carbon (EC), as shown in Figure ES-5, while Organic Carbon (OC) emissions showed much higher variability than Elemental Carbon. An apparent outlier was observed in this correlation; the PM measurement from one test repeat was lower than other test repeats while the EC was comparable.

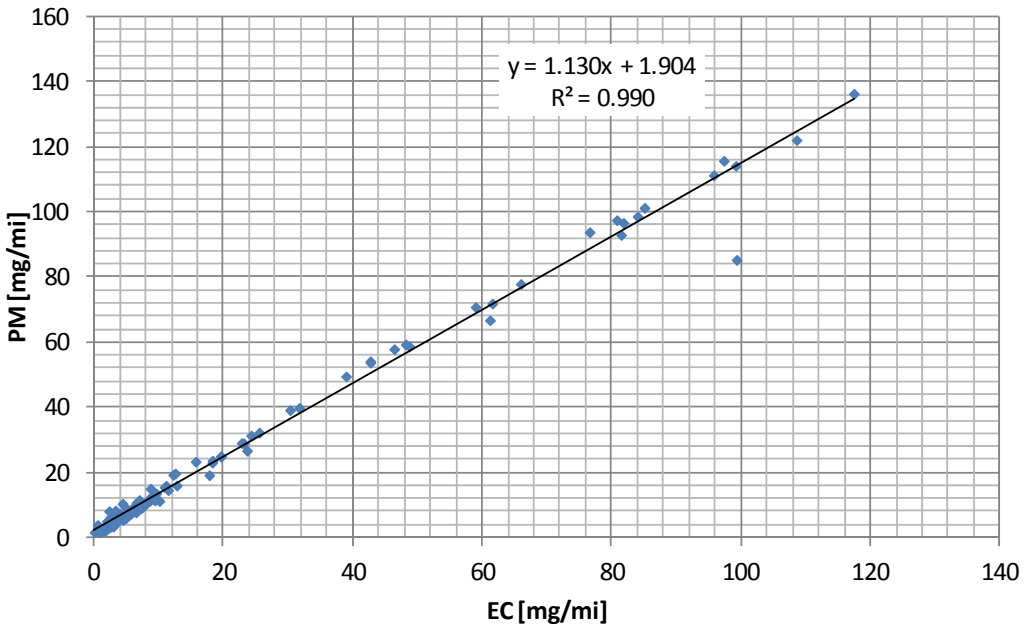


FIGURE ES-5. CORRELATION BETWEEN ELEMENTAL CARBON AND PM EMISSIONS

- Vehicle B showed inconsistent soot mass emission rates over the course of a LA92 drive cycle. Figure ES-6 shows seemingly random step changes in real-time soot mass emissions. Further research may be required to understand this phenomenon.

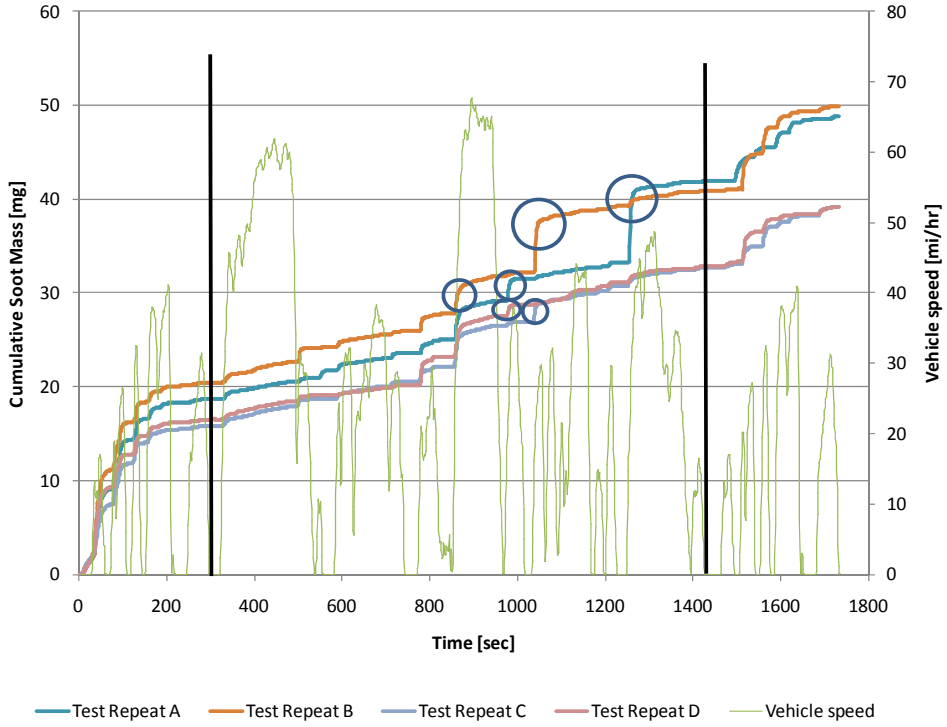


FIGURE ES-6. INCONSISTENT SOOT MASS EMISSIONS OF VEHICLE B

1.0 BACKGROUND

Proposed Corporate Average Fuel Economy (CAFE) and Greenhouse Gas (GHG) emissions standards are significantly more stringent than the current standards. This has influenced manufacturers to develop new engine technologies, such as spark ignited direct injection (SIDI) gasoline engines, to improve fuel economy. Currently many manufacturers are producing both naturally aspirated (NA) and turbo-charged SIDI engines in light-duty vehicles and are meeting both gaseous and particulate matter (PM) emissions standards with 0% ethanol (E0) certification fuel. Europe has implemented, for the first time, a particle number (PN) standard starting with the EURO VI emissions regulations. The California Air Resources Board (CARB) is also investigating using a PN standard.

The 2007 Energy Independence and Security Act (EISA) mandates that significant additional volumes of renewable fuels are to be introduced into the transportation fuel pool in the U.S. It is anticipated that much of the renewable fuel will be ethanol for use in gasoline vehicles. Assuming the EISA mandates are met, ethanol volumes will likely exceed 10 volume percent in gasoline in the near future. As a result, significant efforts were undertaken by the Department of Energy (DOE), the Environmental Protection Agency (EPA), the Coordinating Research Council (CRC), and other organizations to determine whether so-called mid-level ethanol or E15+ blends (e.g., E15 or E20) could be used in the existing motor vehicle fleet without causing harm to those vehicles. As a result of these efforts, the EPA has granted a waiver to allow the use of E15 in 2001 and newer model year vehicles. Also, there is an interest in understanding how increasing the octane rating of a fuel blend affects engine efficiency and fuel economy.

In conversations with CRC, there has been interest in the effects of the calculated particulate mass index (PMI) of a fuel on the performance of a SIDI-equipped vehicle. This index, developed by Aikawa, Sakurai and Jetter[1], is a predictive model which is "based on the weight fraction, vapor pressure, and double bond equivalent (DBE) value of each component in the fuel" from which the PMI could predict the "total PM mass, regardless of engine type or test cycle." That is, the PM Index is proportional to the total PM mass. This work is intended as an initial screening phase in preparation for a more comprehensive evaluation of fuel effects in a variety of SIDI technologies. Therefore, both the fuel and vehicle sets are limited in nature.

[1]Aikawa, K., T. Sakurai, J. Jetter, "Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions," SAE Paper Number 2010-01-2115, October 25, 2010.

2.0 INTRODUCTION

This project is a result of a Statement of Work published by the CRC on which SwRI subsequently bid. In this Statement of Work, CRC was interested in investigating how higher ethanol concentrations in commercially-available fuel affect particulate mass, particulate number, fuel economy, and GHG emissions.

To address how ethanol concentration in fuel affects emissions from modern SIDI engines, three representative vehicles were selected. LA92 drive cycles were conducted while collecting gaseous, particulate mass, elemental carbon, organic carbon, and particle number emissions data.

Six fuels were tested in this program. Two commercially-available E0 gasolines were acquired with different fuel properties. The fuels were selected based on their representation of the upper and lower ends of the range of calculated Particulate Mass Index (PMI) of U.S. summer fuels. It should be noted that the variation in all other properties between the two fuels did not permit evaluation of PMI as a specific parameter. Portions of each gasoline were splash-blended with denatured ethanol to create E10 and E20 fuels. The use of splash blending resulted in changes in all other fuel properties, likewise preventing the evaluation of ethanol content as a specific parameter. For each vehicle/fuel combination, exhaust emissions were measured over two LA92 drive cycles conducted on consecutive days. The result of these tests was a set of data which was studied to gather information about the fuel's ethanol concentration, PMI, vehicle emissions and fuel economy, which will be useful in future test programs.

Before testing, it was hypothesized that the three low PMI fuels would show lower particulate mass emissions than the three high PMI fuels. It was also expected that increasing ethanol addition would correlate with decreasing THC, CO, particle emissions (both mass and number), and fuel economy. It was not fully understood how these fuels would affect the emissions and fuel economy of the different types of vehicles (weight class and emissions classification) relative to each other.

It was also anticipated that unforeseen correlations would arise from the data set collected. As such, part of the purpose of this work was to provide data and insight to guide the direction of future work by the CRC.

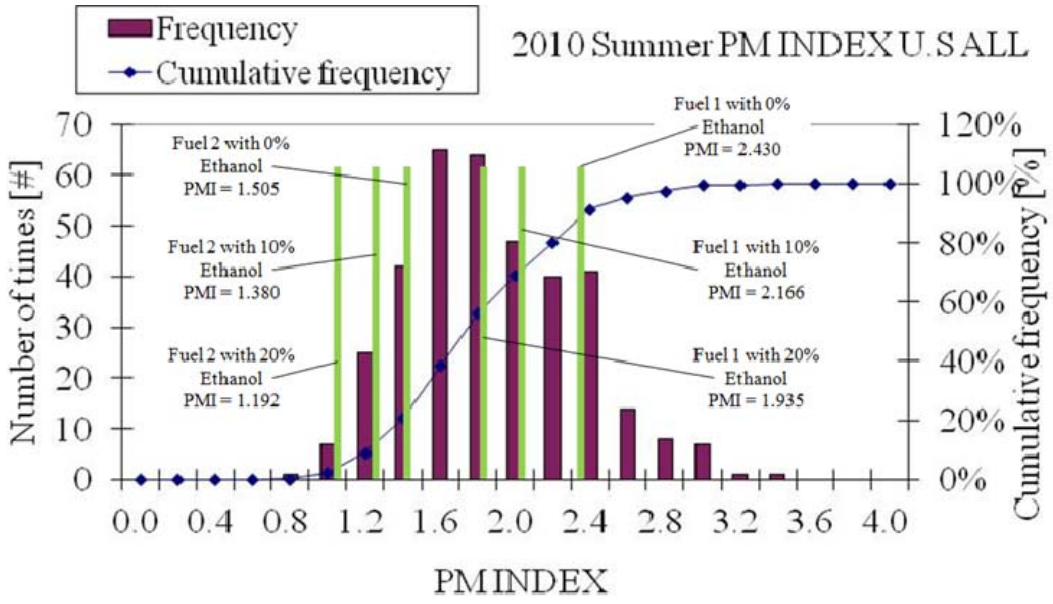
3.0 TEST SETUP

3.1 Test Fuels

3.1.1 Types of Base Fuels Used

Two E0 base fuels were received for this program. These base fuels were chosen to ensure a desired difference in PMI; one had a PMI of 2.430 while the other had a PMI of 1.505. According to Aikawa, Sakurai and Jetter, use of the former fuel should result in higher PM mass emissions than the latter. It should be noted that other fuel properties were not matched, so changes in exhaust emissions cannot be attributed only to PMI.

Honda collected a large set of data and compiled a histogram (Figure 1) showing the PMI of fuels found in the U.S. These data are unpublished at the time of this report and are used with permission from Honda R&D. The two base fuels for this project are within the range of the PMI values of most of the commercially available summer-blend fuels in the U.S.



Note: Unpublished data; Used with permission from Honda R&D

FIGURE 1. HISTOGRAM OF FUEL PMI IN UNITED STATES

3.1.2 Fuel Blending

Fuel grade ethanol was acquired for blending with the two base fuels. The ethanol was analyzed using Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for use as Automotive Spark-Ignition Engine Fuel (ASTM D4806). The two base fuels were splash blended with the fuel grade ethanol to produce E10 and E20 fuels, for a total of six different fuels. A table of the fuels used in this project is provided in Table 1. The two base fuels and four blended fuels were analyzed for RON, MON, sulfur, olefins, aromatics, oxygen, benzene, carbon/hydrogen ratio, RVP, ethanol, water and a full distillation. The complete analyses of all six fuels used in this program are listed in Table 2 and Table 3 and are posted on

the ftp site. Properties of the EEE certification fuel used for initial vehicle checkout are listed in Table 4, and will be discussed in Section 3.2.2.

TABLE 1. TEST FUELS

Base Fuel	Ethanol Concentration	PMI
Fuel 1	0%	2.430
Fuel 1	10%	2.166
Fuel 1	20%	1.935
Fuel 2	0%	1.505
Fuel 2	10%	1.380
Fuel 2	20%	1.192

Blending occurred in a 550-gallon stainless steel tote which was previously steam cleaned and then rinsed with the base fuel to be blended. The blending started by purging the tote with nitrogen to reduce exposure to oxygen and water vapor, and then the base fuel and ethanol were comingled as they were added to the tote to achieve the appropriate fuel ethanol concentration. Mixing continued using a 15 gallon-per-minute pump which had also been previously purged with the base fuel. The pump circulated fuel from the bottom of the tote to the top until the total volume of the tote had been circulated at least 10 times. A nitrogen blanket was maintained in the head space of the tote during mixing. Fuel was then transferred to 55-gallon drums and stored at 45°. The fuel blends remained in a temperature-controlled facility until the morning of a vehicle's fuel change procedure at which point fuel was dispensed as needed. After the fuel change procedure, the fuel was allowed to soak in the vehicle in a temperature controlled environment for a day to stabilize the vehicle's and fuel's temperature before the preconditioning procedure. Further details on this fuel change, preconditioning and testing procedure are provided in Appendix A.

3.2 Test Vehicles

Three vehicles were selected for this program, the details of which are shown in Table 5. These vehicles were selected because they are available, widely used in the U.S. and were equipped with engines using direct fuel injection. All vehicles were two-wheel drive, and all testing was conducted on a two-wheel drive dynamometer. There was interest in selecting vehicles representing both turbocharged and naturally aspirated engine designs as well as vehicles of different weight classes. Additionally, no two vehicles were from the same manufacturer.

Used vehicles with an odometer reading between 4,000 and 10,000 miles were selected for this program so that the engines had already been broken in. However, all available F150s were equipped with premium option packages, so it was more cost effective to purchase a new base model F150 and conduct a break-in procedure. To break in the F150, the vehicle was operated over the Standard Road Cycle (SRC) for 4,000 miles using commercially-available Top Tier qualified gasoline.

TABLE 2. PROPERTIES OF FUEL 1

COMPONENT	ASTM METHOD	0% GA-8565	10% EM-8608-F	20% EM-8610-F
Sulfur, ppm	D5453	<2	2.1	2.2
RVP, psi	D5191	8.4	8.91	8.83
API Gravity	D4052	59.7	58.2	57.2
Oxygen and Oxygenates, vol%	D5599			
Diisopropylether (DIPE), vol %		<0.1	<0.1	<0.1
Ethyl tert-butylether (ETBE), vol %		<0.1	<0.1	<0.1
Ethanol (EtOH), vol %		<0.1	9.78	18.94 (19.35)[a]
Isobutanol (iBA), vol %		<0.1	<0.1	<0.1
Isopropanol (iPA), vol %		<0.1	<0.1	<0.1
Methanol (MeOH), vol %		<0.1	<0.1	<0.1
Methyl tert-butylether (MTBE), vol %		<0.1	<0.1	<0.1
n-Butanol (nBA), vol %		<0.1	<0.1	<0.1
n-Propanol (nPA), vol %		<0.1	<0.1	<0.1
sec-Butanol (sBA), vol %		<0.1	<0.1	<0.1
tert-amyl methylether (TAME), vol %		<0.1	<0.1	<0.1
tert-Butanol (tBA), vol %		<0.1	<0.1	<0.1
tert-Pentanol (tPA), vol %		<0.1	<0.1	<0.1
Total Oxygen, wt%		<0.1	3.62	6.96 (7.11)[a]
Research Octane, (RON)	D2699	94.3	97.6	101
Motor Octane, (MON)	D2700	87	88.4	89.4
Antiknock Index, (R+M)/2		90.7	93	95.2
Water, ppm	D5304	71	1265	2304
Aromatics, vol %	D1319	25	22.28	20.59
Olefins, vol %		4.6	4.78	4.54
Saturates, vol %		70.4	63.13	55.93

[a]Repeat results for fuels EM-8610-F.

Distillation				
COMPONENT	ASTM METHOD	0% GA-8565	10% EM-8608-F	20% EM-8610-F
IBP, ºF	D86	87.1	93	98
5%, °F		114.2	107	117
10%, ºF		132.3	125	130
15%, °F		145.3	133	137
20%, °F		157.4	139	143
30%, °F		181.5	149	153
40%, °F		204.7	156	159
50%, ºF		223.4	208	164
60%, °F		239.9	233	170
70%, °F		260.2	253	245
80%, °F		290.8	283	276
90%, ºF		328.7	324	323
95%, °F		362.5	359	355
EP, ºF		410.5	408	407

TABLE 3. PROPERTIES OF FUEL 2

COMPONENT	ASTM METHOD	0% GA-8589	10% EM-8614-F	20% EM-8615-F
Sulfur, ppm	D5453	10.6	9.7	8.7
RVP, psi	D5191	8.61	9.59	9.45
API Gravity	D4052	60.3	59.1	57.7
Oxygen and Oxygenates, vol%	D5599			
Diisopropylether (DIPE), vol %		<0.1	<0.1	<0.1
Ethyl tert-butylether (ETBE), vol %		<0.1	<0.1	<0.1
Ethanol (EtOH), vol %		<0.1	9.75	20.7
Isobutanol (iBA), vol %		<0.1	<0.1	<0.1
Isopropanol (iPA), vol %		<0.1	<0.1	<0.1
Methanol (MeOH), vol %		<0.1	<0.1	<0.1
Methyl tert-butylether (MTBE), vol %		<0.1	<0.1	<0.1
n-Butanol (nBA), vol %		<0.1	<0.1	<0.1
n-Propanol (nPA), vol %		<0.1	<0.1	<0.1
sec-Butanol (sBA), vol %		<0.1	<0.1	<0.1
tert-amyl methylether (TAME), vol %		<0.1	<0.1	<0.1
tert-Butanol (tBA), vol %		<0.1	<0.1	<0.1
tert-Pentanol (tPA), vol %		<0.1	<0.1	<0.1
Total Oxygen, wt%		<0.1	3.62	7.63
Research Octane, (RON)	D2699	89.7	94.6	98.4
Motor Octane, (MON)	D2700	82.9	85.3	87.9
Antiknock Index, (R+M)/2		86.3	90	93.2
Water, ppm	D5304	51	1244	2386
Aromatics, vol %	D1319	26.8	24.28	21.97
Olefins, vol %		5.6	5.23	4.36
Saturates, vol %		67.6	60.74	52.97

Distillation				
COMPONENT	ASTM METHOD	0% GA-8589	10% EM-8614-F	20% EM-8615-F
IBP, ºF	D86	87.8	91	93
5%, °F		116.6	112	115
10%, ºF		129.9	123	127
15%, °F		141	130	134
20%, °F		151	136	139
30%, °F		171.3	145	149
40%, °F		192.4	152	156
50%, ºF		212.3	184	161
60%, °F		230.2	223	165
70%, °F		249.4	241	230
80%, °F		273.2	268	261
90%, ºF		305.7	305	301
95%, °F		333.7	329	327
EP, ºF		378.3	378	373

TABLE 4. PROPERTIES OF EEE CERTIFICATION FUEL

Component	ASTM Method	Certification Fuel EM-8514-F
Sulfur, wt. %	D5453	0.0035
RVP, psi	D5191	9.1
API Gravity	D4052	59.3
Research Octane, (RON)	D2699	96.6
Motor Octane, (MON)	D2700	88.5
Antiknock Index, (R+M)/2		92.55
Aromatics, vol %	D1319	28
Olefins, vol %		1
Saturates, vol %		71

Distillation		
Component	ASTM Method	Certification Fuel EM-8514-F
IBP, ºF	D86	88
5%, °F		112
10%, ºF		125
20%, °F		146
30%, °F		169
40%, °F		198
50%, ºF		220
60%, °F		230
70%, °F		240
80%, °F		258
90%, ºF		313
95%, °F		336
EP, ºF		402

TABLE 5. DESCRIPTION OF VEHICLES USED IN PROJECT

Vehicle make		VW	Ford	Chevrolet
Vehicle model		GLI	F150XL	Equinox
Model year		2012	2013 New	2011
Engine family		CADXJ02.03UA	DFMXT03.54DX	BGMXJ02.4151
Engine evap. code		CADXR0110238	DFMXR0265NBV	BGMXR0138813
Engine Type		2.0L Turbocharged I4	3.5L TurbochargedV6	2.4L Naturally Aspirated I4
Transmission		6-speed Automatic	6-speed Automatic	6-speed Automatic
Odometer, miles		6311	6*	9415
ECM Calibration I.D.		57812642	KGCT6G2.H32	06J906027J
ECM Calibration Version		000050B2	F6451CE2	290790416C45
Long Term Fuel Trim		0.1%	-7.9%	1.5%
Certification Group		EPA Tier 2 Bin 5; California ULEV II	EPA Tier 2 Bin 5; California: not for sale	EPA Tier 2 Bin 4; California: ULEV qualified
Estimated Test Weight Class [lbs]		3500	6000	4000
GVWR [lbs]		4387	7050	4960
EPA Tier 2 Certification Standard	NMOG, g/mi	0.075	0.075	0.07
	CO, g/mi	3.4	3.4	2.1
	NO_X, g/mi	0.05	0.05	0.04
	PM, g/mi	0.01	0.01	0.01
*Note: 4,000 miles performed on MAD for vehicle break-in prior to testing				

3.2.1 Vehicle Check-in

Upon receipt of the test vehicles, the powertrain control module calibrations were determined with a scanner and reported to the CRC. After the powertrain control module calibration was confirmed, an initial check-in was performed. The following items were included:

1. The vehicle identification number (VIN), test group, and evaporative emissions family were recorded and verified.
2. The vehicles were added to SwRI's test vehicle insurance policy.
3. The vehicles were visually checked for fluid leaks or damage.
4. The exhaust systems were checked for leaks.
5. As-received Long-Term Fuel Trim was recorded at idle with the transmission in drive. In the case of the F150, this was recorded for cylinder bank 1.
6. Fluid levels were checked and topped off as required. The manufacturer's recommended fluids were used for each vehicle.
7. The vehicles were checked for the presence of diagnostic trouble codes (DTCs). None were present with any of the vehicles.
8. The F150 was operated over the Standard Road Cycle (SRC) for 4,000 miles for vehicle break-in using commercially-available Top Tier qualified fuel.
9. A fuel change to EEE certification fuel was performed.

3.2.2 Vehicle Emissions Check-Out Test

Following check-in and setup, each vehicle received a single checkout emissions test over a standard LA92 driving cycle using EEE certification fuel. Analyses of these fuels are provided in Section 3.1.2 in Table 4. Regulated emissions (HC, CO, CO_2, NO_X, and PM) were recorded to confirm proper operation of the emission control systems on the test vehicles. A summary of these results is provided in Table 6. The test results were approved by the CRC-appointed program manager. The complete set of phase-level emissions data is given in Appendix B.

TABLE 6. SUMMARY OF VEHICLE CHECKOUT EMISSIONS TESTS

	NMOG*, g/mi	CO, g/mi	NO_X, g/mi	PM, mg/mi
Vehicle A				
EPA Tier 2 Certification Standard for FTP-75	0.075	1.30	0.05	10
Checkout Test Weighted Results on LA-92	0.033	0.71	0.07	5.7
Vehicle B				
EPA Tier 2 Certification Standard for FTP-75	0.075	1.30	0.05	10
Checkout Test Weighted Results on LA-92	0.020	0.34	0.01	2.9
Vehicle C				
EPA Tier 2 Certification Standard for FTP-75	0.07	2.1	0.04	10
Checkout Test Weighted Results on LA-92	0.043	1.95	0.02	10.9

*Note: NMOG was determined by multiplying NMHC by 1.04 as per CFR Title 40, Part 86, Subpart S, Section 86.1810-01

3.2.3 Vehicle Instrumentation and Preparation

Each vehicle was instrumented and prepared as described below:

- A Marmon flange was welded to the rear tailpipe for emissions testing.
- A thermocouple was installed to measure catalyst inlet temperature.
- A thermocouple was installed to measure engine oil temperature.
- The engine oil was drained using a single flush and fill of the crankcase with a Pennzoil GH-4 of the appropriate viscosity as recommended by the manufacturer.
- Each vehicle was operated over the SRC for 250 miles to degreen the oil.

3.3 Vehicle Testing

Each vehicle/fuel combination was prepared, preconditioned, and tested as specified in the Fuel Change, Conditioning and Test Procedure (Appendix A) and the Catalyst Sulfur Purge Cycle (Appendix C). Two repeated emissions tests were conducted on consecutive days. Within each of the three test vehicles, the order in which fuels were tested was randomized (except for the first and last tests) in an effort to minimize the influence of serial correlation in the final dataset. The last test for each vehicle was a repeat of the first test (conducted with Fuel 1, E0) in order to account for any drift in emissions and/or fuel economy which may have occurred during the several weeks of testing. The order in which each vehicle/fuel combination was tested is given in Table 7.

TABLE 7. TEST SEQUENCE

Week	Vehicle A	Vehicle B	Vehicle C
1	Fuel 1 E0	Fuel 1 E0	Fuel 1 E0
2	Fuel 1 E10	Fuel 1 E10	Fuel 2 E20
3	n/a*	Fuel 2 E20	Fuel 1 E20
4	n/a*	Fuel 2 E0	Fuel 2 E10
5	Fuel 2 E10	Fuel 1 E20	Fuel 2 E0
6	Fuel 2 E0	Fuel 2 E10	Fuel 1 E10
7	Fuel 2 E20	Fuel 1 E0	Fuel 1 E0
8	Fuel 1 E20		
9	Fuel 1 E0		

* Vehicle A was not tested during weeks 3 and 4 due to suspect results. A manufacturer representative on the CRC committee determined the vehicle was in good condition and should proceed with testing.

The emissions drive cycle was the California Air Resources Board LA92 Dynamometer Driving Schedule, often called the Unified Driving Cycle (UDC). A graphic representation of speed versus time for the LA92 is presented in Figure 2.

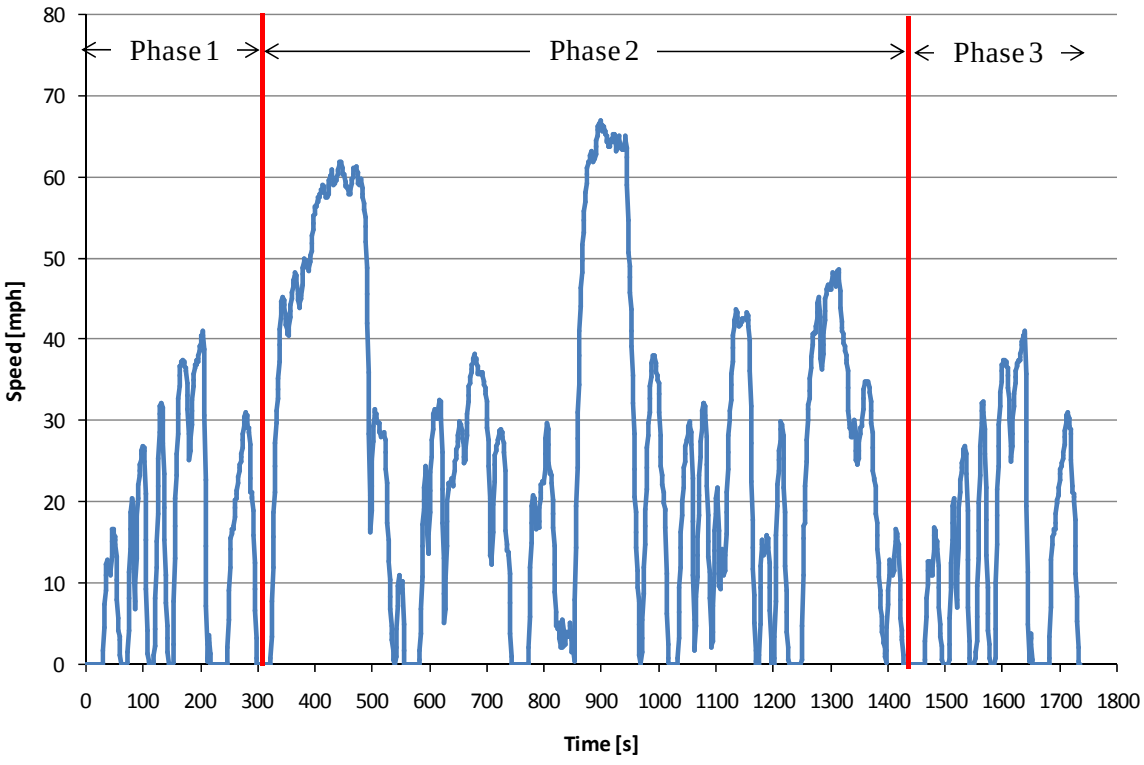


FIGURE 2. LA92 DRIVING CYCLE

For this program the LA92 was conducted as a cold-start, three-phase test, in a manner similar to the light-duty Federal Test Procedure. The LA92 consists of a 300-second cold-start phase (Phase 1) followed by an 1,135-second hot stabilized phase (Phase 2), a 10-minute soak, and a hot-start phase (Phase 3) which is a repeat of the 300-second Phase 1. Overall cycle emissions were calculated in the same manner as the weighted FTP-75 formula, taking actual mileage from the LA92 into account. In this report, the results of the weighted FTP-75 formula will be referred to as the weighted average.

3.3.1 Emissions Chassis Dynamometer Setup

Emissions testing were conducted on a Horiba 48-inch single-roll chassis dynamometer. This dynamometer can electrically simulate inertia weights up to 15,000 lb over the FTP-75, and provides programmable road-load simulation of up to 200 hp continuous at 65 mph. SwRI derived the dynamometer set coefficients based on the test weight class and target road-load coefficients for each vehicle as published in the EPA Test Car List.

One dynamometer and one driver were used for all vehicles and all tests throughout this program. Each pair of repeated tests was conducted on consecutive days. During the overnight soak periods, all vehicles were fitted with a trickle charger to maintain battery conditions. Prior to operating on the dynamometer each day, the vehicle's cold tire pressures were checked and, if needed, set to the manufacturer's specification.

3.3.2 Regulated Emissions

Bagged exhaust emission concentrations of total hydrocarbons (THC), carbon monoxide (CO), methane (for determination of NMHC), oxides of nitrogen (NO_X) and carbon dioxide (CO_2) were measured in a manner consistent with the light-duty vehicle testing protocols given in 40 CFR Part 86, Section 1342. Fuel economy was calculated by the carbon balance method. A Horiba constant volume sampler was used to collect dilute exhaust in inert bags. Dilute exhaust constituents were analyzed as shown in Table 8.

TABLE 8. DILUTE EXHAUST CONSTITUENT ANALYSIS METHODS

Constituent	Analysis Method
Total Hydrocarbon	Flame Ionization Detector (FID)
Methane	Gas Chromatograph
Carbon Monoxide	Non-Dispersive Infrared Detector (NDIR)
Carbon Dioxide	Non-Dispersive Infrared Detector (NDIR)
Oxides of Nitrogen	Chemiluminescent Detector
Nitrous Oxide	Gas Chromatograph
Particulate Mass	Gravimetric Measurement

For the determination of PM mass emissions, a proportional sample of dilute exhaust was drawn through a 47mm Whatman Teflon® membrane filter. The PM sampling method used 40 CFR Part 1065 protocols adapted to light-duty chassis dyno testing. The sample zone was maintained at 47 °C ± 5 °C. A PM2.5 cyclonic separator was used upstream of filter collection. Separate filters were collected for the three phases of the LA92 test cycle.

3.3.3 Unregulated Emissions

3.3.3.1 Nitrous Oxide

Nitrous Oxide (N_2O) was measured with the micro-electron capture detector (micro-ECD) channel of an Agilent Greenhouse Analyzer, 7890A GC (Figure 3). In this measurement, pre-columns vent heavier components, including water and O_2. The ECD uses a radioactive beta particle (electron) emitter; typically a metal foil holding 10 millicuries (370 MBq) of the radionuclide nickel-63. The electrons are formed by collision with auxiliary gas. The electrons are attracted to a positively charged anode, generating a steady current. The sample is carried into the detector by carrier gas and mixed with a stream of 5/95% Methane/Argon mixture flowing through the detector. Analyte molecules then capture the electrons and reduce the current between the collector anode and a cathode. The N_2O concentration is thus proportional to the degree of electron capture. The decrease in detector current due to the loss of the thermal electrons is converted into the digital signal and quantified. The detection level for N_2O is less than 0.32 ppb (parts per billion). This detection limit is ten times lower than the normal concentration of N_2O in the atmosphere.

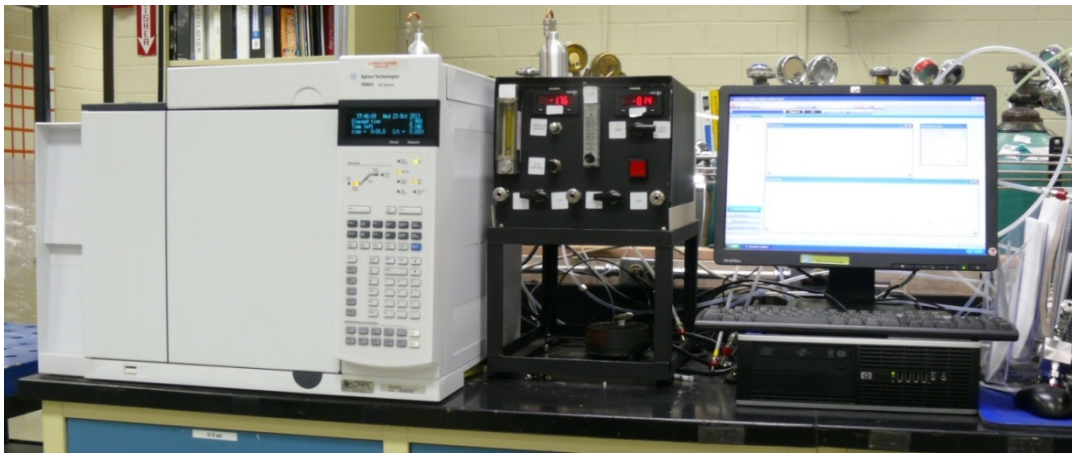


FIGURE 3. AN AGILENT GREENHOUSE ANALYZER AND SAMPLE INTRODUCTION SYSTEM

3.3.3.2 Engine Exhaust Particle Sizer (EEPS)

TSI's EEPS Model 3090, shown in Figure 4, provides real-time information on particle size distribution. It is capable of measuring particles in the range from 5.6 nm to 560 nm in electrical mobility diameter, and provides this information (particle concentration) in 32 separate size bins. The EEPS was used in conjunction with the SwRI Solid Particle Sampling System (SPSS) described in the next section.

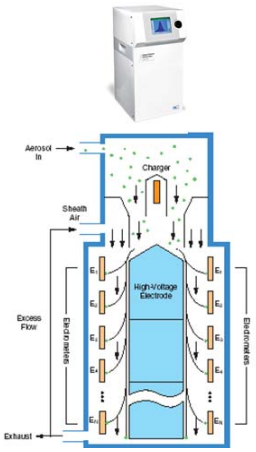


FIGURE 4. ENGINE EXHAUST PARTICLE SIZER (EEPS)

3.3.3.3 Solid Particle Sampling System (SPSS)

The SPSS, shown in Figure 5, was used to sample engine exhaust upstream of the EEPS. The SPSS contains a heated catalyst that strips the exhaust sample of its volatile components. It includes a single stage of dilution where the extracted sample is mixed with filtered air. Throughout this program, the EEPS was used in conjunction with the SPSS for measurement of solid particle size distribution. Typically, the SPSS extracted sample from engine exhaust with a dilution ratio of ~5.50.

FIGURE 5. SOLID PARTICLE SAMPLING SYSTEM

3.3.3.4 Solid Particle Number Measurement System (SPNMS)

The SwRI Solid Particle Number Measurement System (SPNMS) was utilized to sample solid particles greater than 23 nm in diameter in accordance with the Particulate Measurement Program (PMP) protocol. The particles are counted using a TSI model 3790 Condensation Particle Counter (CPC). The CPC 3790 has a 50% counting efficiency for particles 23 nm in diameter. Unlike conventional PMP sampling systems, the SPNMS uses a catalytic stripper to remove the volatile particles rather than an evaporation tube. This system is designed to remove volatiles with a very high efficiency while still maintaining a high penetration of solid particles.

This is extremely important when measuring particles smaller than 23 nm, which is the lower cut-off point of the PMP systems. It has been shown that using an evaporation tube may lead to the recondensation of particles smaller than 23 nm. By oxidizing the volatile material, renucleation/condensation is prevented. In this way, it is possible to attach a TSI CPC 3025A to the SPNMS system and measure solid particles down to 3 nm. The system is shown in Figure 6. The CPC 3790 is inside the red box, and the CPC 3025 is the white instrument as pictured.

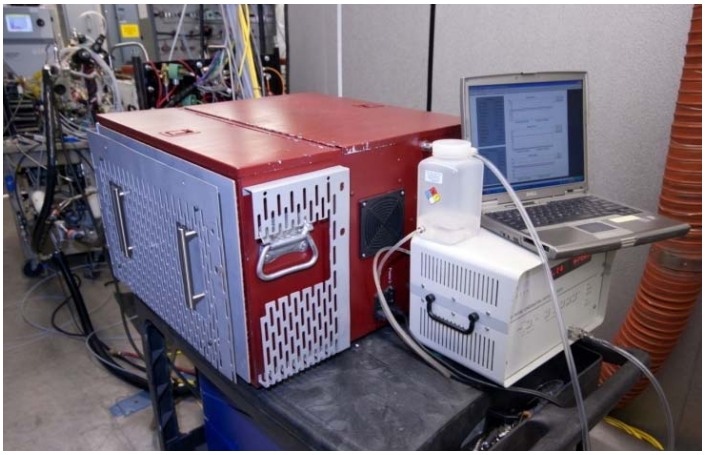


FIGURE 6. SwRI SOLID PARTICLE NUMBER MEASUREMENT SYSTEM

3.3.3.5 Micro Soot Sensor (MSS)

An AVL Micro Soot Sensor, shown in Figure 7, utilizes a photo-acoustic measurement scheme to measure the soot mass concentration in the sample flow. In this method, elemental carbon (soot) particles are exposed to laser light. This increases the temperature of these strongly absorbing particles and heats the surrounding gas, leading to the generation of sound waves that are detected by a sensitive microphone. The signal detected by the microphone is proportional to the concentration of soot mass in the measurement cell. The upper and lower limits of its detection capability are 50 mg/m^3 and 5 µg/m^3, respectively. For all experiments carried out as a part of this project, the MSS was operated with a dilution ratio of 2 between it and the instrument's sampling point at the CVS.

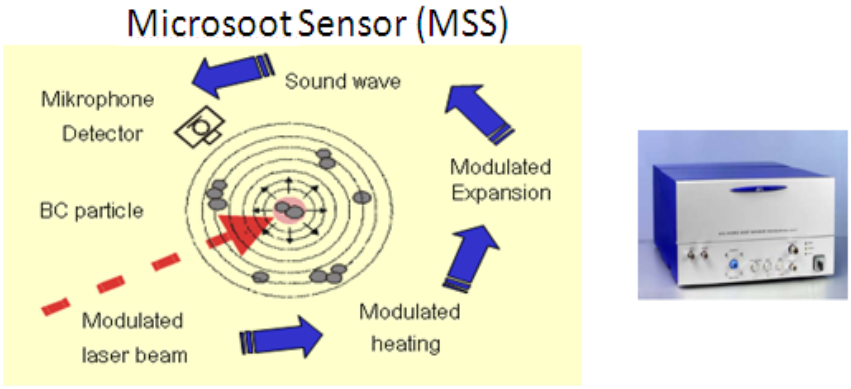


FIGURE 7. AVL MICROSOOT SENSOR (MSS)

3.3.3.6 Elemental Carbon/Organic Carbon

The Thermal/Optical Reflectance (TOR) method was used to measure "organic" (OC) and "elemental" (EC) carbon. This is the recognized method for the determination of organic and elemental carbon on particulates collected on the quartz fiber filters, as described in the literature[2]. This method is based on the principle that different types of carbon-containing particles are converted to gases under different temperature and oxidation conditions. The different carbon fractions from TOR are useful for comparing the specific forms of carbon in the exhaust. The sample for this method was taken from a sample probe placed in the Constant Volume Sampling (CVS) tunnel directly after the PM collection unit (Figure 8).

