# CRC Report No. E-94-1a

# DETERMINATION AND EVALUATION OF NEW PREP CYCLE ON THE FUEL EFFECTS OF GASEOUS EMISSIONS ON SIDI IN-USE VEHICLES

## December 2014

**COORDINATING RESEARCH COUNCIL, INC.**
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# DETERMINATION AND EVALUATION OF NEW PREP CYCLE ON THE FUEL EFFECTS OF GASEOUS EMISSIONS ON SIDI IN-USE VEHICLES

**CRC Project E-94-1a**

**FINAL REPORT**

**SwRI® Project No. 03.19840**

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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 Technology. Technical staff members who contributed to this work were Mr. Matt Blanks, Senior Research Engineer, Light Duty Vehicle Technology; Mr. Peter Lobato, Research Engineer, Light Duty Vehicle Technology; Kevin Whitney, Manager, Light Duty Vehicle Technology; Dr. Imad Abdul-Khalek, Sr. Program Manager, Particle Science & Technology; Mr. Vinay Premnath, Research Engineer, Particle Science & Technology; Ms. Svitlana Kroll, Sr. Research Scientist, Emissions Chemistry; 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

API .....American Petroleum Institute
ASTM .....(Formerly) American Society for Testing and Materials, now ASTM International
CAFE .....Corporate Average Fuel Economy
CARB.....California Air Resources Board
CFR.....Code of Federal Regulation
CPC.....Condensation Particle Counter
CRC .....Coordinating Research Council
CVS.....Constant Volume Sampling
DBE .....Double Bond Equivalent
DHA .....Detailed Hydrocarbon Analysis
DOE .....Department of Energy
DTC .....Diagnostic Trouble Code
EC .....Elemental Carbon
ECD .....Electron Capture Detector
ECM.....Engine Control Module
EEPS .....Engine Exhaust Particle Sizer
EISA.....Energy Independence and Security Act
EPA.....Environmental Protection Agency
FID .....Flame Ionization Detector
FTP……..Federal Test Procedure
GHG.....Greenhouse Gas
HwFET.....Highway Fuel Economy Test
MAF.....Mass Air Flow
MAP.....Manifold Air Pressure
MON .....Motor Octane Number
MSS .....Microsoot Sensor
NA.....Naturally Aspirated
NDIR.....Non-Dispersive Infrared
NMHC .....Non-Methane Hydrocarbon
NMOG .....Non-Methane Organic Gas
OBD .....On Board Diagnostics
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
UDDS.....Urban Dynamometer Driving Schedule
VIN .....Vehicle Identification Number
VOC .....Volatile Organic Compound

# 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 particle number (PN) standard for gasoline-fuelled SIDI vehicles starting with EURO 6 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. A previous pilot study (CRC E-94-1) was performed at SwRI to investigate variations in regulated gaseous, GHG, PM and PN emissions from vehicles equipped with SIDI engines over a range of fuel properties. During this study, it was noted that some vehicles may not have properly adapted to a new fuel prior to being tested, thus giving high variability and confounding the results.

This project, Coordinating Research Council (CRC) E-94-1a, was conducted by Southwest Research Institute (SwRI) to investigate the repeatability of replicate tests measuring gaseous emissions, fuel economy, and PM and PN emissions. In comparison to the pilot program, the E-94-1a study used a more extensive preconditioning procedure before each test replicate. The repeatability between test replicates was determined; this assessed how comparable results would be when switching between fuels having different properties.

The preconditioning procedure was developed by acquiring information from various automakers about what test cycles should be used to allow a vehicle to learn a new fuel. The CRC technical contact then compiled this information and created the preconditioning procedure used in E-94-1a.

To evaluate the extensive preconditioning procedure, two different fuels were assessed. Two different ethanol-free gasoline fuels, which differed by their Particulate Mass Indices (PMI, described in E-94-1), were procured. The lower-PMI fuel was splash-blended with fuel-grade ethanol to produce a fuel with 20% ethanol (E20). The fuel with the higher PMI was not blended with ethanol, and was tested as is (E0). These two resulting test fuels differed substantially in ethanol content (0% and 20%), and PMI (2.066 and 0.7593).

The test fleet consisted of the same three vehicles used in the previous program, E-94-1. These were 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, in a randomized order. That is, Vehicle A is not necessarily the Volkswagen; Vehicle B is not necessarily the Ford, and so on.

**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 two test fuels over the LA92 drive cycle. During this drive cycle, NMHC, CO, $NO_X$, $N_2O$, elemental carbon, organic carbon, sulfate, particulate mass, soot mass, particle number and size and fuel economy were determined. Additionally, fuel properties between the two test fuels were not matched; therefore relationships between the types of fuel and emissions results cannot necessarily be implied. The purpose of this study was not to quantify the effects of changes in fuel properties, but rather to assess the repeatability of measurements of exhaust emissions and fuel economy when alternating vehicle operation between substantially different fuels.

To determine how the emissions and fuel economy repeated when switching fuels, a test sequence was carried out which alternated twice between two different fuels. This sequence allowed each vehicle to adapt to one fuel, then adapt to a different fuel, and then adapt back to its original fuel. That is, emissions and fuel economy measurements for each fuel were replicated twice. For each replicate, cold-start emissions tests were repeated two or three times. Testing on each fuel replicate with all three vehicles was conducted over the course of one week. Each week, the vehicle underwent a fuel change, the new extended preconditioning procedure, and repeated LA92 drive cycles while determining emissions and fuel economy.

The results of this study suggested that each of the three vehicles properly adapted to substantially different fuels and produced repeatable emissions and fuel economy measurements. As an example, PM from Vehicle B is shown in Figure ES-1. Therefore, the preconditioning procedure used in the project is considered to be suitable for future work to study the effects of different fuels on vehicle emissions.

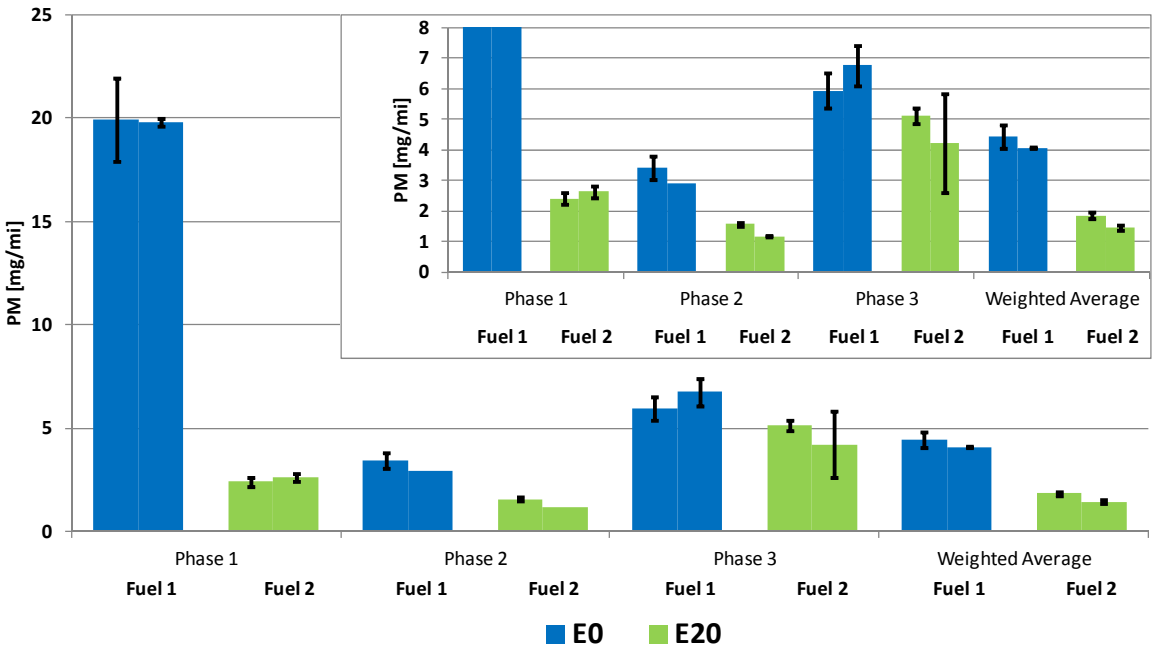



**FIGURE ES-1. VEHICLE B PARTICULATE MASS**

# 1.0 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 determining the repeatability of gaseous emissions, PM and PN emissions and fuel economy when switching between dissimilar fuels. This was investigated in a previous CRC project, E-94-1, the results of which were confounded by poor repeatability when testing the same fuel at different points throughout the project. This study is intended to determine the repeatability in emissions when alternating between different fuels. Both E-94-1 and E-94-1a together are 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.

As a result of the previous CRC project, it was hypothesized that:

a) The preconditioning procedure of the previous program, E-94-1, was insufficient and resulted in certain vehicles not adapting properly to a new fuel, confounding the results when comparing different fuels.
b) A different, longer preconditioning procedure would allow each vehicle to adapt to a new fuel, thus improving repeatability when switching between different fuels
c) The more dissimilar two fuels are, the harder it would be for a vehicle to learn a new fuel; therefore switching a vehicle between two very dissimilar fuels would bracket the worst-case scenario repeatability compared to other, more similar fuels.

To determine the repeatability of testing two dissimilar fuels with modern SIDI engines, three representative vehicles were selected. LA92 drive cycles were conducted while collecting gaseous, fuel economy, particulate mass, soot mass, particle number, elemental carbon, organic carbon and sulfate emissions data as well as continuous onboard diagnostic data (e.g. short-and long-term fuel trim).

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 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. The fuel with lower PMI was splash-blended with denatured ethanol to create a fuel with 20% ethanol (E20). 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 and a set of vehicle data collected from the vehicle's On Board Diagnostic (OBD) network 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 determine how well each vehicle adapted to these fuels.

It was anticipated that unforeseen correlations would arise from the data set collected. As such, part of the purpose of this work, and its predecessor E-94-1, was to provide data and insight to guide the direction of future work by the CRC.

# 2.0 TEST SETUP

## 2.1 Test Fuels

### *2.1.1 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 0.9190 while the other had a PMI of 2.066. It should be noted that other fuel properties were not matched, and ethanol was splash-blended into one of the fuels, so changes in exhaust emissions cannot be attributed only to PMI.

### *2.1.2 Fuel Blending*

Two commercial gasolines were purchased by SwRI from sources selected by CRC. Fuel 1 was transferred from a single bulk tank to fifteen 55-gallon drums, total of 810 gallons, by the contractor. The drums were then transported by motor-freight to SwRI and upon arrival labeled with SwRI fuel code GA-8840 and numbered from 1 to 15. A sample was then taken from each drum. The sample from drum number one received the following analytical evaluations:

- D240 Net Heat of Combustion
- D5599 Oxygenates
- D5291 Carbon / Hydrogen
- D2622 Sulfur
- D6304 Water Content
- D86 Distillation
- D6729 Detailed Hydrocarbon Analysis
- D4052 Specific Gravity

Each of the remaining drum samples were analyzed for specific gravity, oxygenates and water content. Results from these analyses are compiled in Table 1 and Table 2. The detailed hydrocarbon analysis data were transmitted to Honda R&D to determine the PMI of the gasoline; this information is included in the data set. Once the CRC representative approved this fuel, all drums were placed in constant-temperature storage.

Fuel 2 was transported in a tanker truck by a contractor to SwRI where it was transferred into two stainless steel totes, each filled to 349 gallons, and given SwRI fuel code GA-8824. A sample was taken from each tote and analyzed. The analyses from one tote included:

- D240 Net Heat of Combustion
- D5599 Oxygenates
- D5291 Carbon / Hydrogen
- D2622 Sulfur
- D6304 Water Content
- D6729 Detailed Hydrocarbon Analysis
- D4052 Specific Gravity
- D86 Distillation
- PetroSpec Gasoline Analysis

# TABLE 1. PROPERTIES OF FUEL 1

| | | | |
|---|---|---|---|
| | | **Description** | Fuel 1, CGA-8840 |
| | | **Dated** | 2/26/2014 |
| | | **Sample Code** | Drum #1 |
| | | **Laboratory** | FLRD-00193 |
| ***ASTM Method*** | ***Test Request*** | ***Test Units*** | ***Results*** |
| PM Index * | | | 2.066 |
| D240m | Heat of Combustion | | |
| | GROSS | BTU/lb | 20060 |
| | | MJ/kg | 46.661 |
| | | cal/g | 11144.7 |
| | NET | BTU/lb | 18802 |
| | | MJ/kg | 43.732 |
| | | cal/g | 10445.3 |
| D4052 | API Gravity | -- | 60.7 |
| | Specific Gravity | -- | 0.7364 |
| | Density at 15°C | g/L | 0.7362 |
| D5291 | Instrumental Determination of C,H | | |
| | Carbon | wt% | 86.54 |
| | Hydrogen | wt% | 13.8 |
| D2622 | Sulfur by UV | ppm | 3.2 |
| D5599 | Oxygen and Oxygenates | | |
| | Diisopropylether (DIPE) | vol% | <0.1 |
| | Ethyl tert-butylether (ETBE) | vol% | <0.1 |
| | Ethanol (EtOH) | vol% | <0.1 |
| | Isobutanol (iBA) | vol% | <0.1 |
| | Isopropanol (iPA) | vol% | <0.1 |
| | Methanol (MeOH) | vol% | <0.1 |
| | Methyl tert-butylether (MTBE) | vol% | <0.1 |
| | n-Butanol (nBA) | vol% | <0.1 |
| | n-Propanol (nPA) | vol% | <0.1 |
| | sec-Butanol (sBA) | vol% | <0.1 |
| | tert-amyl methylether (TAME) | vol% | <0.1 |
| | tert-Butanol (tBA) | vol% | <0.1 |
| | tert-Pentanol (tPA) | vol% | <0.1 |
| | Total Oxygen | wt% | 0 |
| D6304 | Water by Coulometric Titration | | |
| | Water Content | % | 0.00728 |
| | | ppm | 73 |
| D6729 | Detailed Hydrocarbon Analysis | -- | completed |
| D86 | Distillation | | |
| | IBP | ° F | 77.2 |
| | 5% | ° F | 85.8 |
| | 10% | ° F | 105.3 |
| | 15% | ° F | 123.9 |
| | 20% | ° F | 144.6 |
| | 30% | ° F | 188.9 |
| | 40% | ° F | 217.8 |
| | 50% | ° F | 233.2 |
| | 60% | ° F | 247.7 |
| | 70% | ° F | 266.3 |
| | 80% | ° F | 295 |
| | 90% | ° F | 328 |
| | 95% | ° F | 361.6 |
| | FBP | ° F | 419 |
| | Recovered | mL | 93.7 |
| | Residue | mL | 1.5 |
| | Loss | mL | 4.8 |
| * determined by Jeff Jetter | | | |

# TABLE 2. FUEL 1 DRUM SAMPLES

| | | Descrip. | Fuel 1, CGS-8840 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dated | 2/26/2014 | | | | | | | |
| | | Sample Code | Drum #1 | Drum #13 | Drum #10 | Drum #15 | Drum #6 | Drum #14 | Drum #12 | Drum #9 |
| | | Lab. | FLRD-00193 | FLRD-00194 | FLRD-00195 | FLRD-00196 | FLRD-00197 | FLRD-00198 | FLRD-00199 | FLRD-00200 |
| ***ASTM Method*** | ***Test Request*** | ***Test Units*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** |
| D4052 | API Gravity | -- | 60.7 | 61 | 61.2 | 61.2 | 61.1 | 61.1 | 60.8 | 61.1 |
| | Specific Gravity | -- | 0.7364 | 0.7351 | 0.7344 | 0.7345 | 0.7348 | 0.7347 | 0.7357 | 0.7347 |
| | Density at 15°C | g/L | 0.7362 | 0.7348 | 0.7342 | 0.7343 | 0.7346 | 0.7345 | 0.7354 | 0.7345 |
| | Ethanol (EtOH) | vol% | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| | Total Oxygen | wt% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Water Content | % | 0.00728 | 0.00637 | 0.00728 | 0.00672 | 0.0057 | 0.00668 | 0.00558 | 0.00605 |
| | | **Sample Code** | **Drum #4** | **Drum #3** | **Drum #2** | **Drum #8** | **Drum #11** | **Drum #7** | **Drum #5** | |
| | | **Lab.** | **FLRD-00201** | **FLRD-00202** | **FLRD-00203** | **FLRD-00204** | **FLRD-00205** | **FLRD-00206** | **FLRD-00207** | |
| ***ASTM Method*** | ***Test Request*** | ***Test Units*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | |
| D4052 | API Gravity | -- | 61.1 | 61 | 61.1 | 61 | 61 | 61.1 | 61 | |
| | Specific Gravity | -- | 0.7347 | 0.7351 | 0.7348 | 0.7349 | 0.7349 | 0.7346 | 0.735 | |
| | Density at 15°C | g/L | 0.7345 | 0.7349 | 0.7346 | 0.7347 | 0.7347 | 0.7344 | 0.7348 | |
| | Ethanol (EtOH) | vol% | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | |
| | Total Oxygen | wt% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | Water Content | % | 0.00677 | 0.00591 | 0.0066 | 0.00642 | 0.00592 | 0.00585 | 0.00553 | |

The other tote sample was analyzed for specific gravity, PetroSpec and water content. The detailed hydrocarbon analysis data were transmitted to Honda R&D to determine the PMI of the gasoline; this information is included in the data set. Once the CRC representative approved this fuel, each tote was blended with denatured fuel-grade ethanol, on a weight basis, to bring the ethanol content to approximately 20 percent by volume based on six repeat ASTM D5599 oxygenate analyses. The 200 gallons of denatured fuel-grade ethanol were purchased in four drums and given SwRI fuel code GA-8822. A sample from one of the drums was analyzed to verify that it met the specifications of ASTM D4806-13a. Samples of the other three drums were analyzed for specific gravity to verify that they contained denatured fuel-grade ethanol. The results of all analyses on the denatured fuel-grade ethanol are compiled in Table 3.

The contents of the two totes were then comingled into a single bulk tank and given SwRI fuel code CGB-8851. A sample from this tank was obtained and analyzed which included:

- D240 Net Heat of Combustion
- D5599 Oxygenates
- D5291 Carbon / Hydrogen
- D2622 Sulfur
- D6729 Detailed Hydrocarbon Analysis
- D4052 Specific Gravity
- PetroSpec Gasoline Analysis

Results from these analyses are compiled in Table 4. The detailed hydrocarbon analysis data were transmitted to Honda R&D to determine the PMI of the gasoline and this information is included in the data set. The fuel was then transferred into fifteen new labeled epoxy-lined 55-gallon drums and placed in constant temperature storage.

Additionally, each vehicle underwent a single emissions check-out test, described in Section 2.2.2. This initial check-out test was conducted using EEE certification gasoline, the analysis of which is provided in Table 5.

## 2.2 Test Vehicles

This study used the same three vehicles procured for the E-94-1 pilot study (Table 6). These vehicles were previously selected because they were available, widely used in the U.S. and 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.

The Volkswagen and Chevrolet were purchased used with an odometer reading between 4,000 and 10,000 miles such that the engines had already been broken in. The Ford was purchased new and subsequently underwent 4,000 miles of mileage accumulation as break-in prior to the program E-94-1.

## TABLE 3. PROPERTIES OF DENATURED ETHANOL ANALYSES

| Denatured Ethanol Analyses According to ASTM D4806-13a | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Fuel Code** | GA-8822 | | | |
| | | | **Location** | Drum #1 | Drum #2 | Drum #3 | Drum #4 |
| | | | **Date** | 2/4/2014 | | | |
| | | | **Description** | 1-gallon | 1-quart | 1-quart | 1-quart |
| | | | **Source** | ADM | | | |
| | **D4806-10b Specifications** | | **Laboratory Code** | FLRD-288 | FLRD-289 | FLRD-290 | FLRD-291 |
| **Property** | **Min** | **Max** | **Test Method** | **Result** | **Result** | **Result** | **Result** |
| Acidity, mass % | | 0.007 | ASTM D1613 * | 0.00529 | | | |
| Copper by AA, ppm | | 0.1 | ASTM D3237M ** | <0.01 | | | |
| Existent Gums, mg /100 mL | | | ASTM D381 | | | | |
| Unwashed WT | | | | 2 | | | |
| Washed WT | | 5.0 | | 1.5 | | | |
| API Gravity | | | ASTM D4052 | 46.6 | 46.6 | 46.6 | 46.6 |
| Specific Gravity | | | | 0.7944 | 0.7944 | 0.7943 | 0.7944 |
| Density (g/ml) | | | | 0.7941 | 0.7941 | 0.7941 | 0.7941 |
| Sulfur Content, mass ppm | | 10 (CARB) | ASTM D5453 | 1.8 | | | |
| Ethanol Content, wt% | | | ASTM D5501 | 96.86 | | | |
| EtOH, vol% | 92.1 | | | 96.91 | | | |
| Methanol Content, wt% | | | | 0.01 | | | |
| MeOH, vol% | | 0.5 | | 0.01 | | | |
| Water Content, mass % | | 1.26 | ASTM D6304 *** | 1.2014 | | | |
| Water Content, ppm | | | | 12014 | | | |
| pHe | 6.5 | 9.0 | ASTM D6423 | 8.63 | | | |
| Total Chloride, ppm | | 10 | ASTM D7319 | <1 | | | |
| Total Sulfate, mass ppm | | 4.0 | | <1 | | | |
| Potential Sulfate, ppm | | | | <1 | | | |

* Note from D4806-13a: Denatured fuel ethanol may contain additives, such as corrosion inhibitors and detergents that can affect the titratable acidity of the finished denatured fuel ethanol. Although the base ethanol may meet the acidity specification, the effect of these additives can produce an apparent high titratable acidity of the finished product. SwRI has confirmed that ADM does use a corrosion inhibitor. Also ADM's CofA for this batch shows a D1613 result of 0.001 mass %.
** D3237M was substituted for D1688
*** D6304 was substituted for E1064

# TABLE 4. PROPERTIES OF FUEL 2

| | | **Description** | Fuel 2 (base) | | Fuel 2 (E20) | | **Fuel 2 (E20)** |
|---|---|---|---|---|---|---|---|
| | | | GA-8824 | | CGB-8851 | | **CGB-8851** |
| | | **Dated** | 2/7/2014 | | 3/6/2014 | | 3/12/2014 |
| | | **Sample** | Tote 08-009 | Tote 08-012 | Tote 08-009 | Tote 08-012 | **15 Drums** |
| | | **Laboratory** | FLRD-00286 | FLRD-00287 | FLRD-00322 | FLRD-00323 | FLRD-00359 |
| ***ASTM Method*** | ***Test Request*** | ***Test Units*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** |
| PM Index * | | | 0.918979 | | | | 0.7593 |
| D240m | Heat of Combustion | | | | | | |
| | GROSS | BTU/lb | 20351 | | | | 18695 |
| | | MJ/kg | 47.336 | | | | 43.485 |
| | | cal/g | 11306.1 | | | | 10386.1 |
| | NET | BTU/lb | 18999 | | | | 17376 |
| | | MJ/kg | 44.192 | | | | 40.415 |
| | | cal/g | 10555 | | | | 9653.1 |
| D4052 | API Gravity | -- | 68.8 | 68.8 | 64.3 | 64.3 | 64.2 |
| | Specific Gravity | -- | 0.7066 | 0.7063 | 0.7228 | 0.7228 | 0.7229 |
| | Density at 15°C | g/mL | 0.7064 | 0.7061 | 0.7226 | 0.7226 | 0.7227 |
| D4052 (rerun) | API Gravity | -- | | | 64.3 | 64.2 | |
| | Specific Gravity | -- | | | 0.7228 | 0.7229 | |
| | Density at 15°C | g/mL | | | 0.7226 | 0.7227 | |
| D5291 | Instrumental | | | | | | |
| | Carbon | wt% | 85.34 | | | | 78.07 |
| | Hydrogen | wt% | 14.82 | | | | 14.46 |
| D2622 | Sulfur by UV | ppm | 27.8 | | | | 22.3 |
| D5599 | Oxygen and Oxygenates | | | | | | |
| | Ethanol (EtOH) | vol% | | | | | 20.4161 |
| | Total Oxygen | wt% | | | | | 7.78 |
| max | Ethanol (EtOH) (all 6 runs) | vol% | | | 20.60 | 20.60 | |
| min | | | | | 20.15 | 20.09 | |
| average | | | | | 20.46 | 20.40 | |
| max | Total Oxygen (all 6 runs) | vol% | | | 7.85 | 7.85 | |
| min | | | | | 7.68 | 7.66 | |
| average | | | | | 7.8 | 7.77 | |
| D6304 | Water by Coulometric | | | | | | |
| | Water Content | % | 0.0034 | 0.0038 | | | |
| | | ppm | 34 | 38 | | | |
| D6729 | Detailed Hydrocarbon | -- | completed | | | | completed |
| PetroSpec | MeOH | vol% | <0.3 | <0.3 | | | <0.3 |
| | EtOH | vol% | <0.6 | <0.6 | | | 19.4 |
| | MTBE | vol% | <0.9 | <0.9 | | | <0.9 |
| | ETBE | vol% | <1.9 | <1.9 | | | <1.9 |
| | TAME | vol% | <1.8 | <1.8 | | | <1.8 |
| | DIPE | vol% | <0.9 | <0.9 | | | <0.9 |
| | TBA | vol% | <0.9 | <0.9 | | | <0.9 |
| | TTLWT | wt% | 0 | 0 | | | 7.11 |
| | Benzene | vol% | 0.36 | 0.37 | | | 0.39 |
| | Aromatic | vol% | 13 | 13 | | | 13.3 |
| | Olefins | vol% | 9.2 | 8.9 | | | 6.6 |
| | Saturate | vol% | 77.9 | 78.1 | | | 60.7 |
| | RON | . | 89.9 | 89.9 | | | 96.1 |
| | MON | . | 83.3 | 83.2 | | | 84.8 |
| | RM2 | . | 86.6 | 86.6 | | | 90.5 |
| | DI | . | 1186 | 1181 | | | 1315 |
| | T50 | ° F | 229 | 229 | | | 270 |
| | T90 | ° F | 337 | 337 | | | 321 |
| | E200 | % | 39 | 40 | | | |
| | E300 | % | 86 | 86 | | | |

# TABLE 4 (CONT'D). PROPERTIES OF FUEL 2

| | | **Description** | Fuel 2 (base) | | Fuel 2 (E20) | | **Fuel 2** |
|---|---|---|---|---|---|---|---|
| | | | GA-8824 | | CGB-8851 | | **CGB-8851** |
| | | **Dated** | 2/7/2014 | | 3/6/2014 | | 3/12/2014 |
| | | **Sample Code** | Tote 08-009 | Tote 08-012 | Tote 08-009 | Tote 08-012 | **15 Drums** |
| | | **Laboratory** | FLRD-00286 | FLRD-00287 | FLRD-00322 | FLRD-00323 | FLRD-00359 |
| ***ASTM Method*** | ***Test Request*** | ***Test Units*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** | ***Results*** |
| D86 | Distillation | | | | | | |
| | IBP | ° F | 78 | | | | |
| | 5% | ° F | 90.3 | | | | |
| | 10% | ° F | 103.4 | | | | |
| | 15% | ° F | 114.4 | | | | |
| | 20% | ° F | 126.9 | | | | |
| | 30% | ° F | 155.2 | | | | |
| | 40% | ° F | 183.9 | | | | |
| | 50% | ° F | 205.4 | | | | |
| | 60% | ° F | 220.6 | | | | |
| | 70% | ° F | 234.2 | | | | |
| | 80% | ° F | 252.7 | | | | |
| | 90% | ° F | 293.9 | | | | |
| | 95% | ° F | 329.2 | | | | |
| | FBP | ° F | 364.3 | | | | |
| | Recovered | mL | 96.5 | | | | |
| | Residue | mL | 1 | | | | |
| | Loss | mL | 2.5 | | | | |

* Determined at Honda R&D

**TABLE 5. 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 6. 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 | | 7,446 | 5,203 | 10,591 |
| 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 |
| *Odometer reading at the beginning of E-94-1a | | | | |

### *2.2.1 Vehicle Check-in*

At the beginning of this program, the test vehicles underwent a fuel change to EEE and diagnostic trouble codes (DTCs) were checked. The vehicles were otherwise tested in the condition they were in at the end of the E-94-1 program.

### *2.2.2 Vehicle Emissions Check-Out Test*

Before testing began, each vehicle received a single checkout emissions test over a standard LA92 driving cycle using EEE certification fuel. Analyses of this fuel are provided in Section 2.1.2 in Table 5. 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 7. The test results were approved by the CRC-appointed program manager. The complete set of phase-level emissions data is given in Appendix A.

**TABLE 7. 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 | 0.030 | 0.772 | 0.008 | 7.8 |
| **Vehicle B** | | | | |
| EPA Tier 2 Certification Standard for FTP-75 | 0.075 | 1.30 | 0.05 | 10 |
| Checkout Test Weighted Results on LA-92 | 0.017 | 0.385 | 0.006 | 4.0 |
| **Vehicle C** | | | | |
| EPA Tier 2 Certification Standard for FTP-75 | 0.07 | 2.1 | 0.04 | 10 |
| Checkout Test Weighted Results on LA-92 | 0.033 | 1.512 | 0.008 | 15.7 |

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

### *2.2.3 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 Standard Road Cycle (SRC) for 250 miles to break-in the oil.

## 2.3 Vehicle Testing

The order in which the two fuels were tested was alternated twice, resulting in four tests per vehicle, in order to show that the vehicles could repeatably adapt to a different fuel. That is, each fuel was replicated twice with two or three repeated tests per replicate. Each vehicle/fuel combination was tested over the course of one week, and the order in which testing was conducted is shown in Table 8.

**TABLE 8. TEST SEQUENCE**

| Week | Vehicle A | Vehicle B | Vehicle C |
|---|---|---|---|
| 1 | Fuel 1 E0 | Fuel 1 E0 | Fuel 1 E0 |
| 2 | Fuel 2 E20 | Fuel 2 E20 | Fuel 2 E20 |
| 3 | Fuel 1 E0 | Fuel 1 E0 | Fuel 1 E0 |
| 4 | Fuel 2 E20 | Fuel 2 E20 | Fuel 2 E20 |

Each week began with the fuel change and preconditioning procedure shown in Table 9. This procedure is the primary aspect of E-94-1a, which differed from E-94-1, and was developed in an attempt to ensure each vehicle properly adapted to a new fuel before emissions testing was conducted. The preconditioning procedure was developed by acquiring information from various automakers about what test cycles should be used to allow a vehicle to learn a new fuel. The CRC technical contact then compiled this information and created the preconditioning procedure used in E-94-1a. This procedure is described in further detail in Fuel Change, Conditioning and Test Procedure (Appendix B) and Catalyst Sulfur Purge Cycle (Appendix C).

The preconditioning procedure utilized the Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Driving Schedule (HwFET), the US06 driving schedule, and the LA92 (also called the Unified Driving Cycle, or UDC), described later. Graphic representations of these driving schedules are shown in Figures 1 through 4, respectively.

**TABLE 9. PRECONDITIONING PROCEDURE**

| Day | Step | Task |
|---|---|---|
| 1 | 1 | Fuel Change 1 |
| | 2 | Sulfur Removal Procedure |
| | 3 | Vehicle Coastdowns |
| | 4 | Fuel Change 2 |
| | 5 | Fuel Change 3 |
| | 6 | 12-hour soak |
| 2 | 7 | UDDS (cold-start) |
| | 8 | HwFET |
| | 9 | HwFET |
| | 10 | US06 |
| | 11 | 12-hour soak |
| 3 | 12 | LA92 |
| | 13 | 8-hour soak |

After the fuel change and preconditioning procedure, two repeated emission tests were conducted on consecutive days. The percent-change in each pair of tests were determined; if the percent change was less than the values in Table 10, or if the absolute difference between the two tests was less than 5 mg/mi, the two tests were considered acceptable. Otherwise, a third test was conducted if approved by the CRC technical contacts.

**TABLE 10. TEST REPEATABILITY CRITERIA**

| Pollutant, g/mi | Percent Difference |
|---|---|
| THC | 30% |
| CO | 50% |
| $NO_X$ | 50% |