PM samples were collected on primary and secondary quartz filters using separate filter holders connected in series (Figure 9). The first quartz filter (primary filter) was used to measure OC and EC directly. The second filter was used for correction of gas-phase OC artifact adsorbed by particulate on the primary filter.

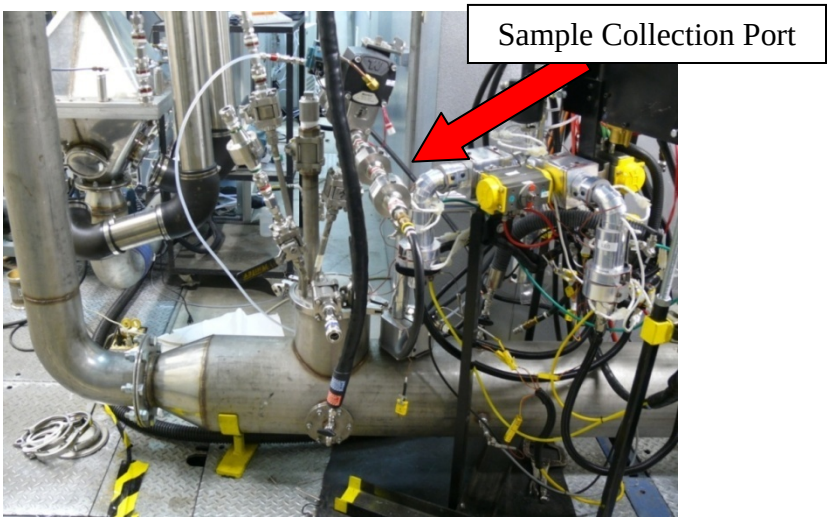


FIGURE 8. EC/OC SAMPLE COLLECTION

FIGURE 9. PRIMARY AND SECONDARY FILTERS ASSEMBLY

[2]M. E. Birch and R. A. Cary (1996), "Elemental Carbon-Based Method for Monitoring Occupational Exposures to Particulate Diesel Exhaust." *Aerosol Science and Technology* **25**, 221-241.

Quartz filters were prebaked at 900°C in an oven filled with inert gas for 8 hours to remove ambient organic contaminants absorbed by the filters. Typically, 900°C is sufficient temperature to remove all possible interferences with thermal/optical analysis. Following baking, filters were kept in pre-cleaned glass jars purged with nitrogen. To minimize the risk of Volatile Organic Compounds (VOC) contaminating the filters, and to allow quicker filter loading at the test cell, they were pre-assembled with Teflon filter rings (Figure 10) inside a weighing chamber equipped with an air filtering system. Two filters (primary and secondary) were collected for each individual phase of the test cycle, and were analyzed on a Sunset Laboratory Inc. Thermal/Optical Carbon Aerosol Analyzer (Figure 11).

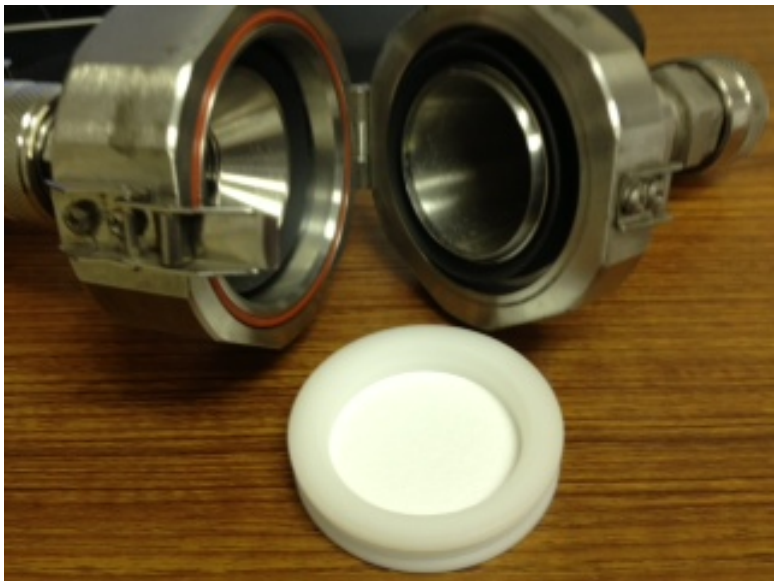


FIGURE 10. PRE-FILTER HOLDER AND PRE-ASSEMBLED FILTER

FIGURE 11. SUNSET LABORATORY THERMAL/OPTICAL LAB CARBON AEROSOL ANALYZER

One sample of ambient air (background) and one sample of dilution air were taken during the entire test, including the time required to load and unload the primary and secondary filters in the filter holder. These two filters, plus the secondary filters, were used as corrections to the overall OC measurement.

At the beginning of the program, up to four punches from each filter were prepared and individually analyzed to confirm uniformity of the particulate distribution on the filter. Results for each fraction (microgram organic C, microgram elemental C and total C) were summed up and normalized for the entire filter (based on the filter surface area). Results of the measurements proved that geometry of the filter holder provided sufficient uniformity of the sample. Based on these results, a single punch was used for the remainder of the measurements.

Results from the analyses of the primary filter were corrected for background (diluted air), for the field blank, and for gas-phase OC artifact obtained from the results from the secondary filter.

3.3.3.7 On-Board Diagnostic Channels

Several OBD channels were recorded continuously throughout the LA92 tests. These channels included short-term fuel trim, long-term fuel trim, engine speed, vehicle speed, coolant temperature, malfunction indicator lamp (MIL) on or off, ignition timing, mass air flow, manifold air pressure, throttle position, and primary oxygen sensor voltage. OBD data were collected with at least a 90% completeness rate and have been uploaded to the ftp site.

4.0 TEST RESULTS

This work was intended as an initial screening phase in preparation for a more comprehensive evaluation of fuel effects in a variety of SIDI technologies. Therefore, both the fuel and vehicle sets are limited in nature. Since testing was limited, no statistical analysis was performed and statistical conclusions cannot be made. The following is a summary of the project results and observations based on the results. A summary of weighted average emissions results from the three test vehicles is provided below in Tables 9 through 14. Complete results for each test are provided on the ftp site.

The results in this section are divided up as Vehicles A, B and C. This order is randomized from the order in which the vehicles are listed in Table 5. Furthermore, results pertaining to CO_2 and fuel economy are further re-ordered, using a random number generator, as Vehicles 1, 2 and 3. That is, Vehicle A does not necessarily correspond to Vehicle 1, and so on.

4.1 Regulated Gaseous Emissions

Bagged THC, CH_4 (for determining NMHC), CO and NO_X emissions were collected on a phase basis throughout testing. Figure 12 shows the THC emissions of Vehicle A for all fuels, organized by phase, base fuel and ethanol content. The intervals overlapping each bar represent the two repeated tests for each vehicle/fuel combination. Each colored bar represents the average of the two repeated tests. In the case of Fuel 1, E0, two repeated tests are shown as two blue bars; these correspond to the two repeated test sequences at the beginning (left-hand blue bar) and end (right-hand blue bar) of this project. Because Phase 1 showed the highest emissions of all the phases due to cold start, the same data are shown in the subset of Figure 12 fitted with a scale appropriate for Phase 2, Phase 3 and the weighted averages. This same type of chart is used throughout this report and in Appendix D.

TABLE 9. VEHICLE A WEIGHTED AVERAGE OF GASEOUS EMISSIONS SUMMARY

Fuel	Ethanol Concentration, %	Test Repeat	THC, g/mi	CO, g/mi	NO_X, g/mi	NMHC, g/mi	N_2O, g/mi
1	0	A*	0.040	1.05	0.009	0.027	2.65
		B*	0.031	0.74	0.007	0.023	2.04
		C*	0.038	0.72	0.009	0.030	2.24
		D*	0.036	0.91	0.010	0.025	2.30
	10	A	0.023	0.77	0.012	0.017	1.65
		B	0.022	0.59	0.009	0.016	1.40
	20	A	0.034	0.82	0.013	0.022	2.76
		B	0.027	0.86	0.009	0.019	2.17
2	0	A	0.038	1.04	0.017	0.026	3.58
		B	0.037	0.73	0.013	0.025	3.25
	10	A	0.037	0.65	0.019	0.027	3.01
		B	0.031	0.72	0.007	0.021	1.48
	20	A	0.037	0.62	0.032	0.029	4.95
		B	0.032	0.68	0.018	0.021	3.19
*Note: Fuel 1 with 0% ethanol was the first (A, B) and last (C, D) fuel run on all three vehicles.							

TABLE 10. VEHICLE A WEIGHTED AVERAGE OF PARTICLE EMISSIONS SUMMARY

Fuel	Ethanol Concentration, vol. %	Test Repeat	PM, mg/mi	EC+OC, mg/mi	Soot Mass, mg/mi	PMP 3790, Particles/mi
1	0	A*	6.3	5.97	3.25	9.77E+12
		B*	6.7	6.53	3.27	9.35E+12
		C*	7.9	6.91	5.07	1.31E+13
		D*	7.7	7.60	5.06	1.30E+13
	10	A	8.6	8.82	4.40	1.14E+13
		B	8.7	7.29	4.42	1.20E+13
	20	A	7.7	6.52	4.77	1.40E+13
		B	8.2	7.10	5.12	1.44E+13
2	0	A	4.1	3.62	2.39	8.40E+12
		B	5.0	4.90	2.81	9.29E+12
	10	A	5.8	4.15	2.96	9.76E+12
		B	6.1	4.82	3.03	9.66E+12
	20	A	5.2	3.57	2.87	8.88E+12
		B	4.7	3.69	3.03	9.54E+12
*Note: Fuel 1 with 0% ethanol was the first (A, B) and last (C, D) fuel run on all three vehicles.						

TABLE 11. VEHICLE B WEIGHTED AVERAGE OF GASEOUS EMISSIONS SUMMARY

Fuel	Ethanol Concentration, %	Test Repeat	THC, g/mi	CO, g/mi	NO_X, g/mi	NMHC, g/mi	N_2O, g/mi
1	0	A*	0.015	0.27	0.017	0.012	0.95
		B*	0.022	0.33	0.016	0.018	1.01
		C*	0.029	0.37	0.008	0.023	1.21
		D*	0.031	0.37	0.008	0.026	0.59
	10	A	0.017	0.24	0.008	0.013	0.43
		B	0.019	0.31	0.008	0.014	0.67
	20	A	0.025	0.35	0.013	0.019	1.10
		B	0.025	0.59	0.006	0.019	0.43
2	0	A	0.029	0.47	0.012	0.023	1.50
		B	0.036	0.48	0.014	0.028	2.25
	10	A	0.030	0.42	0.008	0.023	1.87
		B	0.027	0.50	0.006	0.022	0.93
	20	A	0.022	0.36	0.027	0.017	1.07
		B	0.024	0.35	0.018	0.019	1.52
*Note: Fuel 1 with 0% ethanol was the first (A, B) and last (C, D) fuel run on all three vehicles.							

TABLE 12. VEHICLE B WEIGHTED AVERAGE OF PARTICLE EMISSIONS SUMMARY

Fuel	Ethanol Concentration, vol. %	Test Repeat	PM, mg/mi	EC+OC, mg/mi	Soot Mass, mg/mi	PMP 3790, particles/mi
1	0	A*	5.5	4.59	2.81	9.91E+12
		B*	5.4	4.77	2.77	9.33E+12
		C*	5.8	4.31	3.60	9.99E+12
		D*	5.4	4.47	3.52	9.18E+12
	10	A	5.5	4.86	2.75	8.49E+12
		B	5.6	4.65	2.91	8.69E+12
	20	A	5.1	3.39	2.49	8.23E+12
		B	5.9	3.79	2.98	9.07E+12
2	0	A	3.4	2.47	1.65	6.55E+12
		B	5.1	3.70	2.66	8.12E+12
	10	A	3.5	2.62	1.88	7.60E+12
		B	3.2	2.72	1.77	7.31E+12
	20	A	4.1	3.69	2.14	7.09E+12
		B	3.2	2.71	1.73	6.40E+12
*Note: Fuel 1 with 0% ethanol was the first (A, B) and last (C, D) fuel run on all three vehicles.						

TABLE 13. VEHICLE C WEIGHTED AVERAGE OF GASEOUS EMISSIONS SUMMARY

Fuel	Ethanol Concentration, %	Test Repeat	THC, g/mi	CO, g/mi	NO_X, g/mi	NMHC, g/mi	N_2O, g/mi
1	0	A*	0.028	1.45	0.009	0.019	0.56
		B*	0.020	1.48	0.006	0.013	0.36
		C*	0.032	1.24	0.006	0.024	0.57
		D*	0.030	1.30	0.004	0.022	0.43
	10	A	0.021	1.16	0.006	0.014	0.49
		B	0.022	1.23	0.004	0.013	0.50
	20	A	0.030	1.28	0.003	0.021	0.46
		B	0.030	1.26	0.005	0.021	0.51
2	0	A	0.041	1.99	0.007	0.032	0.85
		B	0.033	1.67	0.010	0.023	0.65
	10	A	0.023	1.50	0.006	0.014	0.60
		B	0.026	1.34	0.006	0.017	0.65
	20	A	0.027	1.15	0.005	0.019	0.47
		B	0.031	1.22	0.008	0.022	0.53

*Note: Fuel 1 with 0% ethanol was the first (A, B) and last (C, D) fuel run on all three vehicles.

TABLE 14. VEHICLE CWEIGHTED AVERAGE OF PARTICLE EMISSIONS SUMMARY

Fuel	Ethanol Concentration, vol. %	Test Repeat	PM, mg/mi	EC+OC, mg/mi	Soot Mass, mg/mi	PMP 3790, particles/mi
1	0	A*	11.5	12.13	7.97	1.61E+13
		B*	11.6	10.57	6.90	1.46E+13
		C*	17.3	14.39	12.36	2.09E+13
		D*	17.7	14.49	12.37	2.15E+13
	10	A	14.3	12.62	8.91	1.86E+13
		B	15.3	13.18	9.50	1.89E+13
	20	A	15.3	13.08	9.36	1.96E+13
		B	14.2	12.28	8.68	1.81E+13
2	0	A	11.9	9.61	7.20	1.52E+13
		B	12.2	10.06	7.42	1.53E+13
	10	A	11.6	10.33	7.02	1.53E+13
		B	11.5	9.22	6.74	1.49E+13
	20	A	8.6	7.21	5.14	1.26E+13
		B	8.8	7.12	5.31	1.28E+13

*Note: Fuel 1 with 0% ethanol was the first (A, B) and last (C, D) fuel run on all three vehicles.

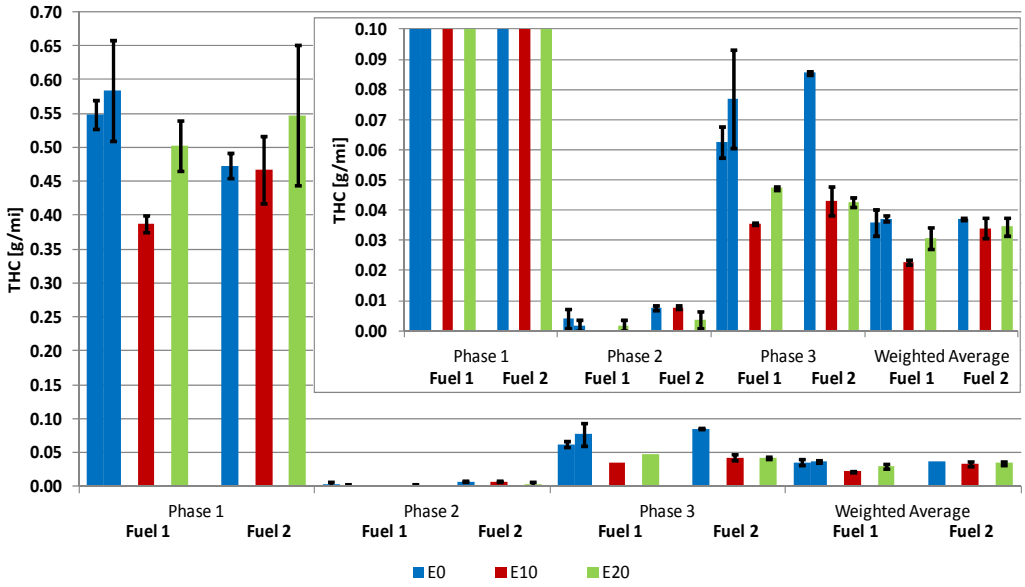


FIGURE 12. VEHICLE A TOTAL HYDROCARBONS

The test procedure was repeated with Fuel 1, E0, at the beginning and end of testing. Between these two repeated test intervals with the same fuel, Vehicles B and C showed a notable shift in emissions. Weighted averages of THC, NMHC and CO increased while NO_X decreased with Vehicle B. On Vehicle C, THC and NMHC increased while CO decreased. The shift in THC emissions is shown in Figures 13 and 14 for Vehicle B and Vehicle C, respectively.

This shift between the first and last sets of repeated measurements on Fuel 1, E0, was also observed for particulate emissions, as is discussed later in Section 4.3. The complete set of regulated gaseous emissions (THC, NMHC, CO, NO_X) results are found in Figures D-1 through D-12 of Appendix D and have been provided on the ftp site.

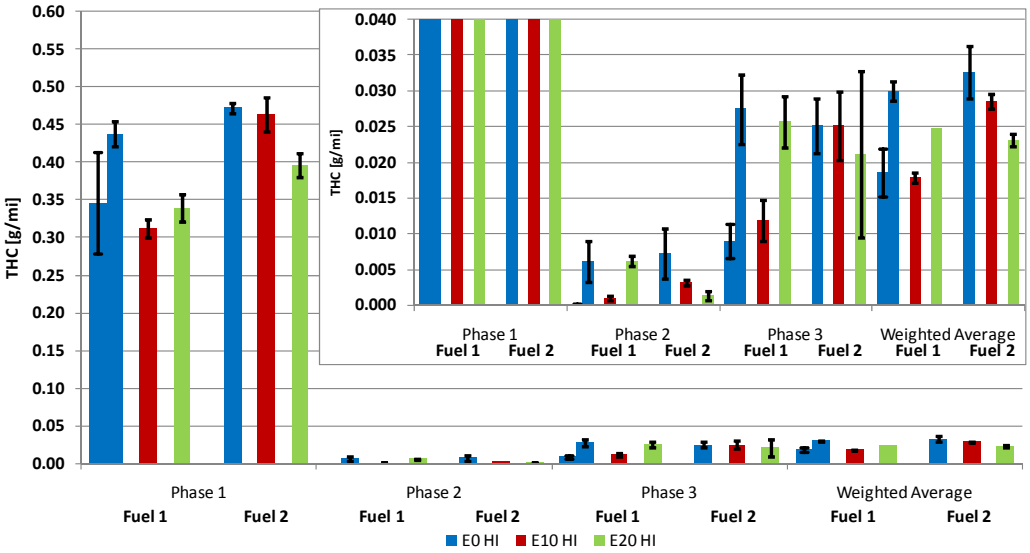


FIGURE 13. VEHICLE B TOTAL HYDROCARBONS

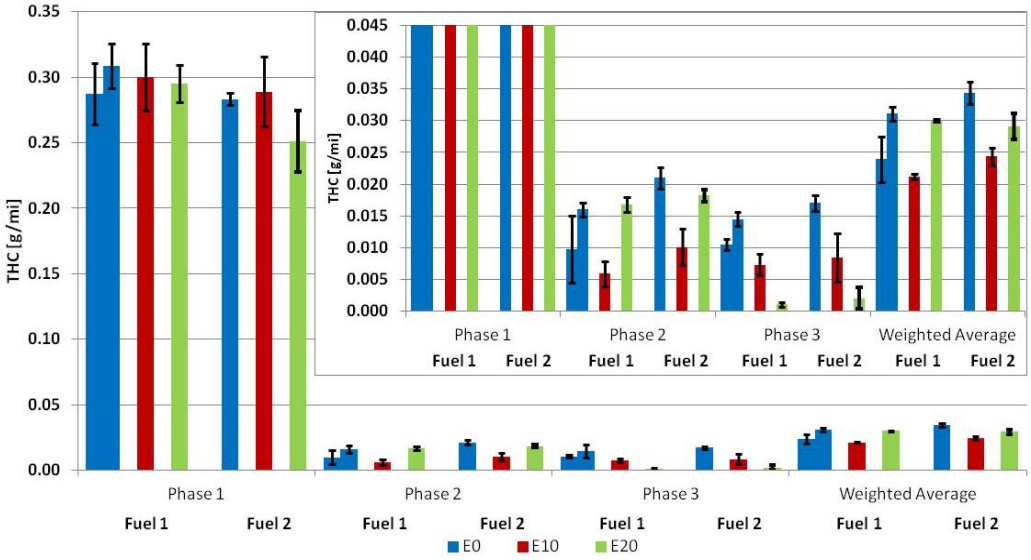


FIGURE 14. VEHICLE C TOTAL HYDROCARBONS

4.2 Greenhouse Gas Emissions and Fuel Economy

Because there has been interest in the impacts of proposed CAFE and GHG emissions standards, three GHG emissions were measured: CO_2, CH_4 and N_2O. According to the EPA[3], one gram of CH_4 has the same global warming potential as 21 grams of CO_2, while one gram of N_2O has the global warming potential of 310 grams of CO_2. As such, more attention is being paid to N_2O emissions as a potent greenhouse gas.

N_2O forms over three-way catalysts just above light-off temperatures from approximately 200°C to 350°C. At these temperatures, NO reacts with CO to form N_2O. As the temperature increases, CO preferentially react with O_2, thus N_2O decreases while N_2 increases. With this mechanism, platinum potentially produces more N_2O than palladium.

Because N_2O formation occurs at lower temperatures once the engine and catalyst reach normal operating temperatures, N_2O decreases. Indeed, N_2O was highest in Phase 1 of the LA92 drive cycle and correlated with THC and CO in all three phases of the LA92.

The total CO_2-equivalent GHG emissions were calculated using Equation (1) for each vehicle. As an example, Figure 15 shows how each of these three GHGs contributes to the total CO_2-equivalent emissions for Vehicle 2. The data shown in Figure 15 are the average of the two repeated tests.

$$Total\ GHG = CO_2\left[\frac{g}{mi}\right] + N_2O\left[\frac{g}{mi}\right] \times 310\left[\frac{g\ CO_2}{g\ N_2O}\right] + CH_4\left[\frac{g}{mi}\right] \times 21\left[\frac{g\ CO_2}{g\ CH_4}\right]$$

Equation (1)

[3] http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2012-Main-Text.pdf

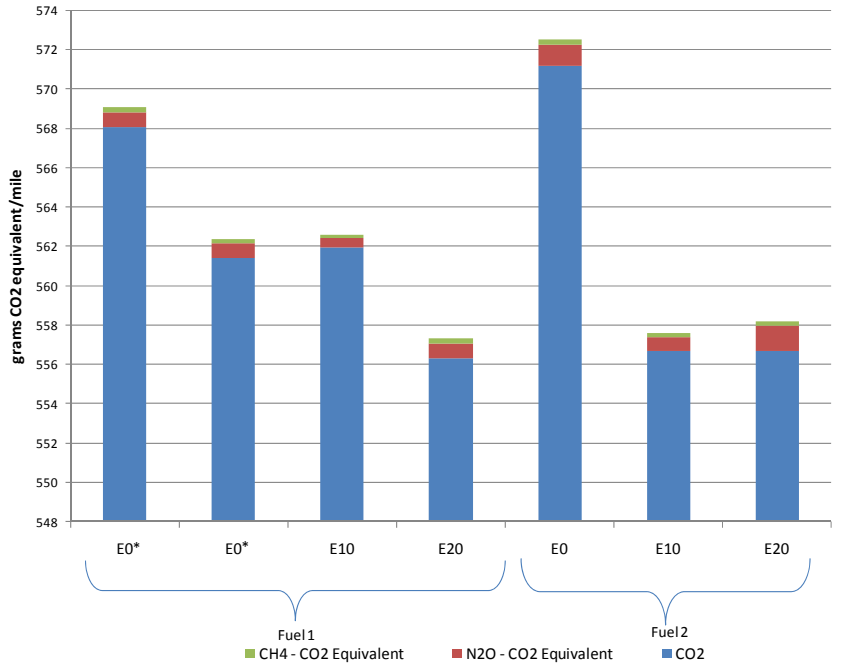


FIGURE 15. WEIGHTED AVERAGES OF GREENHOUSE GAS EMISSIONS FOR VEHICLE 2

Figure 16 shows the total CO_2-equivalent GHG emissions for the three vehicles as an average of the two repeated tests for each fuel.

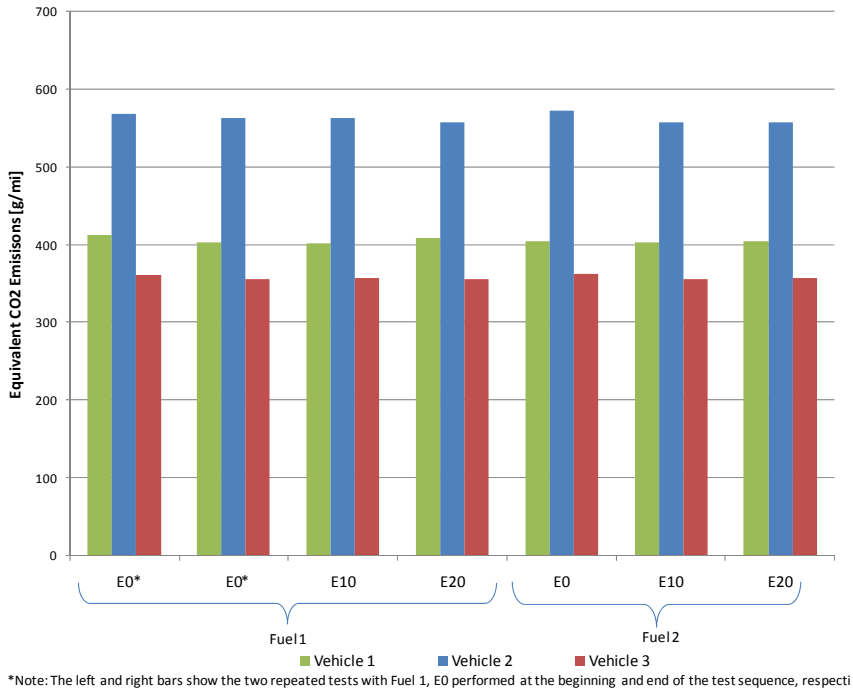


FIGURE 16. EQUIVALENT CO_2 EMISSIONS (GLOBAL WARMING POTENTIAL)

The results of fuel economy measurements for all three vehicles showed an expected trend in which fuel economy decreased with increasing ethanol addition. The results from Vehicle 3 are given below in Figure 17 as an example. This figure was similar to those of the other two vehicles, given in Appendix D.

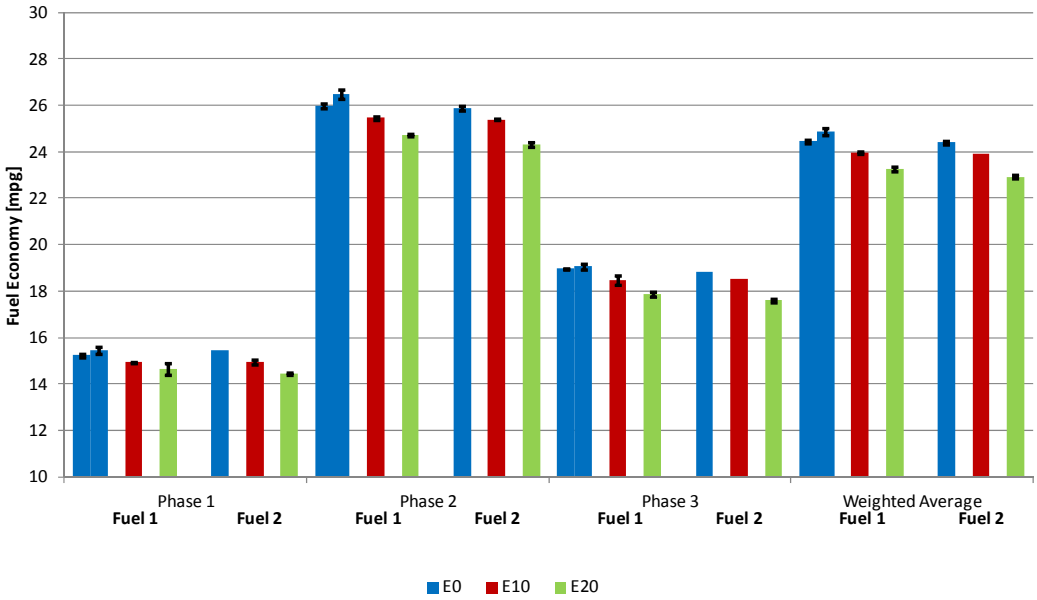


FIGURE 17. VEHICLE 3 FUEL ECONOMY RESULTS

4.3 Particle Emissions

4.3.1 Particulate Mass Emissions

Fuel properties can strongly influence PM emissions. Fuel volatility, oxygen content and presence of aromatics are some fuel properties that dictate PM emissions. Less volatile fuels can result in higher PM emissions as slow droplet evaporation can retard complete fuel-air mixing. Typically, more oxygenated fuels result in lower PM emissions. The presence of more aromatics on the other hand, increases PM emissions as they have higher boiling points. Figures 18 through 20 show phase-level and average weighted LA92 PM emissions for the three vehicles tested in this program.

For a given ethanol addition, Fuel 1 resulted in higher weighted average PM emissions compared to Fuel 2 for Vehicles A and B. Vehicle C did not show this trend, as can be seen in Figure 18, PM emissions of Fuel 2 E0 fall between the two repeated tests of Fuel 1 E0.

Repeated test sequences were conducted at the beginning and end of the project with baseline Fuel 1, E0. These two sets of tests indicated a change in PM emissions for Vehicles A and C. PM emissions at the end of the program were higher than those of the beginning for all three phases for these two vehicles. However, Vehicle B did not show a difference in PM emissions between the beginning and end of the program for any of the phases.

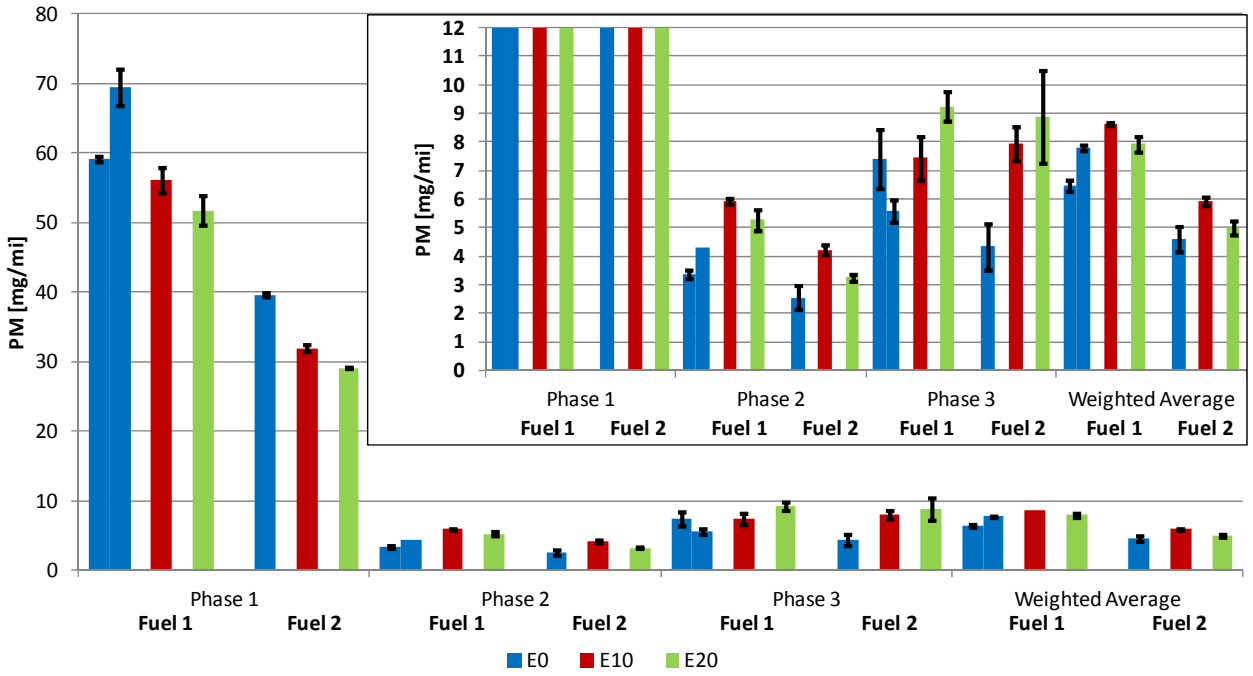


FIGURE 18. PM EMISSIONS FOR VEHICLE A

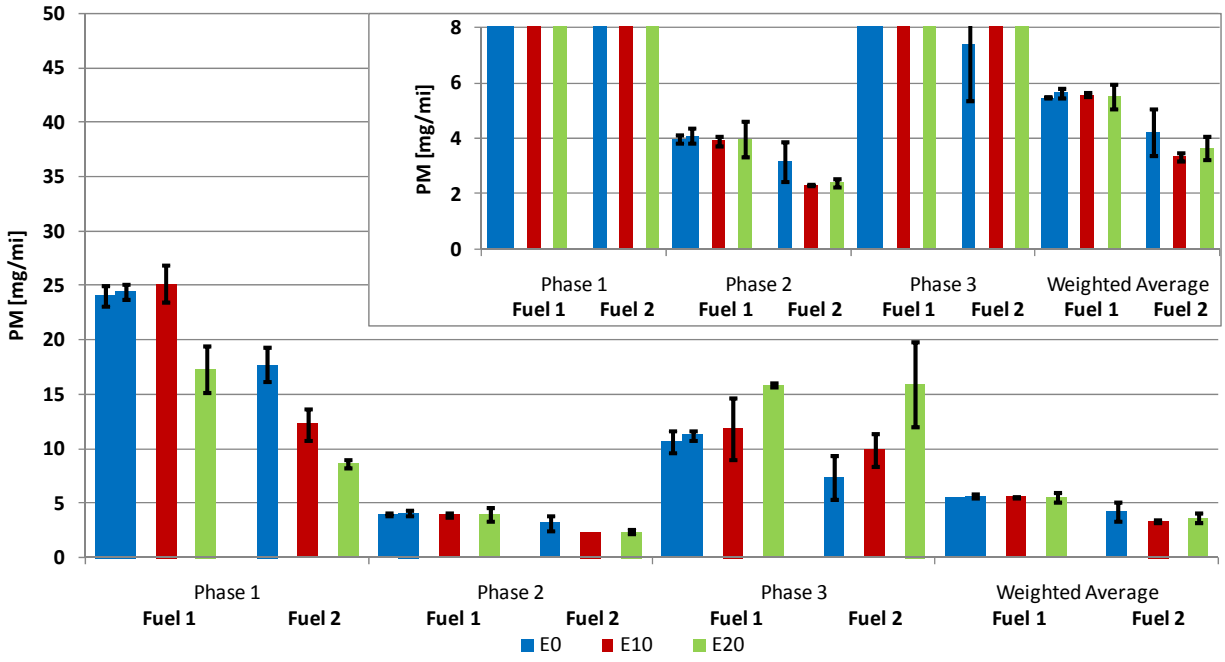


FIGURE 19. PM EMISSIONS FOR VEHICLE B

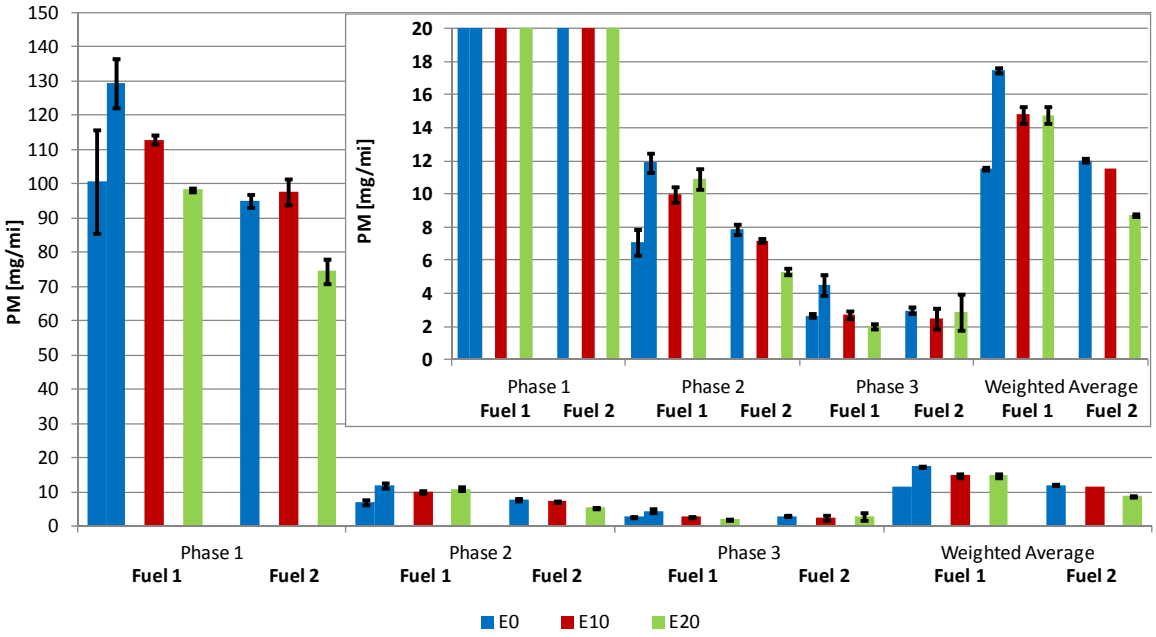


FIGURE 20. PM EMISSIONS FOR VEHICLE C

Figures 21 through 23 show a plot of PM emissions versus PMI for Vehicles A, B and C, respectively. It is important to note that the fuel properties of the two base fuels were not matched, so PM emissions cannot only be attributed the fuel's PMI. Plots of THC, CO, NO_X, and EC versus PMI are provided in Appendix E.

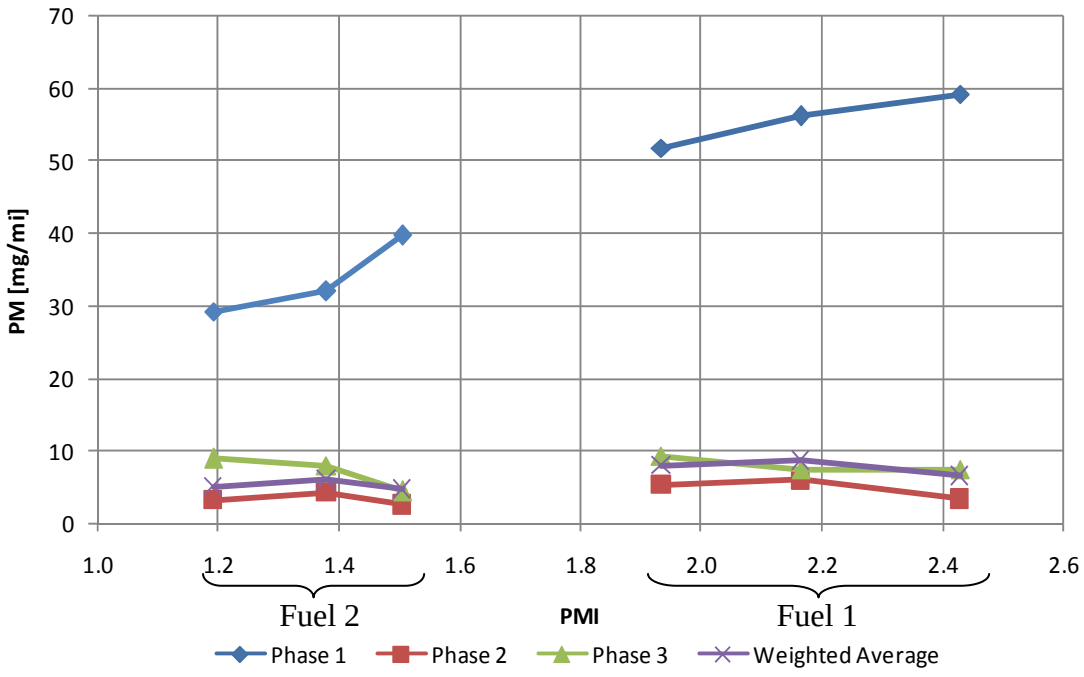


FIGURE 21. PM VERSUS PMI FOR VEHICLE A

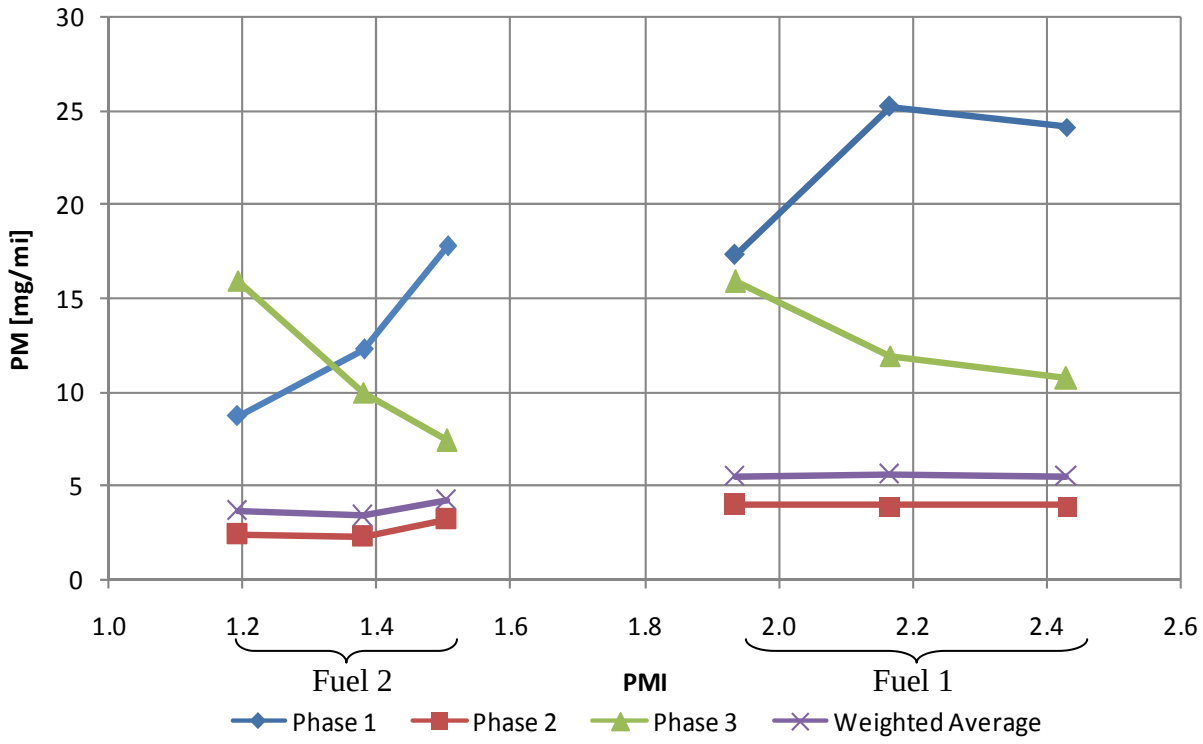


FIGURE 22. PM VERSUS PMI FOR VEHICLE B

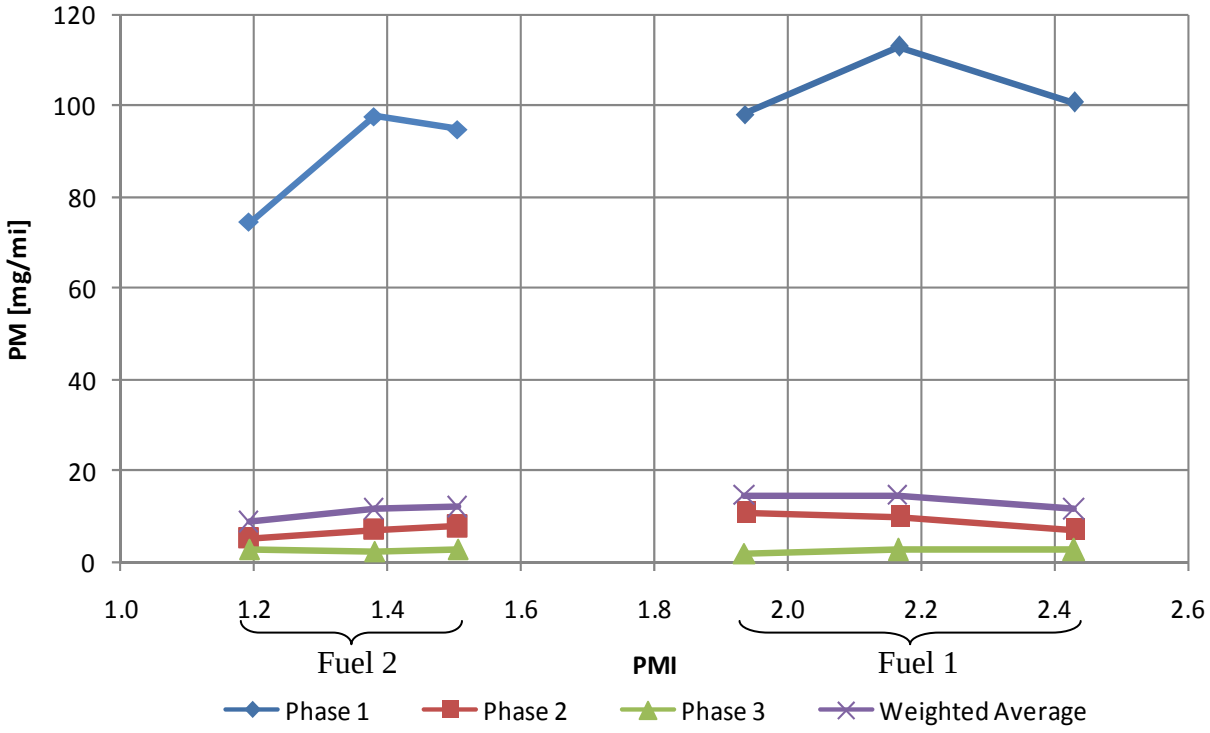


FIGURE 23. PM VERSUS PMI FOR VEHICLE C

4.3.2 Soot Mass Emissions

In addition to PM mass emissions (solid + volatile emissions), soot (black carbon) mass emissions were measured using AVL's micro-soot sensor (MSS), the results of which are shown in Figures 24 through 26. Results show that soot mass largely contributed to PM mass, to the order of 50% to 80% mass fraction. No clear trend was observed between soot mass emissions and ethanol addition.

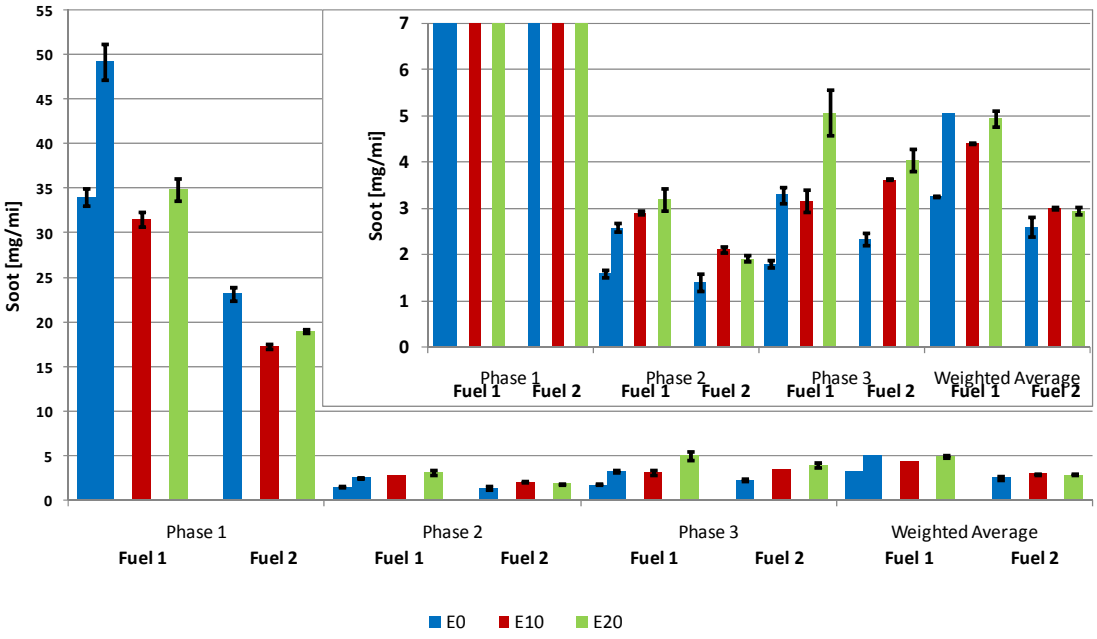


FIGURE 24. SOOT MASS EMISSIONS FOR VEHICLE A

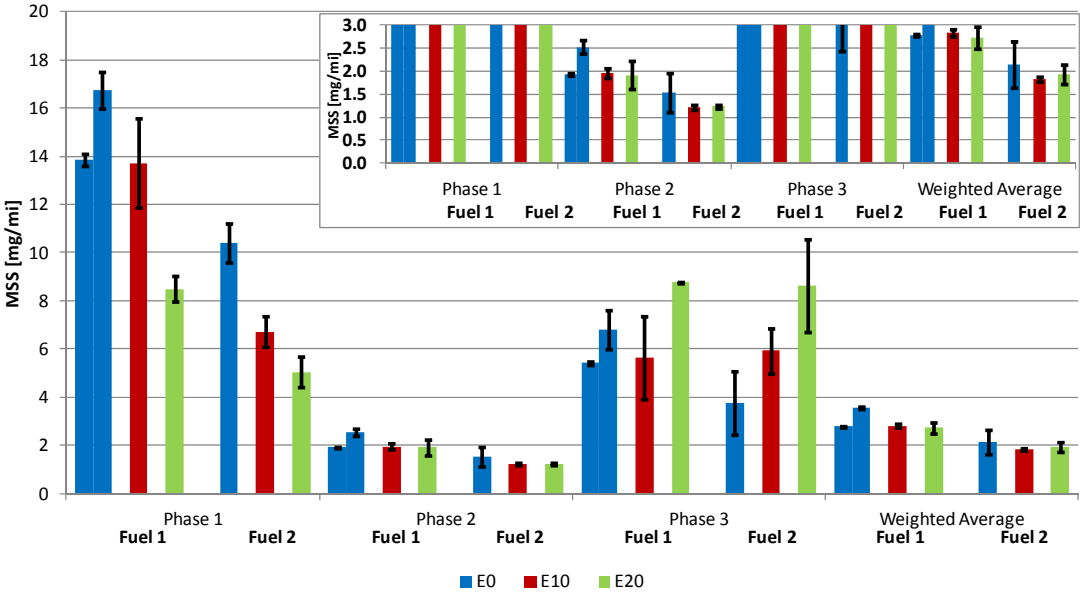


FIGURE 25. SOOT MASS EMISSIONS FOR VEHICLE B

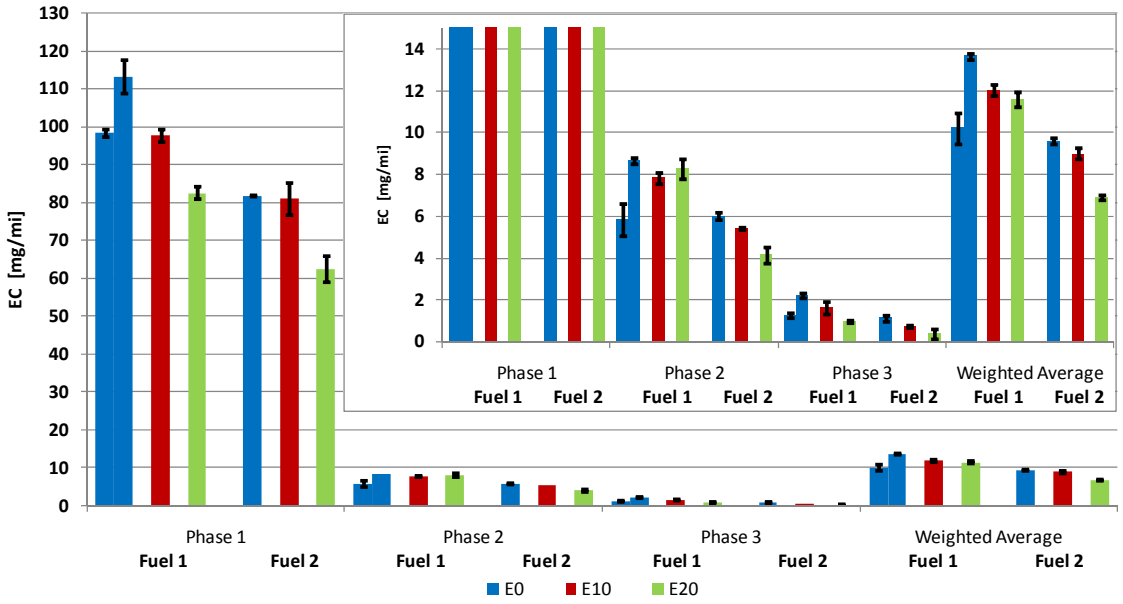


FIGURE 26. SOOT MASS EMISSIONS FOR VEHICLE C

Soot mass emissions, among other particle measurements, showed a shift when testing the same fuel at the beginning and end of the program. Fuel 1 with no ethanol addition was the first and last fuel tested in this program. Ideally, a given fuel would show the same repeatable results when tested at different times, but Figure 27 shows that soot mass emissions from a given vehicle and fuel were not repeatable.

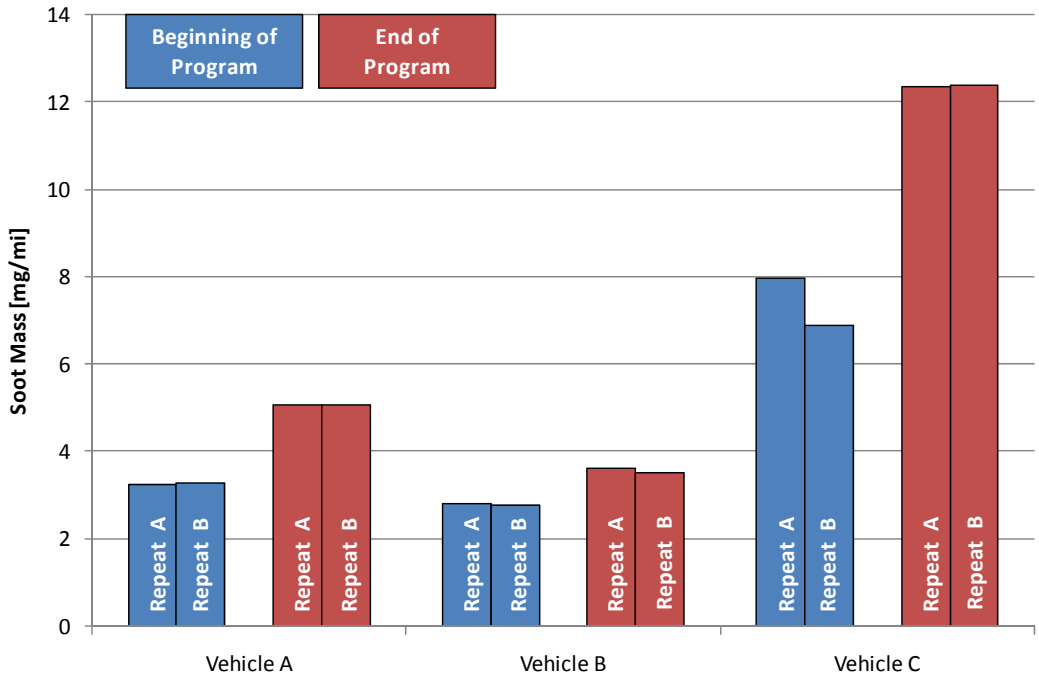


FIGURE 27. SHIFT IN SOOT MASS EMISSIONS BETWEEN BEGINNING AND END OF PROGRAM: FUEL 1, 0% ETHANOL

This shift in emissions that showed a notable change is quantified in Table 15 as the percent change in PM, Soot, THC, CO and NO_X. Two consecutive emission tests (a *data range*, see Figure 28), were run at the beginning of the program, and two emissions tests were run at the end of the program. The values in Table 15 are the percent change in the average of two consecutive tests. It is important to note that the percent changes listed do not show overlapping data ranges. Those that do are listed as "data ranges overlap" since pre- and post-emissions were comparable.

Additionally, repeatability criteria are not computed the same way as percent change. The difference between the two values is described in Figure 31. The percent change describes the change between the beginning and end of the project, while repeatability shows how two consecutive emissions tests compare to each other.

TABLE 15. CHANGE IN EMISSIONS: BEGINNING VERSUS END OF PROJECT

	Percent Change			Repeatability Criteria
	Vehicle A	Vehicle B	Vehicle C	
PM	+20%	data ranges overlap	+51%	n/a
Soot	+55%	+28%	+66%	n/a
THC	data ranges overlap	+61%	+30%	30%
CO	data ranges overlap	+21.7%	-13.2%	50%
NOx	+20.8%	-52.6%	data ranges overlap	50%

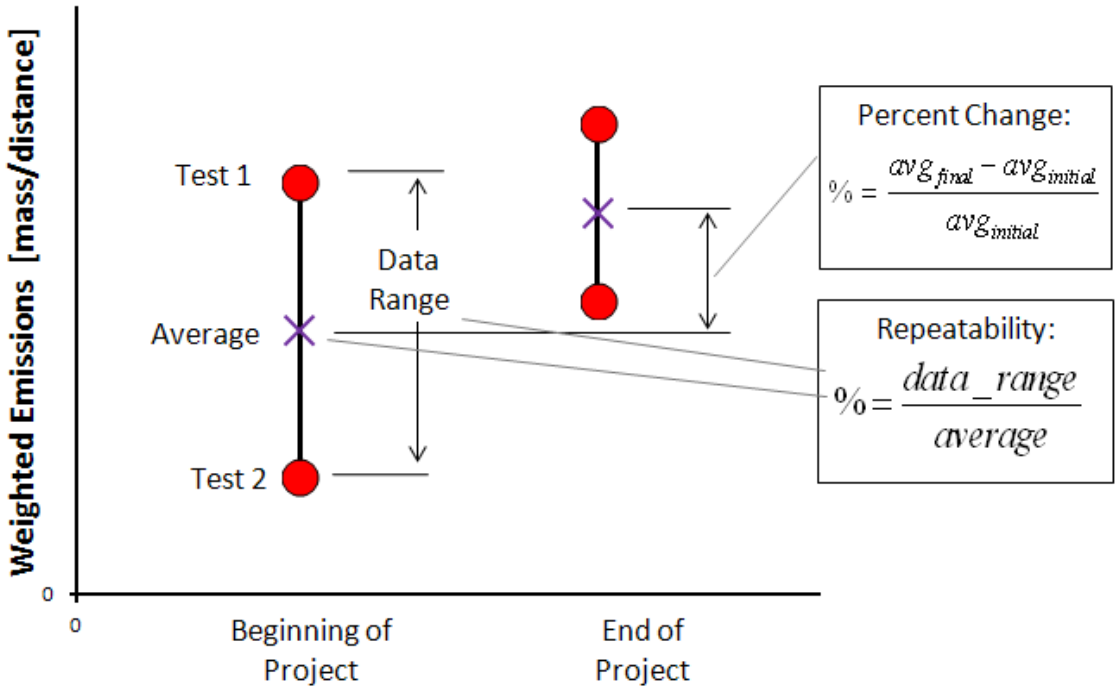


FIGURE 28. DETERMINING TEST REPEATABILITY AND PERCENT CHANGE

Figures 29 through 31 show the long-term fuel trim for all three vehicles on Fuel 1, E0 at the beginning and end of the program. Figure 32 shows that the long-term fuel trim was not the same when testing the same fuel at the beginning and end of the program for one of the vehicles. This suggests that the vehicle's preconditioning before each emissions test was insufficient for the vehicle to adapt properly to a new fuel.

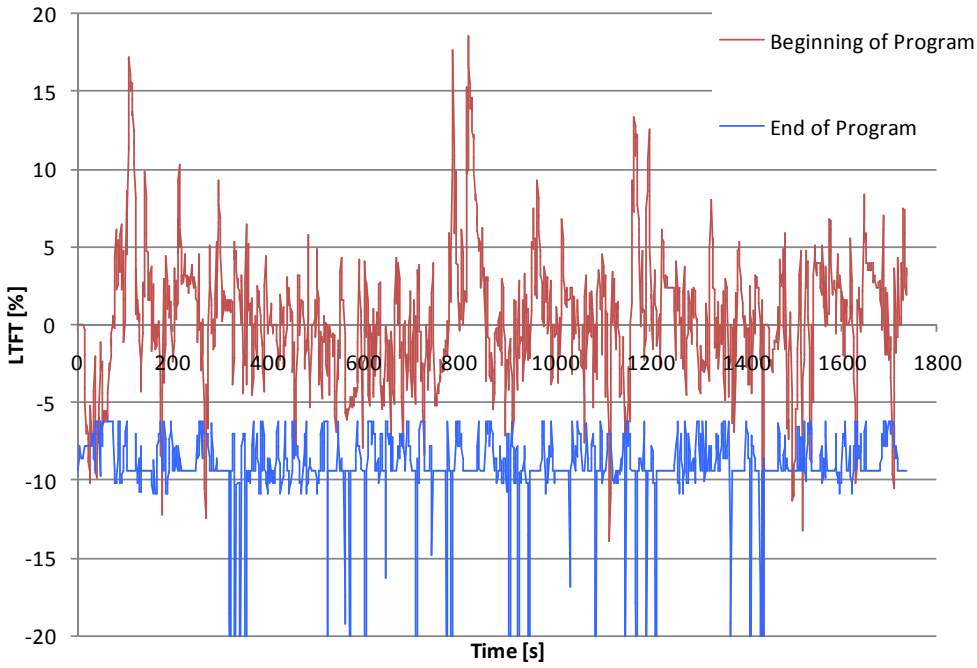


FIGURE 29. SHIFT IN LONG-TERM FUEL TRIM – VEHICLE A

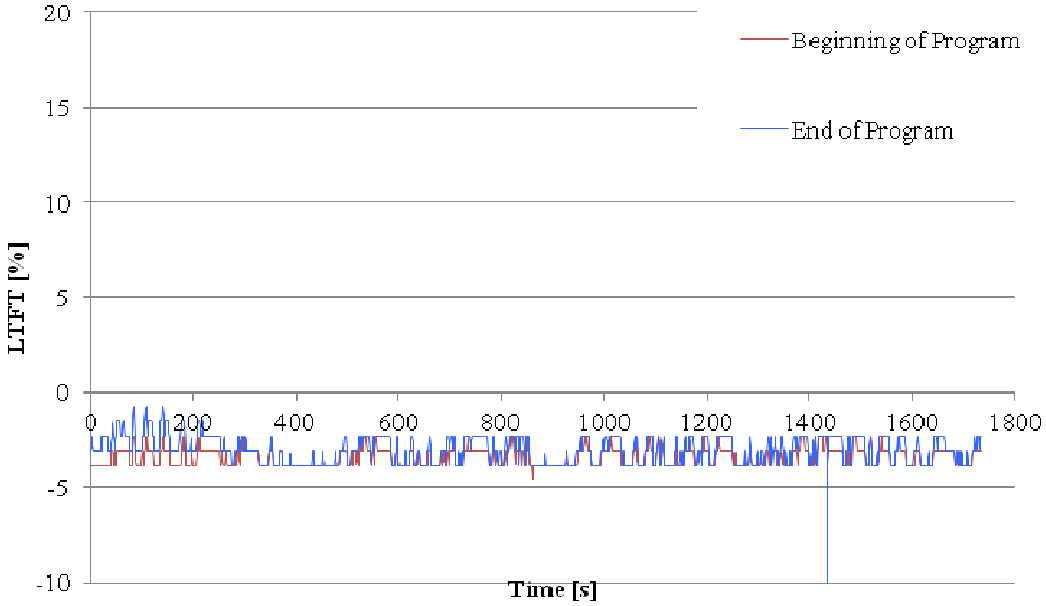


FIGURE 30. SHIFT IN LONG-TERM FUEL TRIM – VEHICLE B

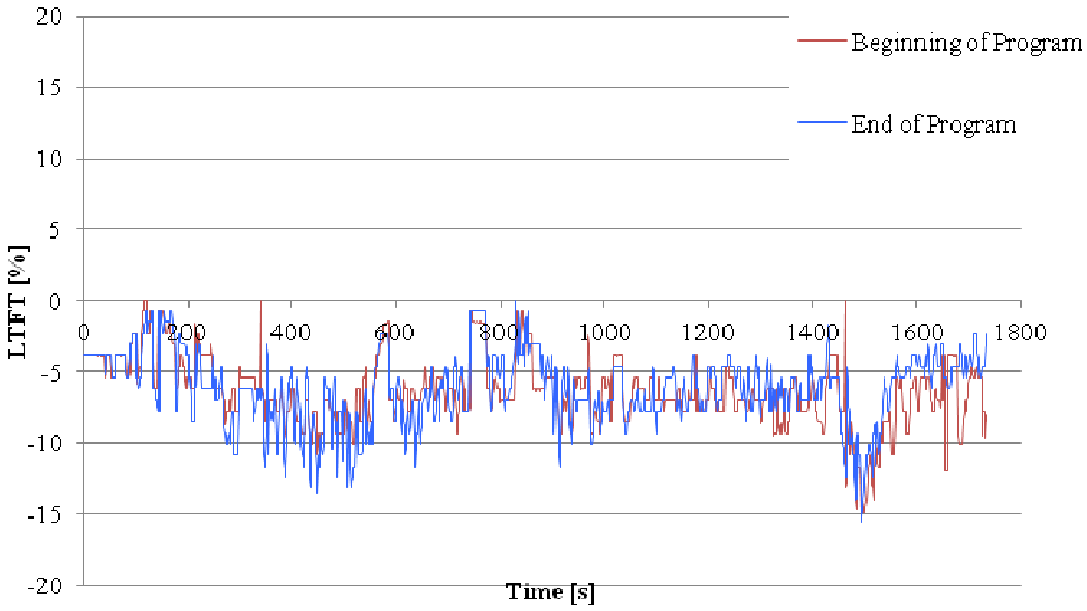


FIGURE 31. SHIFT IN LONG-TERM FUEL TRIM – VEHICLE C

4.3.3 Elemental Carbon /Organic Carbon Analyses (EC/OC)

EC/OC analyses were performed using Sunset Laboratories Inc Lab thermal/optical carbon aerosol analyzer. Results from the primary filters were corrected for the gas–phase organic artifact, for background air and for dilution air.

Overall, total carbon obtained from the analyses (sum of elemental and organic carbon) demonstrated good correlation with total particulate obtained from the PM mass measurements. The weighted averages of total carbon and PM for every test throughout the program are shown in Figure 32. Additionally, the weighted averages of only EC and PM for the each test are shown in Figure 33. An apparent outlier was noted on each figure. All of the data for this outlier was verified. The EC and OC data on this outlier were similar to the other repeats on that fuel, but the PM data were different, which caused this point to be lower than the trend.

The majority of the PM consisted of elemental carbon. Figures 34 through 36 show elemental carbon emissions for Vehicles A, B and C respectively. Trends for elemental carbon match those observed from the PM mass and soot mass measurements. There was no apparent impact in the EC emissions within the same type of fuel with increasing ethanol addition.

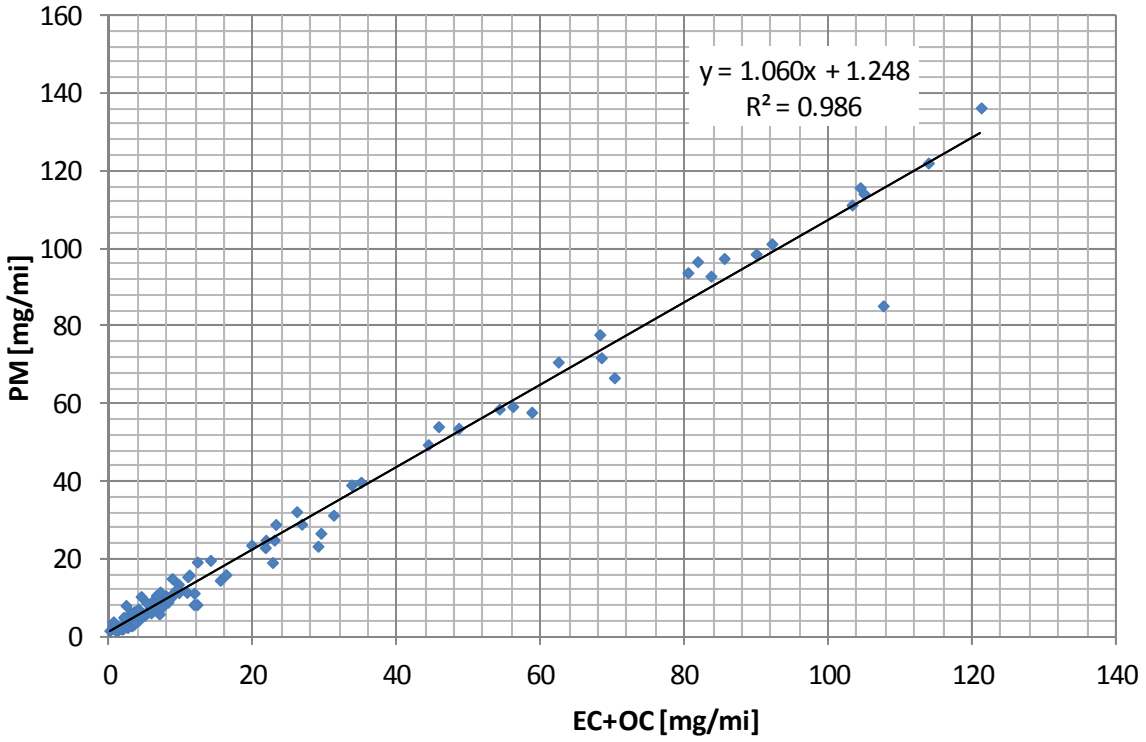


FIGURE 32. CORRELATION BETWEEN TOTAL CARBON AND PM FILTER MEASUREMENT

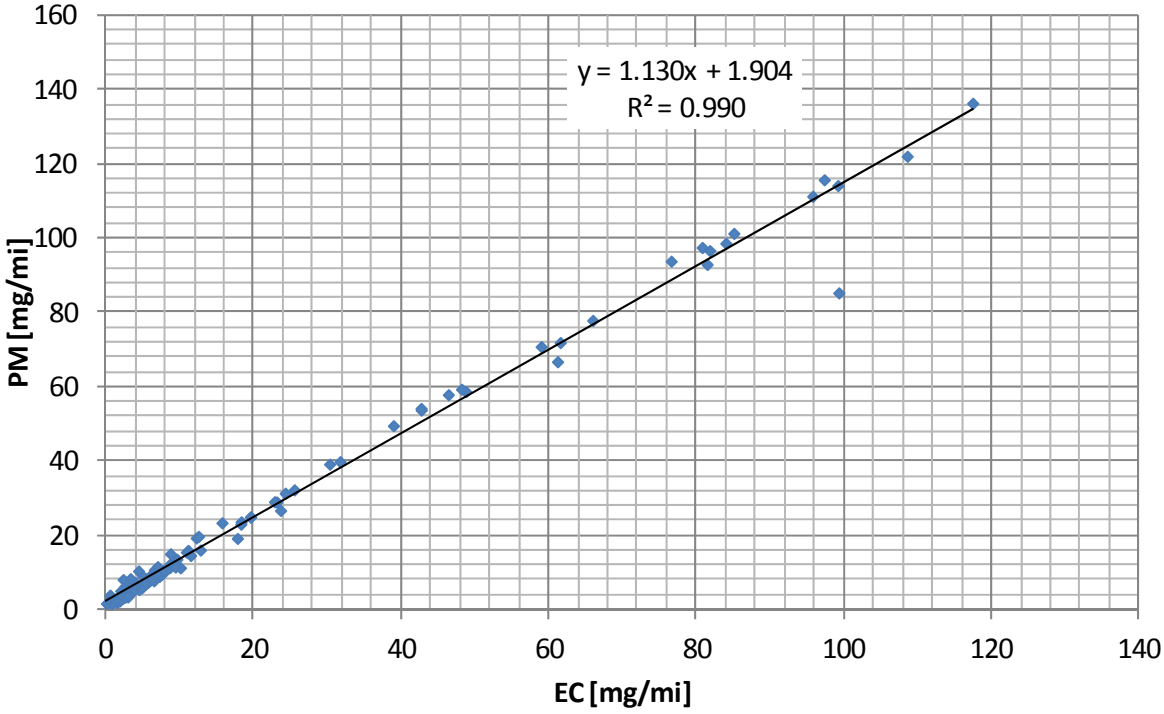


FIGURE 33. CORRELATION BETWEEN ELEMENTAL CARBON AND PM FILTER MEASUREMENT

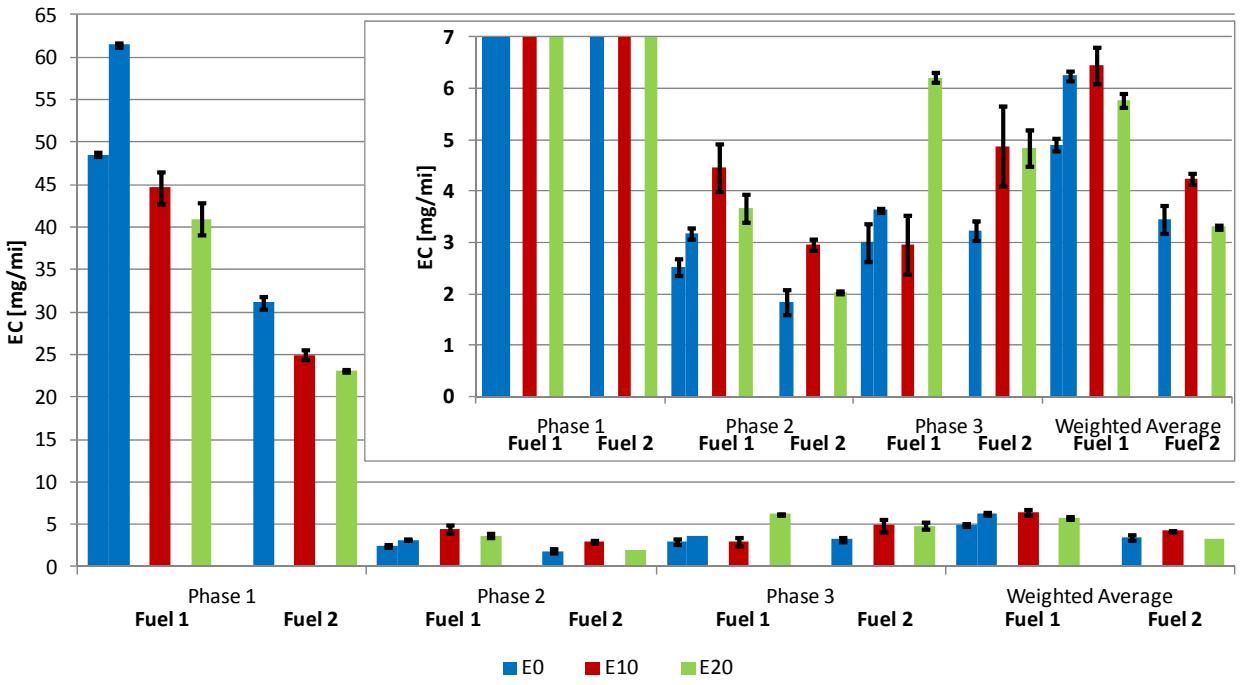


FIGURE 34. VEHICLE A ELEMENTAL CARBON

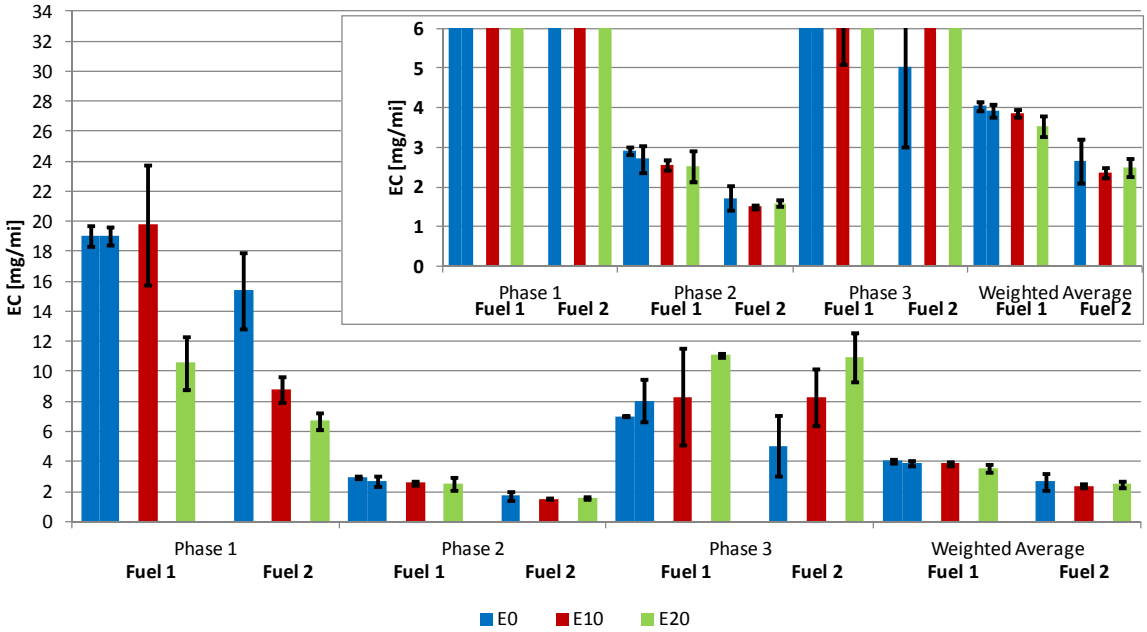


FIGURE 35. VEHICLE B ELEMENTAL CARBON

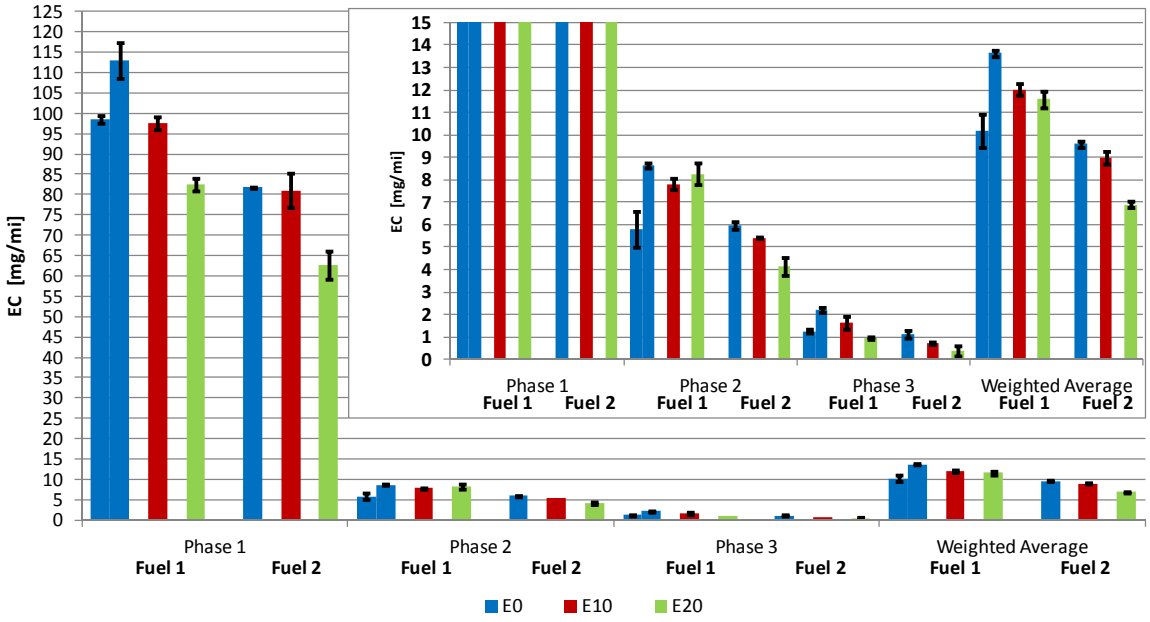


FIGURE 36. VEHICLE C ELEMENTAL CARBON

Organic fraction carbon (OC) was much lower than EC for most of the tests phases, and displayed higher variability between tests. Correction for the VOC artifact, as described in Section 3.3.3.6, practically eliminated any measured OC from several of the Phase 2 and Phase 3 samples. PM emissions in Phases 2 and 3 were low enough to result in OC measurements being mostly noise. Figures 37 through 39 show OC emissions for Vehicles A, B and C, respectively.