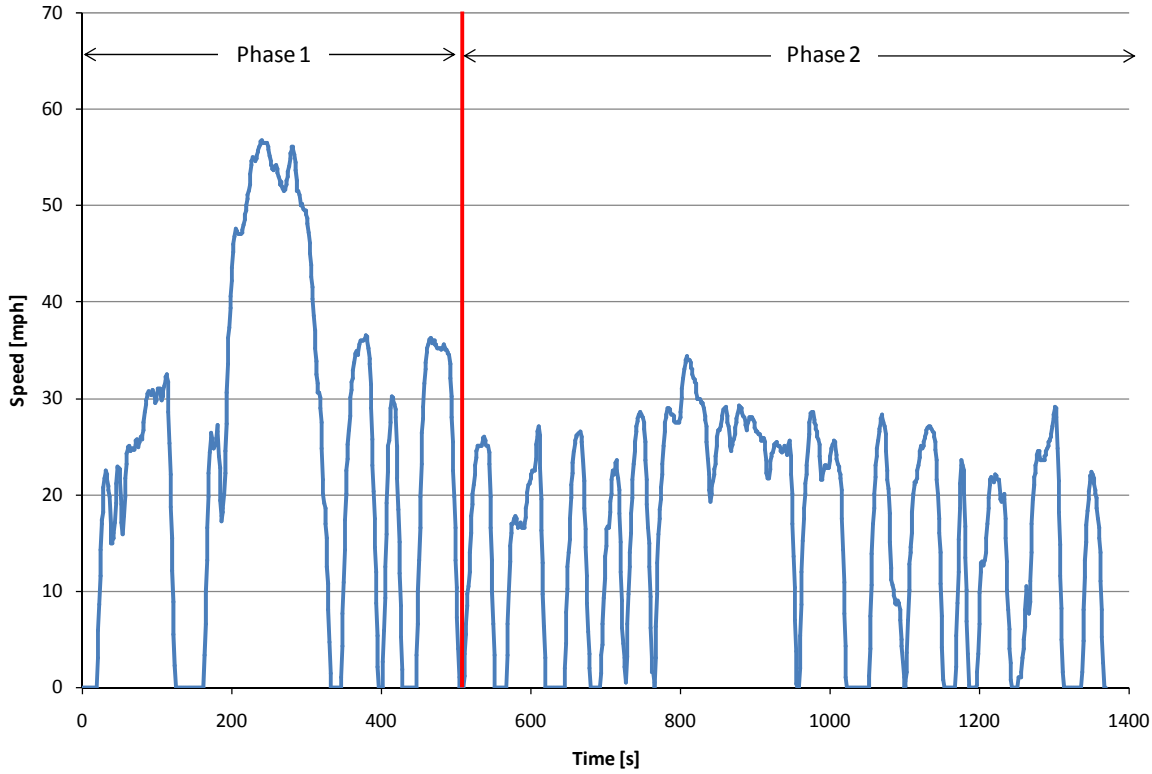



**FIGURE 1. URBAN DYNAMOMETER DRIVING SCHEDULE**

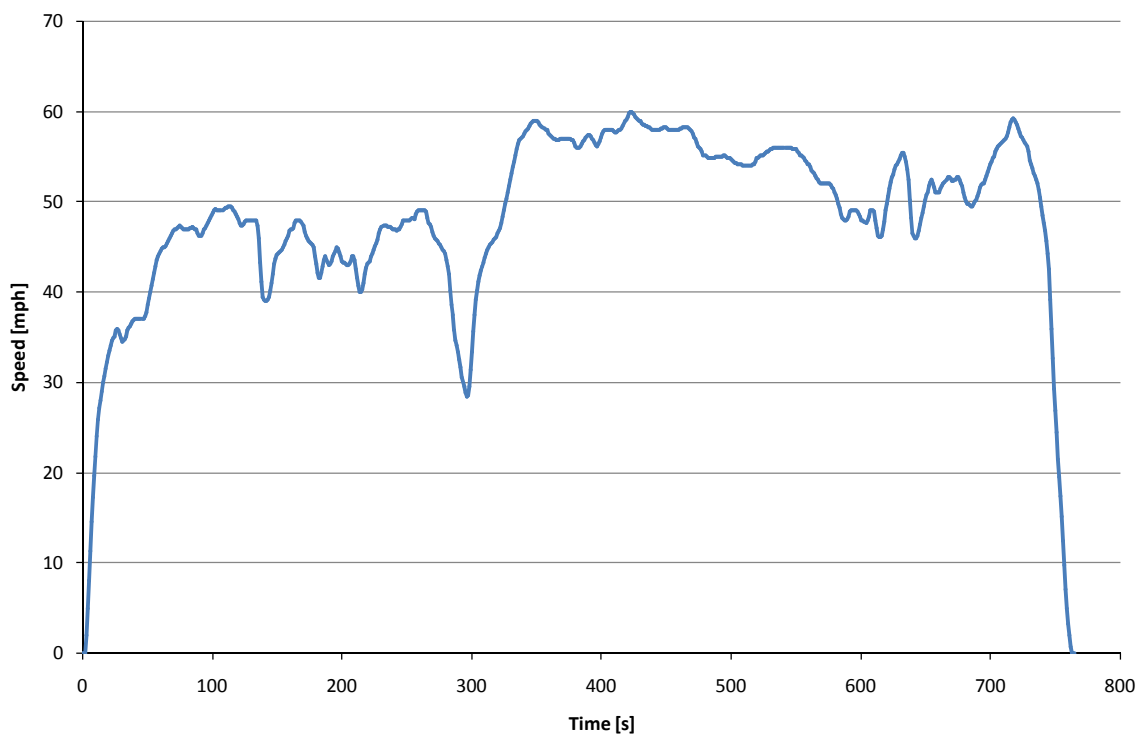



**FIGURE 2. HIGHWAY FUEL ECONOMY DRIVING SCHEDULE**

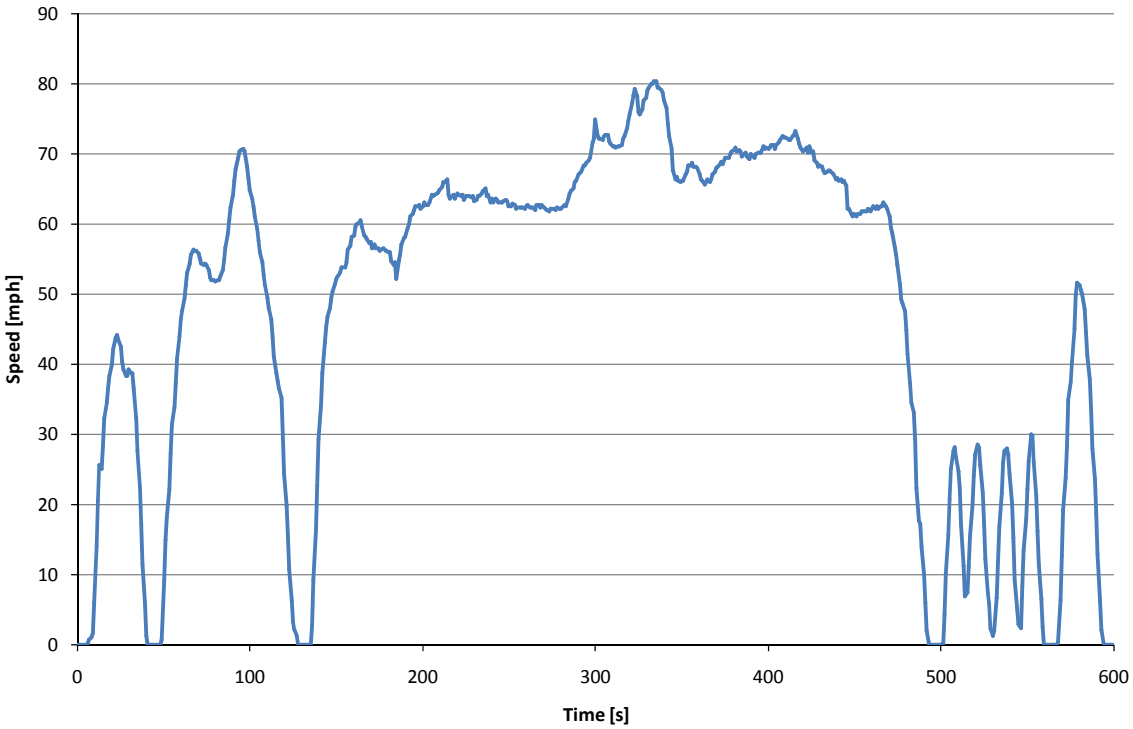



**FIGURE 3. US06 DRIVING SCHEDULE**

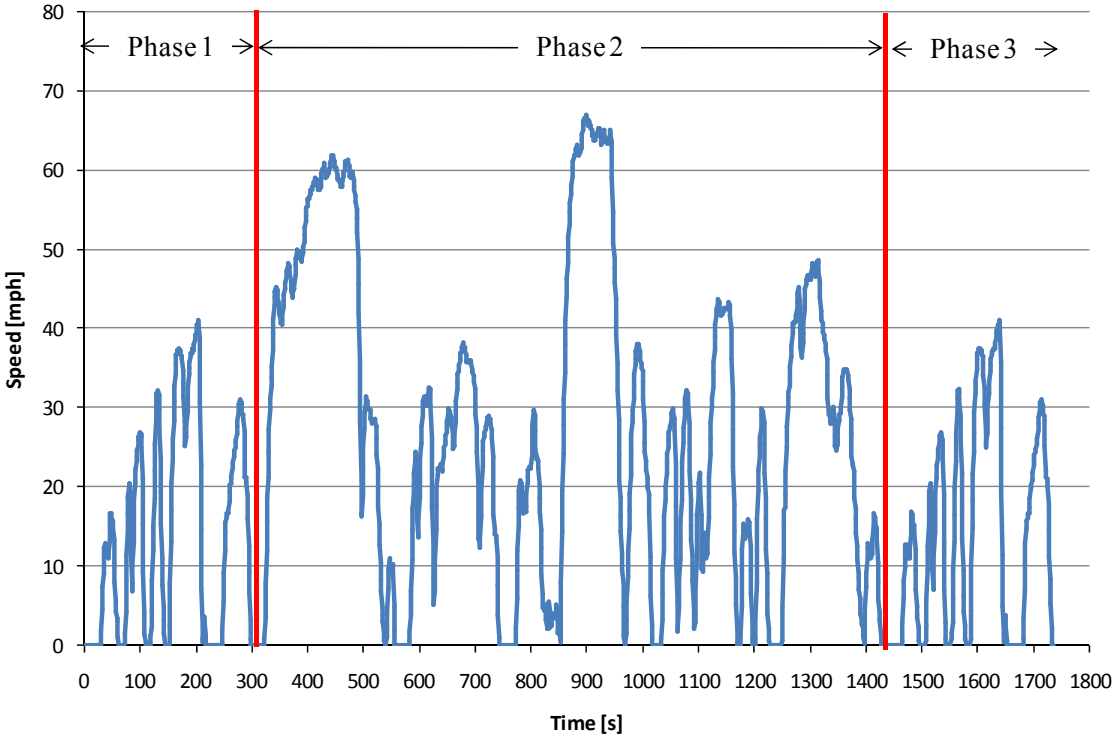



**FIGURE 4. LA92 DRIVING CYCLE**

The emissions drive cycle was the California Air Resources Board LA92 Dynamometer Driving Schedule, often called the Unified Driving Cycle (UDC). 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 a 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. Further details of the emission test procedure are described in Appendices B and C as well.

### *2.3.1 Emissions Chassis Dynamometer Setup*

Emissions testing was 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.

The same dynamometer and driver as the previous study, E-94-1, 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.

### *2.3.2 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. Fuel economy was calculated by the carbon balance method as given in 40 CFR Part 600. A Horiba constant volume sampler was used to collect dilute exhaust in inert bags. Dilute exhaust constituents were analyzed as shown in Table 11.

**TABLE 11. 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.

### *2.3.3 Unregulated Emissions*

#### *2.3.3.1 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 5). In this measurement, pre-columns vent heavier components, including water and $O_2$. The micro-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.

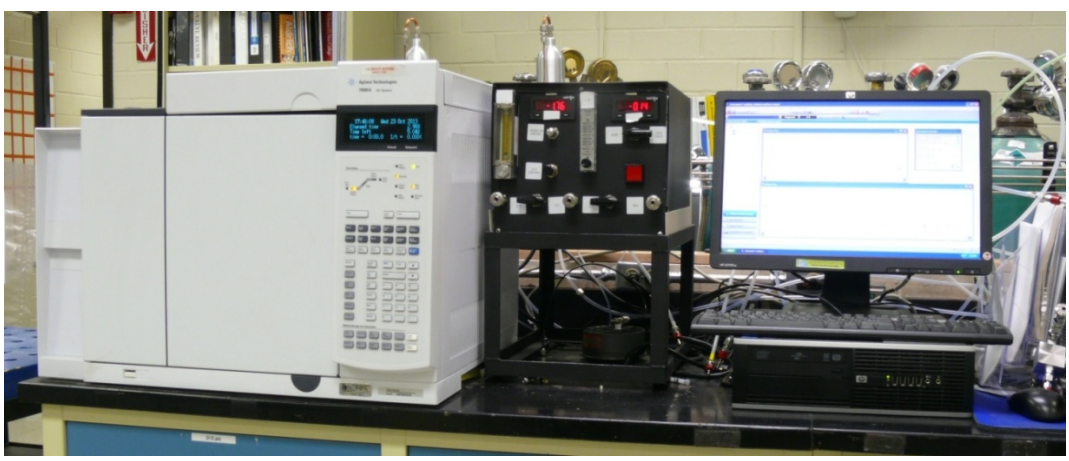


**FIGURE 5. AN AGILENT GREENHOUSE ANALYZER AND SAMPLE INTRODUCTION SYSTEM**

#### *2.3.3.2 Engine Exhaust Particle Sizer (EEPS)*

TSI's EEPS Model 3090, shown in Figure 6, 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.

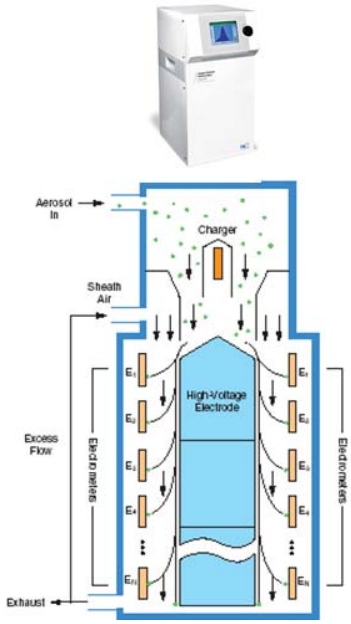



**FIGURE 6. ENGINE EXHAUST PARTICLE SIZER (EEPS)**

*2.3.3.3 Solid Particle Sampling System (SPSS)*

The SPSS, shown in Figure 7, 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 7. SOLID PARTICLE SAMPLING SYSTEM**

*2.3.3.4 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 8. The CPC 3790 is inside the red box, and the CPC 3025 is the white instrument as pictured.

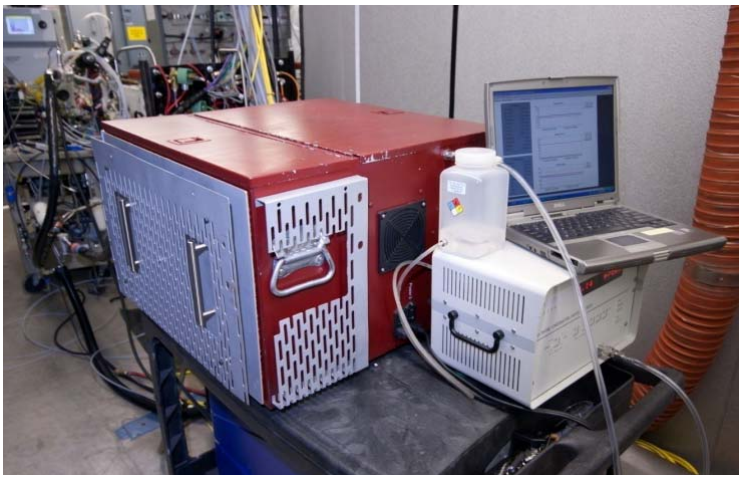


**FIGURE 8. SwRI SOLID PARTICLE NUMBER MEASUREMENT SYSTEM**

*2.3.3.5 Micro Soot Sensor (MSS)*

An AVL Micro Soot Sensor, shown in Figure 9, 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 $\mu g/m^3$, 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 Constant Volume Sampling (CVS) tunnel.

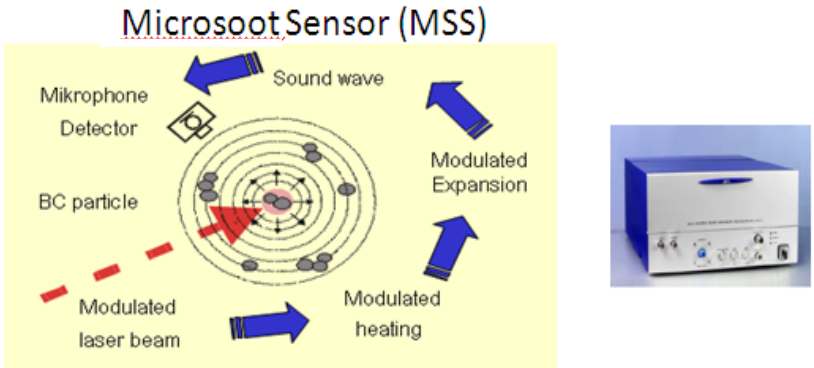



**FIGURE 9. AVL MICROSOOT SENSOR (MSS)**

*2.3.3.6 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[1]. 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 CVS tunnel directly after the PM collection unit (Figure 10).

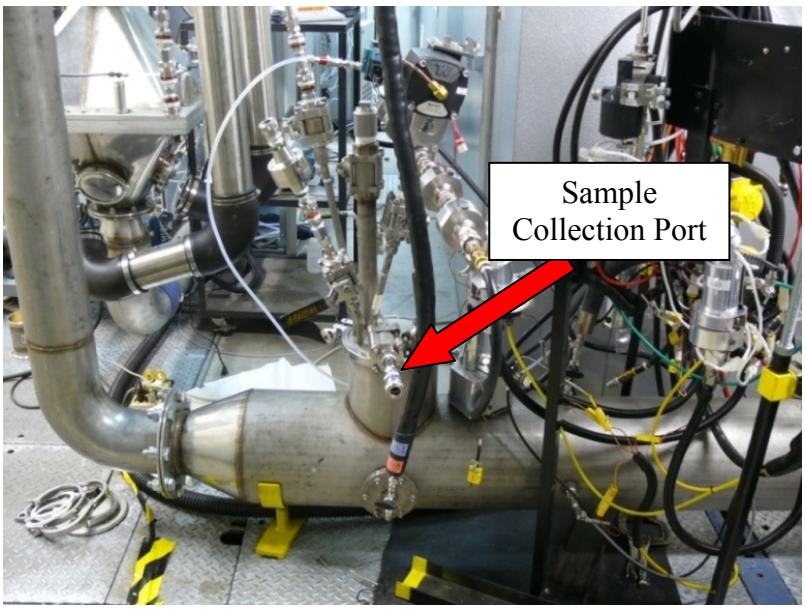



**FIGURE 10. EC/OC SAMPLE COLLECTION**

[1]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.

PM samples were collected on primary and secondary quartz filters using separate filter holders connected in series (Figure 11). 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 11. PRIMARY AND SECONDARY FILTERS ASSEMBLY**

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 12) 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 13).

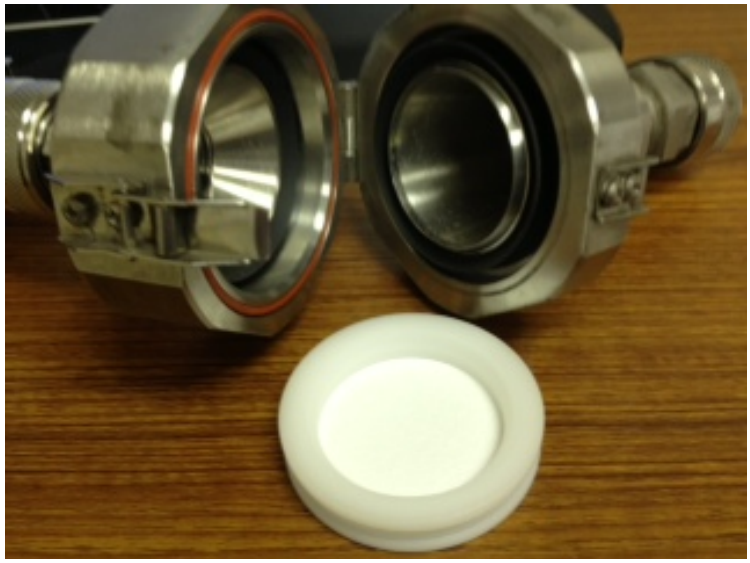


**FIGURE 12. PRE-FILTER HOLDER AND PRE-ASSEMBLED FILTER**

**FIGURE 13. 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 E-94-1 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. As a result, a single punch was used for all EC/OC measurements on the E-94-1a program.

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.

*2.3.3.7 Sulfate*

Sulfate and sulfuric acid was collected on a separate filter and converted to ammonium sulfate ($(NH_4)_2SO_4$) by exposure to ammonia vapor. This ammonization step was performed to "fix" the sulfuric acid as the ammonium sulfate salt. The soluble sulfate salts will be leached from the filter with a measured volume of 60 percent isopropanol/40 percent water solution.

An aliquot of this extract was injected into an ion chromatograph. Anions were separated by the analytical column (Dionex® Ion Pak AS4A-SC 2mm) and passed through a conductivity detector. The retention time on the column provides identification of the sulfate anion, and the

intensity of the signal corresponds to the concentration detected. Calibration was performed with external standards of known concentration.

*2.3.3.8 On-Board Diagnostic Channels*

Several OBD channels were recorded continuously throughout the LA92 tests. A complete list of the channels recorded throughout testing is provided in Table 12. The complete data sets are available on the ftp site. It should be noted that the three vehicles did not have the same set of sensors (e.g. a manifold air pressure sensor rather than a mass air flow sensor), therefore the set of data collected between the three vehicles is not identical.

**TABLE 12. RECORDED OBD CHANNELS**

| | VW | Ford | Chevrolet |
|---|---|---|---|
| Throttle Position | X | X | X |
| Manifold Absolute Pressure (MAP) | Not available | X | X |
| Mass Air Flow (MAF) | X | Not available | X |
| Spark Timing | X | X | X |
| Commanded Equivalence Ratio | X | X | X |
| Lambda – Pre-Catalyst | X | X | Not available |
| O2 Switching Sensor – Pre-Catalyst | Not available | Not available | X |
| O2 Switching Sensor – Post-Catalyst | X | X | X |
| Calculated Load | X | X | X |
| Absolute Load | X | X | X |
| Short-Term Fuel Trim – bank 1 | X | X | X |
| Short-Term Fuel Trim – bank 2 | Not available | X | Not available |
| Long-Term Fuel Trim – bank 1 | X | X | X |
| Long-Term Fuel Trim – bank 2 | Not available | X | Not available |
| Engine Speed | X | X | X |
| Coolant Temperature | X | X | X |
| Commanded Evaporative Purge | X | X | X |
| Evaporative System Vapor Pressure | Not available | X | X |
| Intake Air Temperature | X | X | X |

# 3.0 TEST RESULTS

## 3.1 Emissions and Fuel Economy Results

This work was intended as an initial experiment to determine test-to-test repeatability 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 scope. No statistical conclusions were made. The following is a summary of the project results and pertinent observations. A summary[2] of weighted average emissions results from the three test vehicles is provided below in Tables 13 through 18, and fuel economy results are shown in Table 19.

The results in this section are shown by a vehicle code (A, B and C) which has been randomized relative to the order in which the vehicles are listed in Table 6. Furthermore, fuel economy results in Table 19 and fuel economy and $CO_2$ results in Appendix D 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.

**TABLE 13. VEHICLE A GASEOUS EMISSIONS**

| Fuel | Ethanol Content, % | Week | Test Repeat | THC, g/mi | CO, g/mi | $NO_X$, g/mi | NMHC, g/mi | $N_2O$, g/mi |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | A | 0.047 | 1.16 | 0.011 | 0.034 | 2.86 |
| | | | B | 0.052 | 1.05 | 0.015 | 0.038 | 3.50 |
| | | 3 | A | 0.038 | 1.38 | 0.013 | 0.026 | 2.86 |
| | | | B | 0.047 | 1.46 | 0.006 | 0.034 | 2.32 |
| | | | C | 0.051 | 1.18 | 0.008 | 0.038 | 2.68 |
| 2 | 20 | 2 | A | 0.034 | 0.79 | 0.018 | 0.021 | 4.26 |
| | | | B | 0.040 | 0.71 | 0.015 | 0.025 | 3.69 |
| | | 4 | A | 0.041 | 1.03 | 0.020 | 0.027 | 4.84 |
| | | | B | 0.040 | 0.89 | 0.018 | 0.025 | 4.46 |

**TABLE 14. VEHICLE B GASEOUS EMISSIONS**

| Fuel | Ethanol Content, % | Week | Test Repeat | THC, g/mi | CO, g/mi | $NO_X$, g/mi | NMHC, g/mi | $N_2O$, g/mi |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | A | 0.016 | 0.33 | 0.017 | 0.014 | 1.78 |
| | | | B | 0.017 | 0.31 | 0.011 | 0.015 | 1.94 |
| | | 3 | A | 0.019 | 0.38 | 0.016 | 0.015 | 1.88 |
| | | | B | 0.019 | 0.30 | 0.018 | 0.016 | 1.75 |
| 2 | 20 | 2 | A | 0.024 | 0.54 | 0.020 | 0.020 | 2.16 |
| | | | B | 0.024 | 0.46 | 0.032 | 0.020 | 2.11 |
| | | 4 | A | 0.027 | 0.53 | 0.005 | 0.021 | 2.39 |
| | | | B | 0.026 | 0.43 | 0.008 | 0.021 | 2.34 |

[2] Complete results for each test are provided on the ftp site.

## TABLE 15. VEHICLE C GASEOUS EMISSIONS

| Fuel | Ethanol Content, % | Week | Test Repeat | THC, g/mi | CO, g/mi | $NO_X$, g/mi | NMHC, g/mi | $N_2O$, g/mi |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | A | 0.031 | 1.34 | 0.004 | 0.022 | 0.60 |
| | | | B | 0.024 | 1.40 | 0.005 | 0.016 | 0.61 |
| | | 3 | A | 0.027 | 1.32 | 0.004 | 0.018 | 0.72 |
| | | | B | 0.018 | 1.48 | 0.004 | 0.011 | 0.60 |
| | | | C | 0.015 | 1.25 | 0.005 | 0.010 | 0.73 |
| 2 | 20 | 2 | A | 0.015 | 1.30 | 0.009 | 0.007 | 0.64 |
| | | | B | 0.030 | 1.66 | 0.007 | 0.018 | 0.88 |
| | | | C | 0.027 | 1.28 | 0.007 | 0.016 | 0.84 |
| | | 4 | A | 0.028 | 1.24 | 0.006 | 0.018 | 0.81 |
| | | | B | 0.029 | 1.03 | 0.007 | 0.018 | 0.83 |

## TABLE 16. VEHICLE A PARTICLE EMISSIONS

| Fuel | Ethanol Content, % | Week | Test Repeat | PM, mg/mi | EC+OC, mg/mi | MSS, mg/mi | PMP 3790, particles/mi |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | A | 7.2 | 7.56 | 4.77 | 1.19E+13 |
| | | | B | 7.4 | 7.14 | 4.73 | 1.12E+13 |
| | | 3 | A | 7.5 | 7.65 | 4.92 | 1.18E+13 |
| | | | B | 8.4 | 7.56 | 5.06 | 1.16E+13 |
| | | | C | 8.2 | 6.43 | 5.24 | 1.21E+13 |
| 2 | 20 | 2 | A | 1.8 | 1.08 | 0.91 | 4.26E+12 |
| | | | B | 1.8 | 1.95 | 0.99 | 4.62E+12 |
| | | 4 | A | 1.8 | 3.53 | 1.00 | 4.26E+12 |
| | | | B | 1.7 | 1.39 | 1.01 | 4.33E+12 |

## TABLE 17. VEHICLE B PARTICLE EMISSIONS

| Fuel | Ethanol Content, % | Week | Test Repeat | PM, mg/mi | EC+OC, mg/mi | MSS, mg/mi | PMP 3790, particles/mi |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | A | 4.8 | 3.87 | 3.22 | 9.58E+12 |
| | | | B | 4.0 | 3.90 | 2.75 | 8.97E+12 |
| | | 3 | A | 4.0 | 2.81 | 2.50 | 8.31E+12 |
| | | | B | 4.1 | 3.13 | 2.46 | 7.92E+12 |
| 2 | 20 | 2 | A | 1.7 | 1.36 | 0.85 | 3.16E+12 |
| | | | B | 1.9 | 1.66 | 1.12 | 3.27E+12 |
| | | 4 | A | 1.5 | 1.09 | 0.62 | 2.51E+12 |
| | | | B | 1.4 | 2.08 | 0.83 | 2.93E+12 |

**TABLE 18. VEHICLE C PARTICLE EMISSIONS**

| Fuel | Ethanol Content, % | Week | Test Repeat | PM, mg/mi | EC+OC, mg/mi | MSS, mg/mi | PMP 3790, particles/mi |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | A | 14.9 | 14.44 | 11.19 | 1.96E+13 |
| | | | B | 14.5 | 13.88 | 10.56 | 1.85E+13 |
| | | 3 | A | 14.6 | 13.82 | 10.32 | 1.78E+13 |
| | | | B | 15.3 | 13.93 | 11.00 | 1.84E+13 |
| | | | C | 12.8 | 11.78 | 9.15 | 1.68E+13 |
| 2 | 20 | 2 | A | 3.0 | 2.39 | 1.88 | 6.77E+12 |
| | | | B | 3.5 | 2.77 | 2.18 | 7.15E+12 |
| | | | C | 2.7 | 3.12 | 1.75 | 5.99E+12 |
| | | 4 | A | 2.6 | 2.25 | 1.71 | 5.96E+12 |
| | | | B | 2.5 | 2.23 | 1.71 | 6.35E+12 |

**TABLE 19. FUEL ECONOMY**

| Fuel | Ethanol Content, % | Week | Fuel Economy, mi/gal | | |
|---|---|---|---|---|---|
| | | | Vehicle 1 | Vehicle 2 | Vehicle 3 |
| 1 | 0 | 1 | 21.8 | 15.5 | 24.7 |
| | | | 22.0 | 15.5 | 24.7 |
| | | 3 | 21.8 | 15.6 | 24.7 |
| | | | 21.6 | 15.6 | 24.8 |
| | | | 20.0 | 14.4 | 22.6 |
| 2 | 20 | 2 | 19.3 | 14.0 | 22.6 |
| | | | 20.2 | n/a | n/a |
| | | 4 | 20.0 | 14.3 | 22.5 |
| | | | 20.0 | 14.3 | 22.5 |
| | | | 21.8 | 15.5 | 24.7 |

Sulfate was measured in the exhaust as well. In each test except one, any amount of Sulfate in the exhaust was below the detection limit of the method used to measure Sulfate. The one exception was in Phase 3 of Vehicle 3's first test (Fuel 1, E0). The measured Sulfate was 7.66 µg/mi.

The lower detection limit in sulfate was determined and provided in Table 20. This means that for tests in which Sulfate was reported as zero, the amount of sulfate in the exhaust could physically be between zero and the lower detection limit. The lower detection limit in determining the mass of sulfate in a single filter was 0.1 µg per filter. Taking into account exhaust flow rates and distance, the lower detection limit is proved in mg/mi in Table 20.

**TABLE 20. SULFATE DETECTION LIMITS**

| | Sulfate, mg/mi | | |
|---|---|---|---|
| | Vehicle 1 | Vehicle 2 | Vehicle 3 |
| Phase 1 | 0.05 | 0.07 | 0.06 |
| Phase 2 | 0.01 | 0.01 | 0.01 |
| Phase 3 | 0.05 | 0.07 | 0.06 |

Bagged THC, $CH_4$ (for determining NMHC), CO and $NO_X$ emissions were collected for each phase of the LA92 drive cycle for all testing. Figure 14 shows the THC emissions of Vehicle A, organized by phase and test fuel. The intervals overlapping each bar represent the highest and lowest repeated test for each vehicle/fuel combination. Each colored bar represents the average of all of the tests for a given week. The two adjacent bars of the same color represent the results of a given fuel for two different weeks that fuel was tested, so that the repeatability may be directly compared. The order in which the fuels were tested was given in Table 4. 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 14 fitted with a scale appropriate for Phase 2, Phase 3 and the weighted averages. This same type of chart is used to show the complete data set in Appendix D, and Figure 14 is shown as an example.

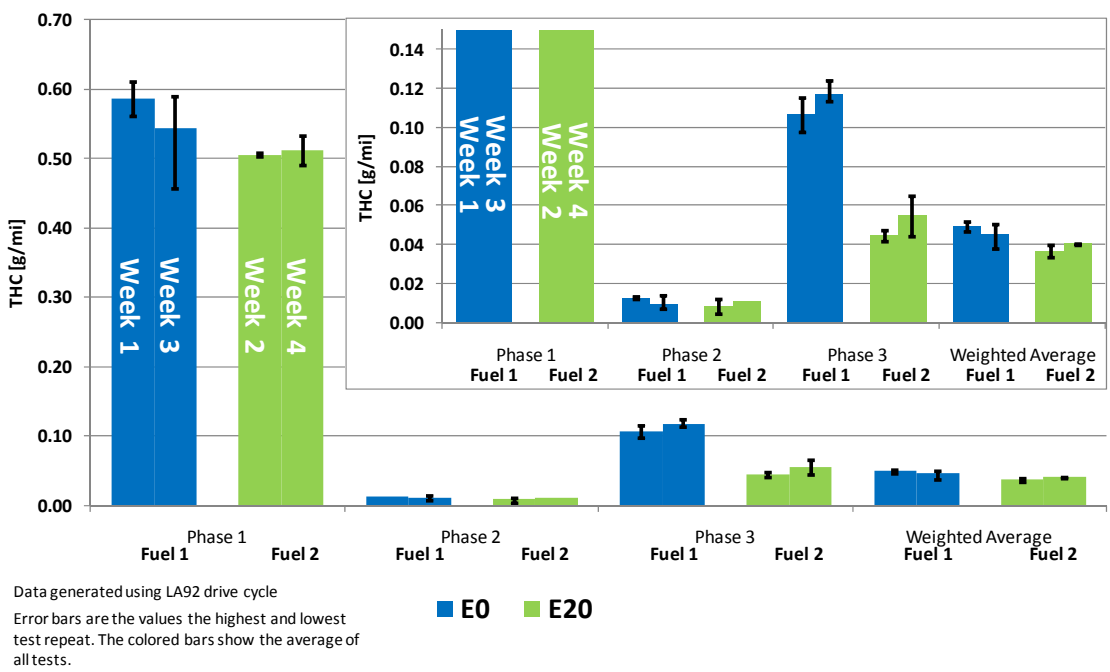



**FIGURE 14. VEHICLE A TOTAL HYDROCARBONS**

## 3.2 Precision and Repeatability

Data were analyzed for repeat measurement error (test-to-test variability within the series of 2 or 3 repeat measurements while the fuel was in the vehicle) and repeatability error (variability over replicates of testing with full fuel switching and preconditioning averaged over repeat measurements).

In E-94-1, each of six fuels (Fuel code 1 and Fuel code 2 with 0%, 10%, and 20% EtOH) was tested once on each of three vehicles, with one fuel (Fuel code 1 with 0% EtOH) replicated by testing at the beginning and end of the fuel sequence for each vehicle. There were three degrees of freedom for estimating repeatability precision and 21 degrees of freedom for estimating measurement error. Figure 15 shows the results of the weighted average PM in E-94-1.

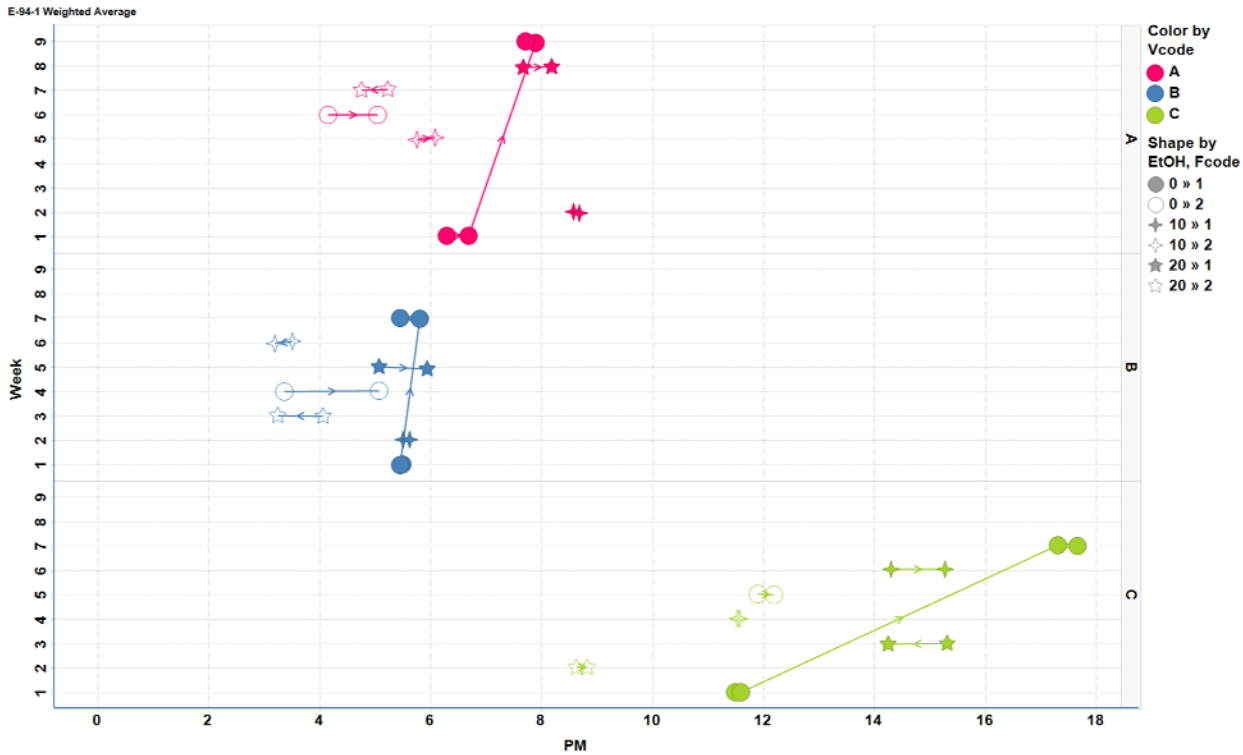



**FIGURE 15. E-94-1 WEIGHTED AVERAGE PM MG/MI MEASUREMENTS**

In E-94-1a, each of two fuels (Fuel code 1 with 0% EtOH and Fuel code 2 with 20% EtOH) were replicated in three vehicles. For each vehicle, the fuels were alternated in the same sequence. Within each replicate, two or three repeat measurements were made. There were six degrees of freedom for estimating repeatability precision and 15 degrees of freedom for estimating measurement error. Figure 16 shows the results of the weighted average PM in E-94-1a.

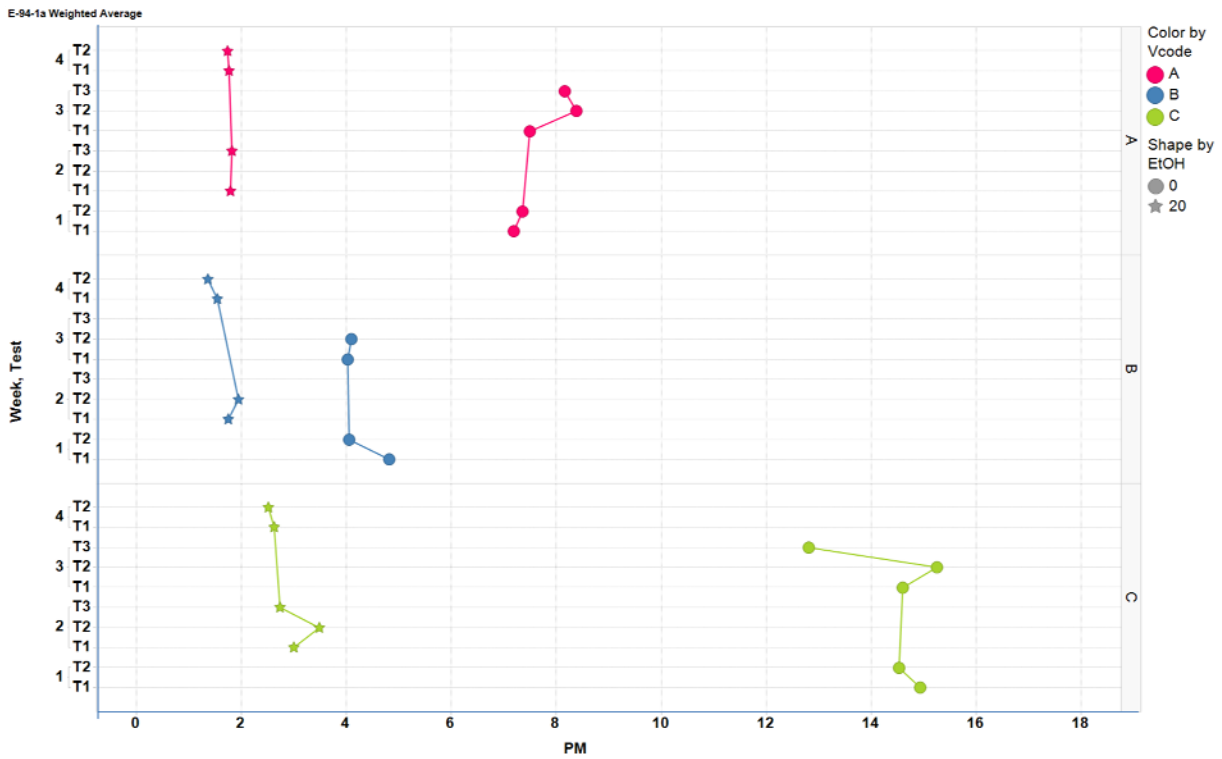



**FIGURE 16. E-94-1a WEIGHTED AVERAGE PM MG/MI MEASUREMENTS**

The results of precision calculations are shown in Table 21 for weighted averages of key results. The comparison might be most easily seen in coefficients of variation. There were large improvements in precision for total hydrocarbons, (THC), fuel economy (FE), particulate matter (PM), and particles > 23 nm (PM3790). Carbon monoxide (CO) precision deteriorated by about a third; $NO_x$ precision deteriorated in relative terms, but by a small amount in absolute terms – all results were very low.

Repeated measurement precision changed little between E-94-1 and E-94-1a. The table also indicates by red fonts where potential outliers exist. The top part of the table is calculated all in original units. Shading in the top indicates where there might be a need for transformation. The bottom part of the table is calculated for usual transformations – inversion of FE or changing to fuel consumption and natural logarithms for all other results. Shading in the bottom part of the table indicates where the usual transformation was too strong, meaning that the residuals in transformed results looked worse than in original units. The precision of the repeatability and repeated measurements was also assessed. This is provided below in Table 22.