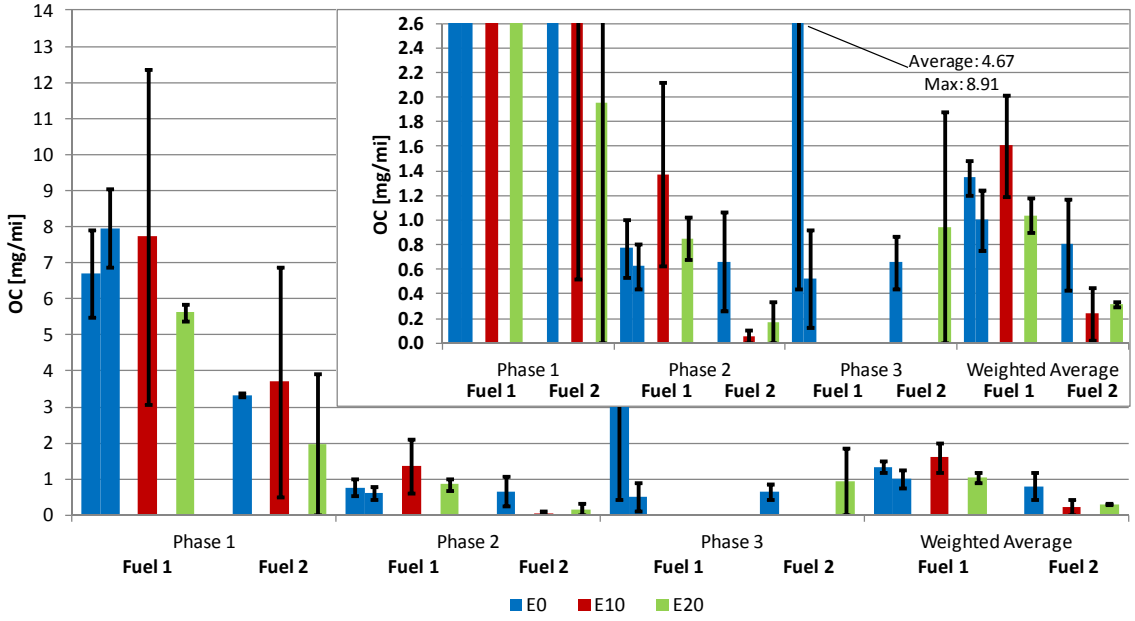


FIGURE 37. VEHICLE A ORGANIC CARBON

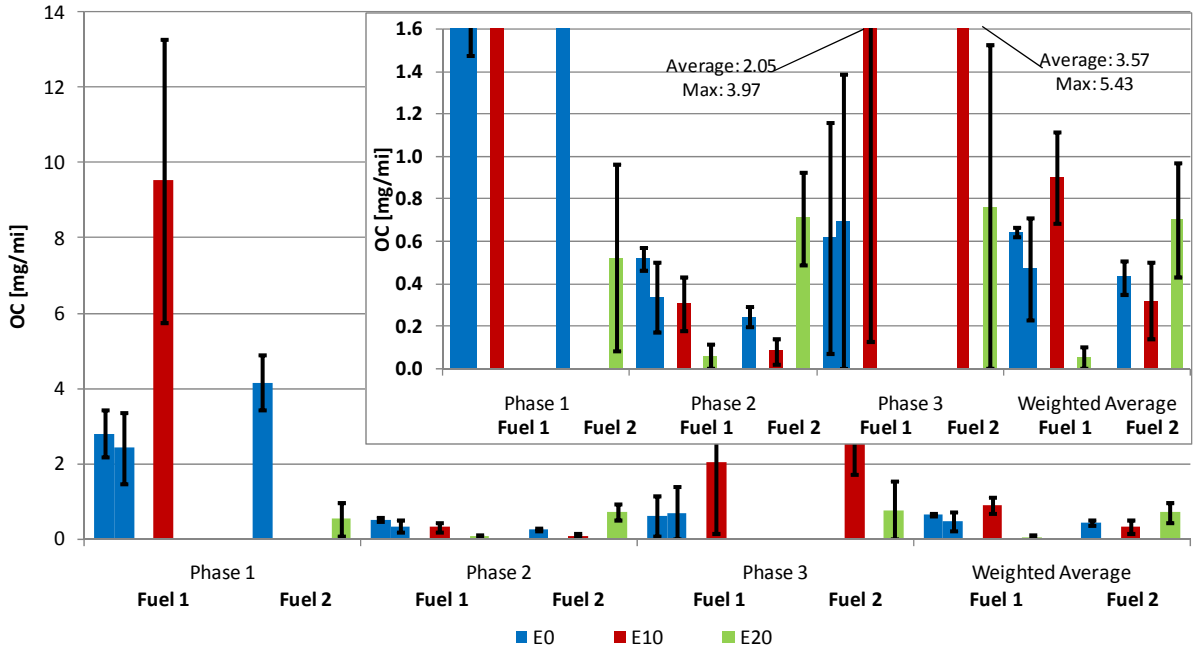


FIGURE 38. VEHICLE B ORGANIC CARBON

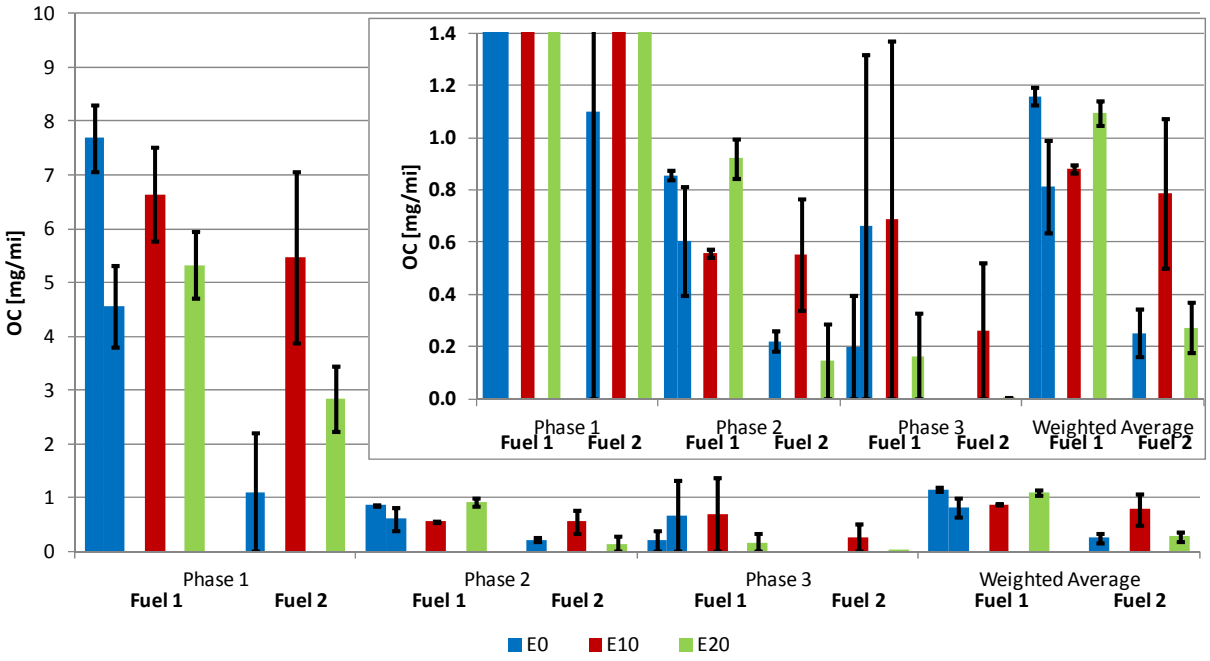


FIGURE 39. VEHICLE C ORGANIC CARBON

4.3.4 Particle Number (PN) Emissions

Particle number emissions measured with the CPC 3790 and CPC 3025 tracked each other well throughout the program in terms of trending on a phase-wise basis. As an example, Figures 40 and 41 show results from the two CPCs for Vehicle A.

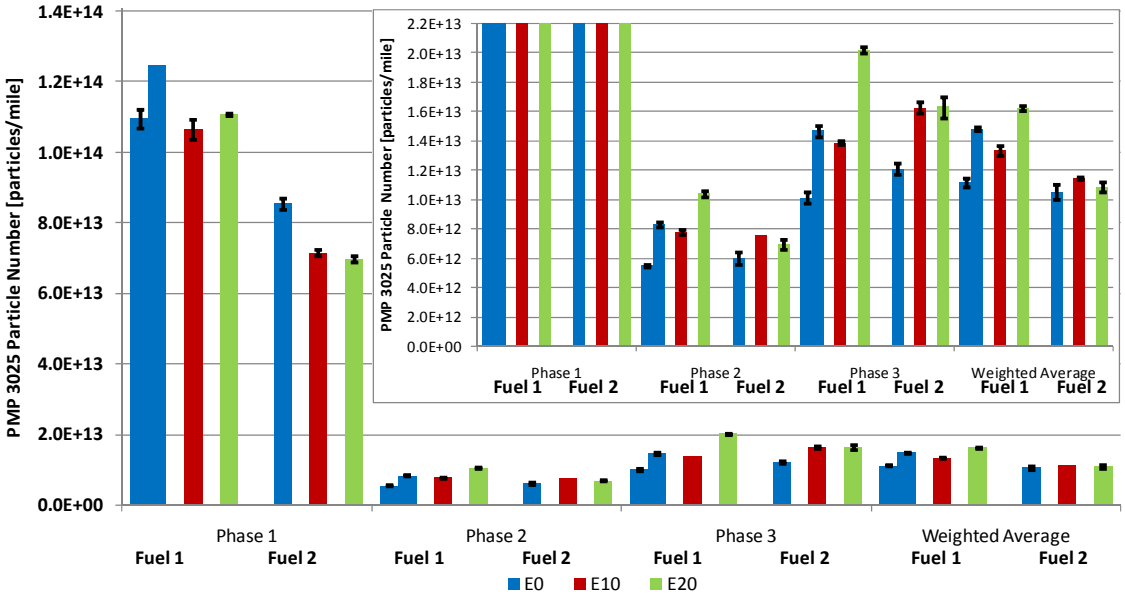


FIGURE 40. SOLID PARTICLE NUMBER EMISSIONS MEASURED BY CPC 3025 (>3 NM) FOR VEHICLE A

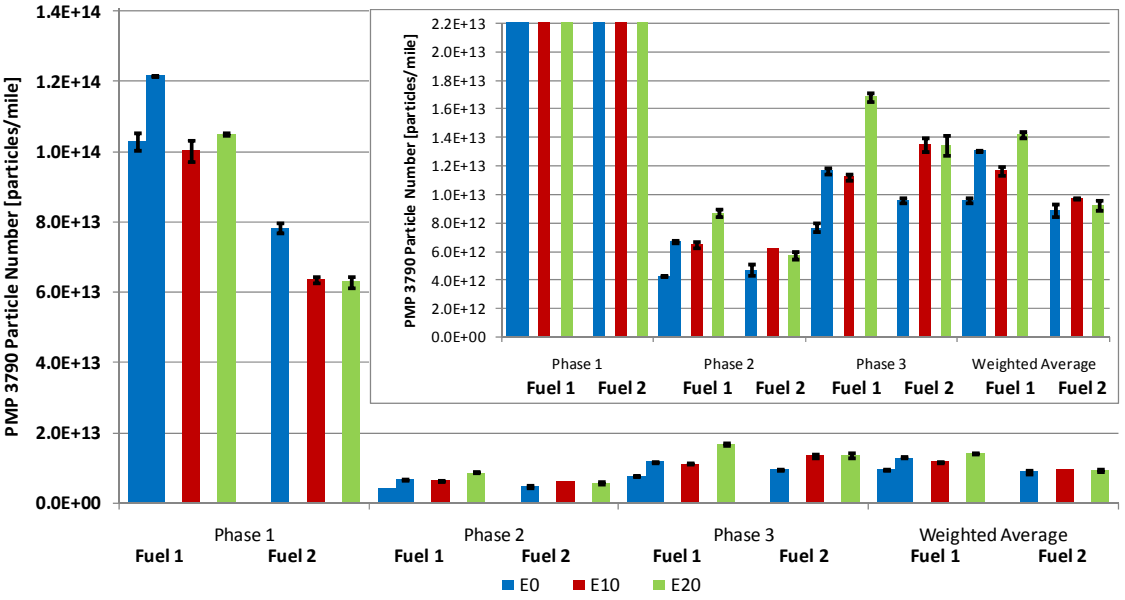


FIGURE 41. SOLID PARTICLE NUMBER EMISSIONS MEASURED BY CPC 3790 (>23 NM) FOR VEHICLE A

The average $\frac{\text{CPC 3025}}{\text{CPC 3790}}$ ratio was calculated for each phase for each vehicle (Table 16); a ratio greater than 1 indicates the presence of solid particles in the 3 nm to 23 nm size bin. Table 16 gives a sense of the amount of total particles that are in this smallest size bin. Phase-wise particle size distributions provide further insight into these ratios. Particle size distributions are discussed in the next section, Section 4.3.5. Additionally, the trends observed in the PN measurements correlated well with soot mass observations (micro-soot sensor). PN emissions for Vehicles B and C for CPC 3790 are shown in Figures 42 and 43, while those for the CPC 3025 are shown in Appendix E.

TABLE 16. $\frac{CPC3025}{CPC3790}$ RATIO

	Phase 1	**Phase 2**	**Phase 3**
Vehicle A	1.06	1.3	1.3
Vehicle B	1.07	1.2	1.1 to 1.2
Vehicle C	0.96	1.1	1.4

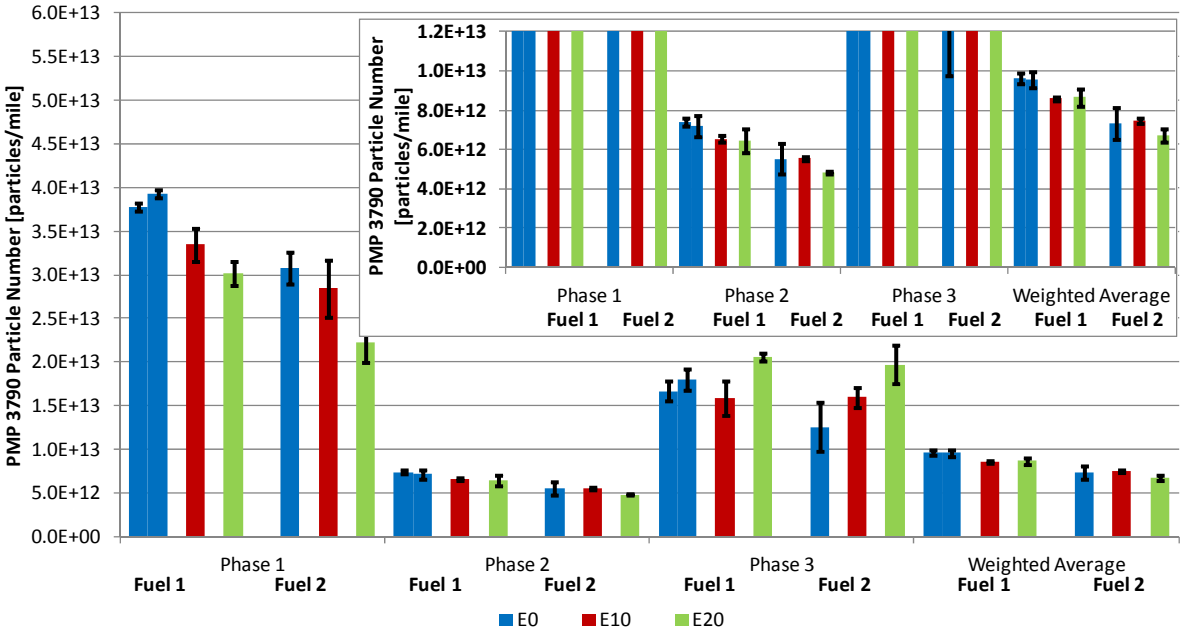


FIGURE 42. SOLID PARTICLE NUMBER EMISSIONS MEASURED BY CPC 3790 (>23 NM) FOR VEHICLE B

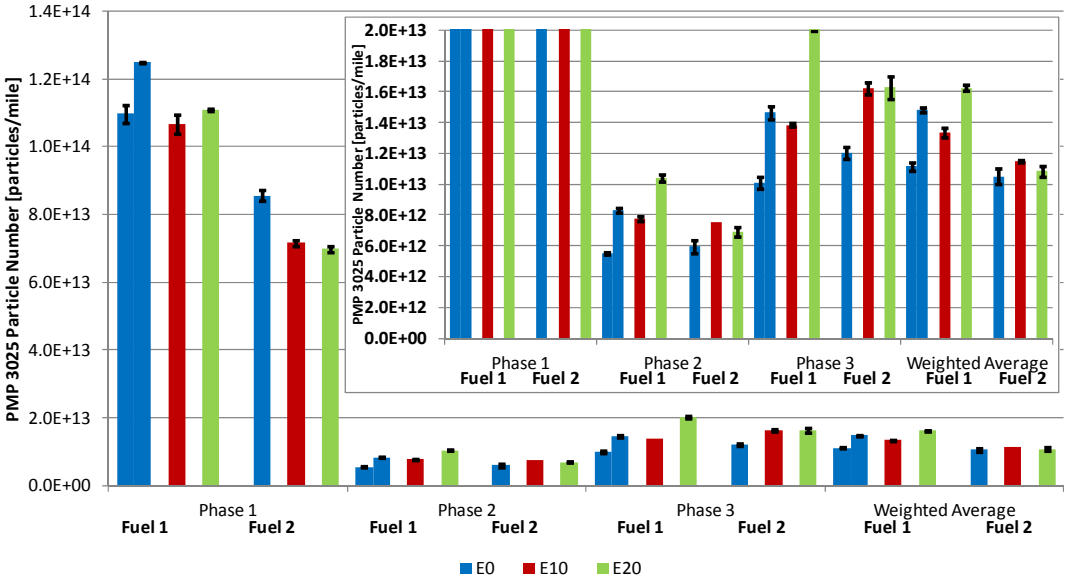


FIGURE 43. SOLID PARTICLE NUMBER EMISSIONS MEASURED BY CPC 3790 (>23 NM) FOR VEHICLE C

4.3.5 Particle Size Distribution

TSI's model 3790 Engine Exhaust Particle Sizer (EEPS) was used to measure real time particle size distribution. The EEPS was used in conjunction with the Solid Particle Sampling System (SPSS) as described in Section 3.3.3. Typical size distributions observed for the three test phases for each vehicle are shown in Figures 44 through 46.

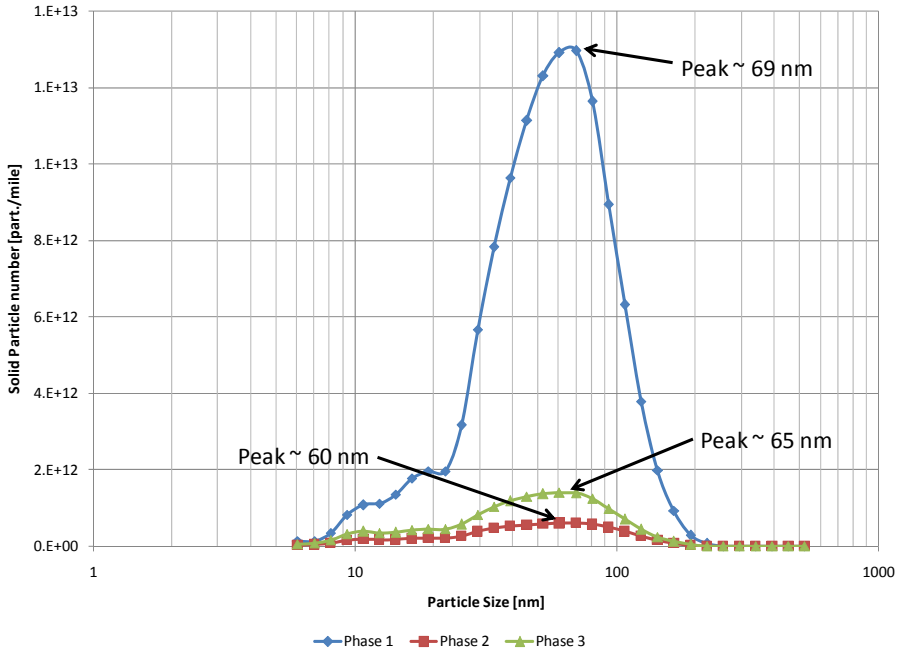


FIGURE 44. TYPICAL PARTICLE SIZE DISTRIBUTION FOR VEHICLE A

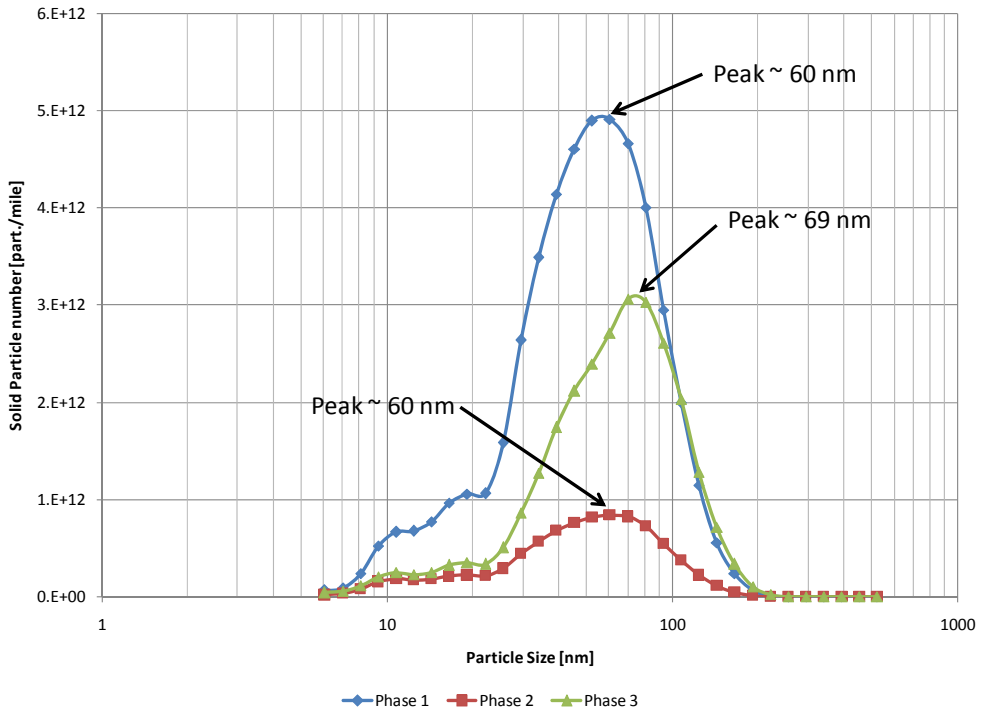


FIGURE 45. TYPICAL PARTICLE SIZE DISTRIBUTION FOR VEHICLE B

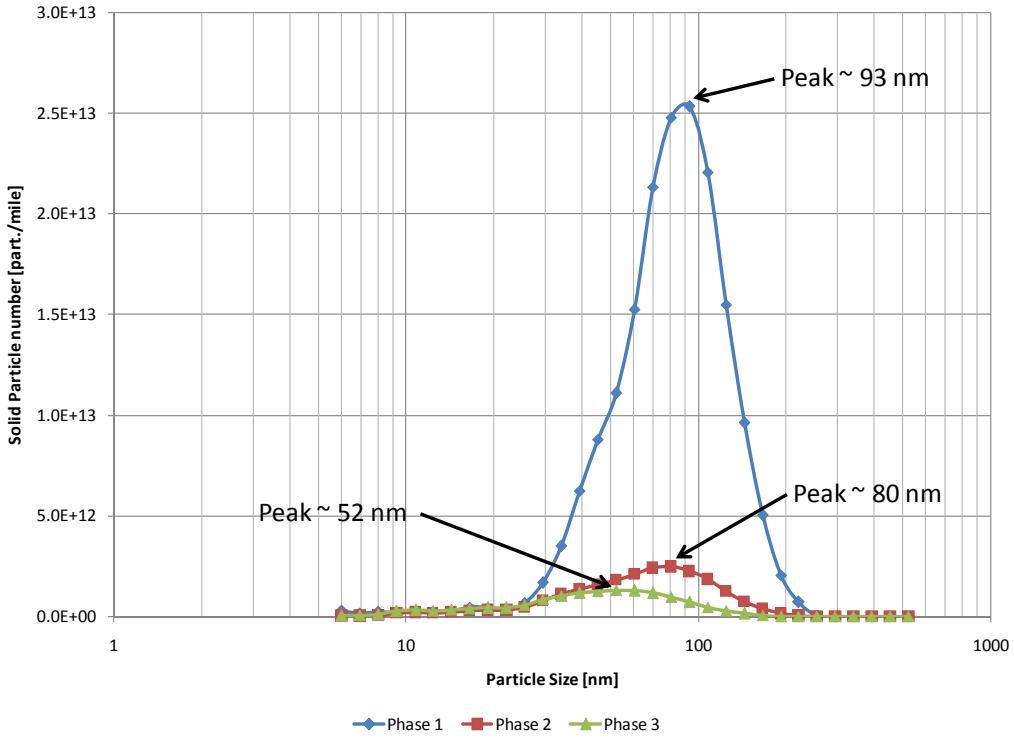


FIGURE 46. TYPICAL PARTICLE SIZE DISTRIBUTION FOR VEHICLE C

4.3.6 Real-time Particle Emissions

Figures 47 and 48 show typical real-time continuous traces of soot mass and solid particle number emissions for all three vehicles. The vehicle speed trace is overlaid on these graphs. As evidenced by Figures 50 and 51, cold-start acceleration events in Phase 1 contribute significantly towards cumulative emissions for all three vehicles.

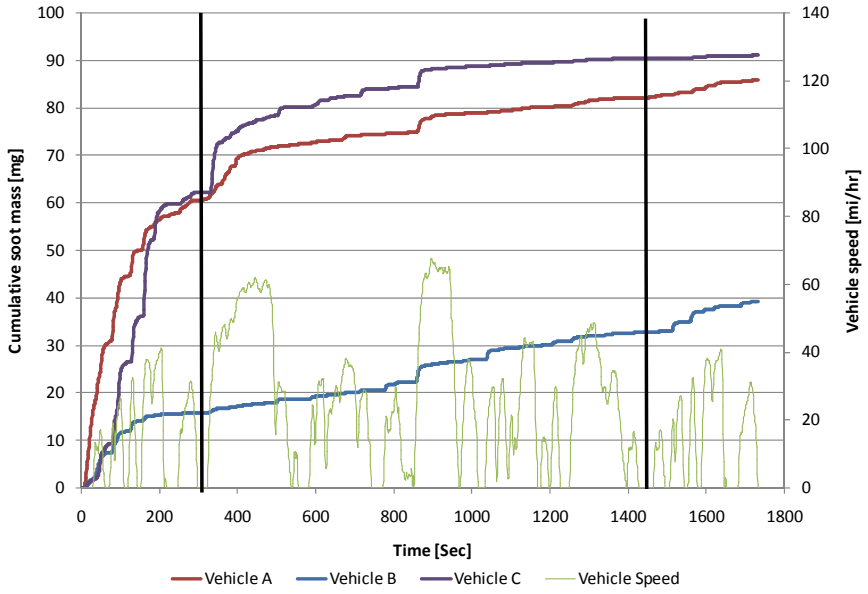


FIGURE 47. SOOT MASS EMISSIONS PROFILE FORVEHICLES A, B AND C; FUEL 1 WITH 0% ETHANOL

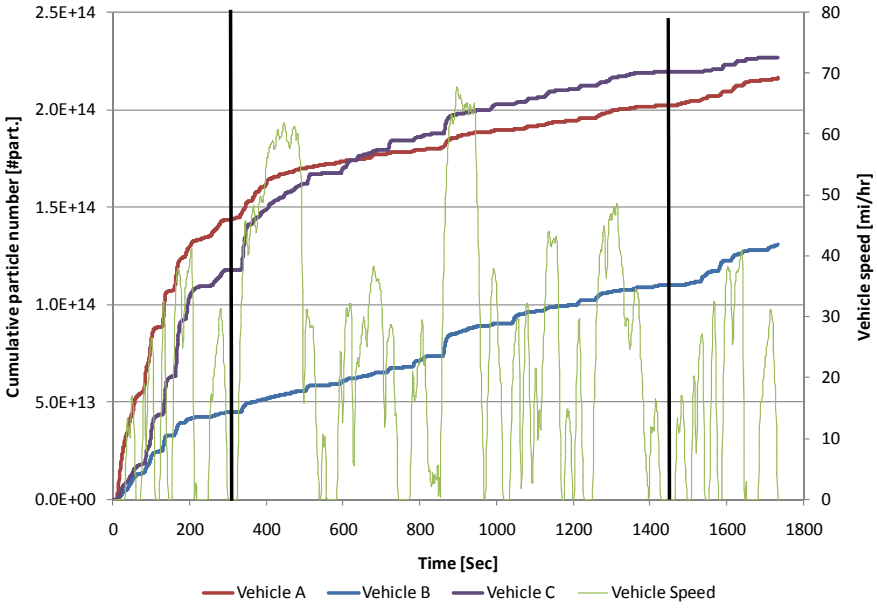


FIGURE 48. CPC 3790 TOTAL SOLID PARTICLE NUMBER EMISSIONS PROFILE (>23nm); FUEL 1 WITH 0% ETHANOL

Figure 49 highlights an interesting phenomenon observed for Vehicle B. The graph is composed of two sets of tests conducted with Fuel 1, 0% ethanol, one set from the beginning of the program and another one performed at the end as a drift check test. The circled regions show the differential occurrences of change in emission profiles, although, the final levels were very comparable. It was speculated that the vehicle's PM emissions spiked intermittently, possibly a result of the vehicle's calibration. This phenomenon was unique to Vehicle B, and further research may be required to understand its occurrence.

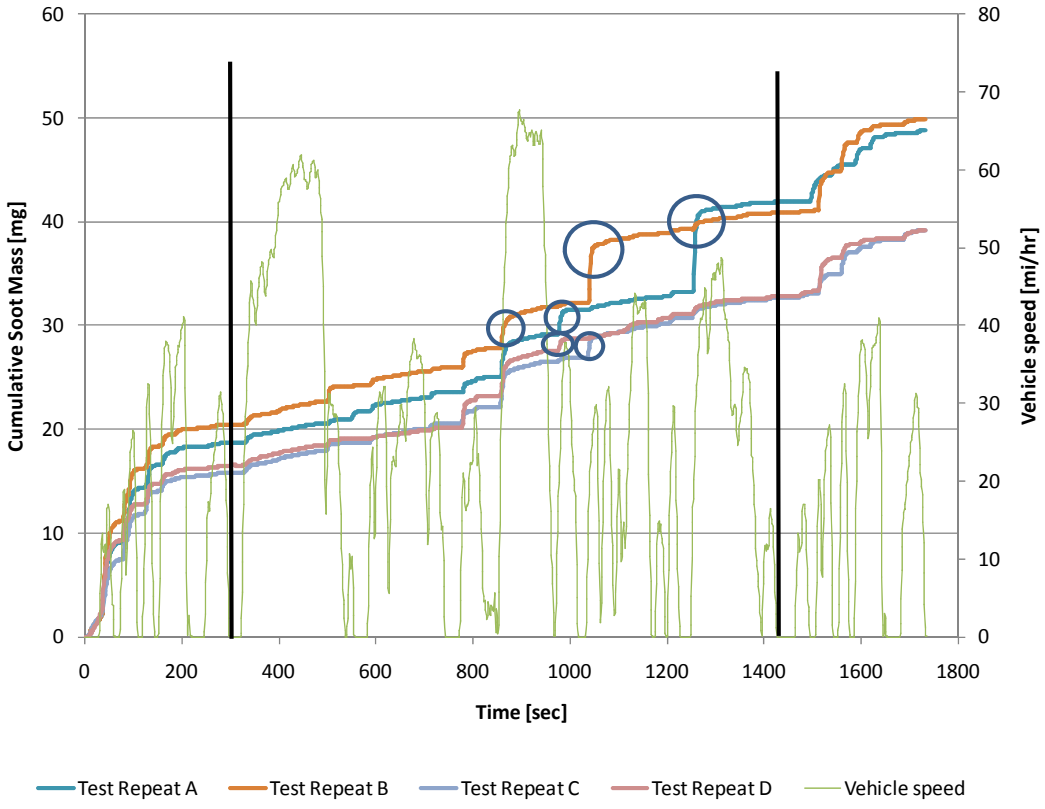


FIGURE 49. VARIABLE JUMPS IN SOOT MASS CONCENTRATIONS FOR VEHICLE B; FUEL 1 WITH 0% ETHANOL

5.0 OBSERVATIONS

Three modern direct-injected vehicles were tested to investigate how fuel ethanol addition and particle mass indices affect regulated gaseous, greenhouse gases, and particle emissions. The vehicles were tested using the California Unified Cycle (LA92). Two commercial hydrocarbon gasolines that differ in all properties, including PMI levels which span the range of those calculated based on surveys of the U.S. fuel supply in the summer of 2010, were each splash-blended with denatured ethanol at volume concentrations of 0%, 10% and 20%. This yielded a total of six fuels for testing. More data are needed to draw any firm conclusions regarding correlations between fuel PMI and emissions; however, the key observations from this project were:

1. Particulate emissions and some of the gaseous changed to varying degrees on the vehicles when tested on the same E0 fuel at the beginning and end of the test sequence. It was theorized that the vehicle conditioning procedure was not sufficient, and that future work is needed to determine this.

2. As expected, increased ethanol addition was consistent with decreased fuel economy, while there appeared to be no change in fuel economy between Fuel 1 and Fuel 2.

3. Particle emissions did not always decrease with increasing ethanol addition.

4. Soot mass emissions correlated closely with PM mass emissions. Additionally, PM mass emissions consisted primarily of Elemental Carbon, while Organic Carbon emissions showed much higher variability than Elemental Carbon.

5. Fuel 1 showed higher weighted average PM and PN emissions than Fuel 2 for any given ethanol addition (E0, E10, E20, respectively), with the exception of the results for Vehicle C with 0% ethanol.

6. Vehicle B showed inconsistent and seemingly random increases in soot mass emissions over the course of a LA92 drive cycle. Further research may be required to understand this phenomenon.

6.0 RECOMMENDATIONS FOR FUTURE WORK

A catalytic converter changes the gaseous (and, to a lesser extent, the particulate) emissions from a vehicle engine. For a new vehicle, this change is primarily a function of catalyst temperature. As a result, the apparent response of a vehicle to different fuel types can be affected by how quickly and repeatably the catalyst heats up. While the pre-catalyst temperature was measured throughout this program, measuring the post-catalyst temperature to determine the temperature change across the catalyst would be helpful in diagnosing changes in emissions.

The air-fuel ratio of an engine can also have a profound impact on fuel economy and emissions, both gaseous and particulate. For future work, it would informative to install a wide-band O_2 sensor, if space is available, to measure the air-fuel ratio of the vehicle's engine-out exhaust. Should emissions shift throughout testing, determining whether or not the A/F ratio is also changing would be very helpful.

The emissions and long-term fuel trims measured on two of the vehicles changed when tested with the same fuel at the beginning and end of project. More work could be done to study the vehicle conditioning procedure and its impact on how a modern SIDI vehicle learns and adapts to a new fuel. It would also be useful to study how a vehicle's emissions and fuel trims change over a longer time frame, such as four to five weeks. This could lead towards developing better preconditioning procedures for research purposes.

APPENDIX A

FUEL CHANGE, CONDITIONING, AND TEST PROCEDURE

FUEL CHANGE, CONDITIONING, AND TEST PROCEDURE

1. Drain vehicle fuel completely via fuel rail whenever possible.
2. Turn vehicle ignition to RUN position for 30 seconds to allow controls to allow fuel level reading to stabilize. Confirm the return of fuel gauge reading to zero.
3. Turn ignition off. Fill fuel tank to 30% with the next test fuel in sequence. Fill-up fuel temperature must be less than 50°F.
4. Start vehicle and execute catalyst sulfur removal procedure described in Appendix C. Apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system. Engine oil temperature in the sump will be measured and recorded during the sulfur removal cycle.
5. Perform four vehicle coast downs from 70 to 30 mph, with the last two measured. The vehicle will be checked for any obvious and gross source of change in the vehicle's mechanical friction if the individual run fails to meet the following repeatability criteria: 1) maximum difference of 0.5 seconds between back-to-back coastdown runs from 70 to 30 mph; and 2) maximum ±7 percent difference in average 70 to 30 mph coastdown time from the running average for a given vehicle.
6. Drain fuel and refill to 30% with test fuel. Fill-up fuel must be less than 50°F.
7. Drain fuel again and refill to 40% with test fuel. Fill-up fuel must be less than 50°F.
8. Take a fuel sample from the vehicle's fuel rail to be tested for ethanol content and octane number.
9. Check vehicle for diagnostic trouble codes (DTC). If new codes are detected the CRC Program Manager will be contacted.
10. Soak vehicle for at least 12 hours to allow fuel temperature to stabilize to the test temperature.
11. Move vehicle to test area without starting engine.
12. Start vehicle and perform 2-phase (bags 1 and 2) LA92 cycle. During these prep cycles, apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system.
13. Allow vehicle to idle in park for two minutes, then shut-down the engine for 2-5 minutes.
14. Start vehicle and perform the second 2-phase (bags 1 and 2) LA92 cycle. During these prep cycles, apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system.
15. Allow vehicle to idle in park for two minutes, then shut-down the engine for 2-5 minutes.
16. Start vehicle and perform 2-phase (bags 1 and 2) LA92 cycles. During these prep cycles, apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system.
17. Allow the vehicle to idle for two minutes, then shut down the engine in preparation for the soak.
18. Move vehicle to soak area without starting the engine.
19. Park vehicle in soak area at proper temperature (75 °F) for at least 8 hours and no more than 24 hours. During the soak period, maintain the nominal charge of the vehicle's battery using an appropriate charging device.
20. Move vehicle to test area without starting engine.
21. Perform LA92 cycle emissions test.
22. Move vehicle to soak area without starting the engine.

23. Park vehicle in soak area of proper temperature for 8-24 hours. During the soak period, maintain the nominal charge of the vehicle's battery using an appropriate charging device.
24. Move vehicle to test area without starting the engine.
25. Perform LA92 emissions test.
26. Move vehicle to soak area without starting the engine.
27. Determine whether third replicate is necessary, based on repeatability criteria (to be provided by CRC prior to start of test program).
28. If a third replicate is required, repeat steps 23 – 25.If third replicate is not required, return to step 1 and proceed with next fuel in test sequence.