## TABLE 21. PRECISIONS COMPARISON E-94-1a VERSUS E-94-1 (WEIGHTED AVERAGE)

| | | Repeatability | | | | | | Repeated Measurement | |
|---|---|---|---|---|---|---|---|---|---|
| | | E94-1a | | | E94-1 | | | E94-1a | E94-1 |
| | Units | Estimated σ | Mean | % Coeff. of Variation [a] | Estimated σ | Mean | % Coeff. of Variation [a] | Estimated σ | Estimated σ |
| **Original Units** | | | | | | | | | |
| THC | g/mi | 0.0031 | 0.0299 | 10.3 | 0.0055 | 0.0286 | 19.2 | 0.0047 | 0.0032 |
| CO | g/mi | 0.1215 | 0.9215 | 13.2 | 0.0886 | 0.8474 | 10.5 | 0.1191 | 0.1084 |
| $NO_x$ | g/mi | 0.0059 | 0.0120 | 49.4 | 0.0037 | 0.0104 | 35.8 | 0.0030 | 0.0037 |
| FE | mi/gal | 0.0638 | 19.8065 | 0.3 | 0.2689 | 20.0840 | 1.3 | 0.1965 | 0.1423 |
| PM | mg/mi | 0.3368 | 5.4346 | 6.2 | 2.4830 | 8.1220 | 30.6 | 0.5378 | 0.4502 |
| PMP3790 | part/mi | 5.67E+11 | 87.5E+11 | 6.5 | 27.8E+11 | 119E+11 | 23.3 | 4.83E+11 | 5.37E+11 |
| **Usual Transformations** | | | | | | | | | |
| lnTHC | ln(g/mi) | 0.1285 | -3.5749 | -3.6 | 0.2307 | -3.5789 | -6.4 | 0.1862 | 0.1136 |
| lnCO | ln(g/mi) | 0.1112 | -0.2113 | -52.6 | 0.1056 | -0.3110 | -34.0 | 0.1106 | 0.1444 |
| $lnNO_x$ | ln(g/mi) | 0.4340 | -4.5846 | -9.5 | 0.3455 | -4.7066 | -7.3 | 0.2265 | 0.2861 |
| 1/FE | gal / 1000 mi | 0.1850 | 52.5560 | 0.4 | 0.5870 | 51.6700 | 1.1 | 0.5640 | 0.4220 |
| lnPM | ln(mg/mi) | 0.0955 | 1.3735 | 7.0 | 0.1858 | 1.9807 | 9.4 | 0.0746 | 0.0883 |
| lnPMP3790 | ln(part/mi) | 0.0701 | 29.6209 | 0.2 | 0.1833 | 30.0564 | 0.6 | 0.0557 | 0.0535 |

Yellow highlighting indicates evidence of need for transformation.
Orange highlighting indicates evidence that usual transformation was too strong.
Red font indicates potential outliers.
[a] % Coefficient of Variation = 100 x estimated σ / Mean

## TABLE 22. PRECISION, ESTIMATES OF Σ

| | Repeatability | | Repeated Measurement | |
|---|---|---|---|---|
| | E94-1a | E94-1 | E94-1a | E94-1 |
| THC | 0.0031 | 0.0055 | 0.0047 | 0.0032 |
| CO | 0.1215 | 0.0886 | 0.1191 | 0.1084 |
| $NO_x$ | 0.0059 | 0.0037 | 0.0030 | 0.0037 |
| FE | 0.0638 | 0.2689 | 0.1965 | 0.1423 |
| PM | 0.3368 | 2.4830 | 0.5378 | 0.4502 |
| PMP3790 | 5.67E+11 | 2.78E+12 | 4.83E+11 | 5.37E+11 |
| **Usual Transformations** | | | | |
| lnTHC | 0.1285 | 0.2307 | 0.1862 | 0.1136 |
| lnCO | 0.1112 | 0.1056 | 0.1106 | 0.1444 |
| $lnNO_x$ | 0.4340 | 0.3455 | 0.2265 | 0.2861 |
| 1/FE | 0.0002 | 0.0006 | 0.0006 | 0.0004 |
| lnPM | 0.0955 | 0.1858 | 0.0746 | 0.0883 |
| lnPMP3790 | 0.0701 | 0.1833 | 0.0557 | 0.0535 |

Yellow highlighting indicates evidence of need for transformation.
Orange highlighting indicates evidence that usual transformation was too strong.
Red font indicates potential outliers.

Each vehicle's long-term fuel trim was recorded throughout the program (Figures 17, 18, & 19). In these figures, the long-term fuel trim was consistent when testing the same fuel at multiple times throughout the project. Additionally, a clear shift can be seen as the result of the two different fuels tested.

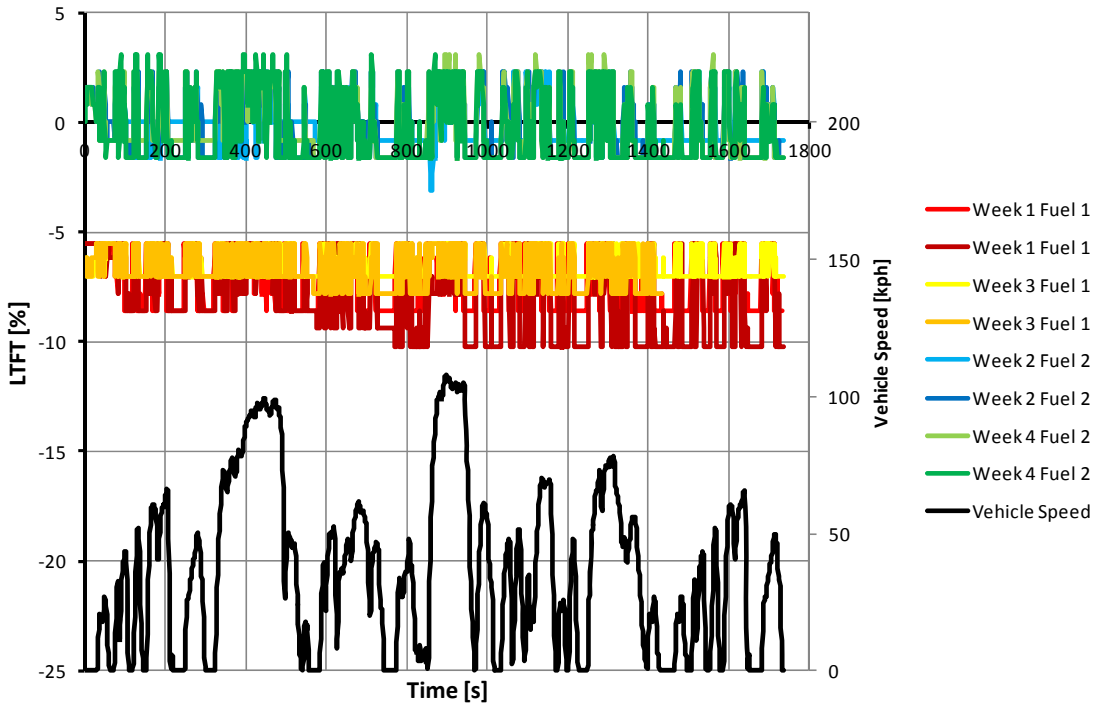



**FIGURE 17. VEHICLE A LONG TERM FUEL TRIM**

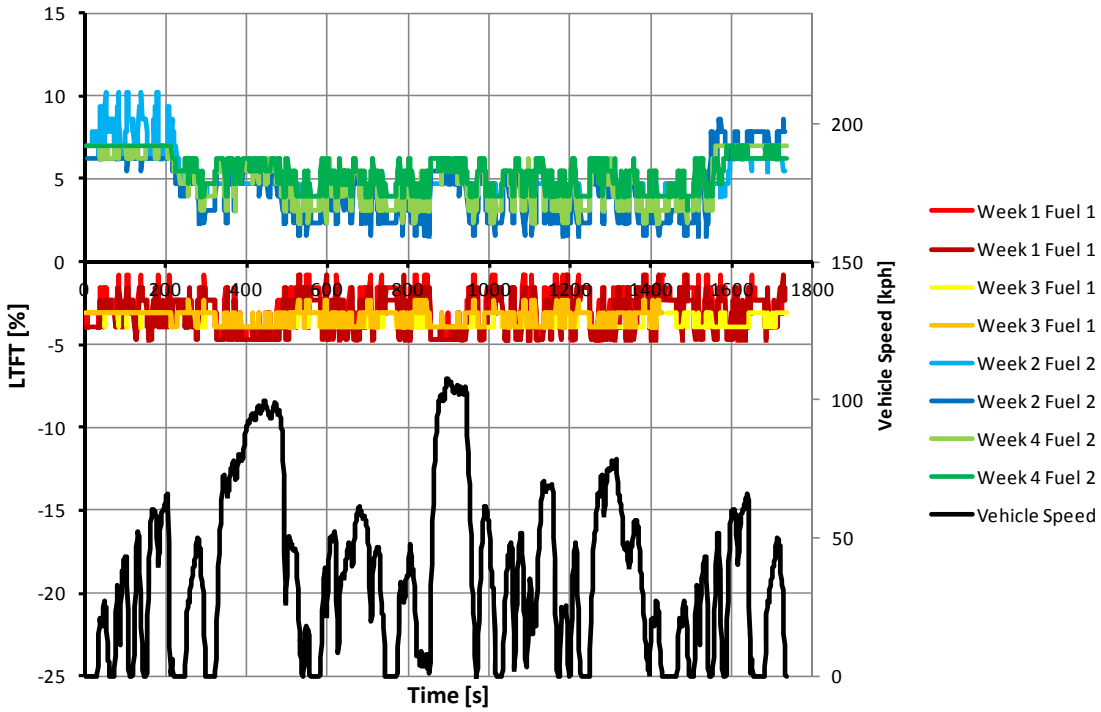



**FIGURE 18. VEHICLE B LONG TERM FUEL TRIM**

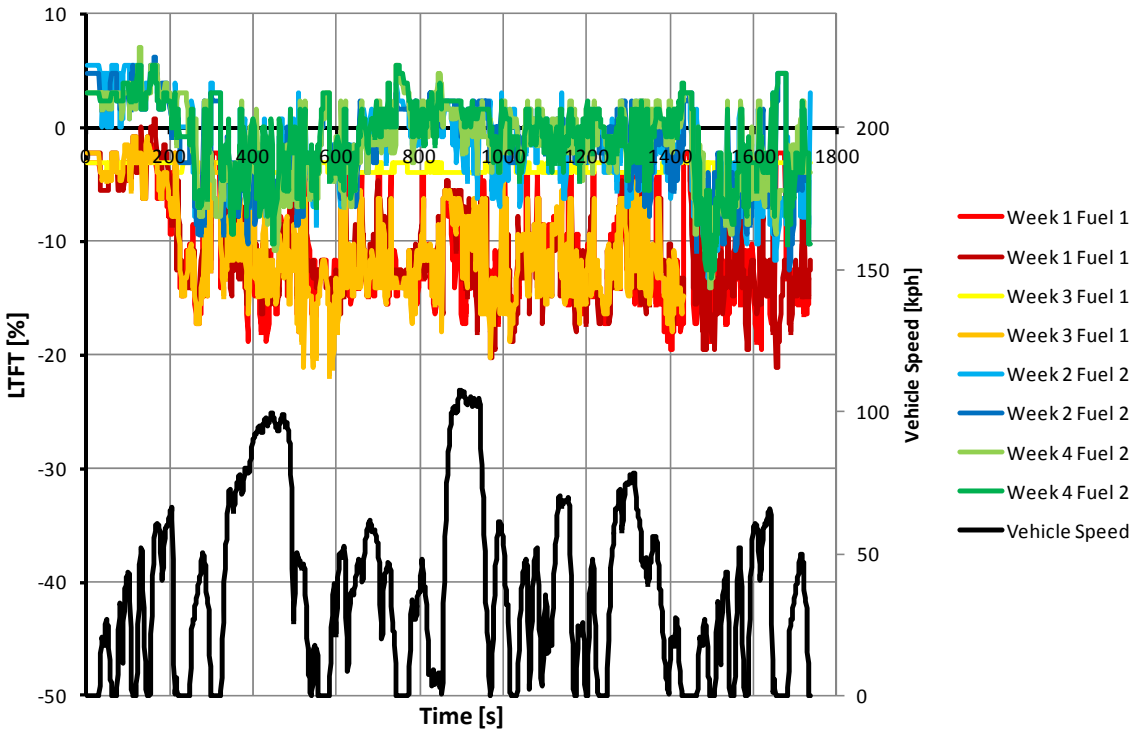



**FIGURE 19. VEHICLE C LONG TERM FUEL TRIM**

## 4.0 OBSERVATIONS AND FUTURE RECOMMENDATIONS

This project, E-94-1a, investigated the repeatability of gaseous emissions, fuel economy, PM and PN emissions when alternating between two different fuels. The results of a preceding CRC program, E-94-1, showed inconsistent emissions results when alternating between different fuels, the results of which suggested that vehicles did not properly adapt to different fuels.

Therefore, this project used a different, more extensive, preconditioning procedure before each test and showed emissions results repeated when shifting between fuels. It should be noted that the purpose of this project was not to study the effects of these two fuels on vehicle emissions, but rather to determine the repeatability of the overall test procedure.

The program (E-94-1a) determined that use of a more extensive vehicle preconditioning procedure when switching between two dissimilar fuels produced test results that were repeatable at an acceptable level, and that this preconditioning procedure should therefore be applied to future work. The next project CRC is considering, E-94-2, involves studying the impacts of eight different gasoline fuels on vehicle exhaust emissions.

# APPENDIX A

## EMISSIONS AT START OF STUDY

## TABLE A-1. EMISSIONS AT START OF STUDY: VEHICLE A

| | THC, g/mi | NMOG,[a] g/mi | CO, g/mi | $NO_X$, g/mi | PM, mg/mi |
|---|---|---|---|---|---|
| EPA Test Car List Results for FTP-75 | 0.05 | n/a | 1.3 | 0.01 | |
| Checkout Test Weighted Results on LA-92 | 0.03 | 0.03 | 0.78 | 0.01 | 7.9 |
| Checkout Test Results on LA-92 Phase 1 | 0.47 | 0.49 | 3.68 | 0.09 | 43.8 |
| Checkout Test Results on LA-92 Phase 2 | 0.00 | 0.00 | 0.62 | 0.00 | 5.7 |
| Checkout Test Results on LA-92 Phase 3 | 0.08 | 0.08 | 0.60 | 0.01 | 8.7 |

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

## TABLE A-2. EMISSIONS AT START OF STUDY: VEHICLE B

| | THC, g/mi | NMOG,[a] g/mi | CO, g/mi | $NO_X$, g/mi | PM, mg/mi |
|---|---|---|---|---|---|
| EPA Test Car List Results for FTP-75 [b] | 0.02 | n/a | 0.37 | 0.01 | |
| Checkout Test Weighted Results on LA-92 | 0.02 | 0.02 | 0.39 | 0.01 | 4.1 |
| Checkout Test Results on LA-92 Phase 1 | 0.32 | 0.33 | 4.08 | 0.11 | 12.6 |
| Checkout Test Results on LA-92 Phase 2 | 0.00 | 0.00 | 0.19 | 0.00 | 3.4 |
| Checkout Test Results on LA-92 Phase 3 | 0.00 | 0.00 | 0.12 | 0.00 | 6.8 |

[a] Note: NMOG was determined by multiplying NMHC by 1.04 as per CFR Title 40, Part 86, Subpart S, Section 86.1810-01
[b] Results from a manual transmission vehicle

## TABLE A-3. EMISSIONS AT START OF STUDY: VEHICLE C

| | THC, g/mi | NMOG,[a] g/mi | CO, g/mi | $NO_X$, g/mi | PM, mg/mi |
|---|---|---|---|---|---|
| EPA Test Car List Results for FTP-75 | 0.02 | n/a | 0.57 | 0.01 | |
| Checkout Test Weighted Results on LA-92 | 0.03 | 0.03 | 1.54 | 0.01 | 15.9 |
| Checkout Test Results on LA-92 Phase 1 | 0.28 | 0.29 | 6.04 | 0.01 | 119.7 |
| Checkout Test Results on LA-92 Phase 2 | 0.02 | 0.02 | 1.30 | 0.01 | 10.6 |
| Checkout Test Results on LA-92 Phase 3 | 0.01 | 0.01 | 1.16 | 0.00 | 5.8 |

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

# APPENDIX B

## 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 allowing fuel level reading to stabilize. Confirm the return of fuel gauge reading to zero.
3. Turn ignition off. Fill fuel tank with 12 gallons of the next test fuel in sequence. Fill-up fuel temperature must be less than 50°F.
4. Disconnect battery terminal for one minute, then reconnect.
5. Start vehicle and execute catalyst sulfur removal procedure described in Appendix B. Apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system.
6. 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.
7. Drain fuel and refill to 40% with test fuel. Fill-up fuel must be less than 50°F.
8. Drain fuel again and refill to 40% with test fuel. Fill-up fuel must be less than 50°F.
9. Take a fuel sample from the vehicle's fuel rail to be tested for ethanol content.
10. Soak vehicle for at least 12 hours to allow fuel temperature to stabilize to the test temperature. During the soak period, maintain the nominal charge of the vehicle's battery using an appropriate charging device.
11. Move vehicle to test area without starting engine.
12. Perform cold prep cycle (UDDS + HwFET + HwFET + US06)
13. Check vehicle for diagnostic trouble codes (DTC). If new codes are detected the CRC Program Manager will be contacted.
14. Soak vehicle for at least 12 hours to allow fuel temperature to stabilize to the test temperature. During the soak period, maintain the nominal charge of the vehicle's battery using an appropriate charging device.
15. Move vehicle to test area without starting engine.
16. Start vehicle and perform LA92 prep cycle. During the prep cycle, apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system.
17. Move vehicle to soak area without starting the engine.
18. 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.
19. Move vehicle to test area without starting engine.
20. Perform LA92 cycle emissions test.
21. Move vehicle to soak area without starting the engine.
22. 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.
23. Move vehicle to test area without starting the engine.
24. Perform LA92 emissions test.
25. Move vehicle to soak area without starting the engine.
26. Determine whether third replicate is necessary, based on repeatability criteria (to be provided by CRC prior to start of test program).
27. If a third replicate is required, repeat Steps 21 – 23. If third replicate is not required, return to step 1 and proceed with next fuel in test sequence.