APPENDIX B

CHECK-OUT EMISSIONS RESULTS FOR VEHICLES A, B, AND C

TABLE D-1. CHECKOUT EMISSONS RESULTS FOR VEHICLE A

	THC, g/mi	CO, g/mi	NO_X, g/mi	PM, mg/mi
EPA Test Car List Results for FTP-75	0.05	1.30	0.01	
Checkout Test Weighted Results on LA-92	0.05	0.71	0.07	5.7
Checkout Test Results on LA-92 Phase 1	0.34	2.73	0.10	34.6
Checkout Test Results on LA-92 Phase 2	0.03	0.59	0.07	3.8
Checkout Test Results on LA-92 Phase 3	0.05	0.77	0.02	8.2

TABLE D-2. CHECKOUT EMISSIONS RESULTS FOR VEHICLE B

	THC, g/mi	CO, g/mi	NO_X, g/mi	PM, mg/mi
EPA Test Car List Results for FTP-75*	0.02	0.37	0.01	
Checkout Test Weighted Results on LA-92	0.02	0.34	0.01	2.9
Checkout Test Results on LA-92 Phase 1	0.32	3.02	0.13	15.2
Checkout Test Results on LA-92 Phase 2	0.01	0.19	0.01	1.8
Checkout Test Results on LA-92 Phase 3	0.01	0.23	0.00	6.9
*Results from a manual transmission vehicle				

TABLE D-3. CHECKOUT EMISSIONS RESULTS FOR VEHICLE C

	THC, g/mi	CO, g/mi	NO_X, g/mi	PM, mg/mi
EPA Test Car List Results for FTP-75	0.02	0.57	0.01	
Checkout Test Weighted Results on LA-92	0.05	1.95	0.02	10.9
Checkout Test Results on LA-92 Phase 1	0.34	7.36	0.02	91.1
Checkout Test Results on LA-92 Phase 2	0.04	1.65	0.02	6.9
Checkout Test Results on LA-92 Phase 3	0.02	1.74	0.00	2.0

APPENDIX C

CATALYST SULFUR PURGE CYCLE

CATALYST SULFUR PURGE CYCLE

This procedure is designed to cause the vehicle to transiently run rich at high catalyst temperature, to remove accumulated sulfur from the catalyst, via hydrogen sulfide formation. The catalyst inlet temperature and the exhaust A/F ratio will be monitored during this procedure. It is required to demonstrate that the catalyst inlet temperature must exceed 700°C during the WOT accelerations and that rich fuel/air mixtures are achieved during WOT. If these parameters are not achieved, increased loading on the dynamometer could be added for this protocol (but not during the emissions test). Increased loading is not included in this proposal.

1. Drive the vehicle from idle to 55 mph and hold speed for 5 minutes (to bring catalyst to full working temperature).
2. Reduce vehicle speed to 30 mph and hold speed for one minute.
3. Accelerate at WOT (wide-open throttle) for a minimum of 5 seconds, to achieve a speed in excess of 70 mph. Continue WOT above 70 mph, if necessary to achieve 5-second acceleration duration. Hold the peak speed for 15 seconds and then decelerate to 30 mph.
4. Maintain 30 mph for one minute.
5. Repeat steps 3 and 4 to achieve 5 WOT excursions.
6. One sulfur removal cycle has been completed.
7. Repeat steps 1 to 5 for the second sulfur removal cycle.
8. The protocol is complete if the necessary parameters have been achieved.