# APPENDIX C

## CATALYST SULFUR PURGE CYCLE

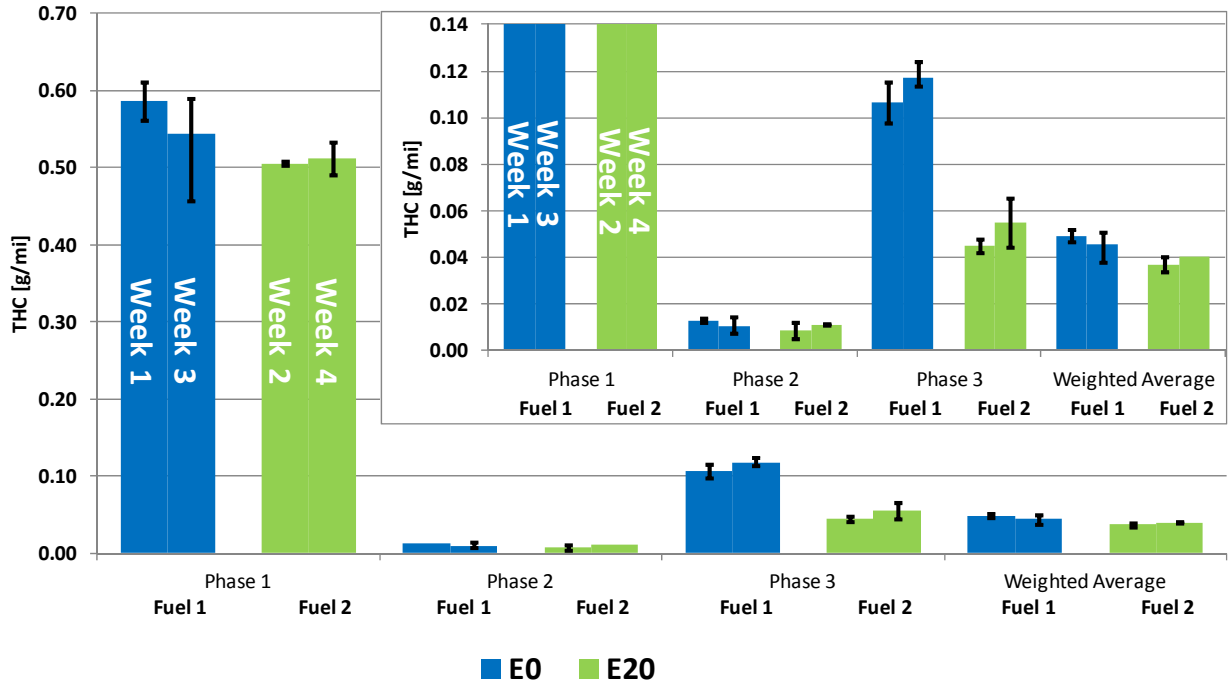
## CATALYST SULFUR PURGE CYCLE

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




Interval on each bar represents the lowest and highest individual measurement; the bar represents the average