APPENDIX D

COMPLETE EMISSIONS RESULTS

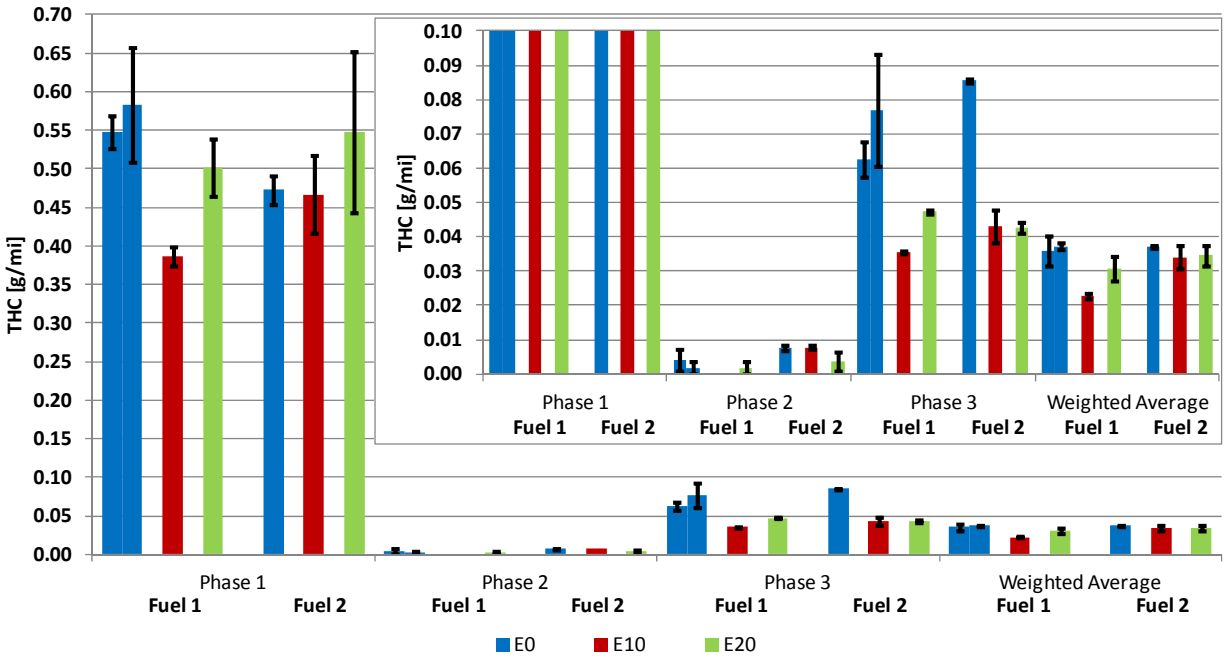


FIGURE D-1. VEHICLE A TOTAL HYDROCARBONS

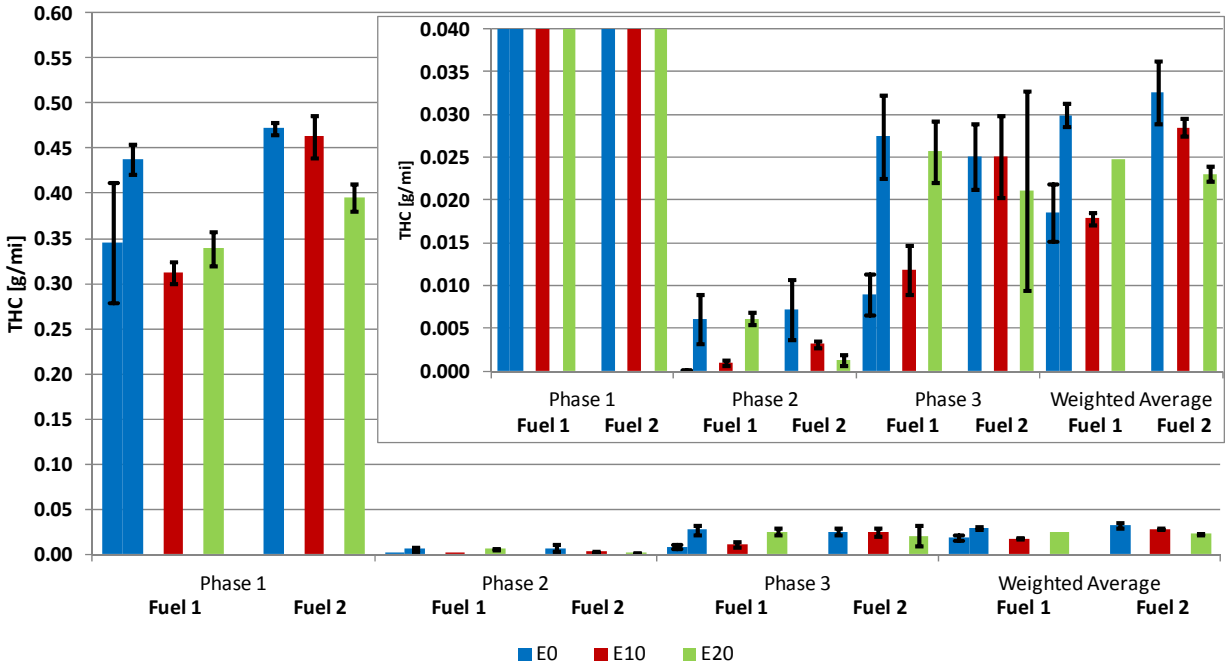


FIGURE D-2. VEHICLE B TOTAL HYDROCARBONS

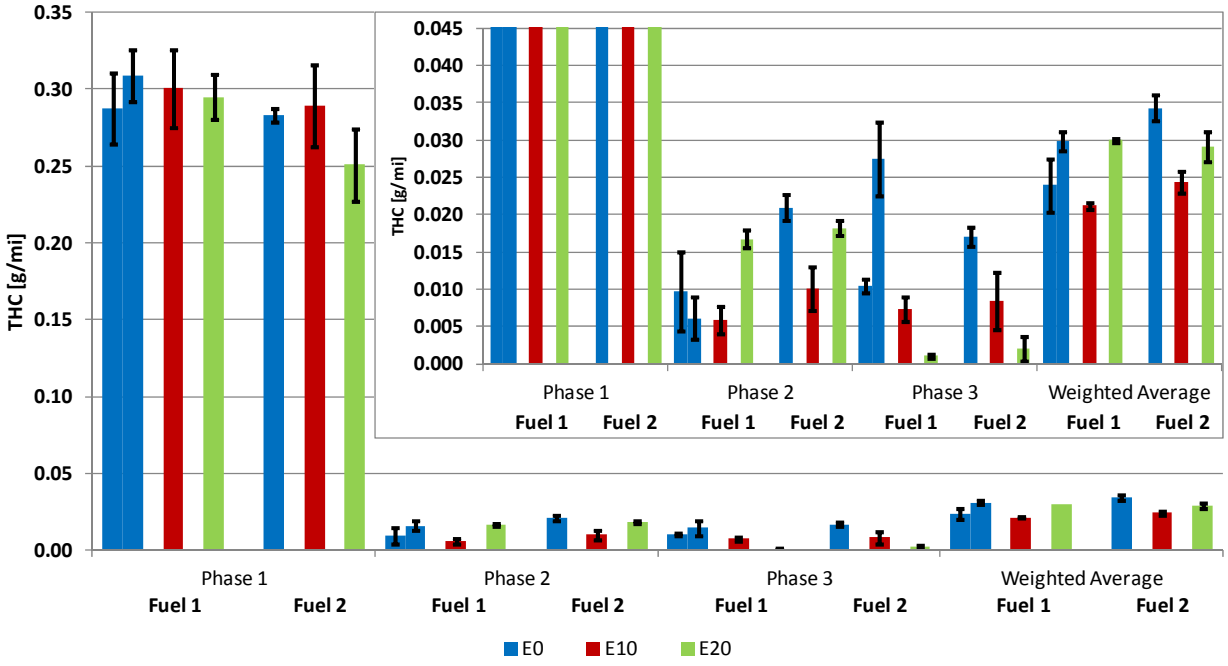


FIGURE D-3. VEHICLE C TOTAL HYDROCARBONS

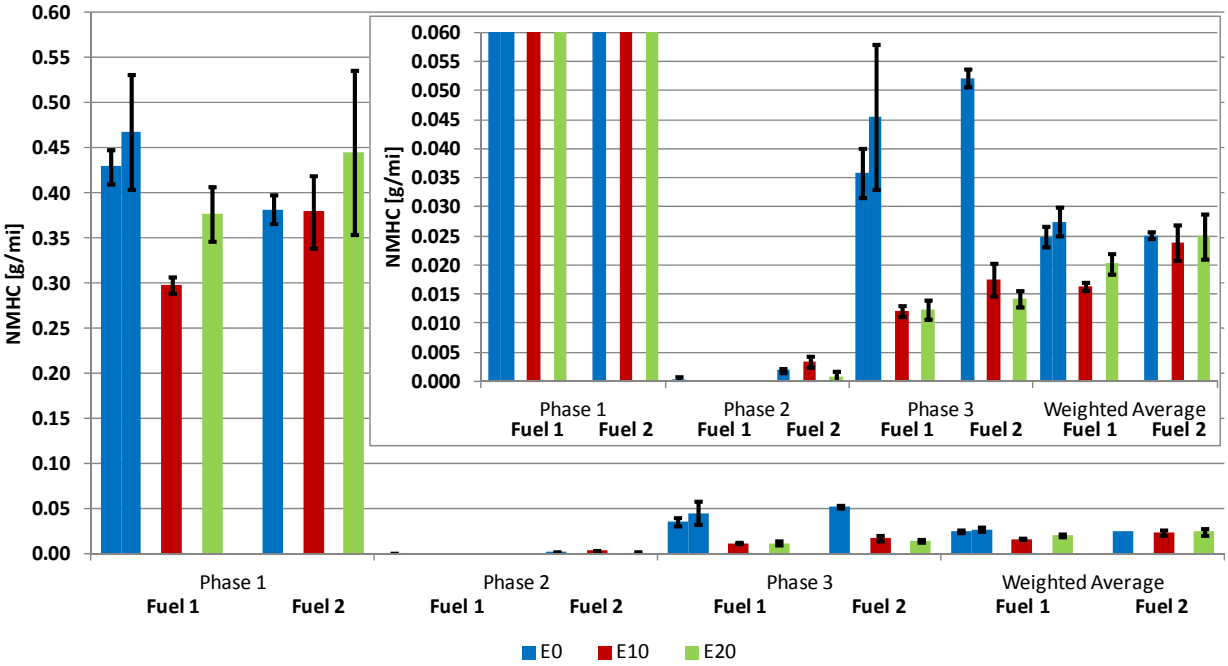


FIGURE D-4. VEHICLE A NON-METHANE HYDROCARBONS

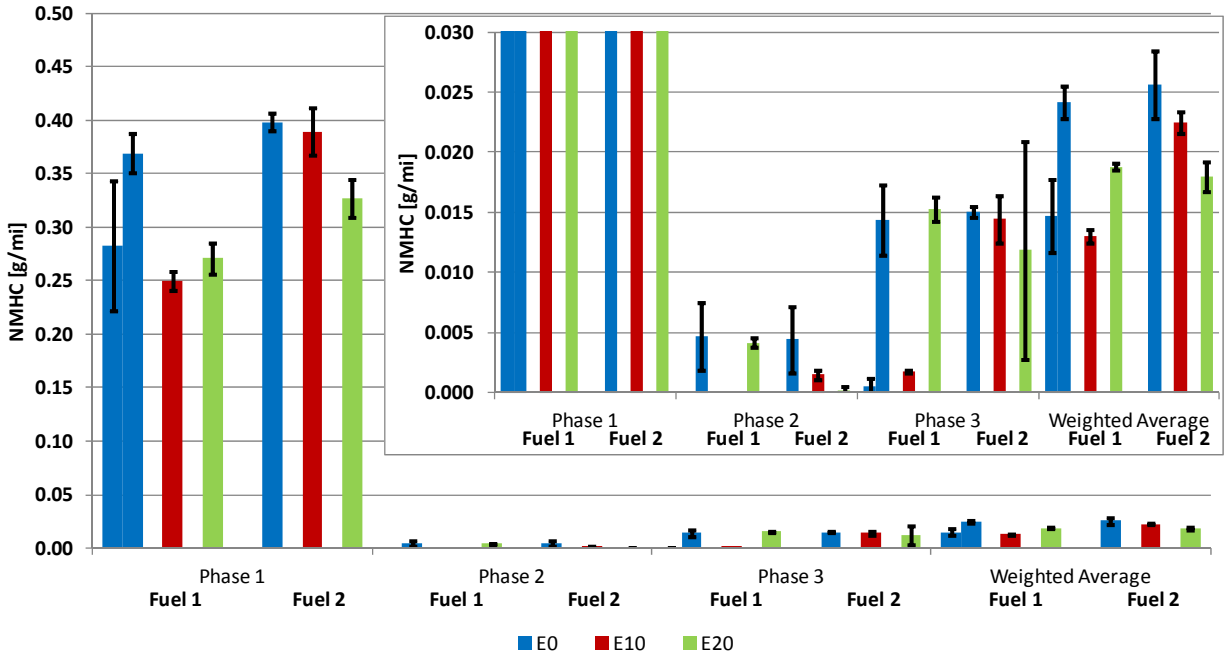


FIGURE D-5. VEHICLE B NON-METHANE HYDROCARBONS

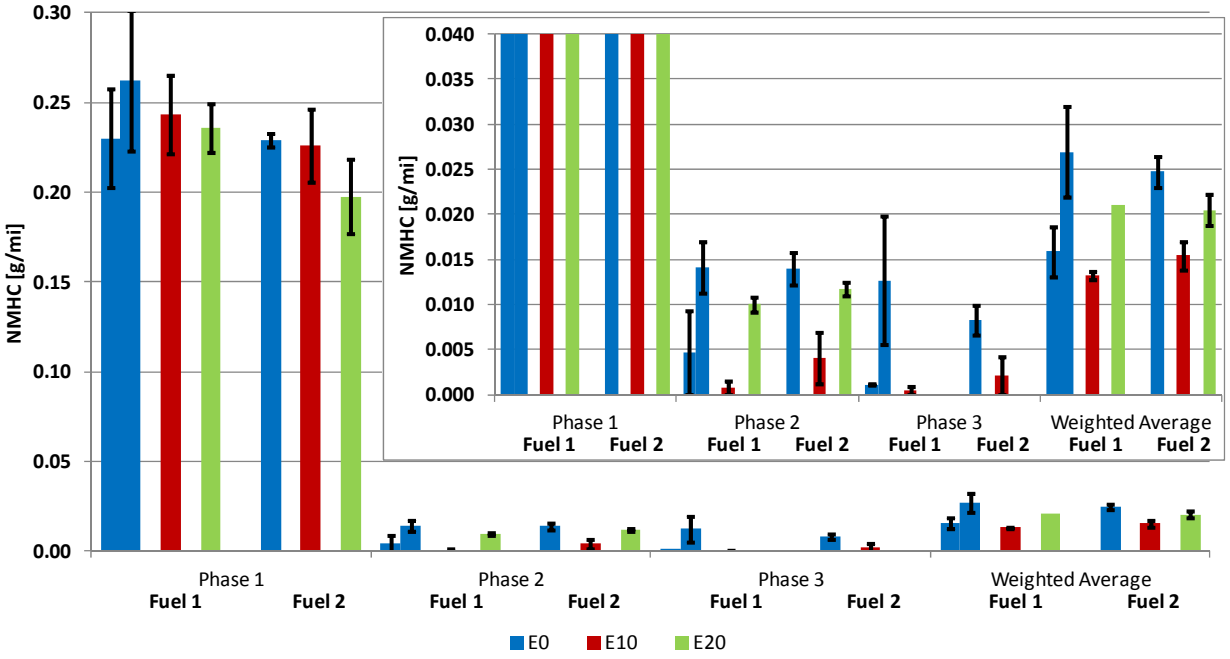


FIGURE D-6. VEHICLE C NON-METHANE HYDROCARBONS

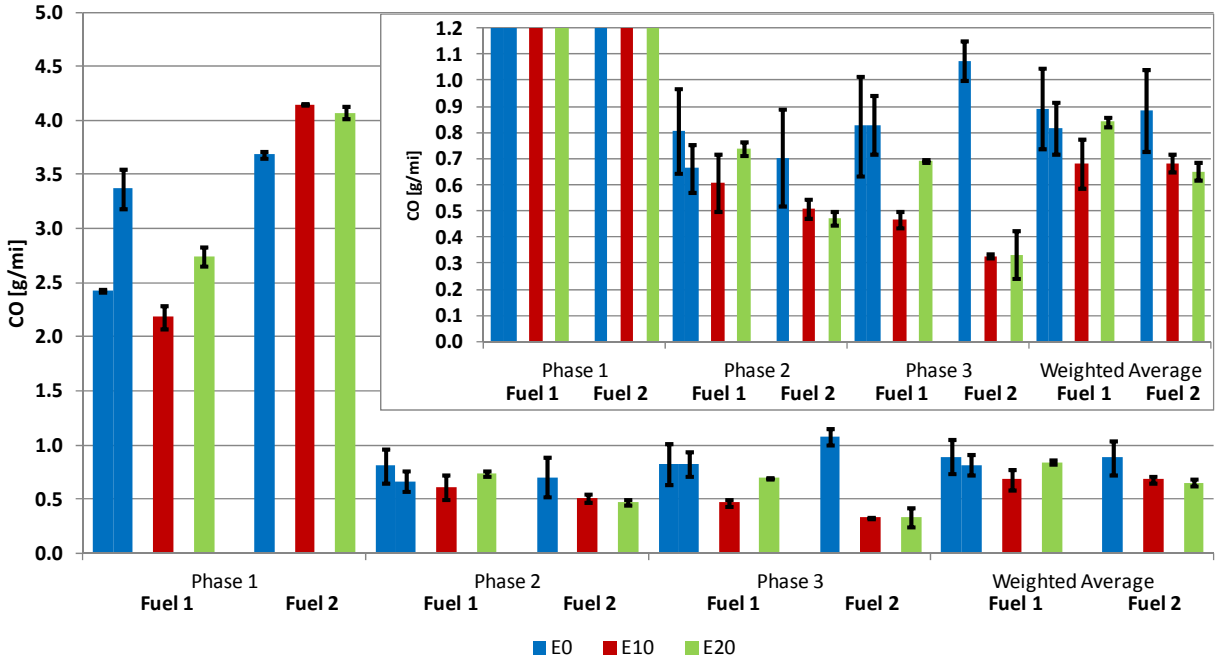


FIGURE D-7. VEHICLE A CARBON MONOXIDE

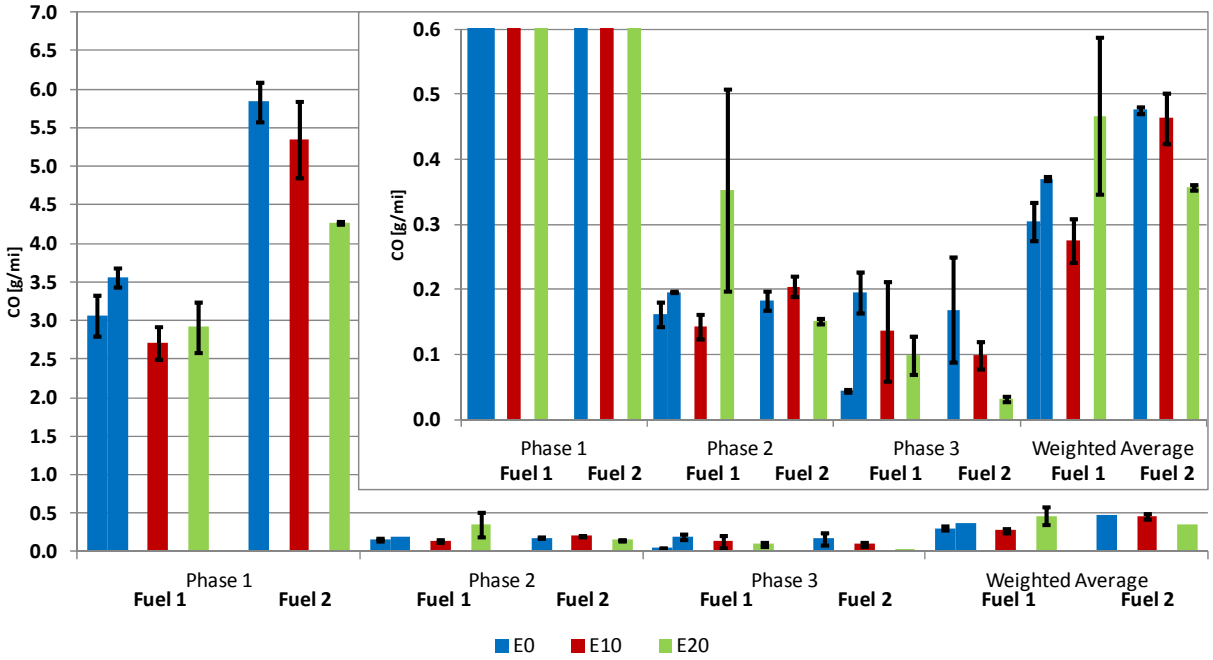


FIGURE D-8. VEHICLE B CARBON MONOXIDE

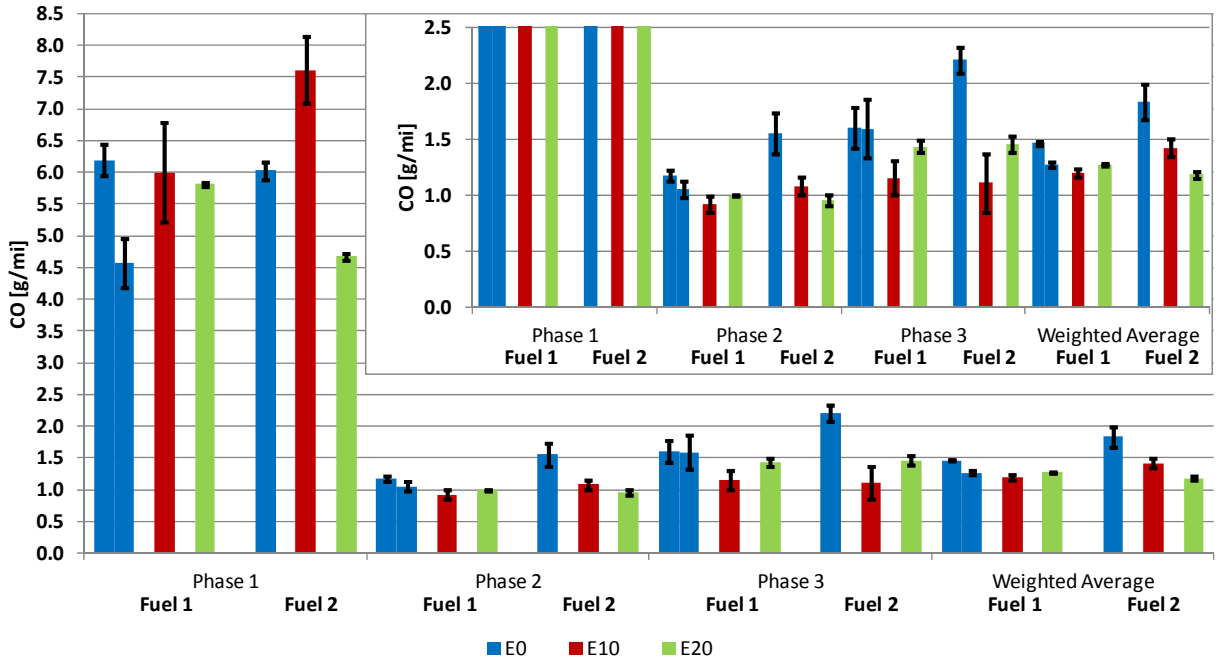


FIGURE D-9. VEHICLE C CARBON MONOXIDE

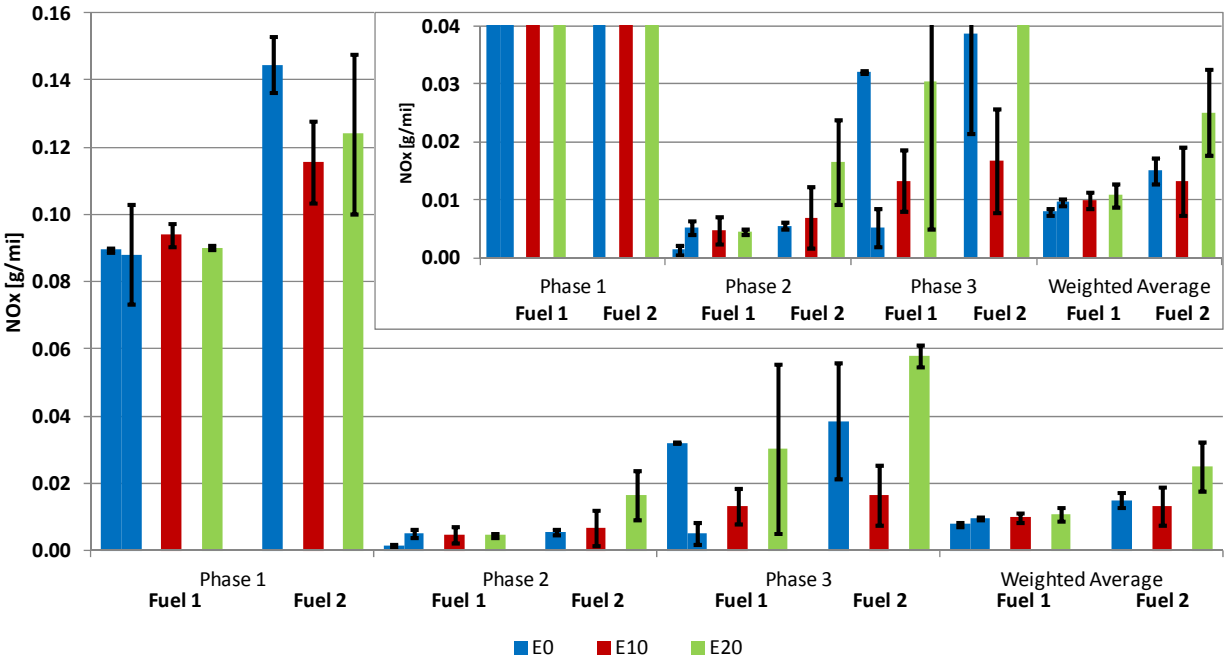


FIGURE D-10. VEHICLE A OXIDES OF NITROGEN

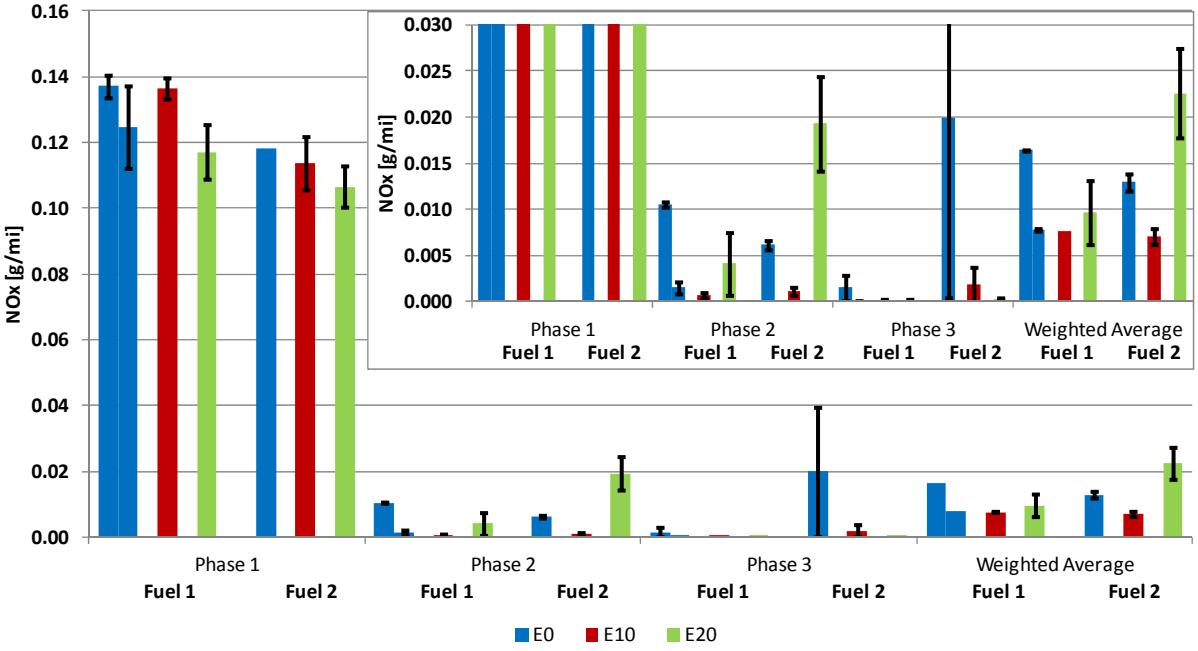


FIGURE D-11. VEHICLE B OXIDES OF NITROGEN

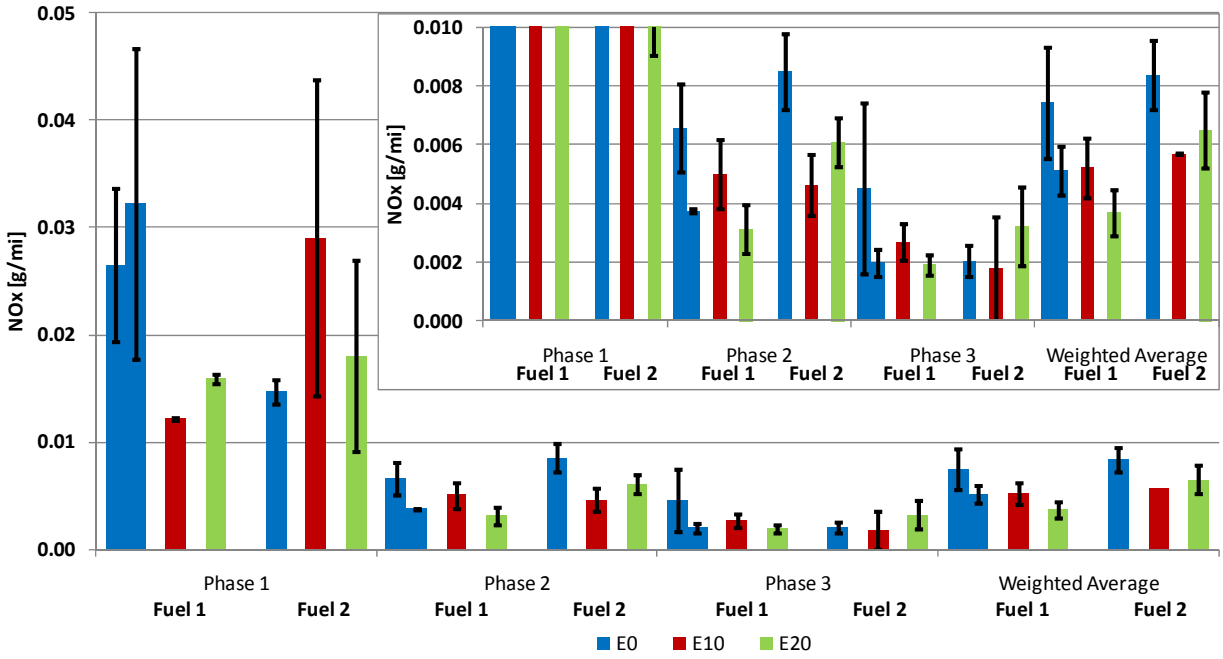


FIGURE D-12. VEHICLE C OXIDES OF NITROGEN

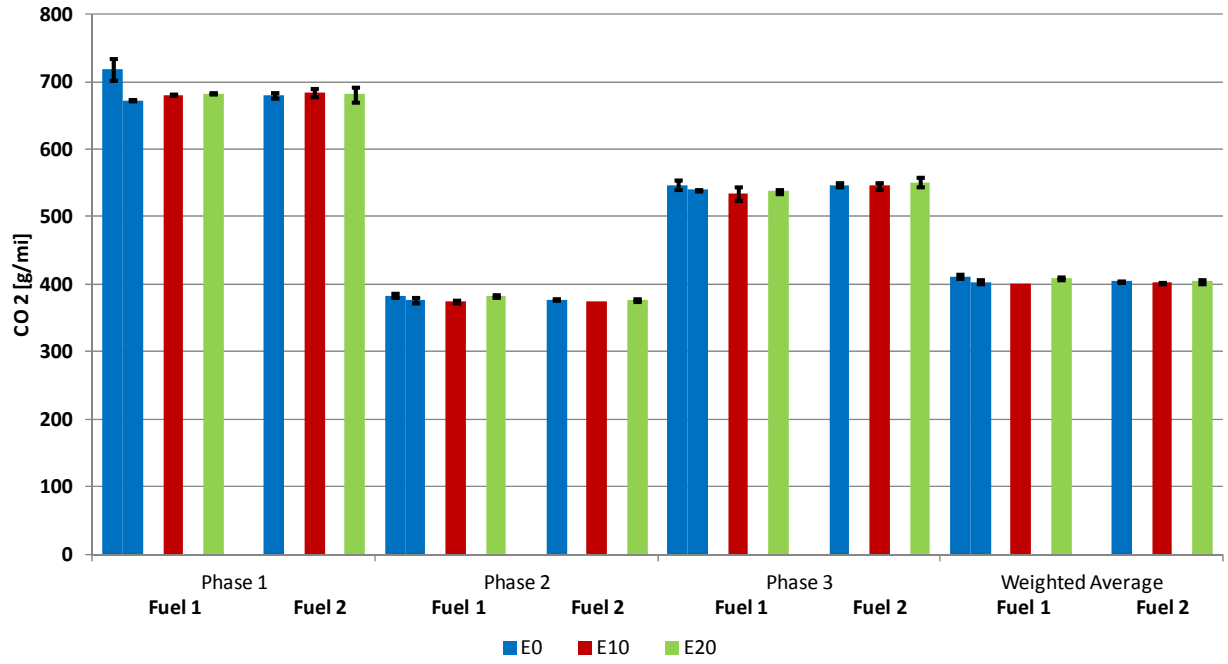


FIGURE D-13. VEHICLE 1 CARBON DIOXIDE

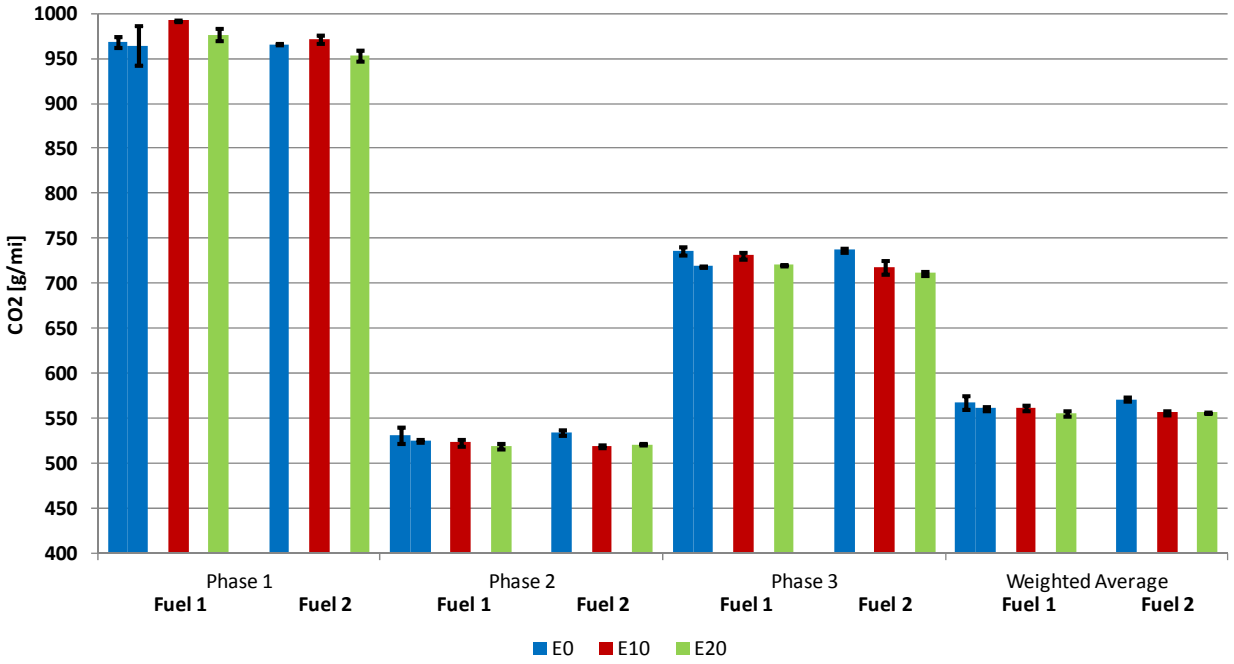


FIGURE D-14. VEHICLE 2 CARBON DIOXIDE

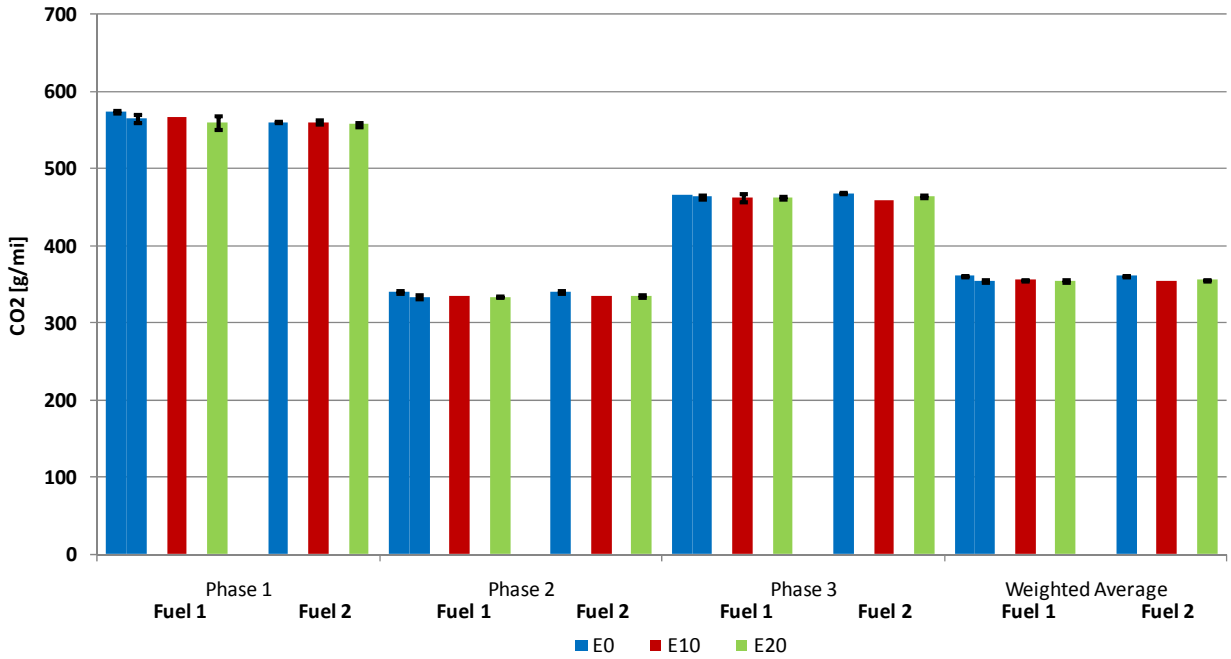


FIGURE D-15. VEHICLE 3 CARBON DIOXIDE

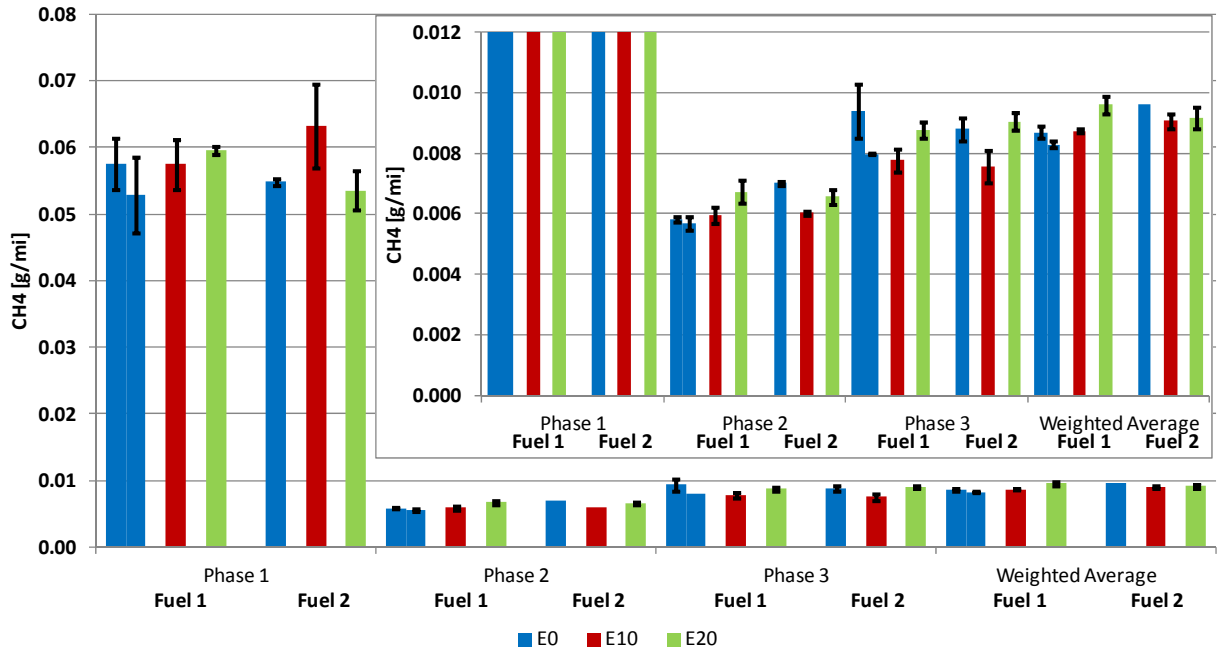


FIGURE D-16. VEHICLE 1 METHANE

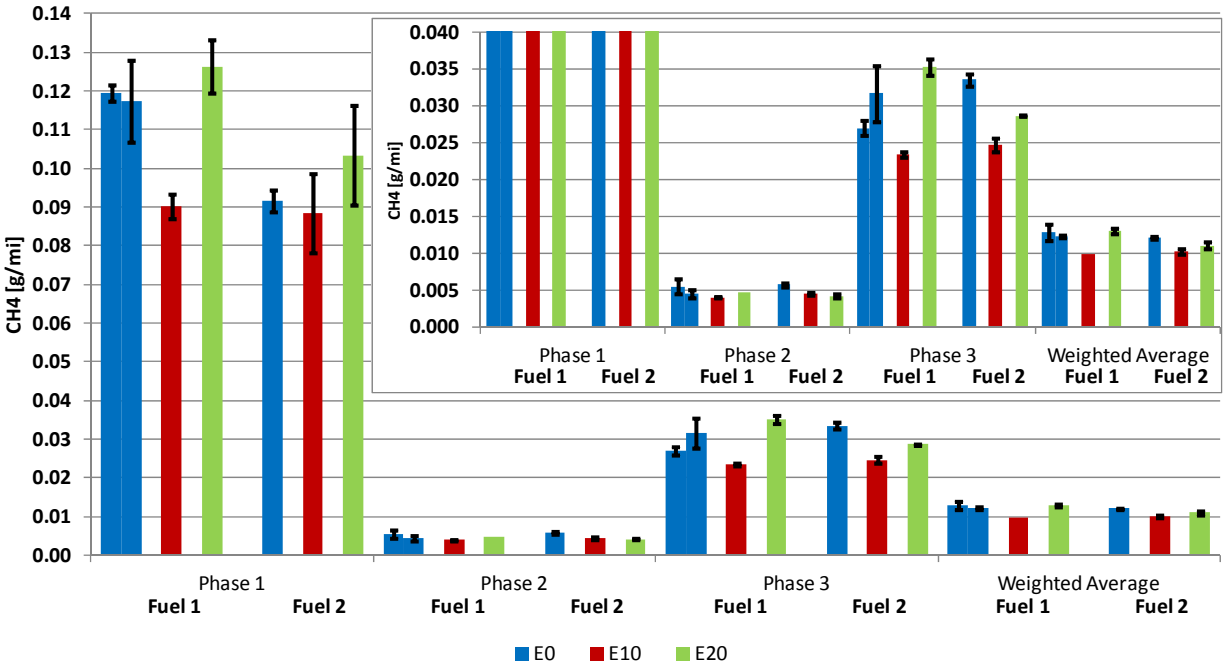


FIGURE D-17. VEHICLE 2 METHANE

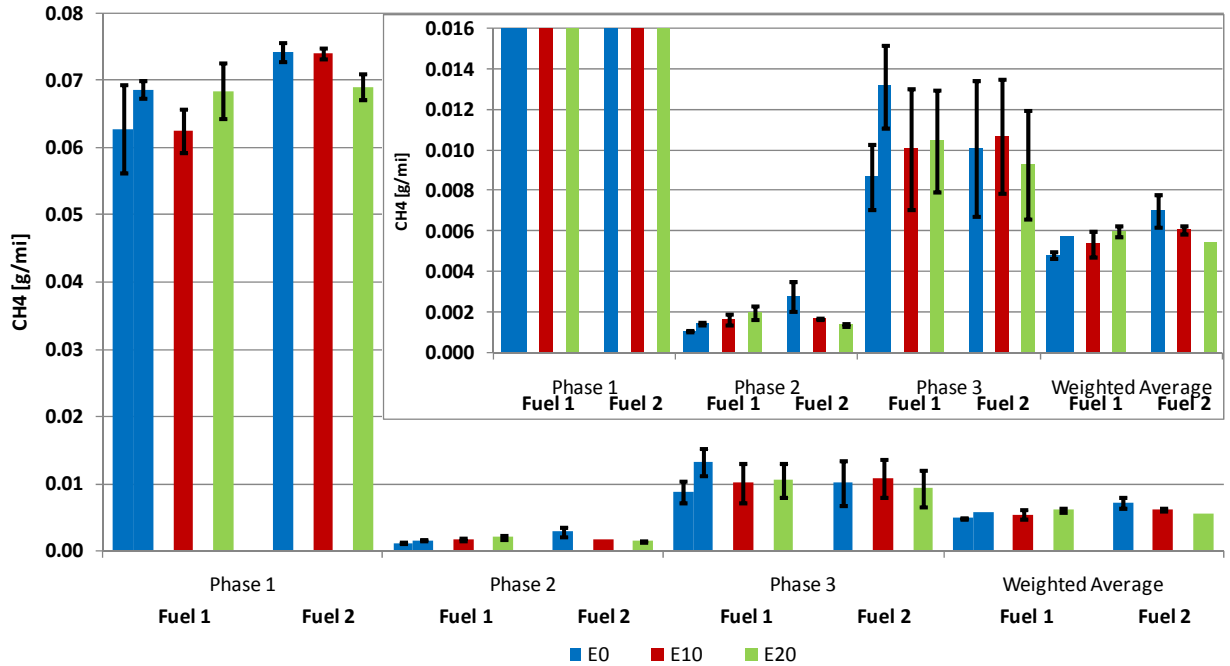


FIGURE D-18. VEHICLE 3 METHANE

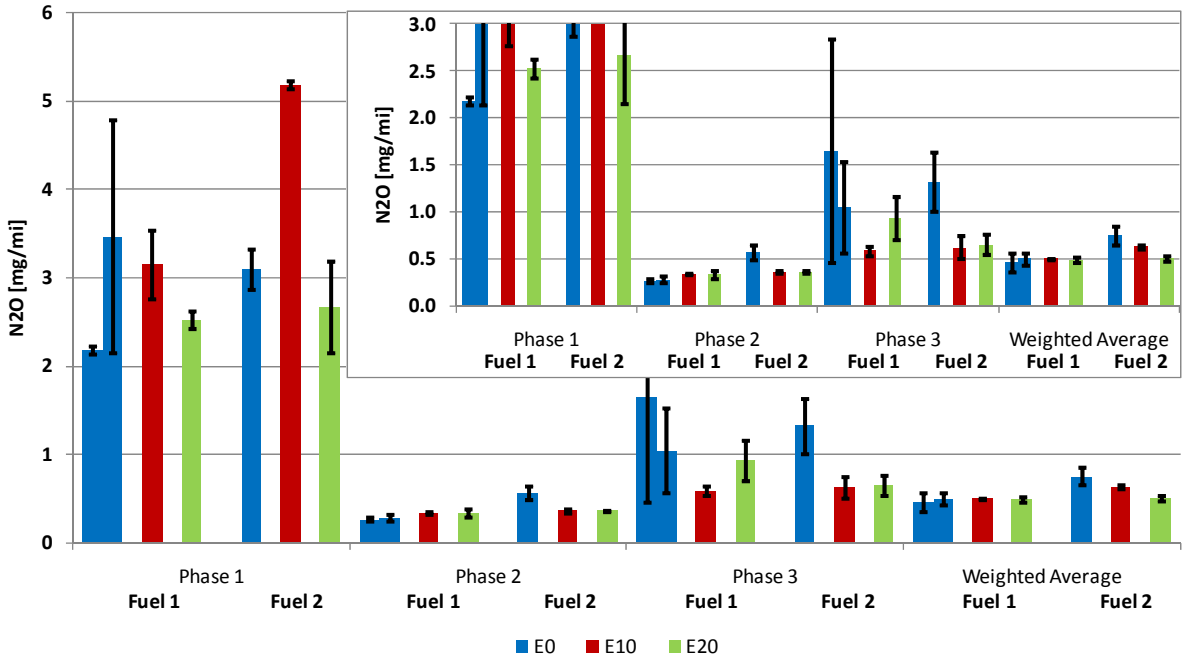


FIGURE D-19. VEHICLE 1 NITROUS OXIDE

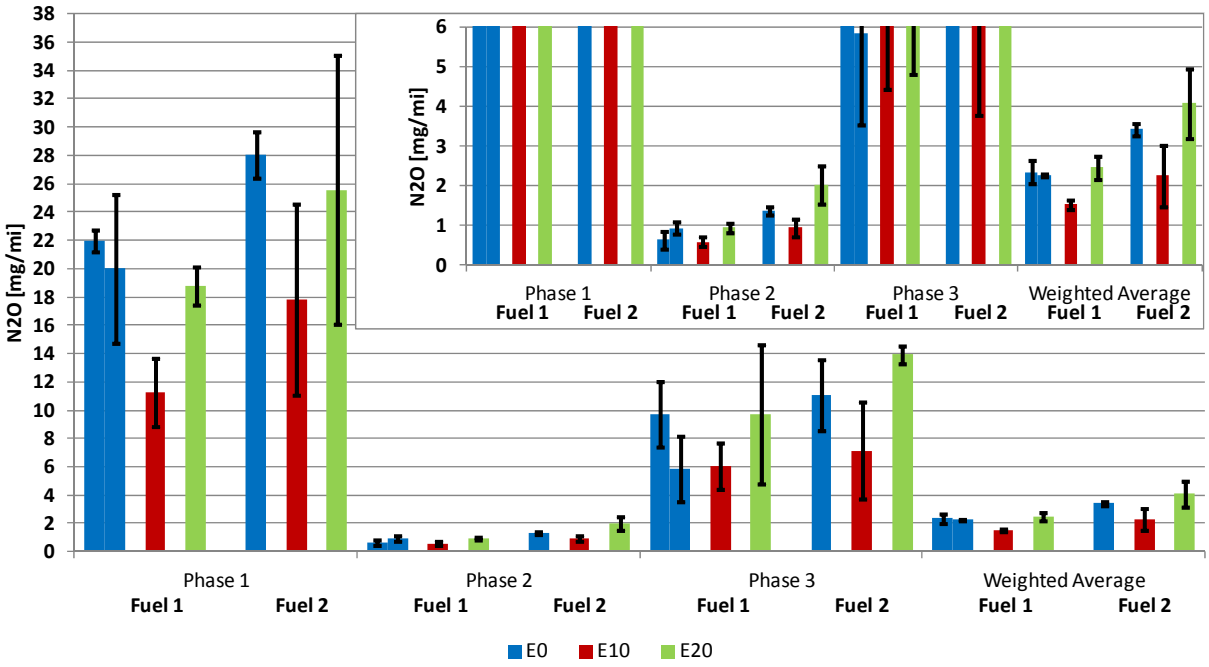


FIGURE D-20. VEHICLE 2 NITROUS OXIDE

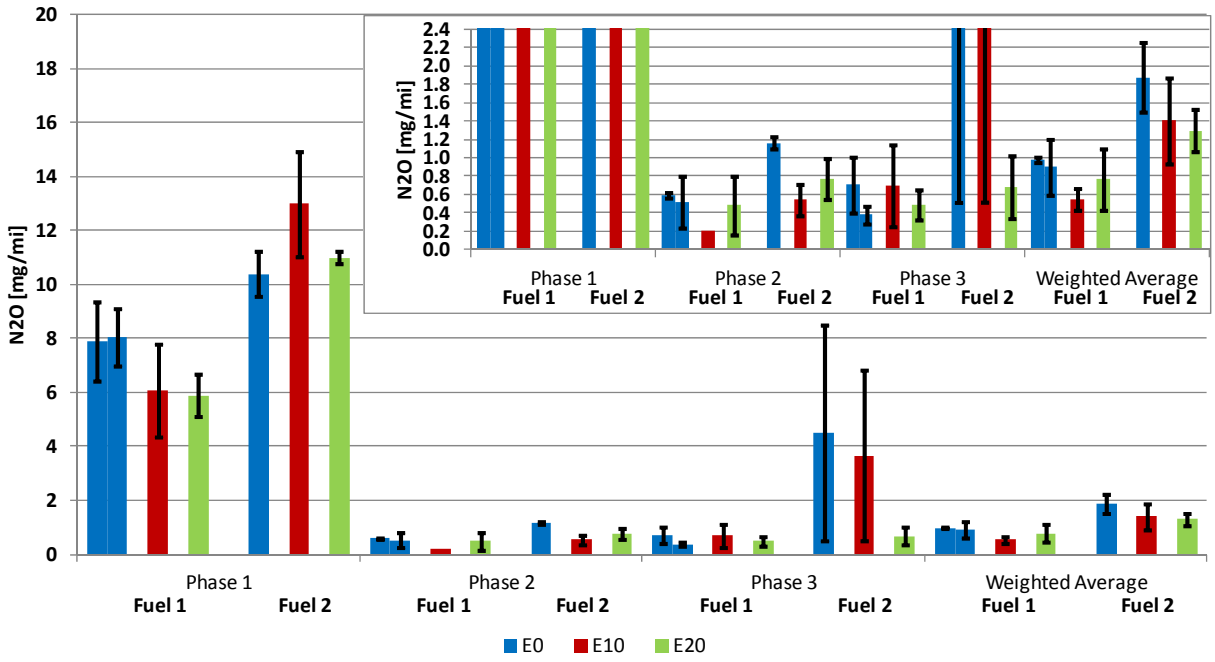