**FIGURE D-1. VEHICLE A TOTAL HYDROCARBONS**

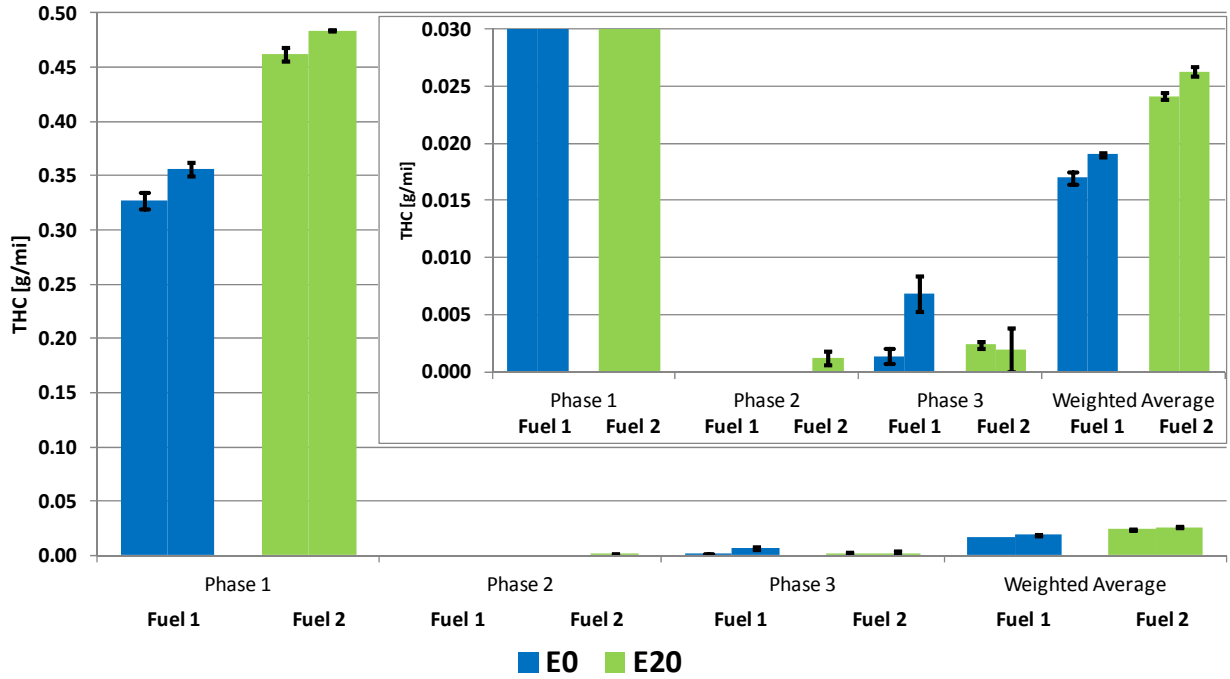



**FIGURE D-2. VEHICLE B TOTAL HYDROCARBONS**

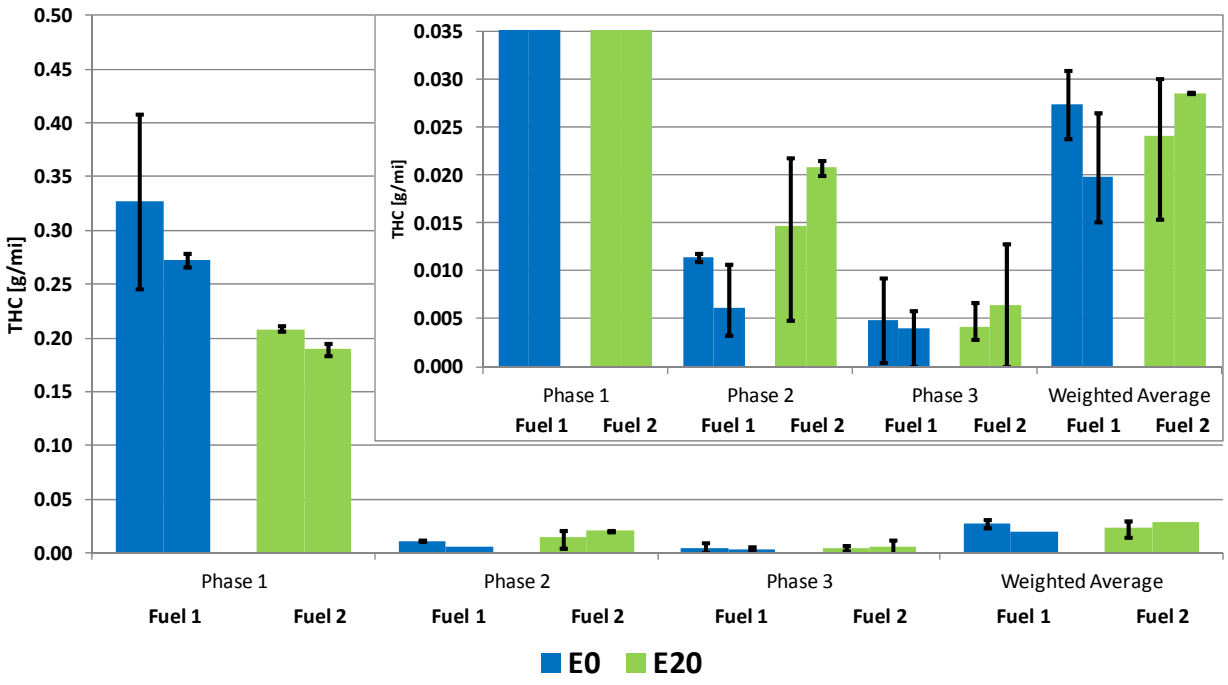



**FIGURE D-3. VEHICLE C TOTAL HYDROCARBONS**

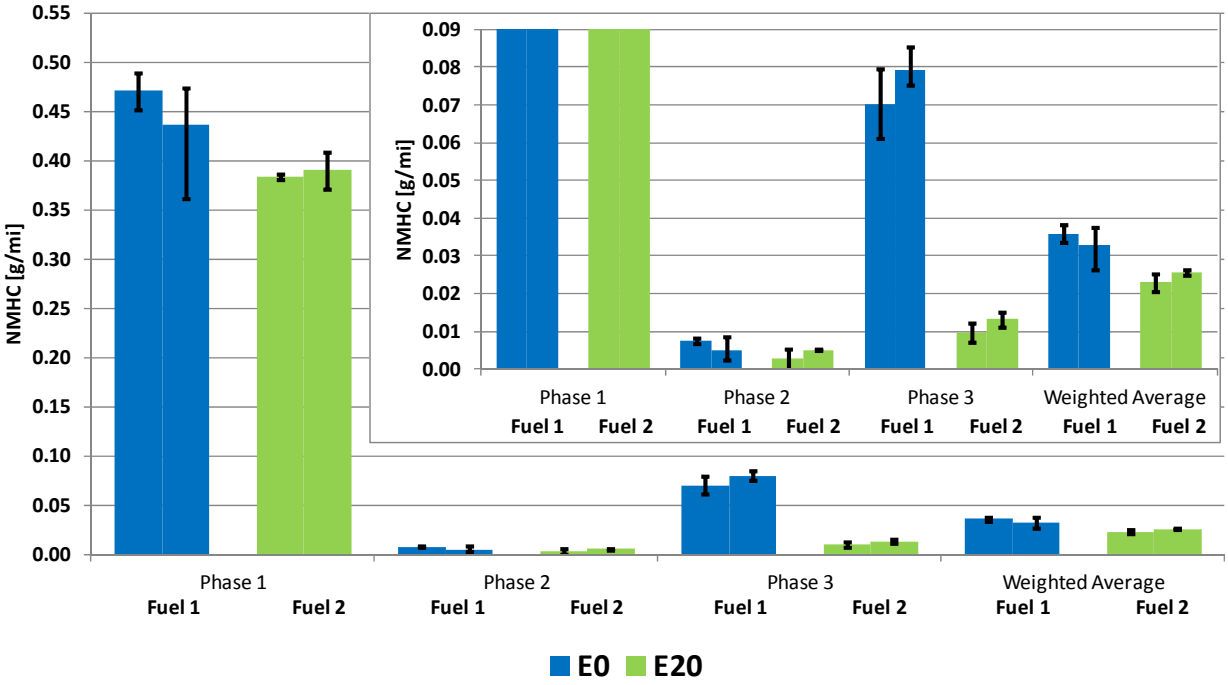



**FIGURE D-4. VEHICLE A NON-METHANE HYDROCARBONS**

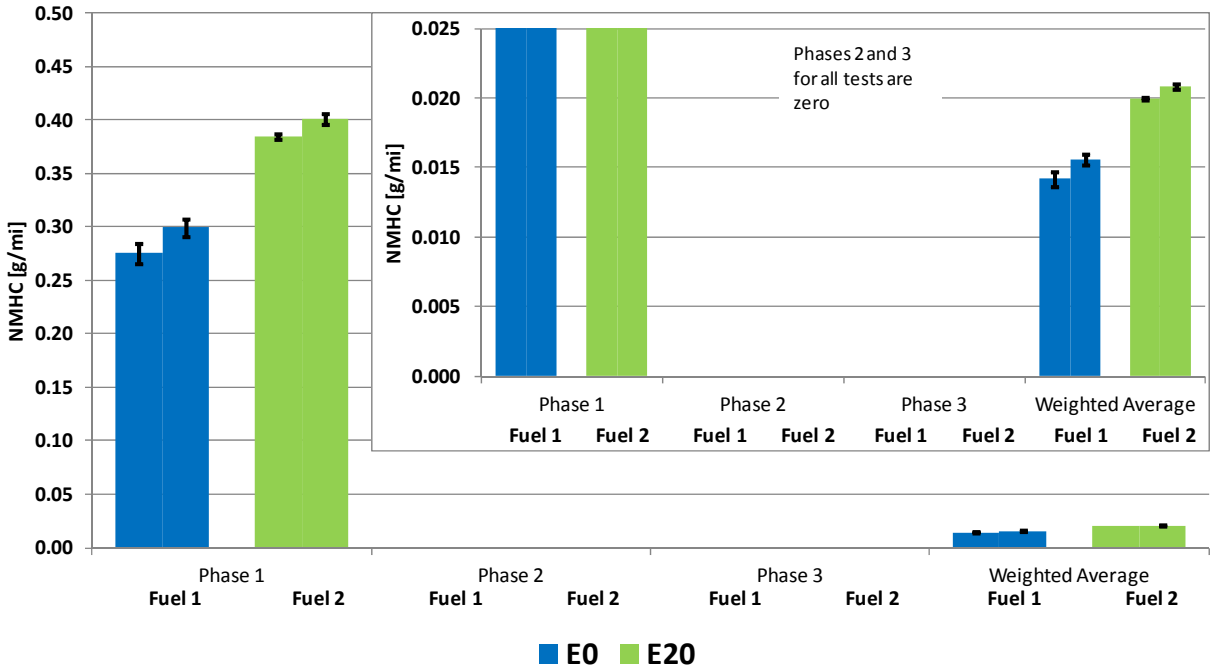



**FIGURE D-5. VEHICLE B NON-METHANE HYDROCARBONS**

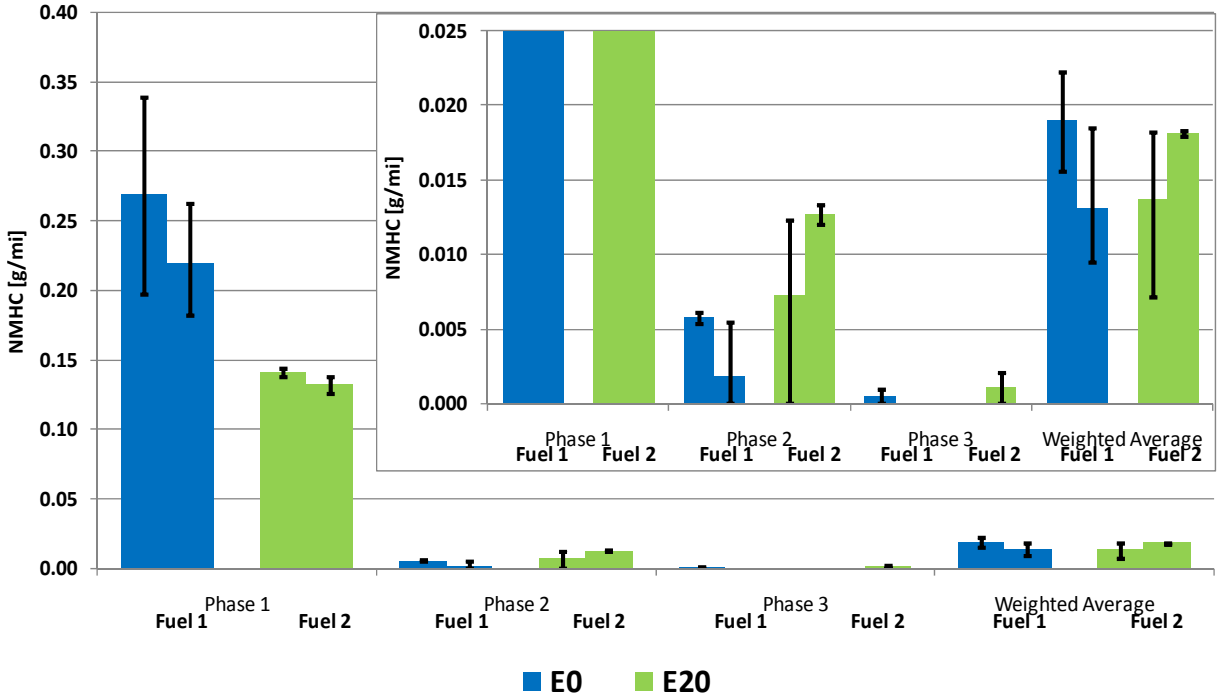



**FIGURE D-6. VEHICLE C NON-METHANE HYDROCARBONS**

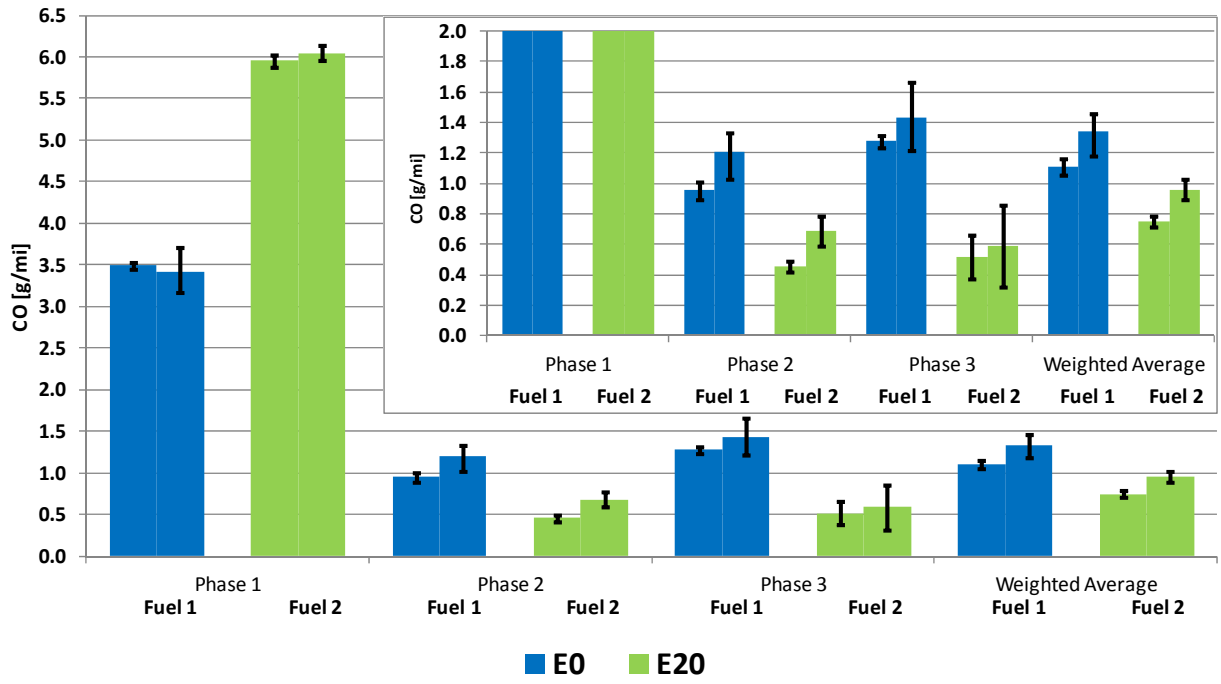



**FIGURE D-7. VEHICLE A CARBON MONOXIDE**

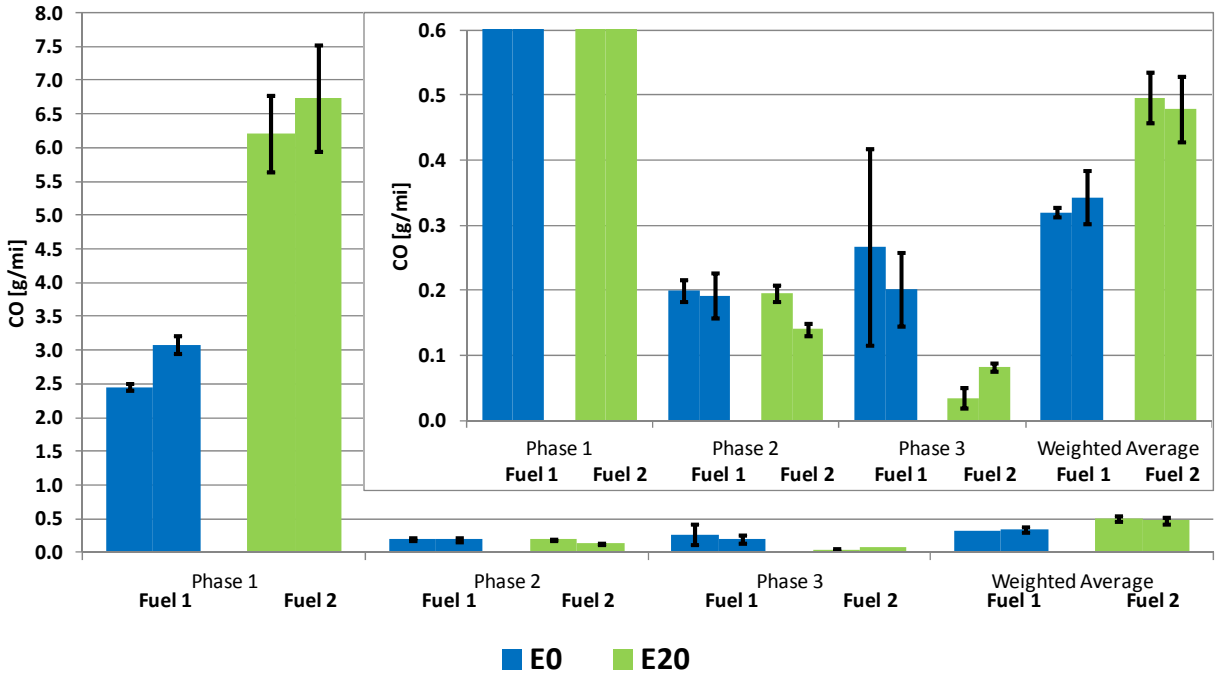



**FIGURE D-8. VEHICLE B CARBON MONOXIDE**

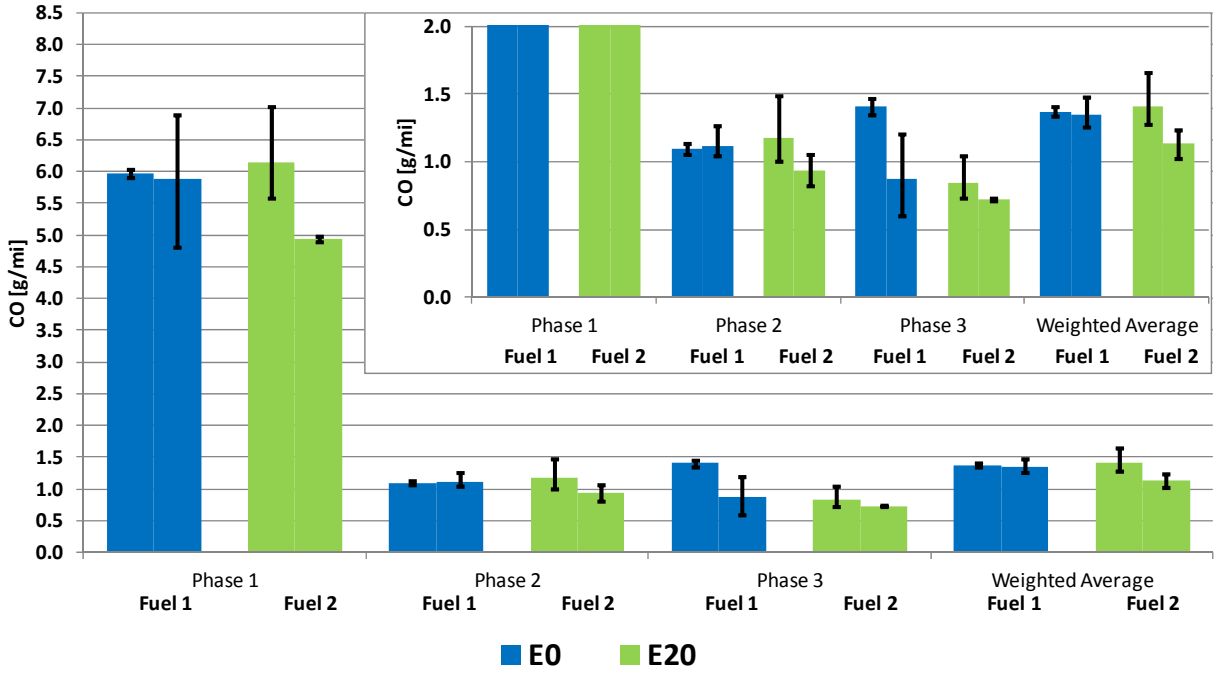



**FIGURE D-9. VEHICLE C CARBON MONOXIDE**

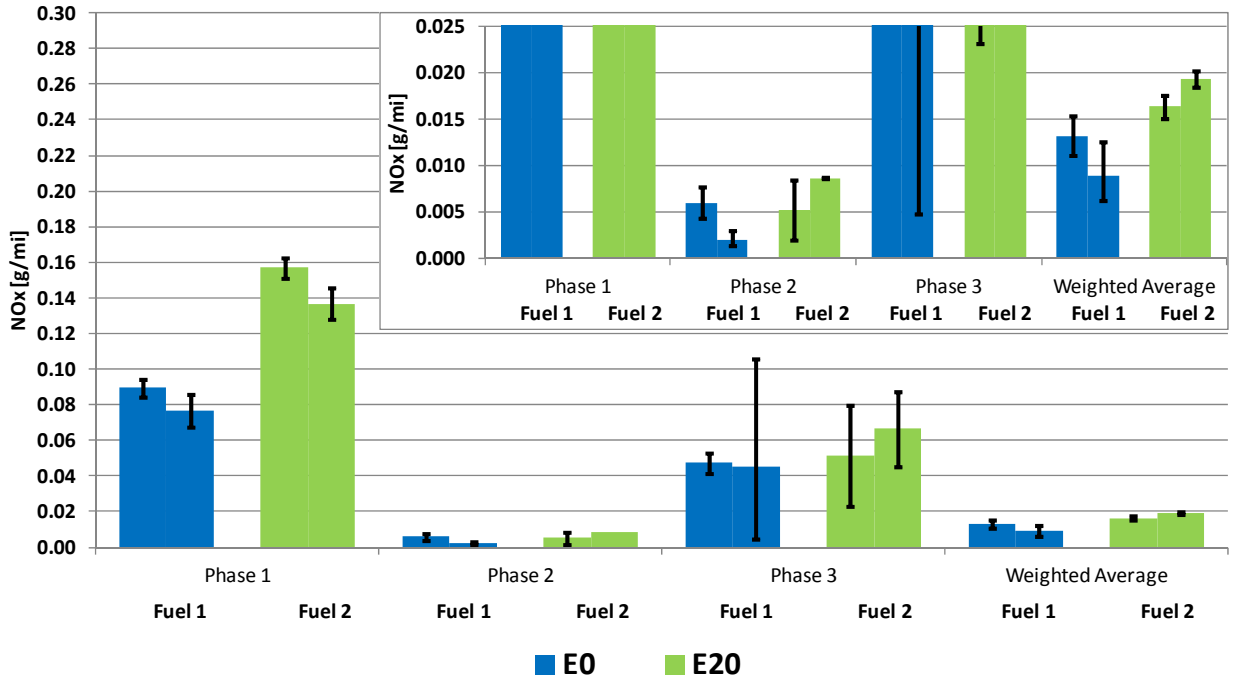



**FIGURE D-10. VEHICLE A OXIDES OF NITROGEN**

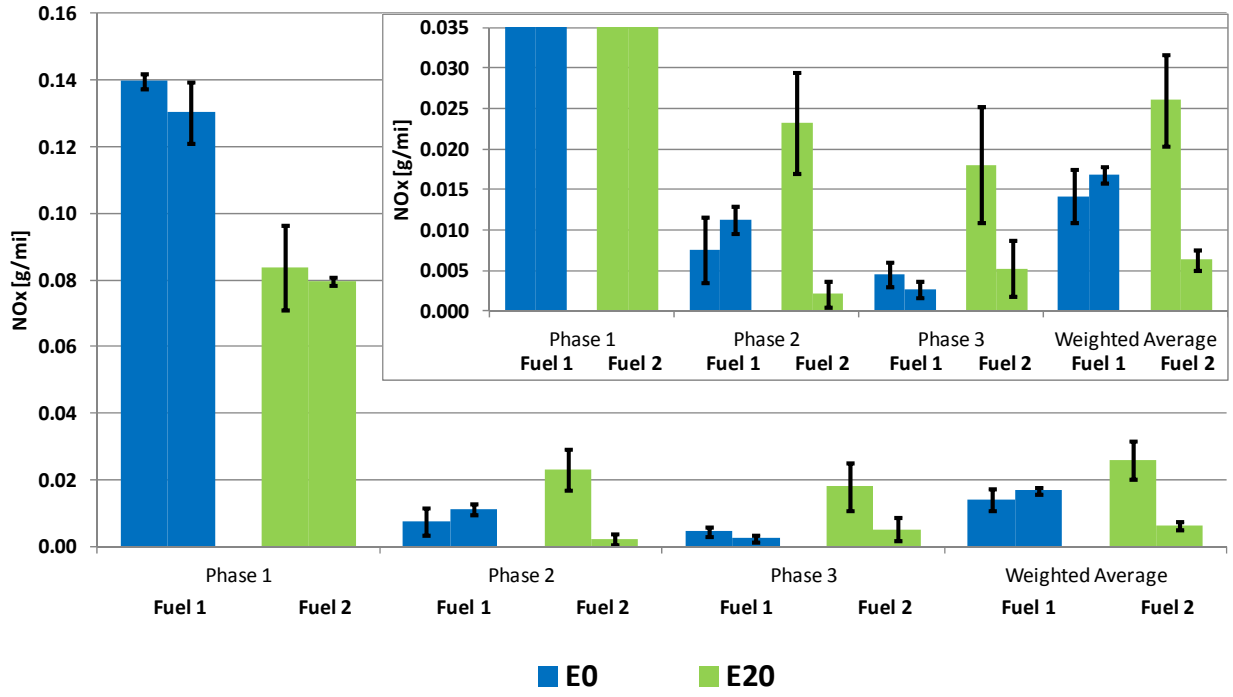