FIGURE D-21. VEHICLE 3 NITROUS OXIDE

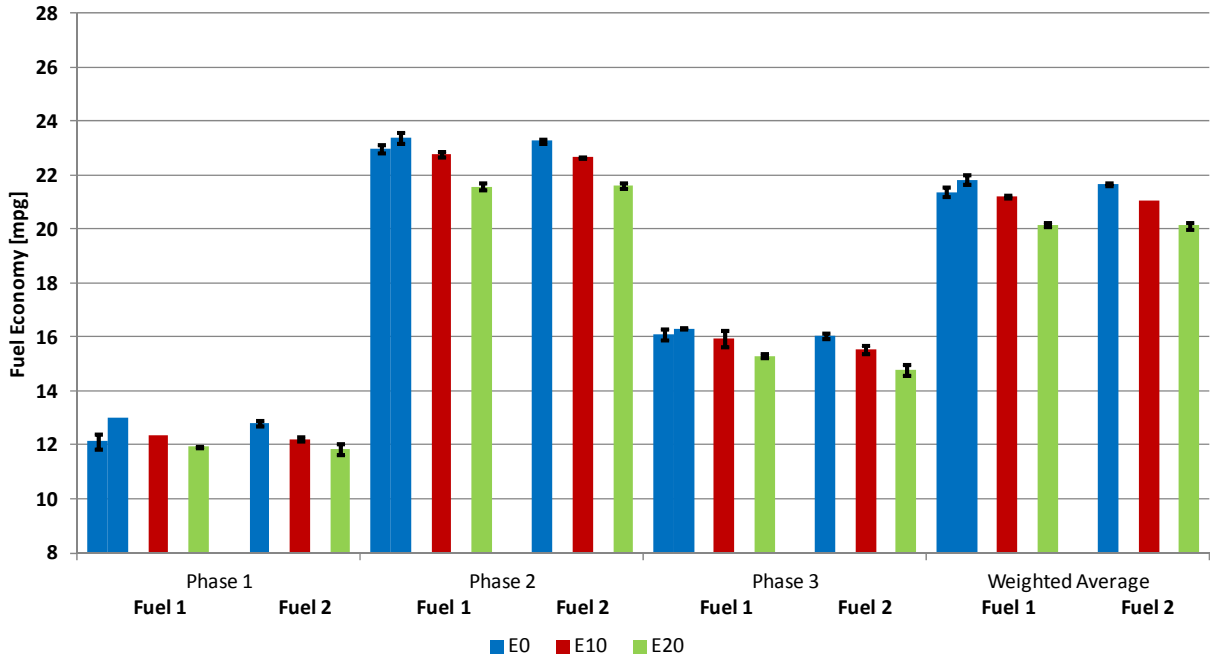


FIGURE D-22. VEHICLE 1 FUEL ECONOMY

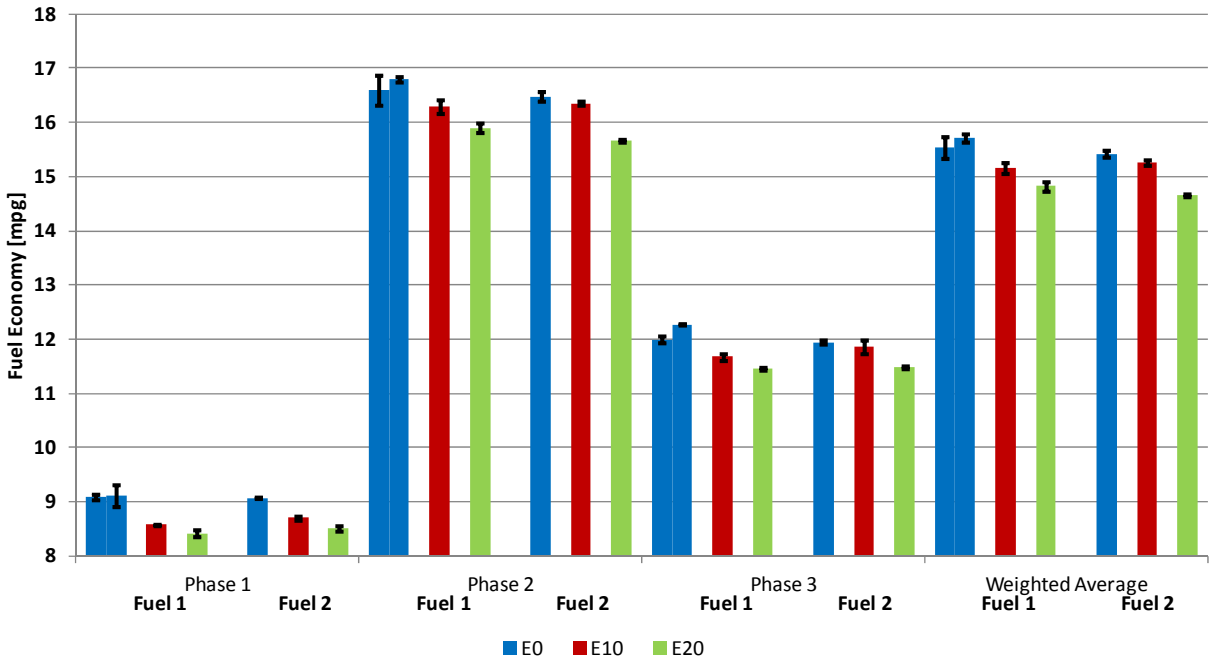


FIGURE D-23. VEHICLE 2 FUEL ECONOMY

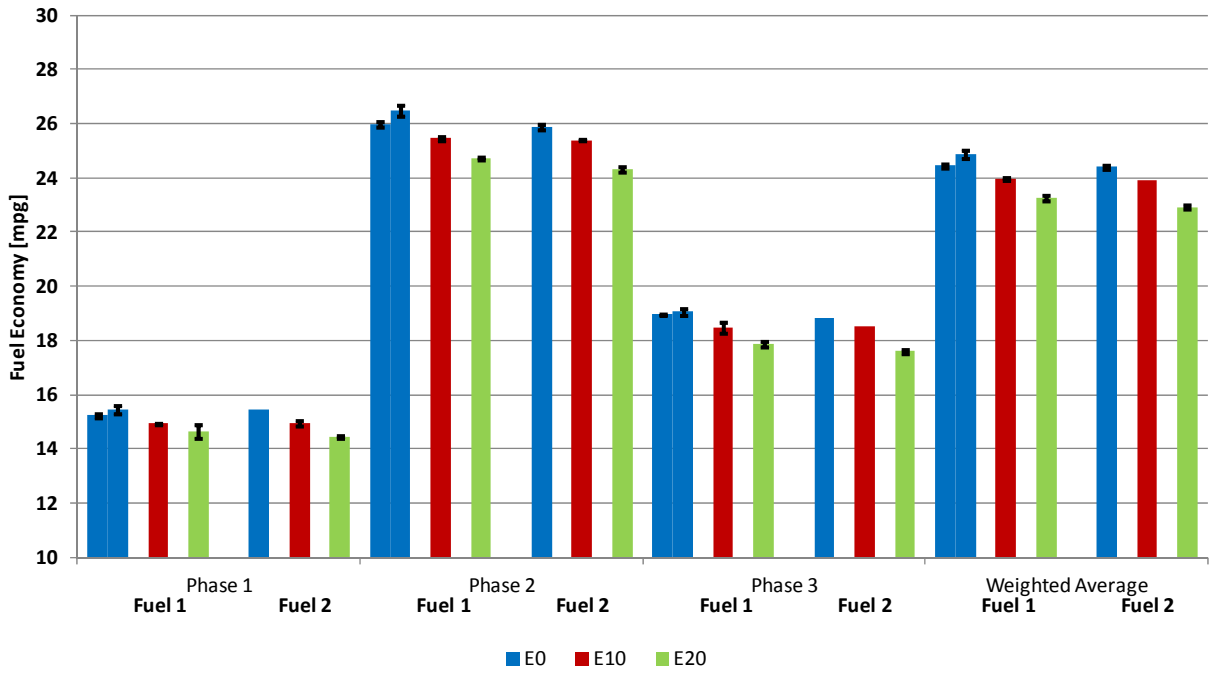


FIGURE D-24. VEHICLE 3 FUEL ECONOMY

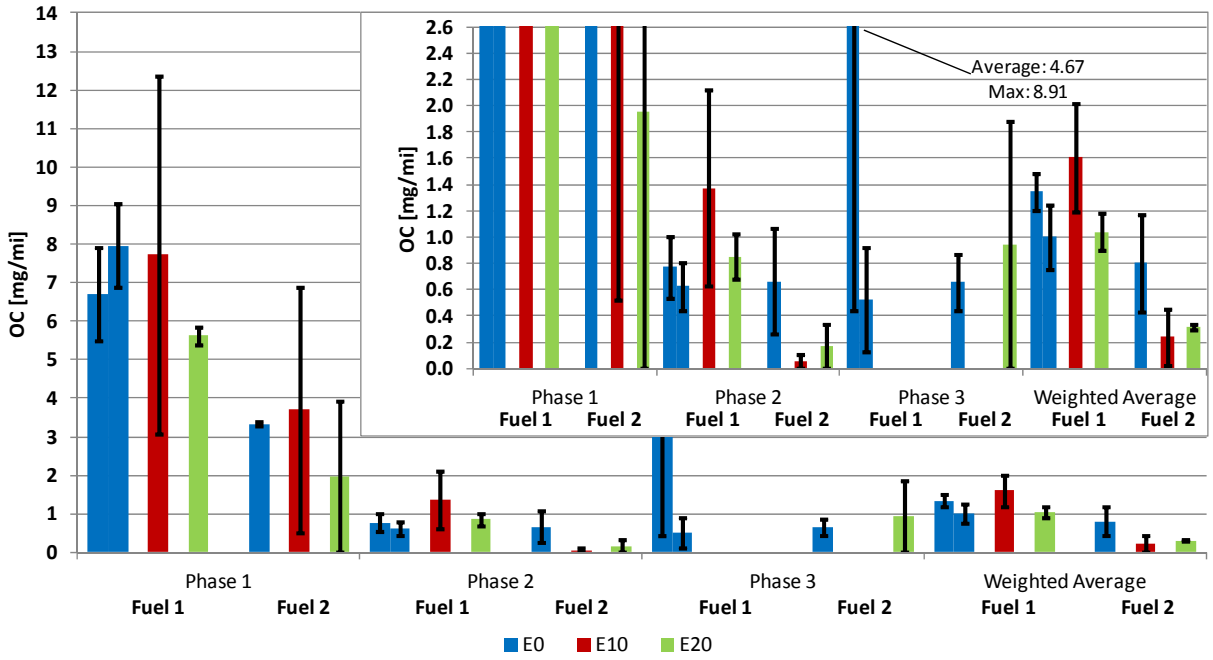


FIGURE D-25. VEHICLE A ORGANIC CARBON

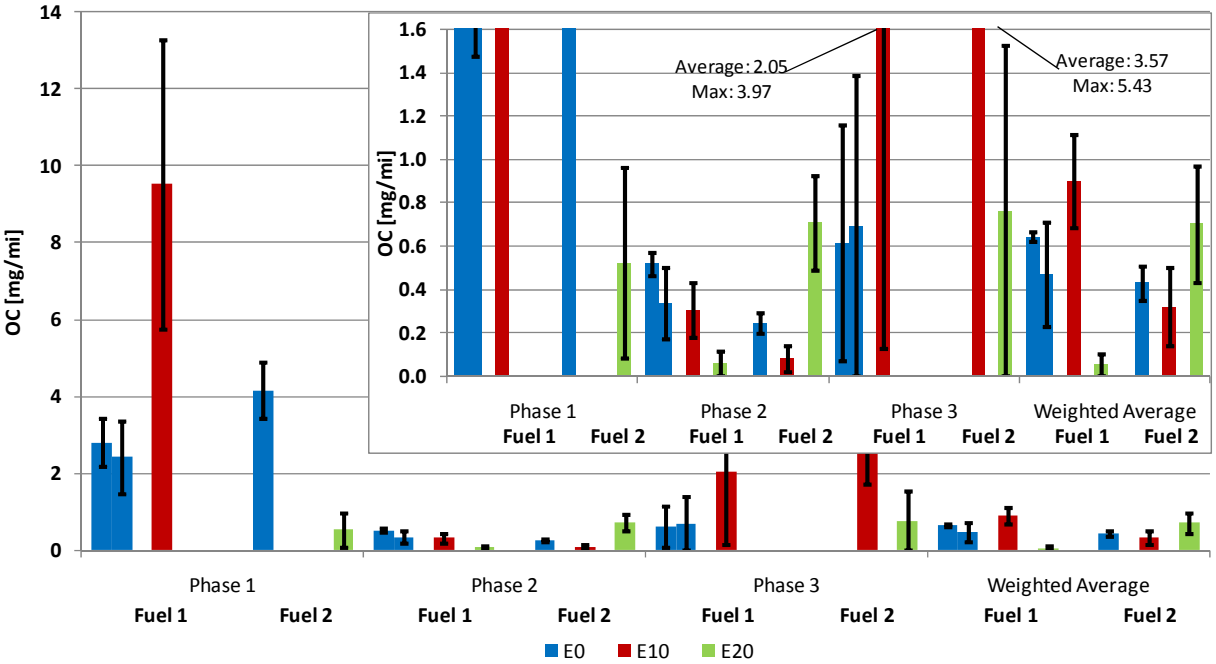


FIGURE D-26. VEHICLE B ORGANIC CARBON

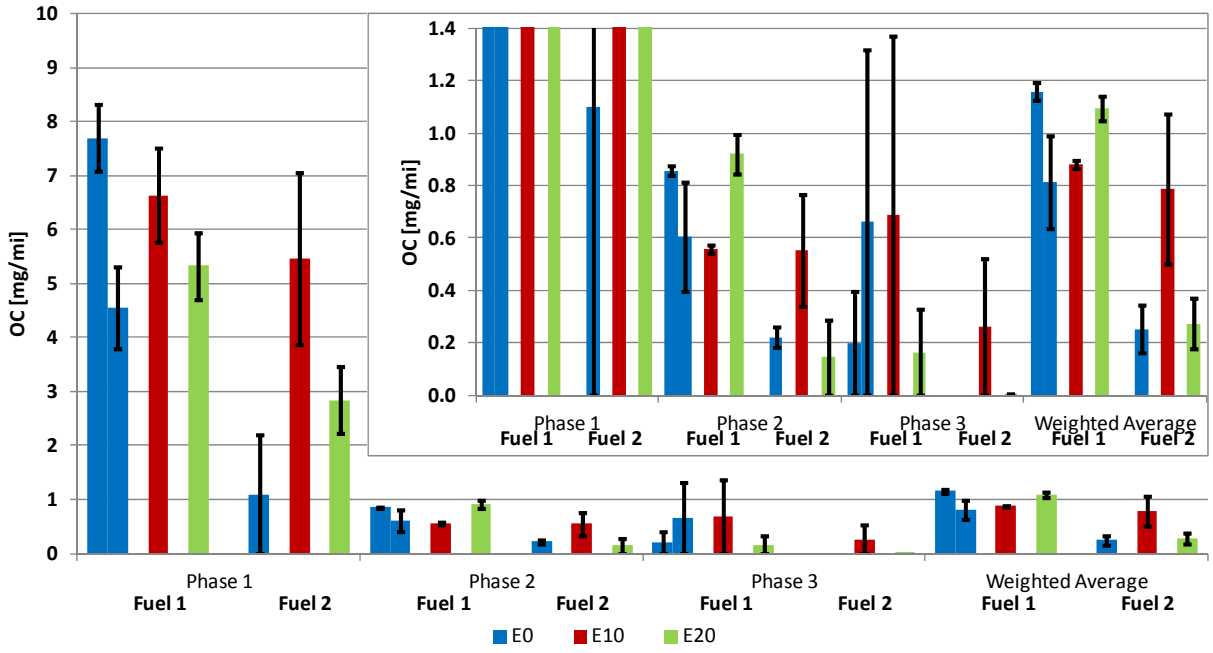


FIGURE D-27. VEHICLE C ORGANIC CARBON

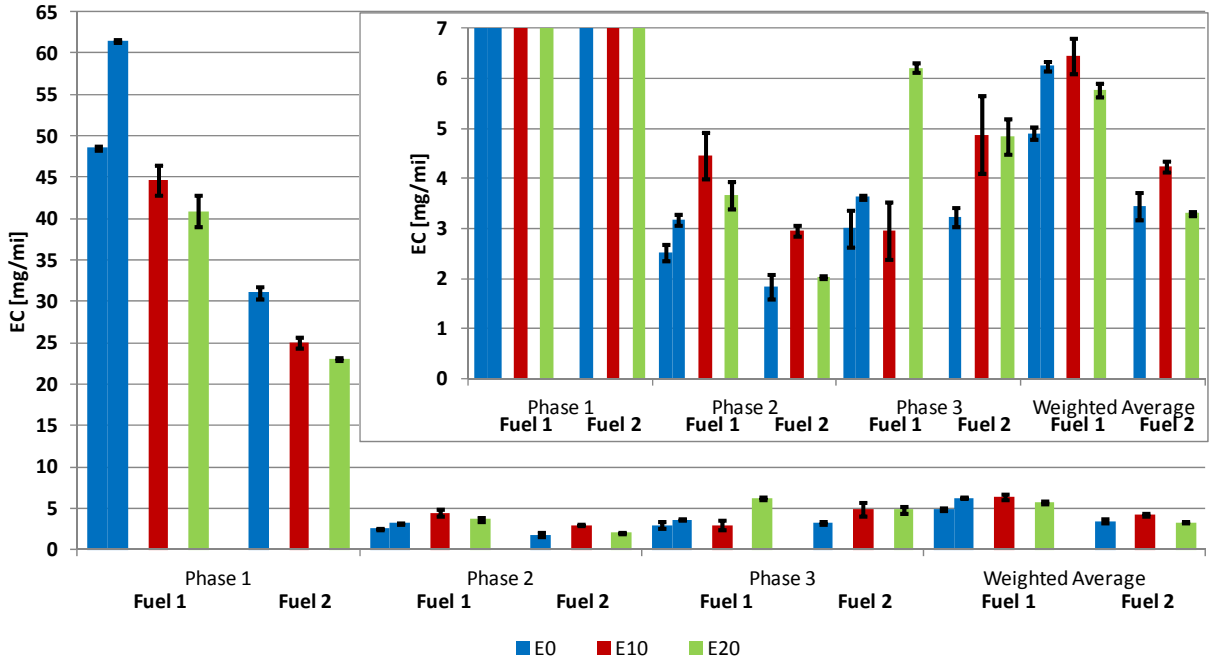


FIGURE D-28. VEHICLE A ELEMENTAL CARBON

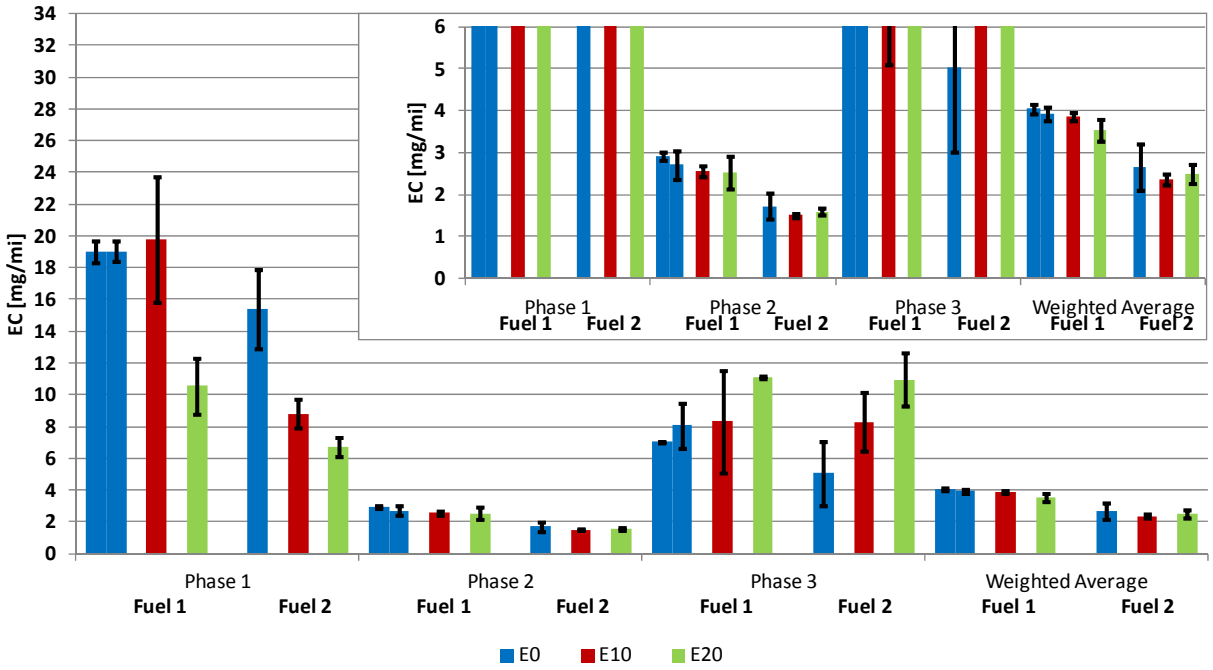


FIGURE D-29. VEHICLE B ELEMENTAL CARBON

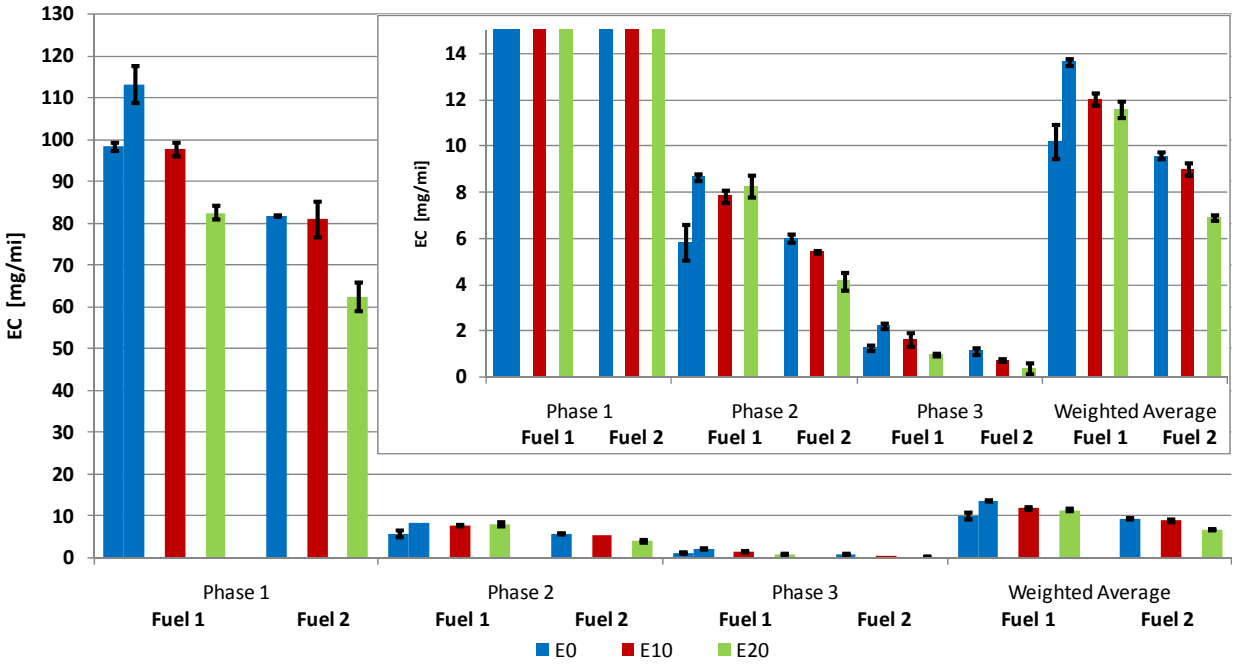


FIGURE D-30. VEHICLE C ELEMENTAL CARBON

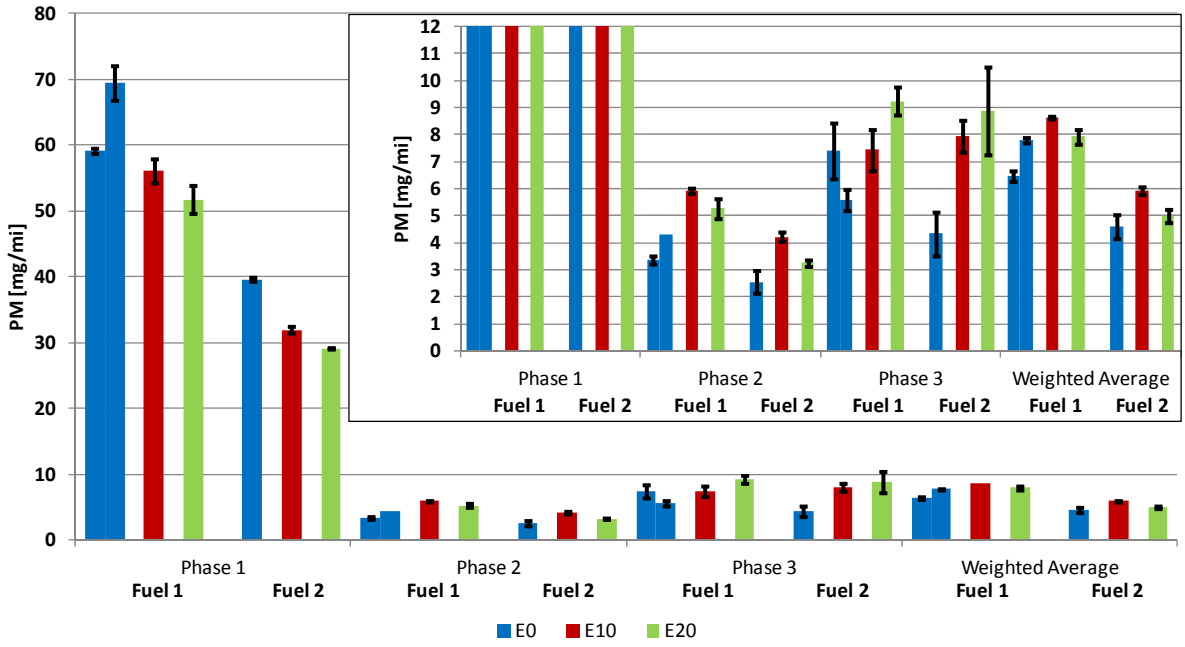


FIGURE D-31. VEHICLE A PARTICULATE MASS - GRAVIMETRIC

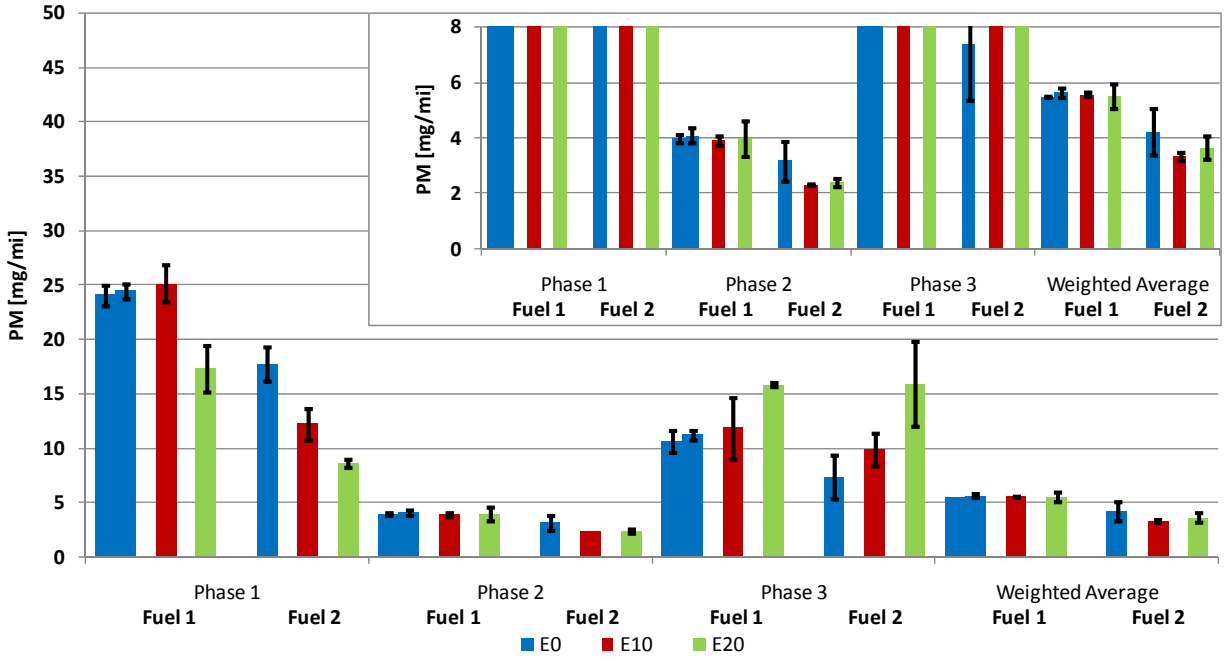


FIGURE D-32. VEHICLE B PARTICULATE MASS - GRAVIMETRIC

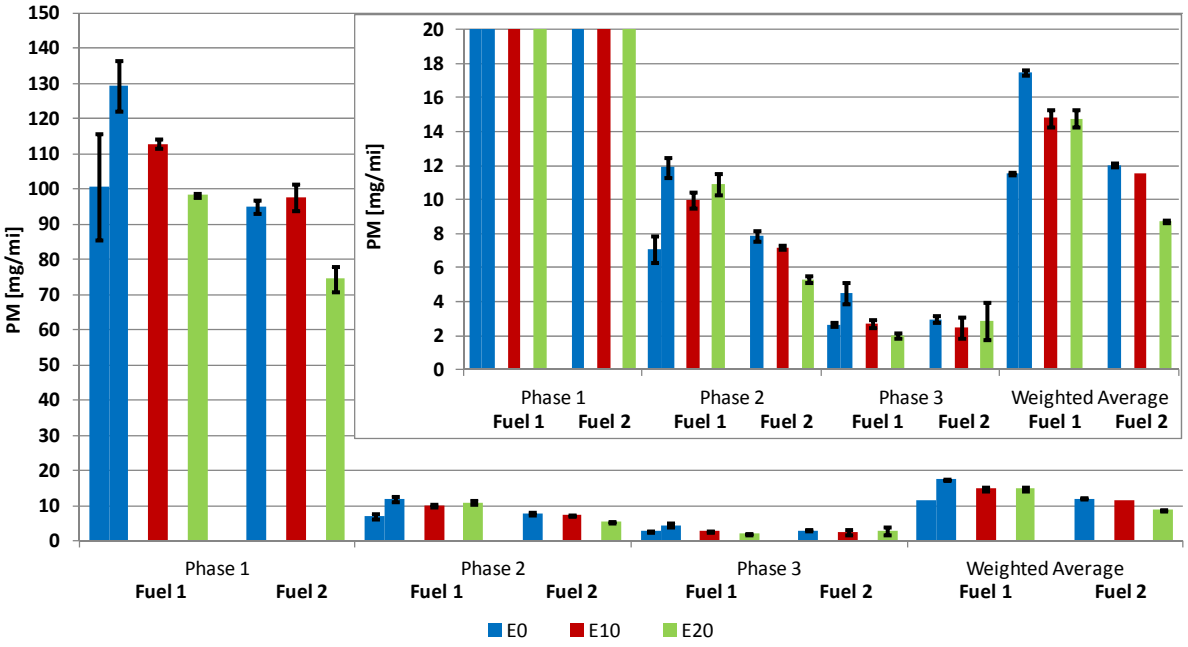


FIGURE D-33. VEHICLE C PARTICULATE MASS - GRAVIMETRIC

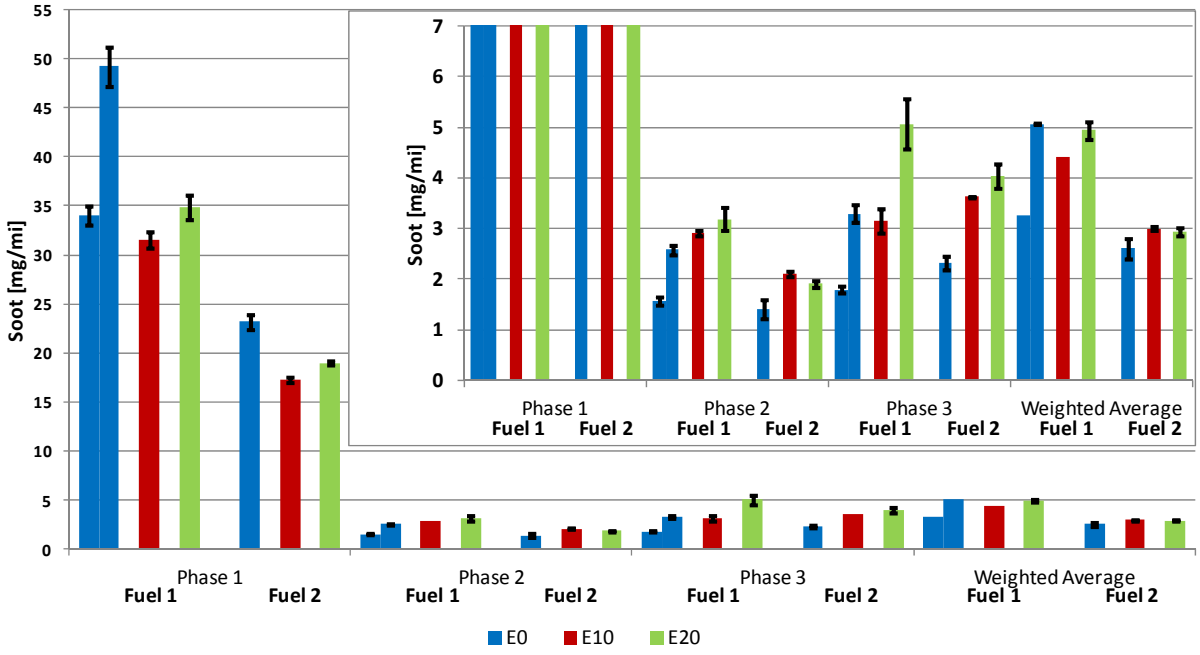


FIGURE D-34. VEHICLE A SOOT MASS – MICROSOOT SENSOR

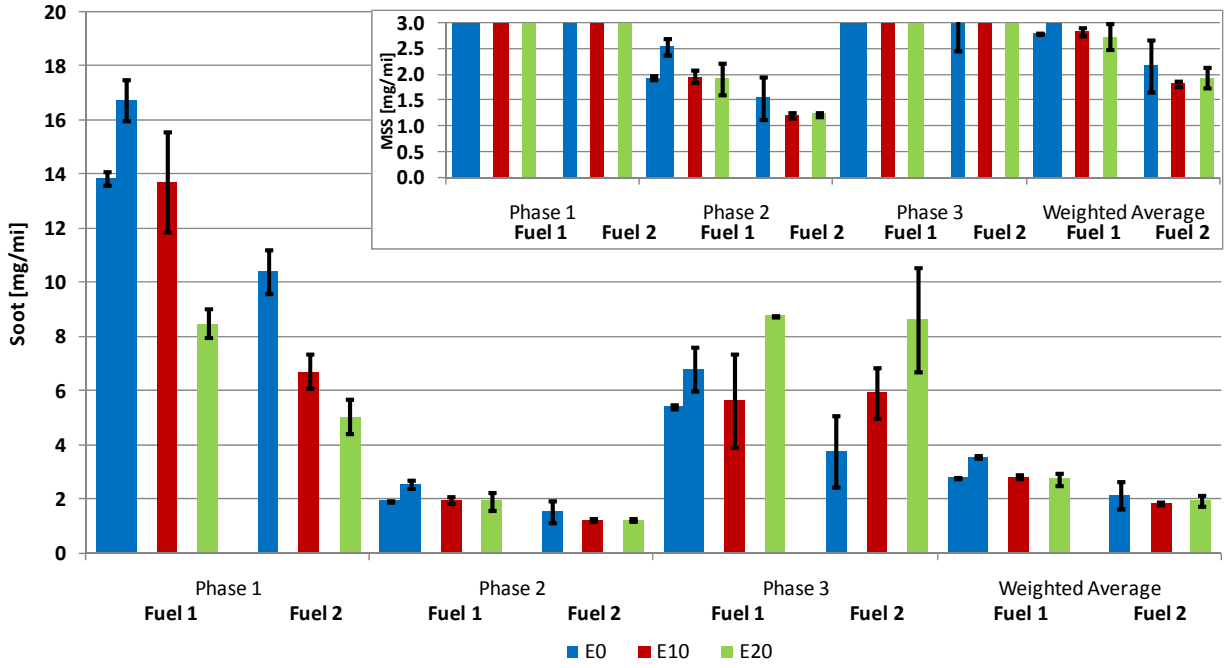


FIGURE D-35. VEHICLE B SOOT MASS – MICROSOOT SENSOR

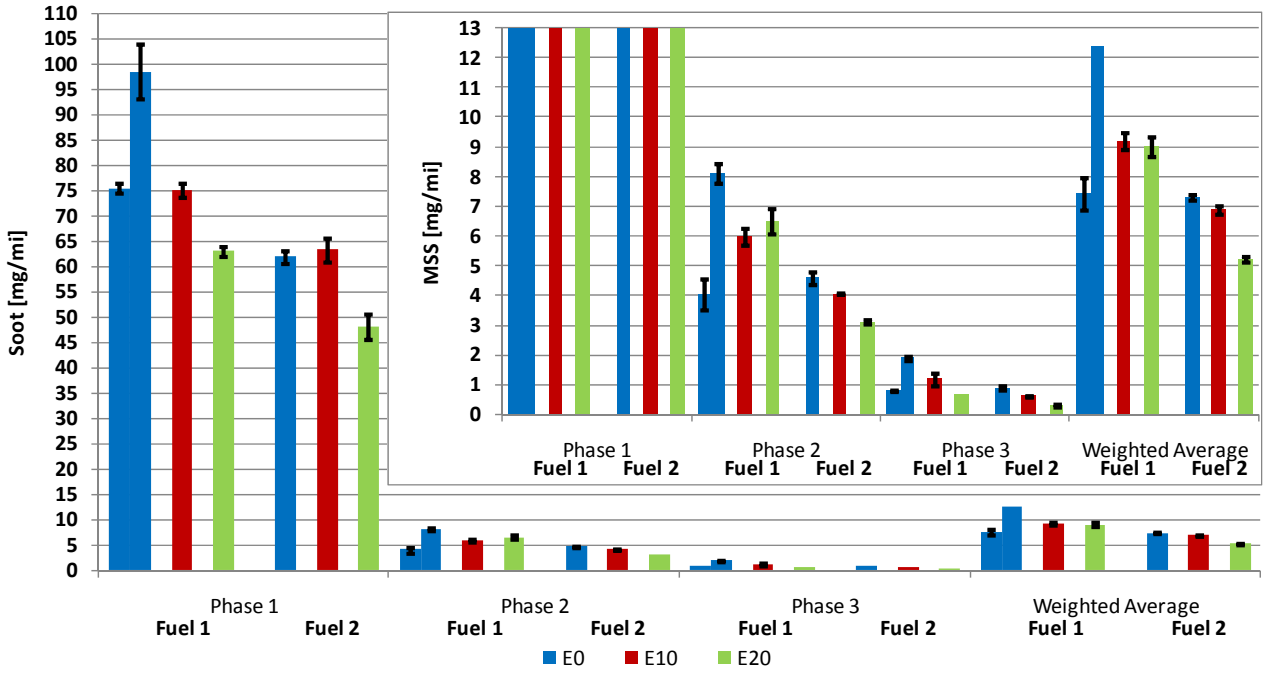


FIGURE D-36. VEHICLE C SOOT MASS – MICROSOOT SENSOR

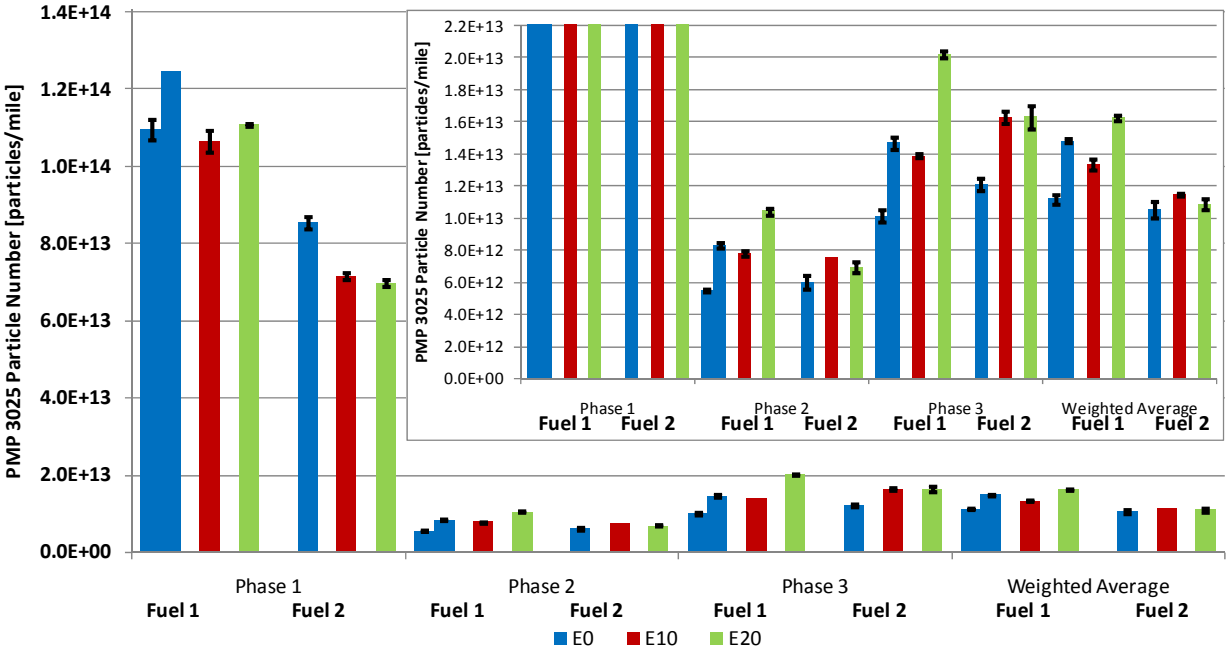


FIGURE D-37. VEHICLE A PARTICLE COUNT > 3NM – CPC3025

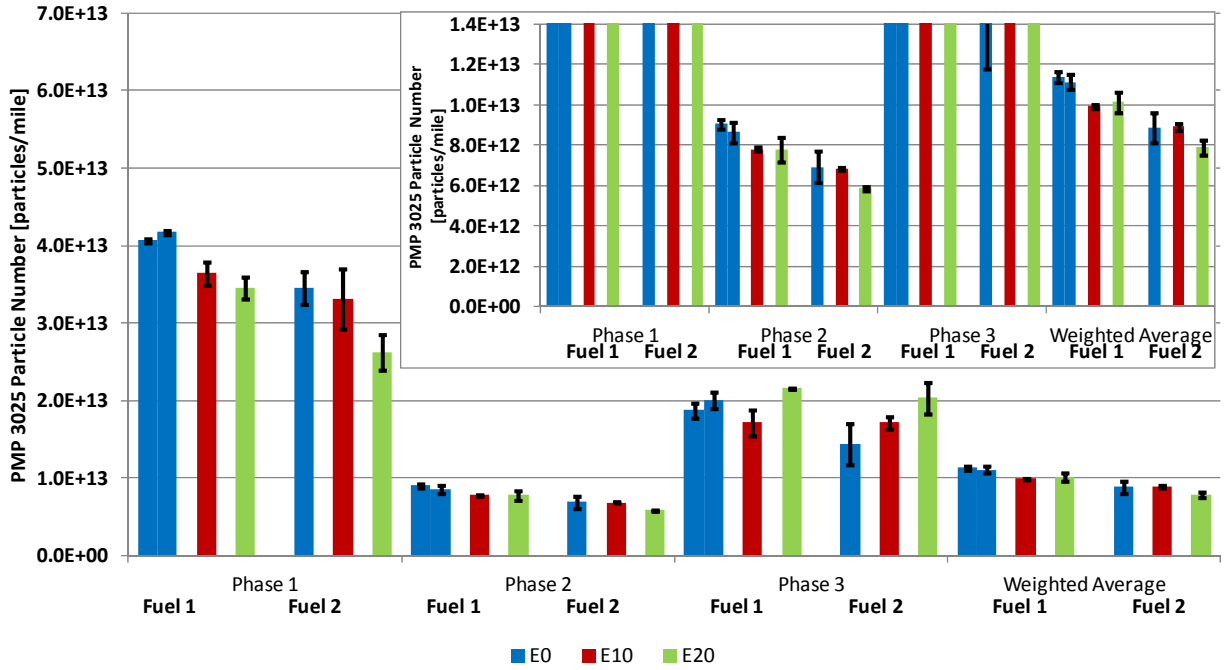


FIGURE D-38. VEHICLE B PARTICLE COUNT > 3NM – CPC3025

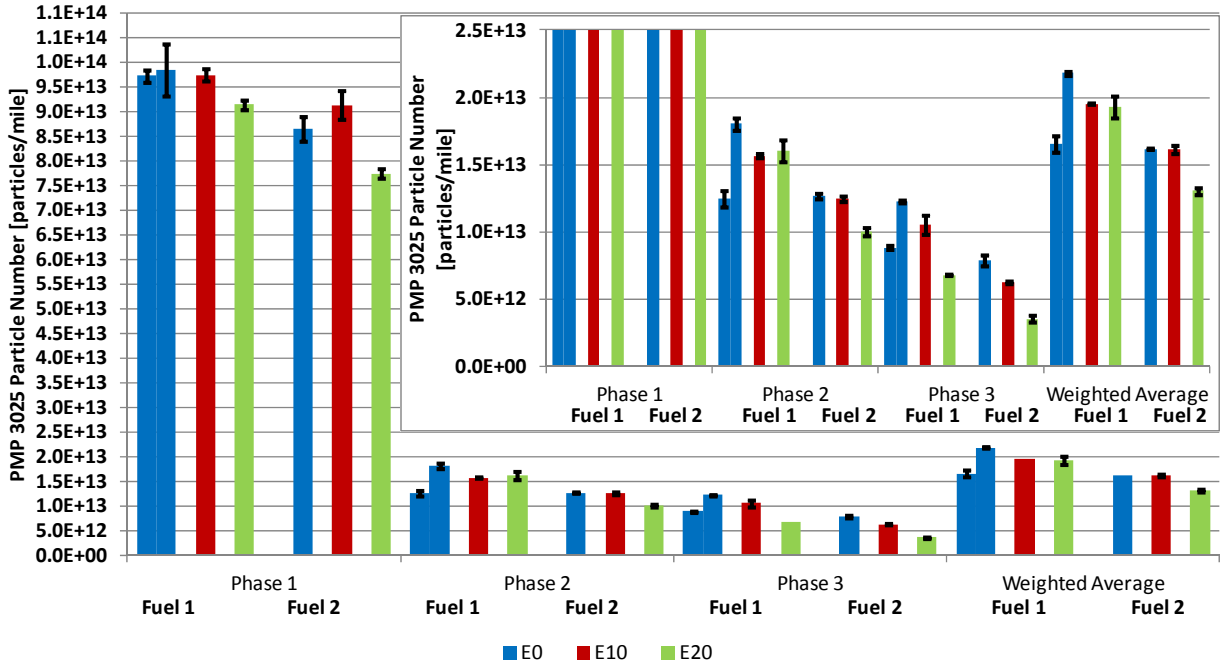


FIGURE D-39. VEHICLE C PARTICLE COUNT > 3NM – CPC3025

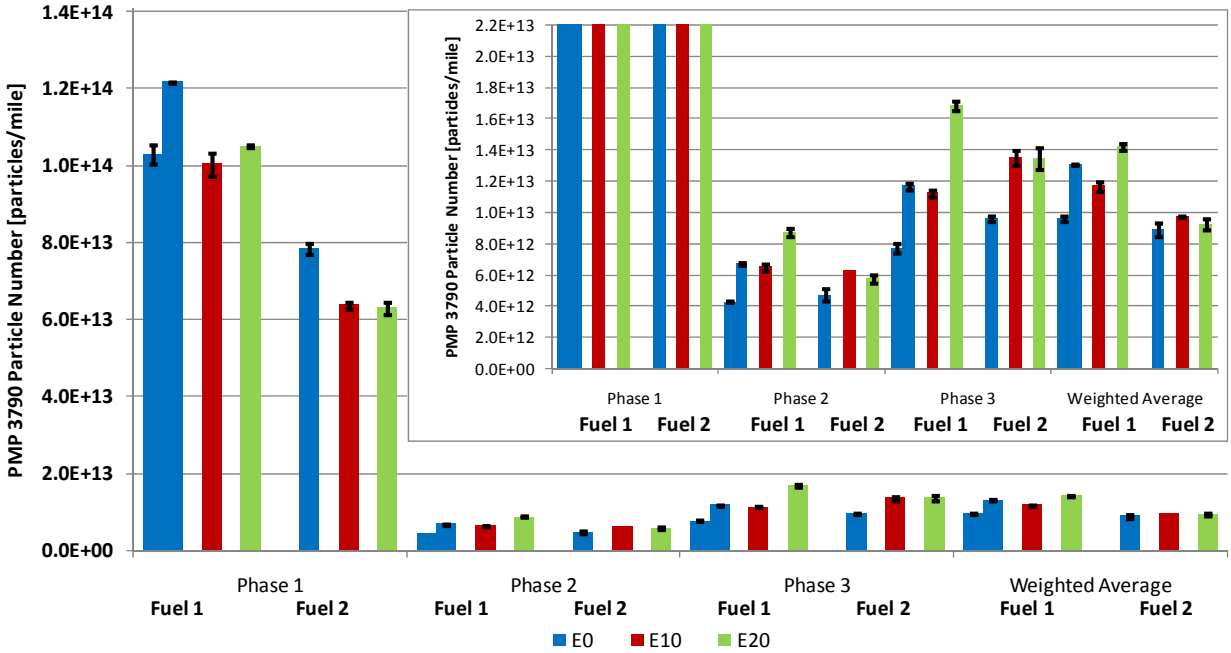


FIGURE D-40. VEHICLE A PARTICLE COUNT > 23NM – SPNMS

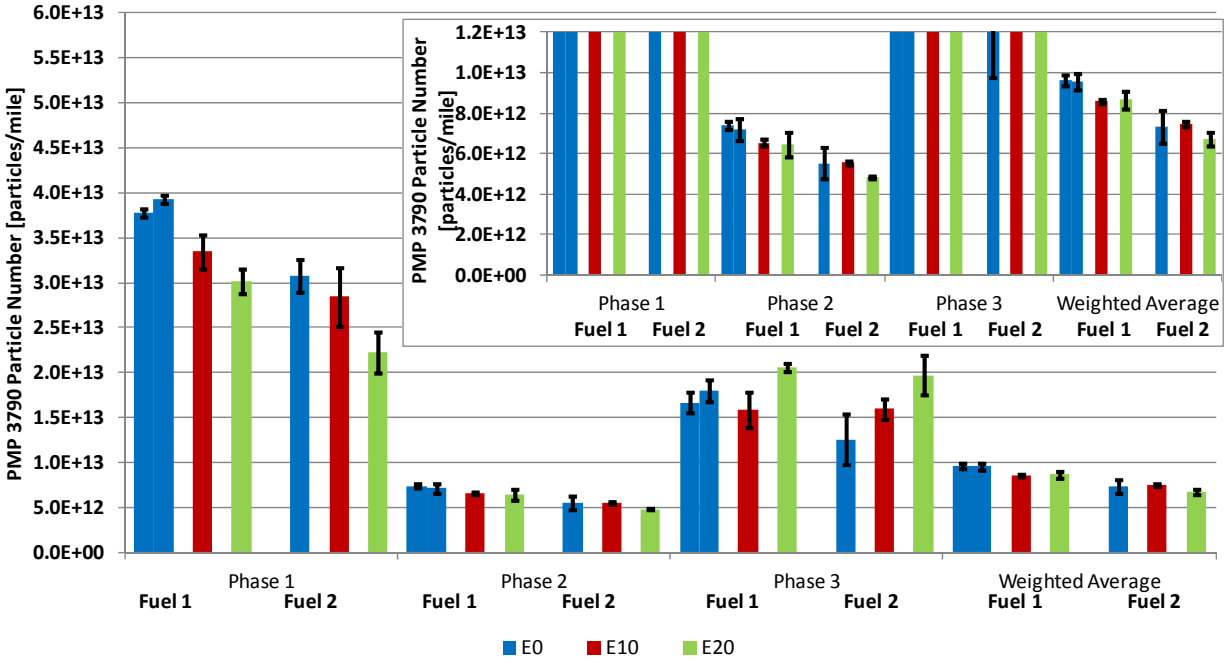


FIGURE D-41. VEHICLE B PARTICLE COUNT > 23NM – SPNMS

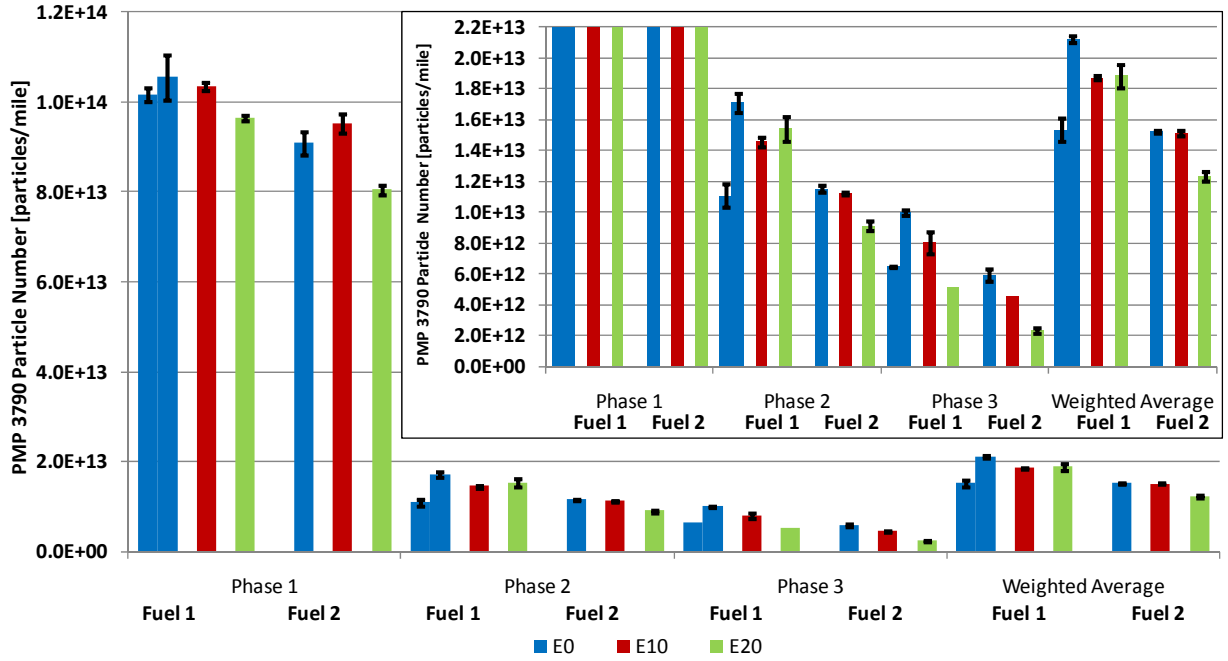


FIGURE D-42. VEHICLE C PARTICLE COUNT > 23NM – SPNMS

APPENDIX E

THC, CO, NO_X, N_2O, EC and PM EMISSIONS PLOTTED VERSUS PMI

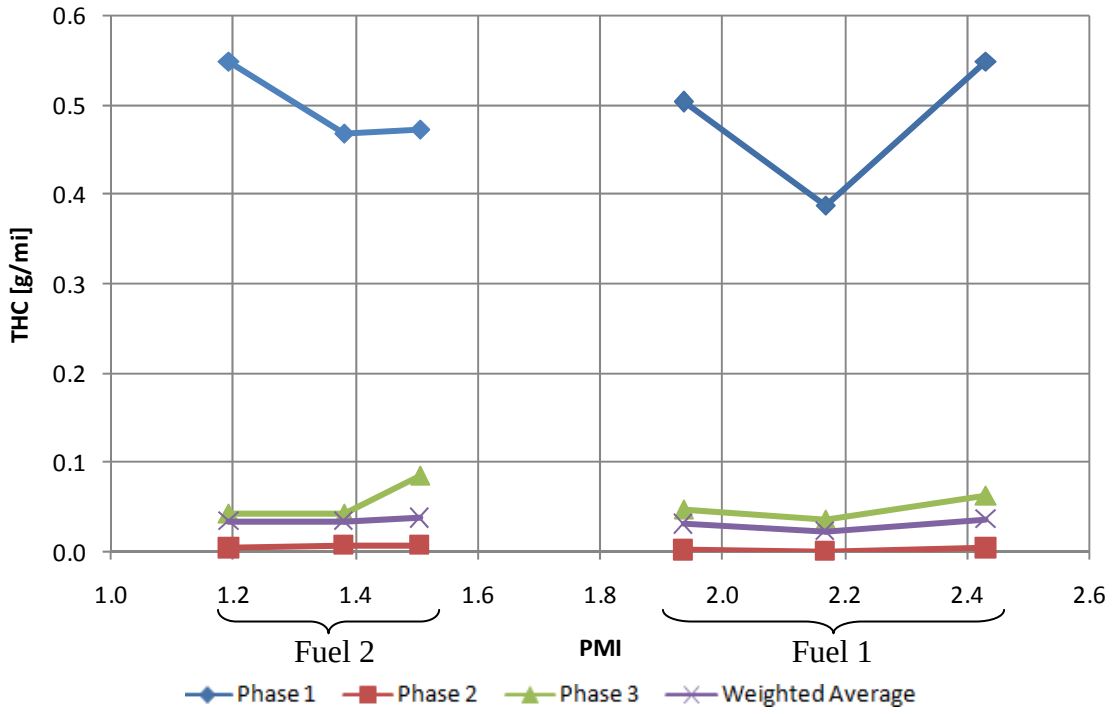


FIGURE E-1. THC VERSUS PMI FOR VEHICLE A

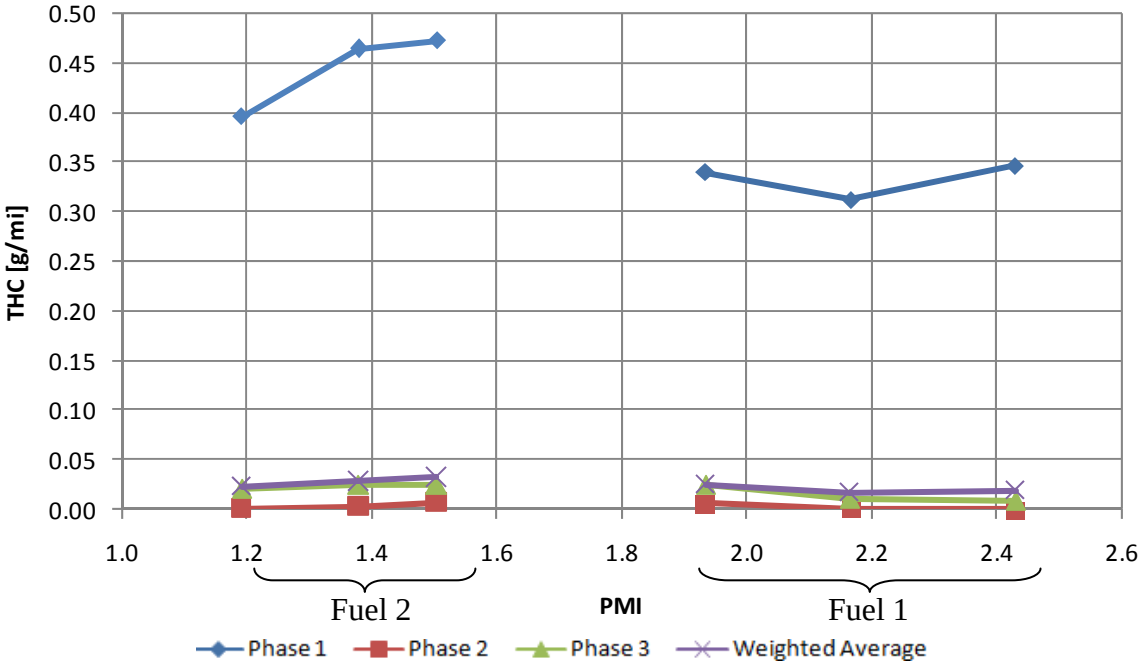


FIGURE E-2. THC VERSUS PMI FOR VEHICLE B

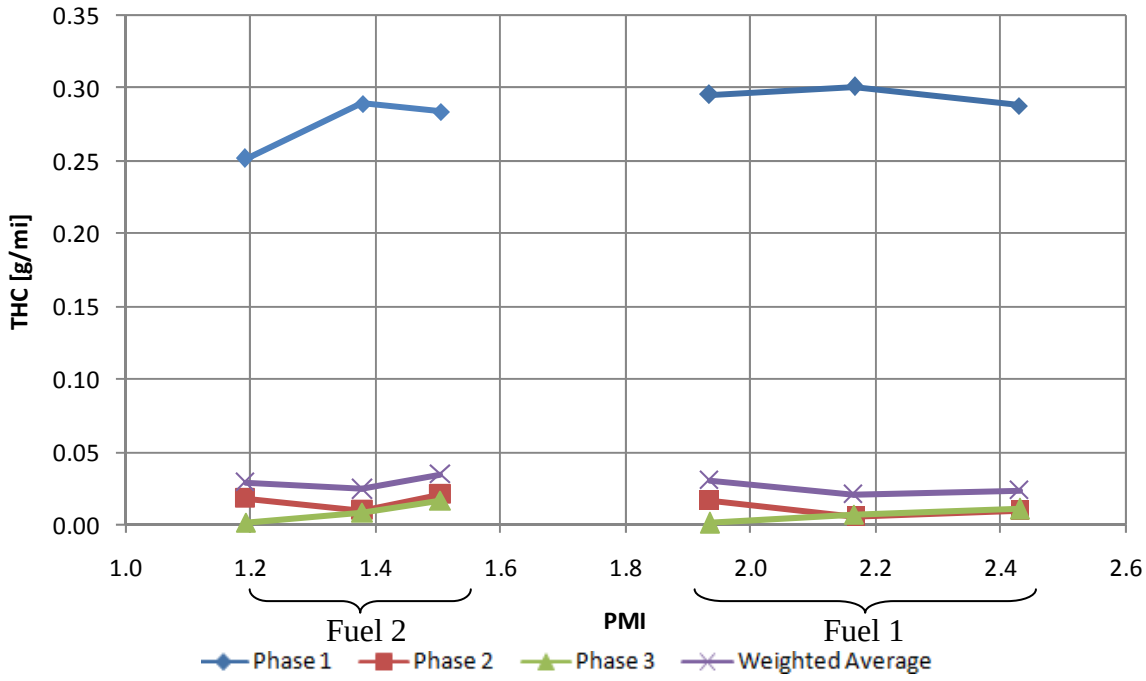


FIGURE E-3. THC VERSUS PMI FOR VEHICLE C

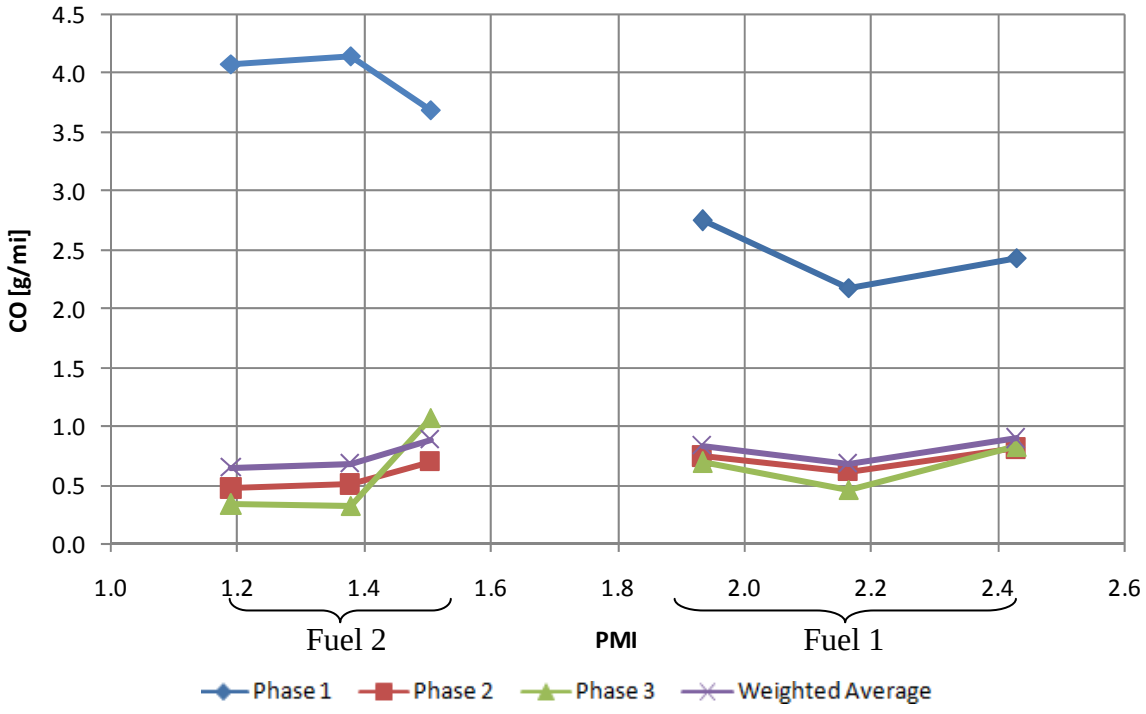


FIGURE E-4. CO VERSUS PMI FOR VEHICLE A

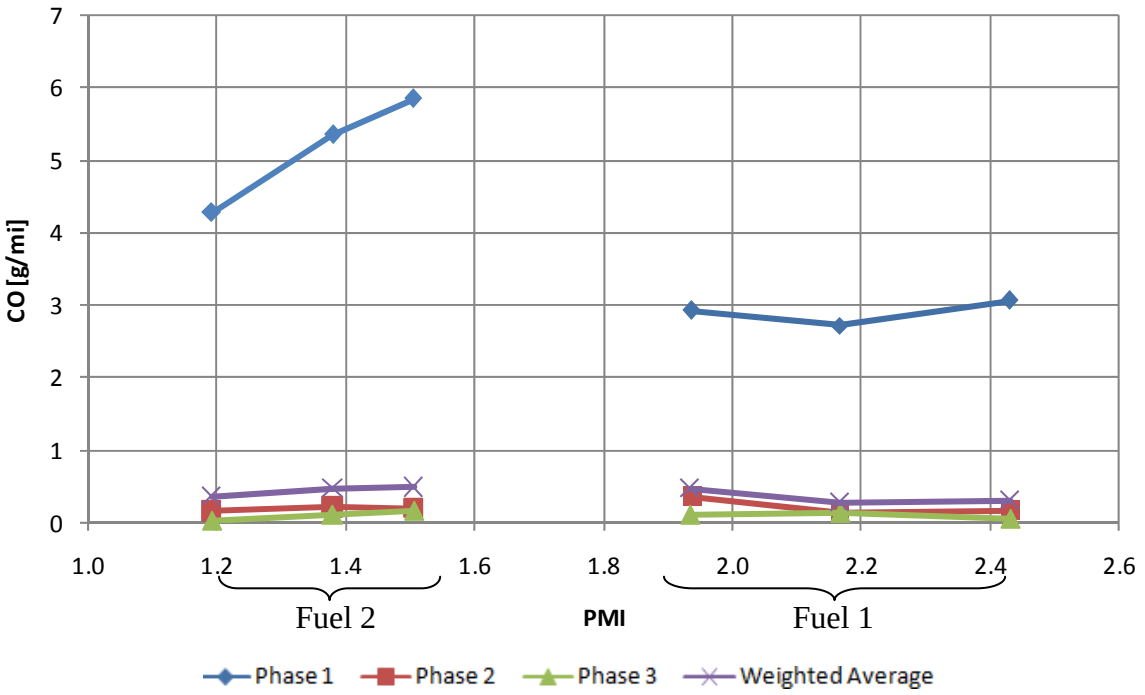


FIGURE E-5. CO VERSUS PMI FOR VEHICLE B

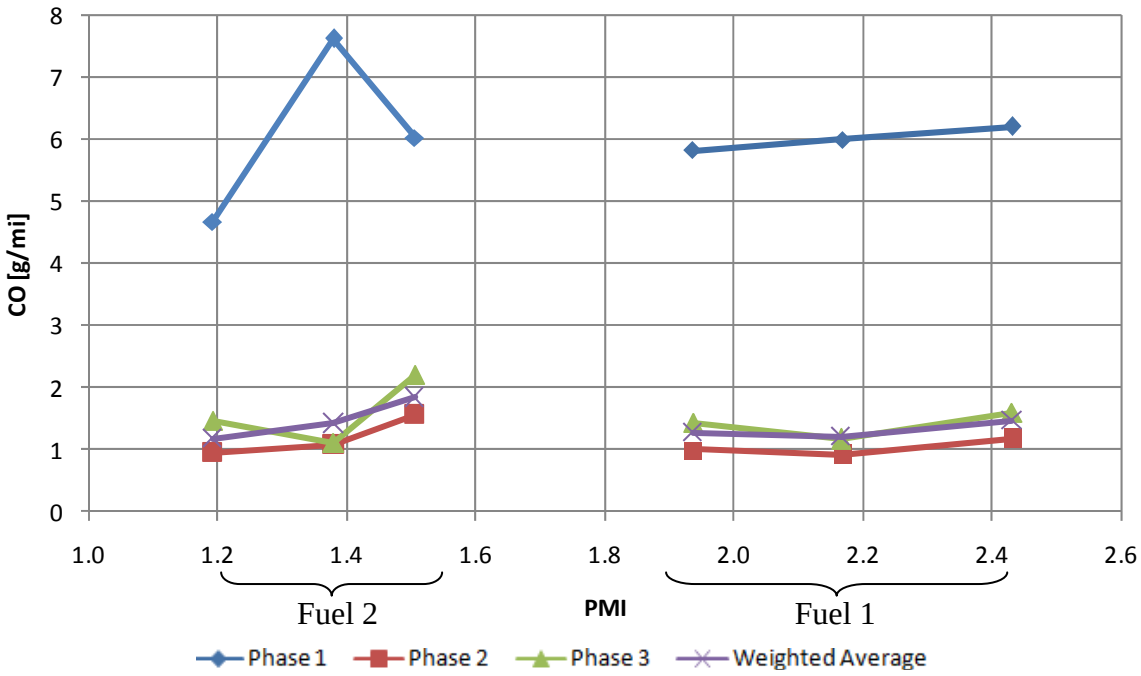


FIGURE E-6. CO VERSUS PMI FOR VEHICLE C

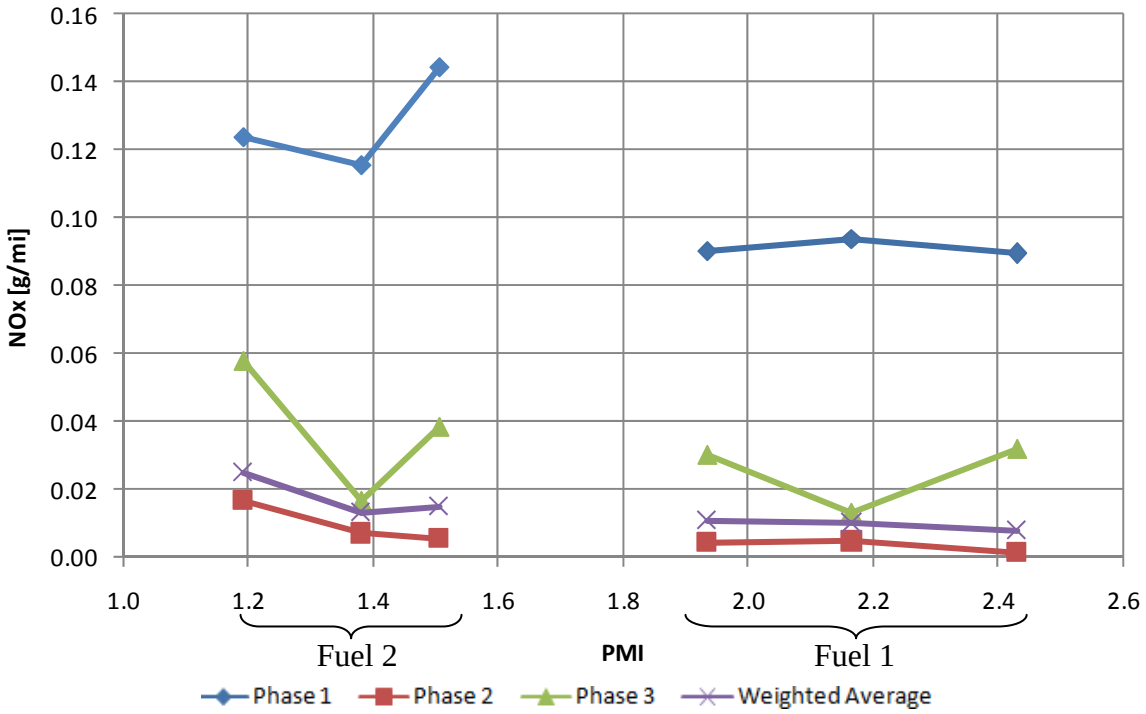


FIGURE E-7. NO_X VERSUS PMI FOR VEHICLE A

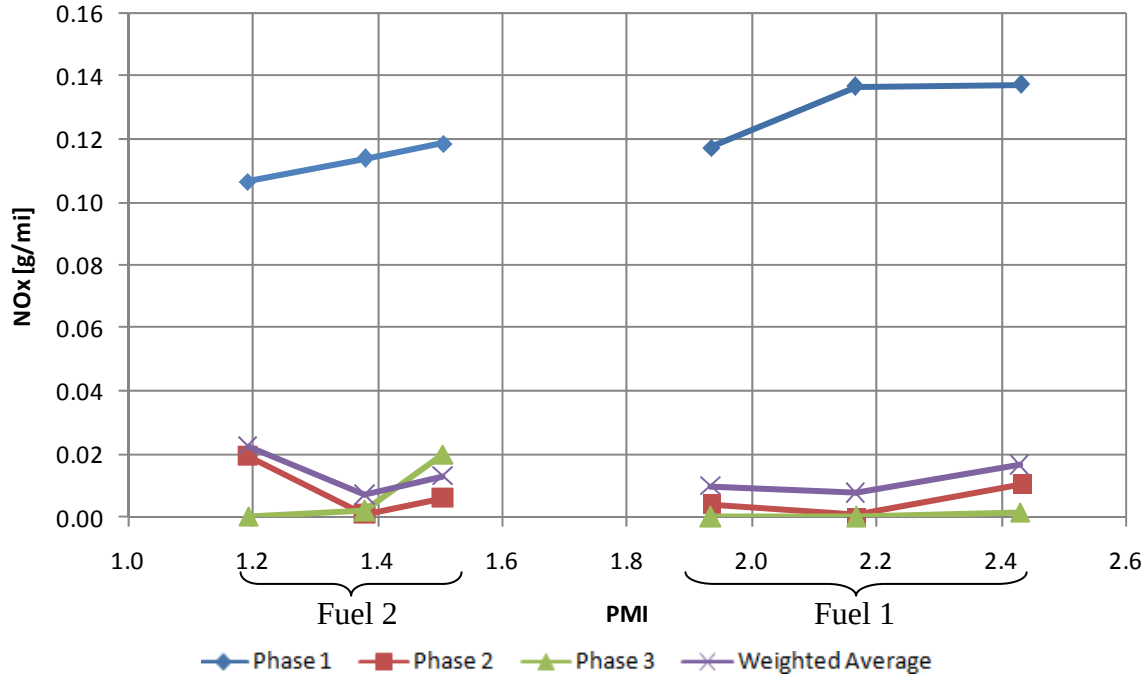


FIGURE E-8. NO_X VERSUS PMI FOR VEHICLE B

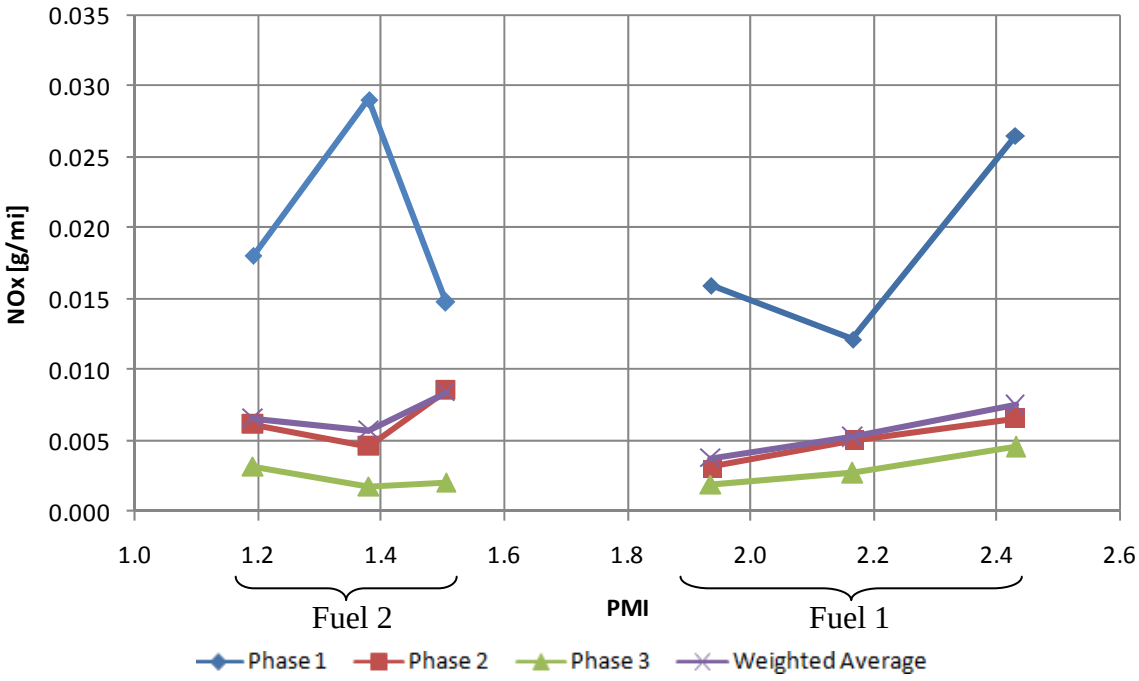


FIGURE E-9. NO_X VERSUS PMI FOR VEHICLE C

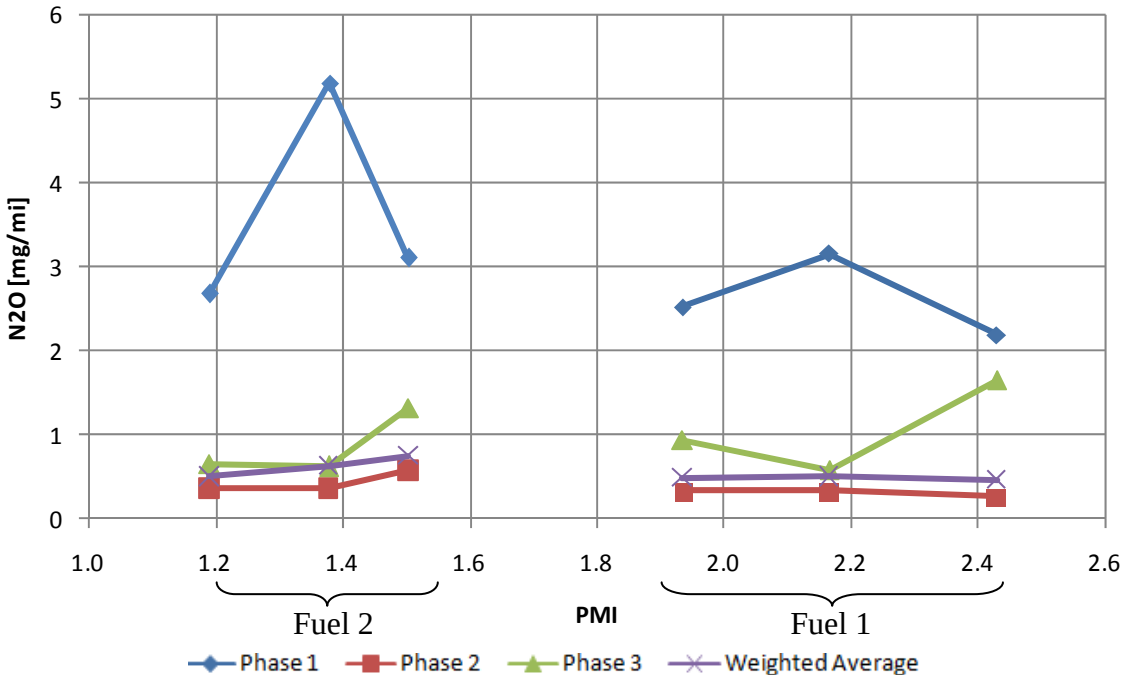


FIGURE E-10. N_2O VERSUS PMI FOR VEHICLE 1

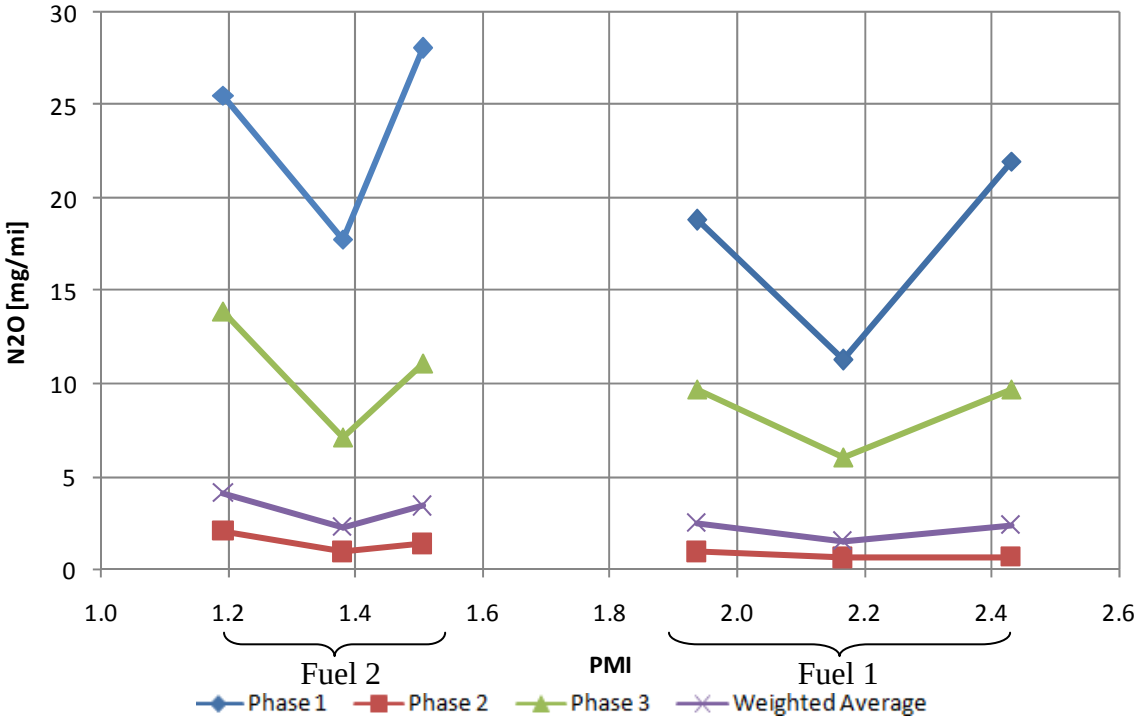


FIGURE E-11. N_2O VERSUS PMI FOR VEHICLE 2

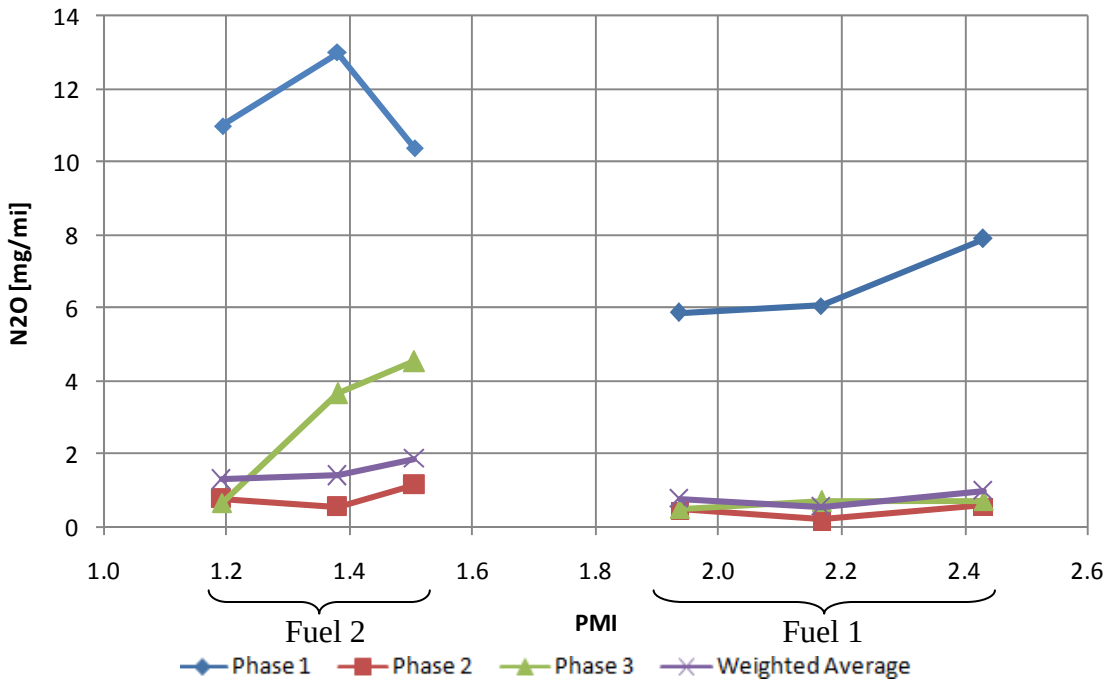


FIGURE E-12. N_2O VERSUS PMI FOR VEHICLE 3

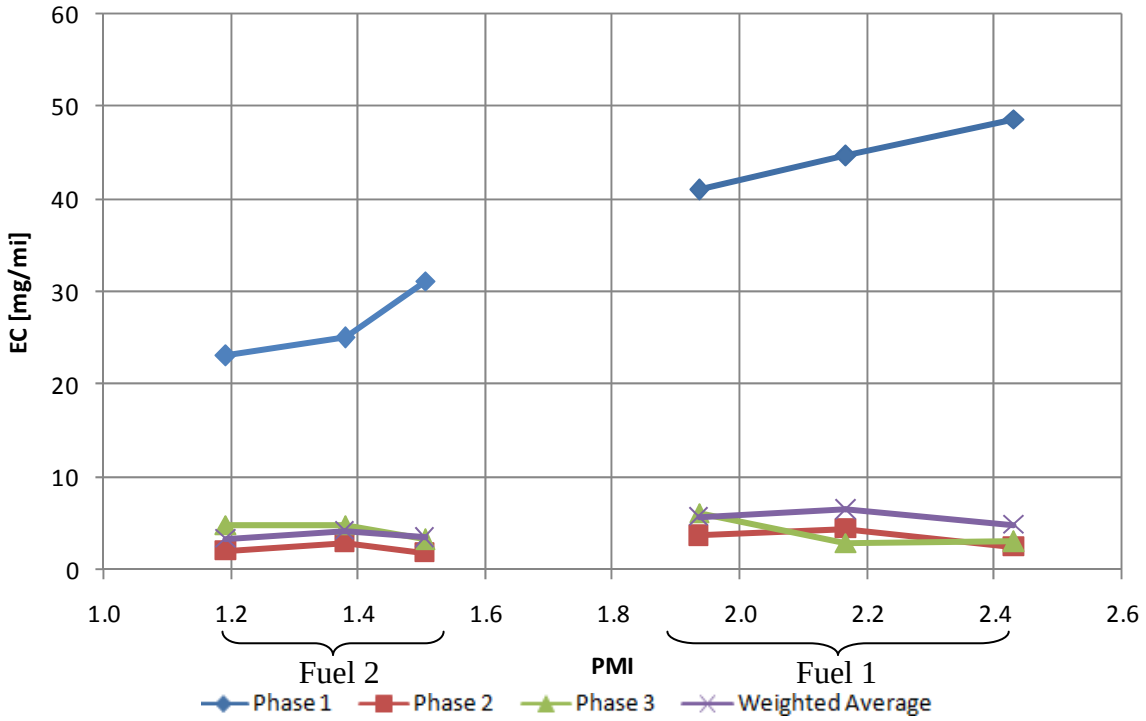


FIGURE E-13. EC VERSUS PMI FOR VEHICLE A

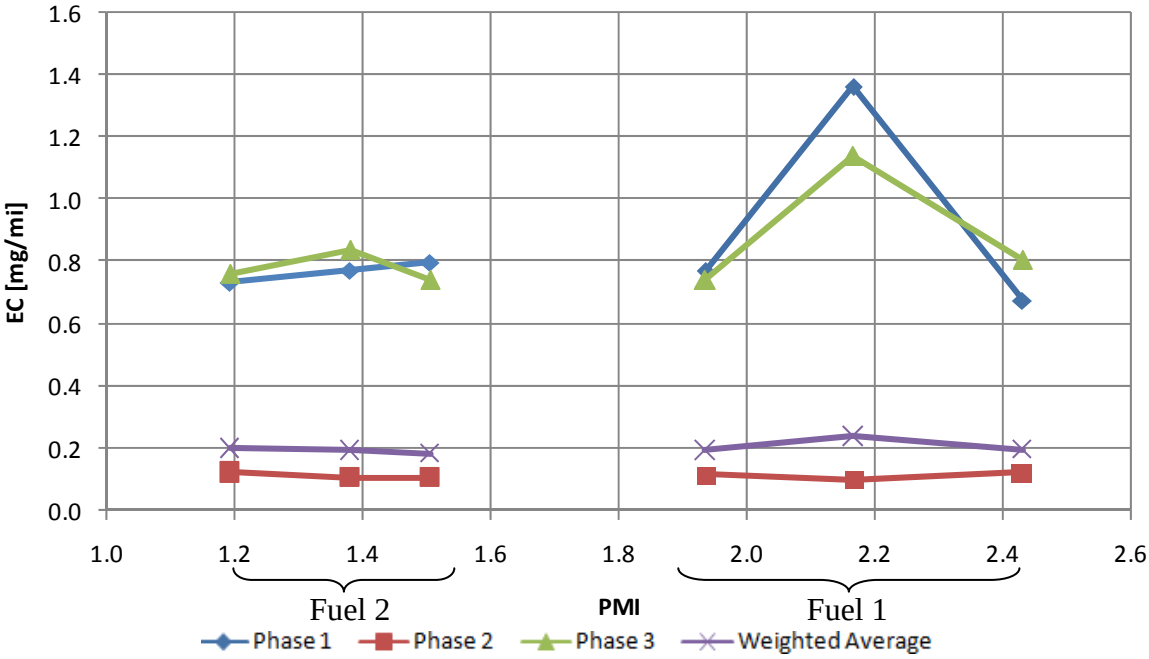


FIGURE E-14. EC VERSUS PMI FOR VEHICLE B

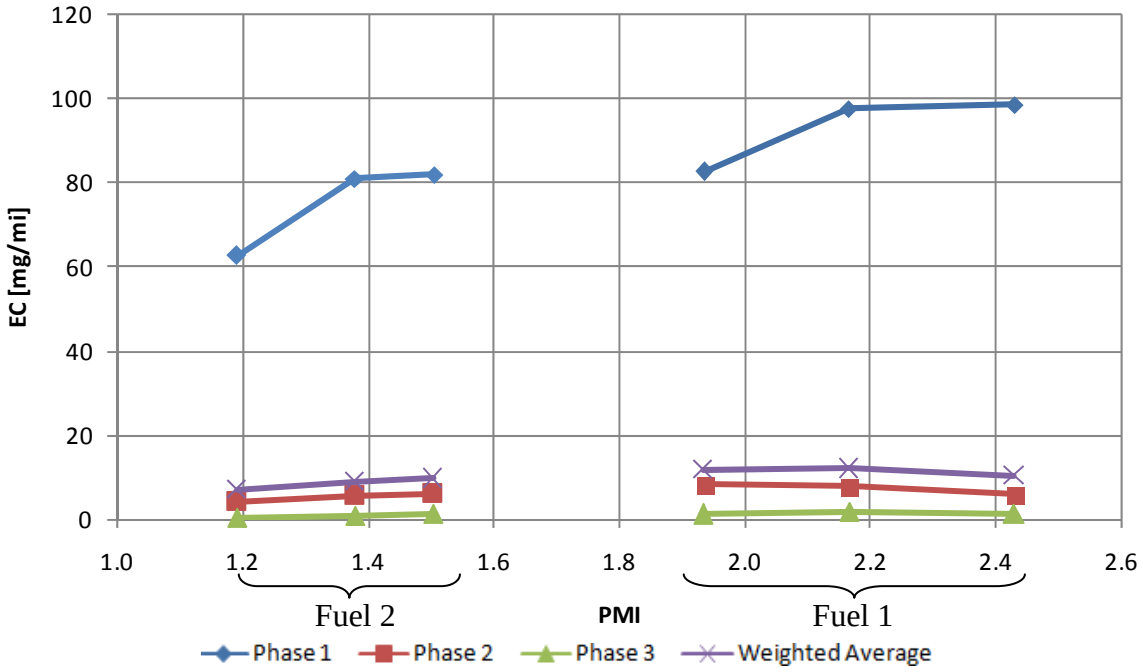


FIGURE E-15. EC VERSUS PMI FOR VEHICLE C

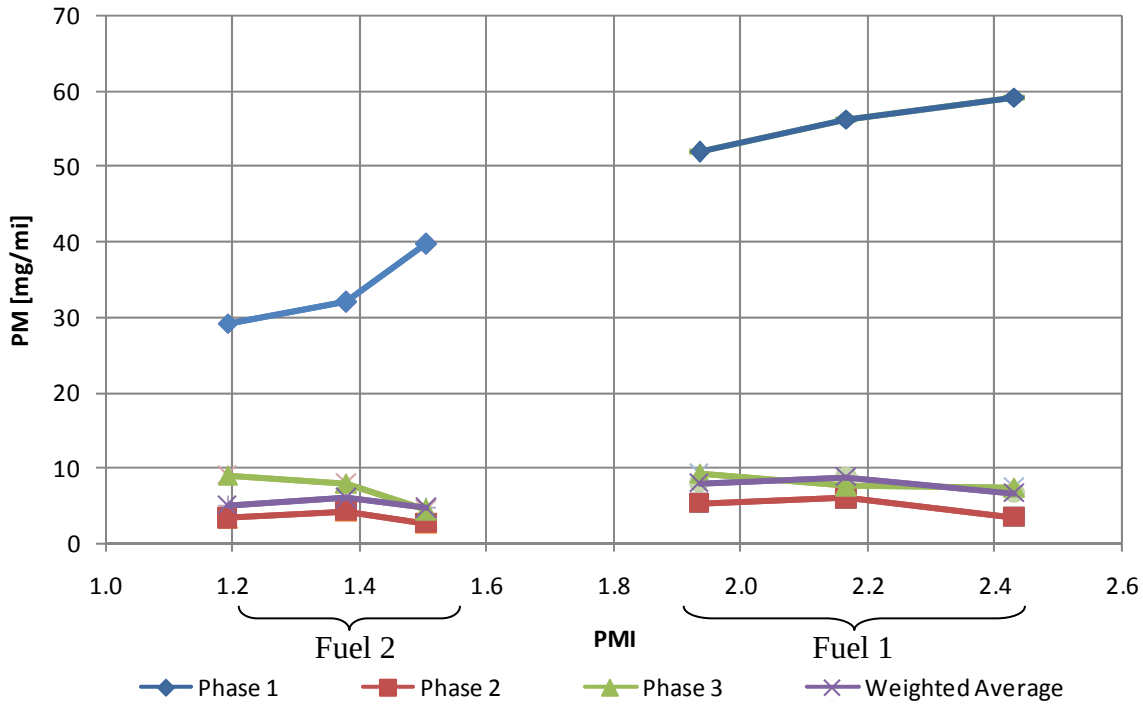


FIGURE E-16. PM VERSUS PMI FOR VEHICLE A

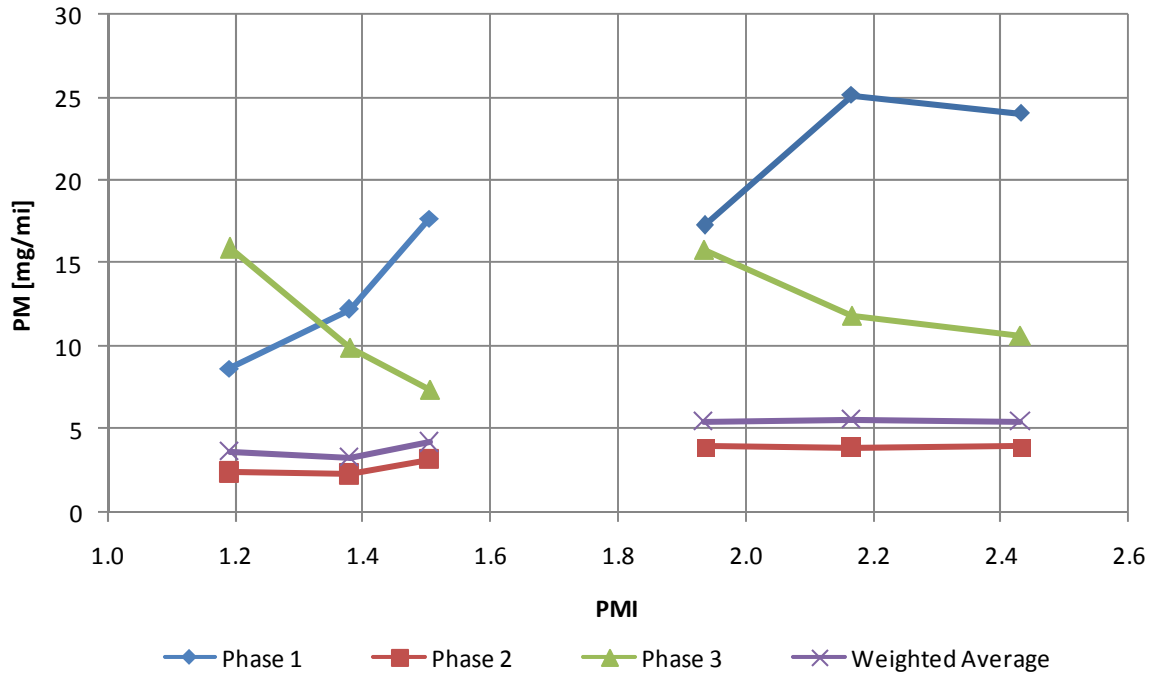


FIGURE E-17. PM VERSUS PMI FOR VEHICLE B

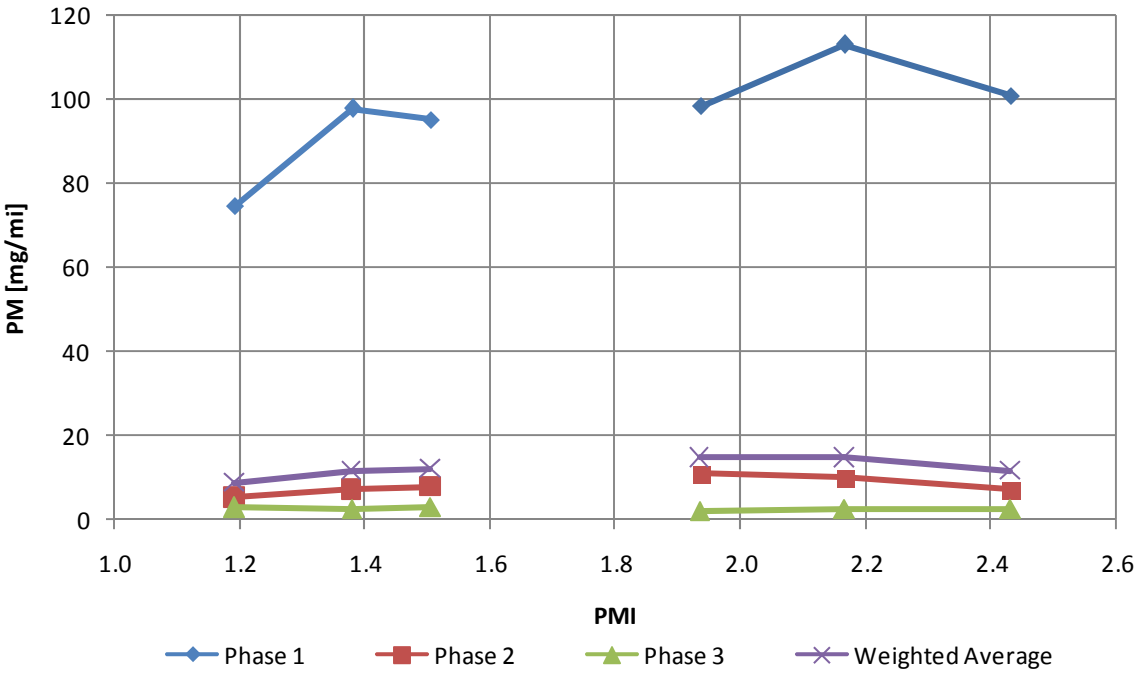


FIGURE E-18. PM VERSUS PMI FOR VEHICLE C