**FIGURE D-11. VEHICLE B OXIDES OF NITROGEN**

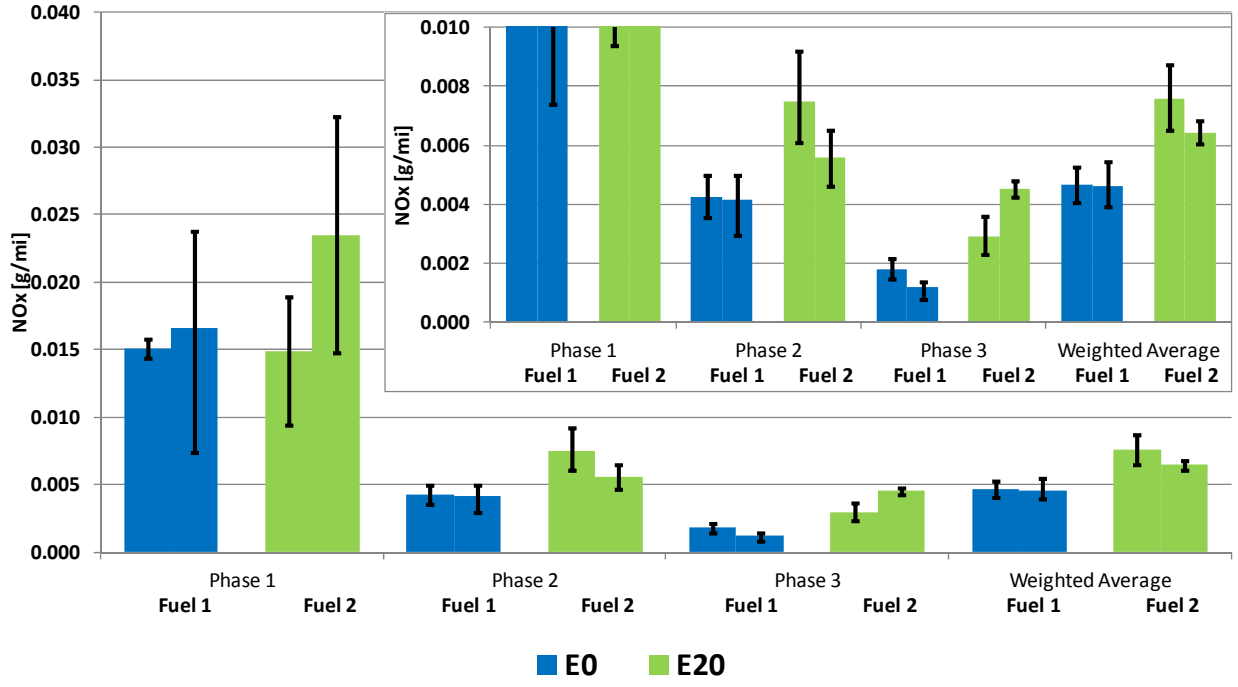



**FIGURE D-12. VEHICLE C OXIDES OF NITROGEN**

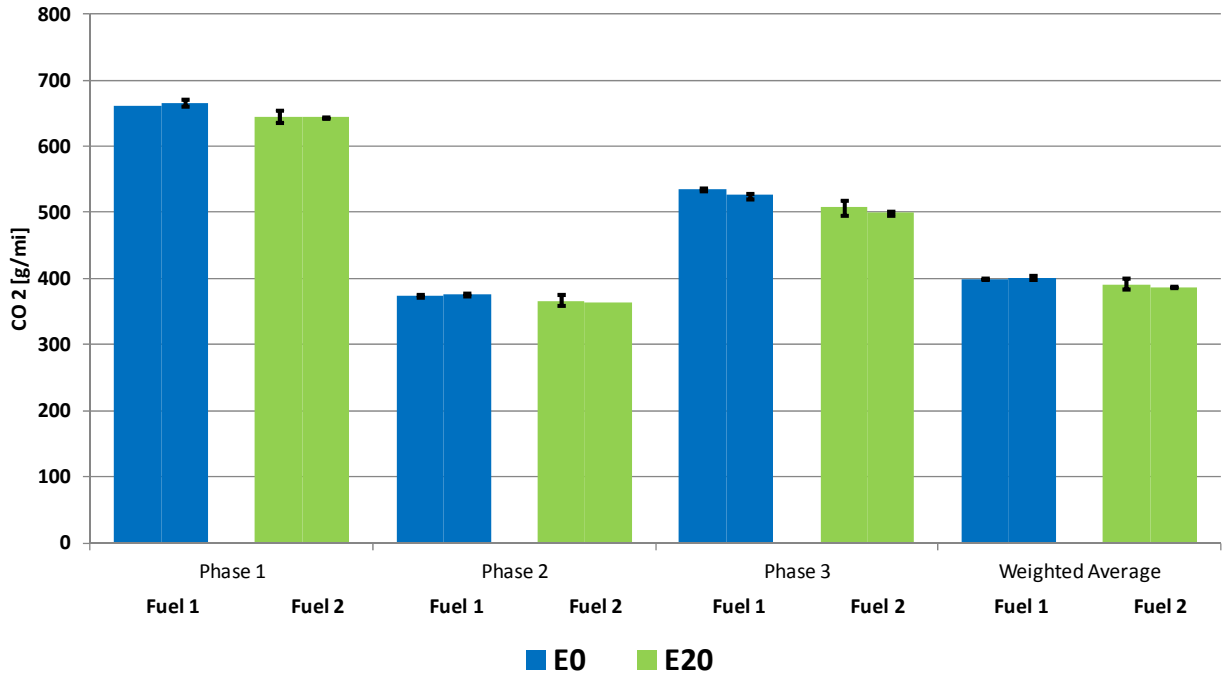



**FIGURE D-13. VEHICLE 1 CARBON DIOXIDE**

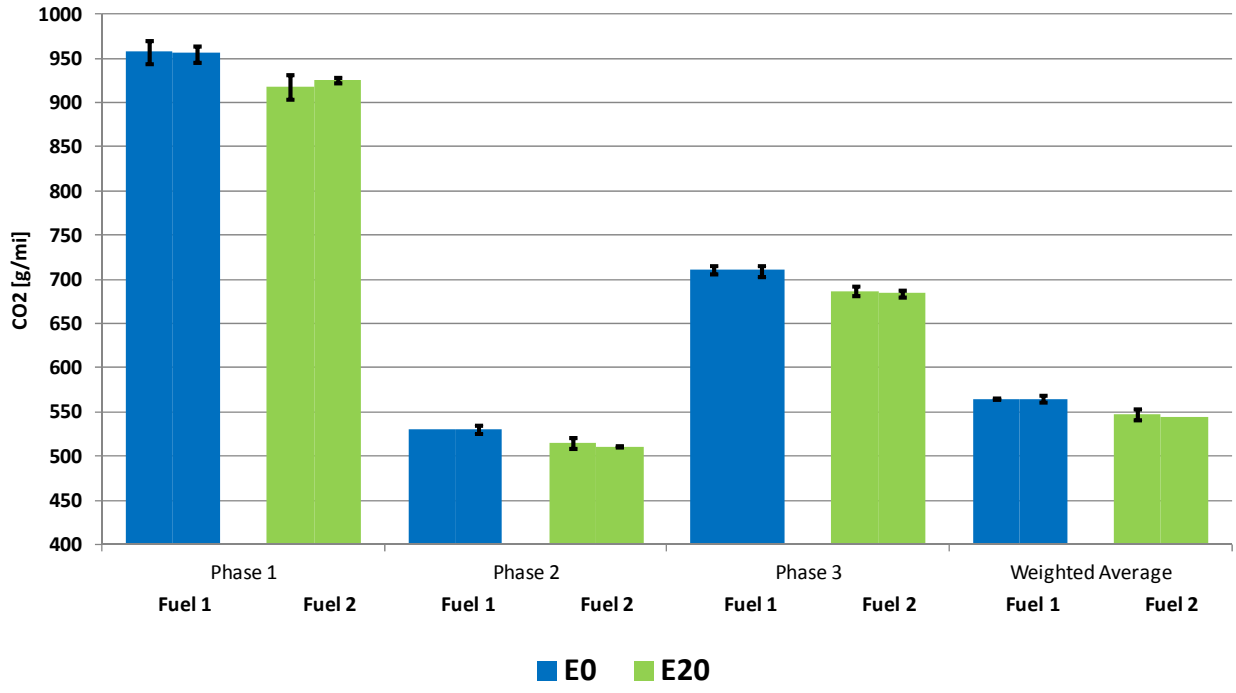



**FIGURE D-14. VEHICLE 2 CARBON DIOXIDE**

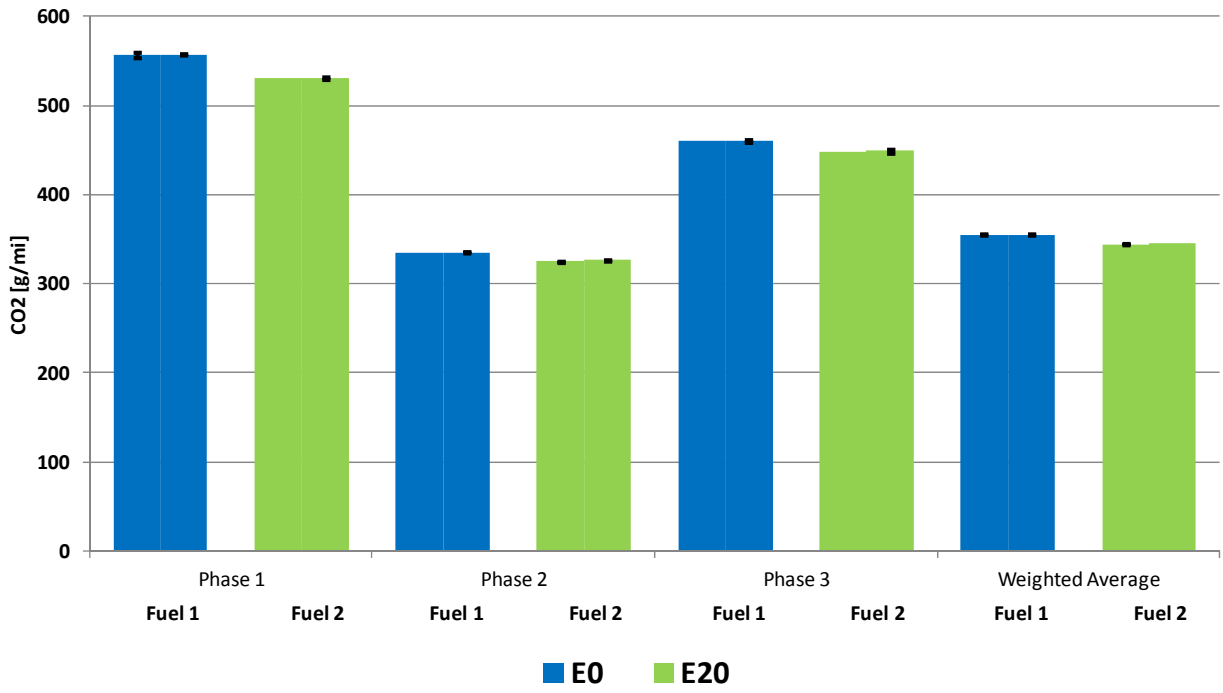



**FIGURE D-15. VEHICLE 3 CARBON DIOXIDE**

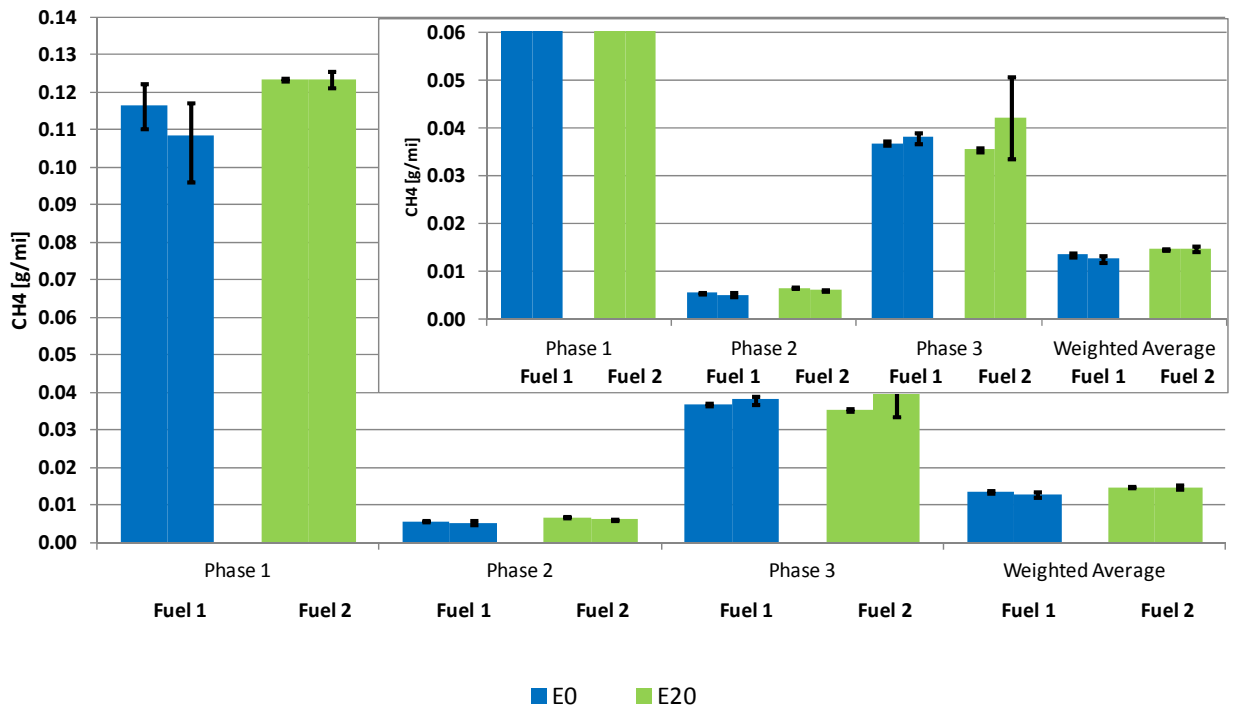



**FIGURE D-16. VEHICLE A METHANE**

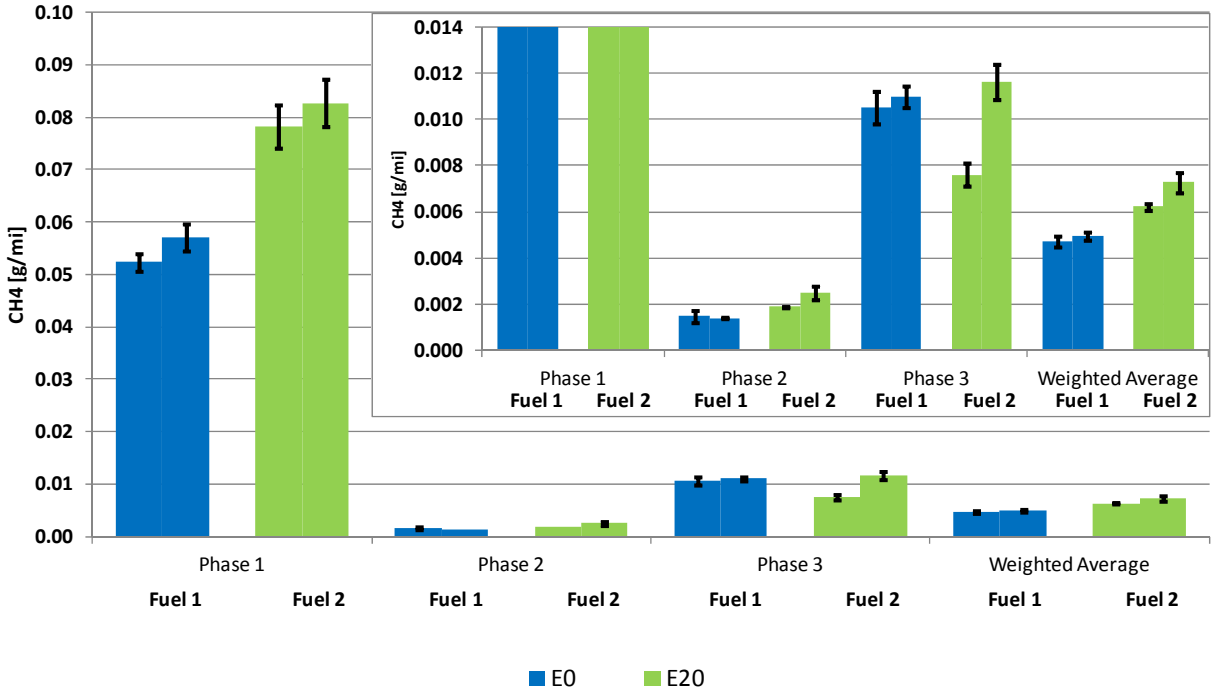



**FIGURE D-17. VEHICLE B METHANE**

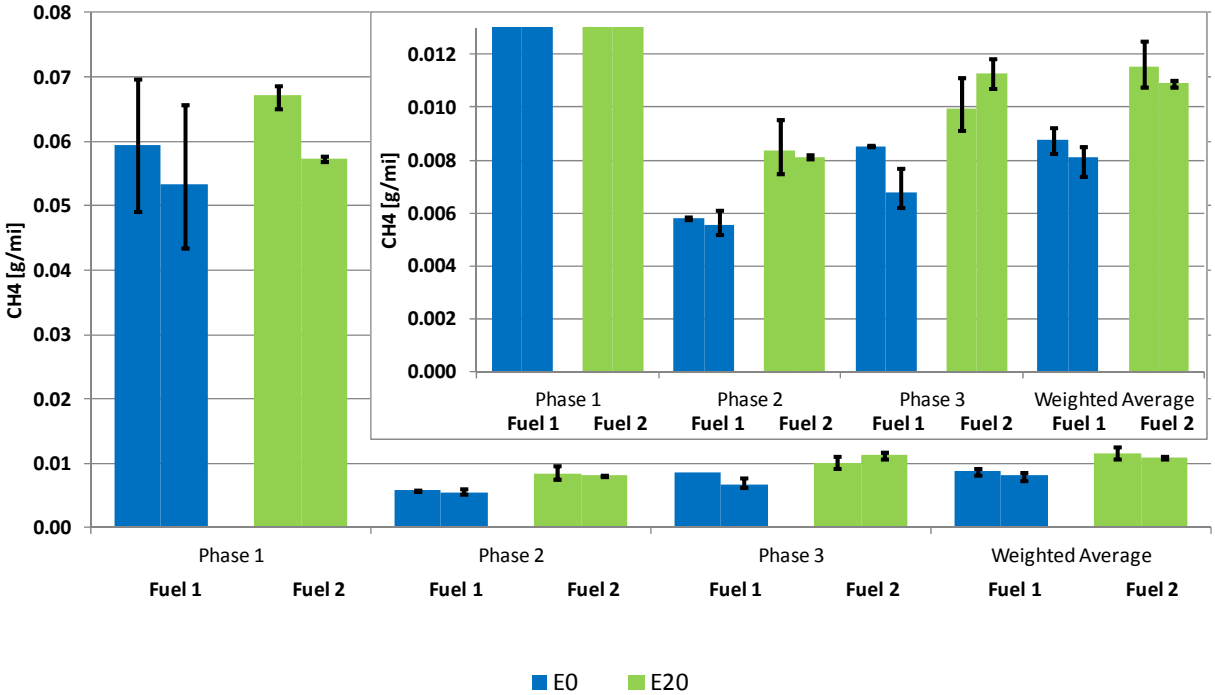



**FIGURE D-18. VEHICLE C METHANE**

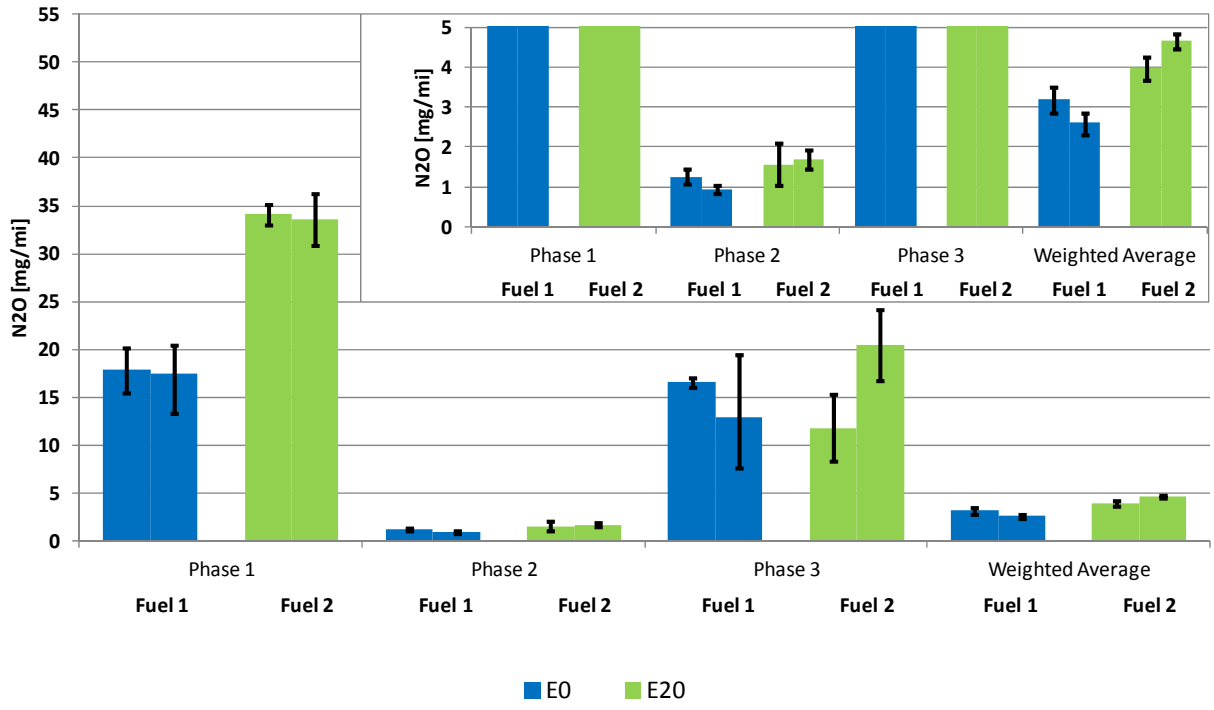



**FIGURE D-19. VEHICLE A NITROUS OXIDE**

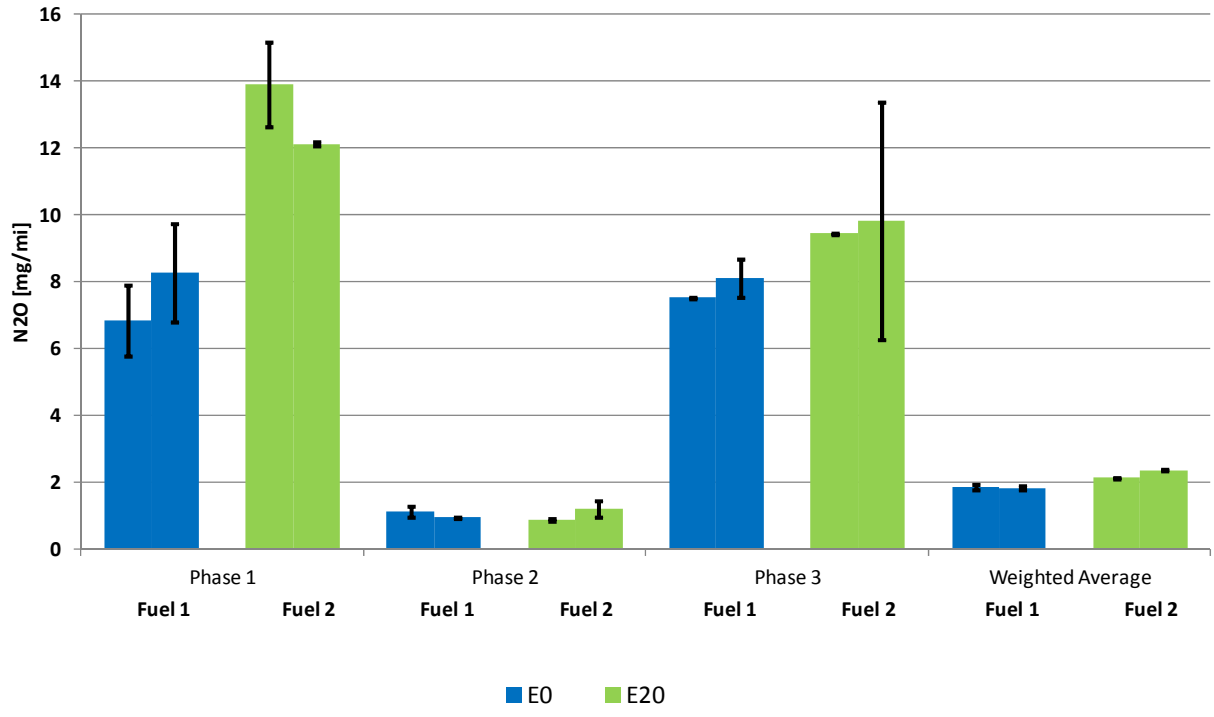



**FIGURE D-20. VEHICLE B NITROUS OXIDE**

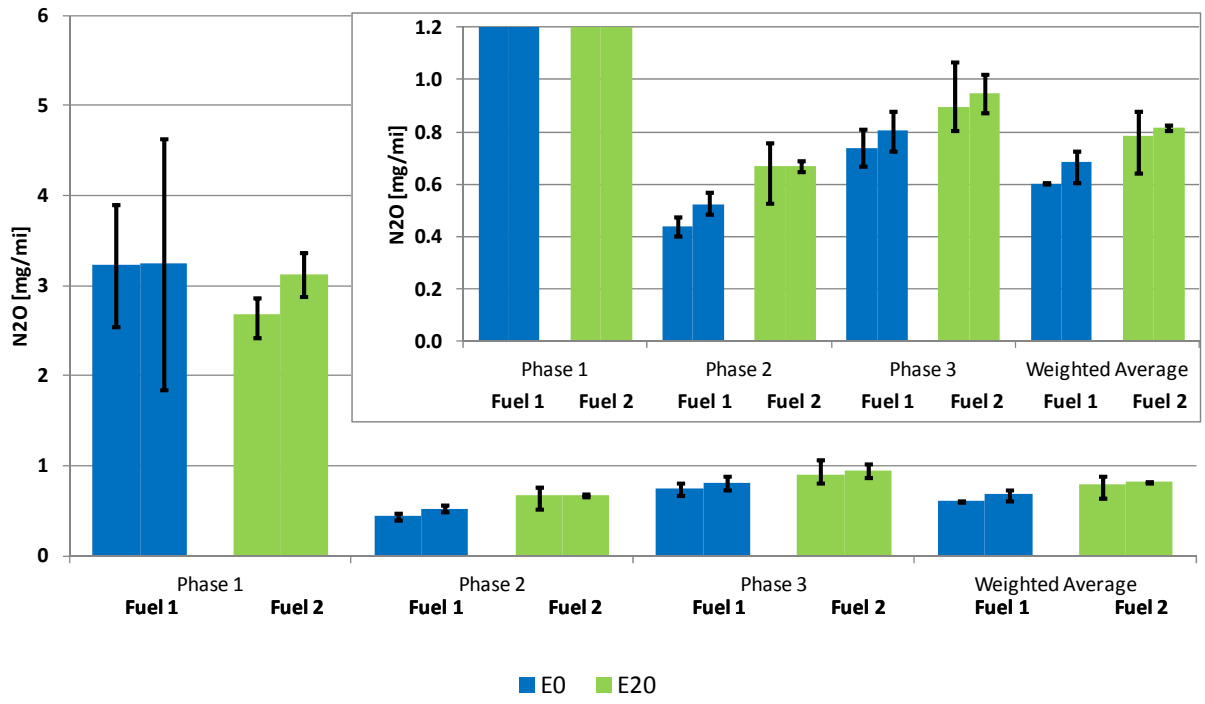



**FIGURE D-21. VEHICLE C NITROUS OXIDE**

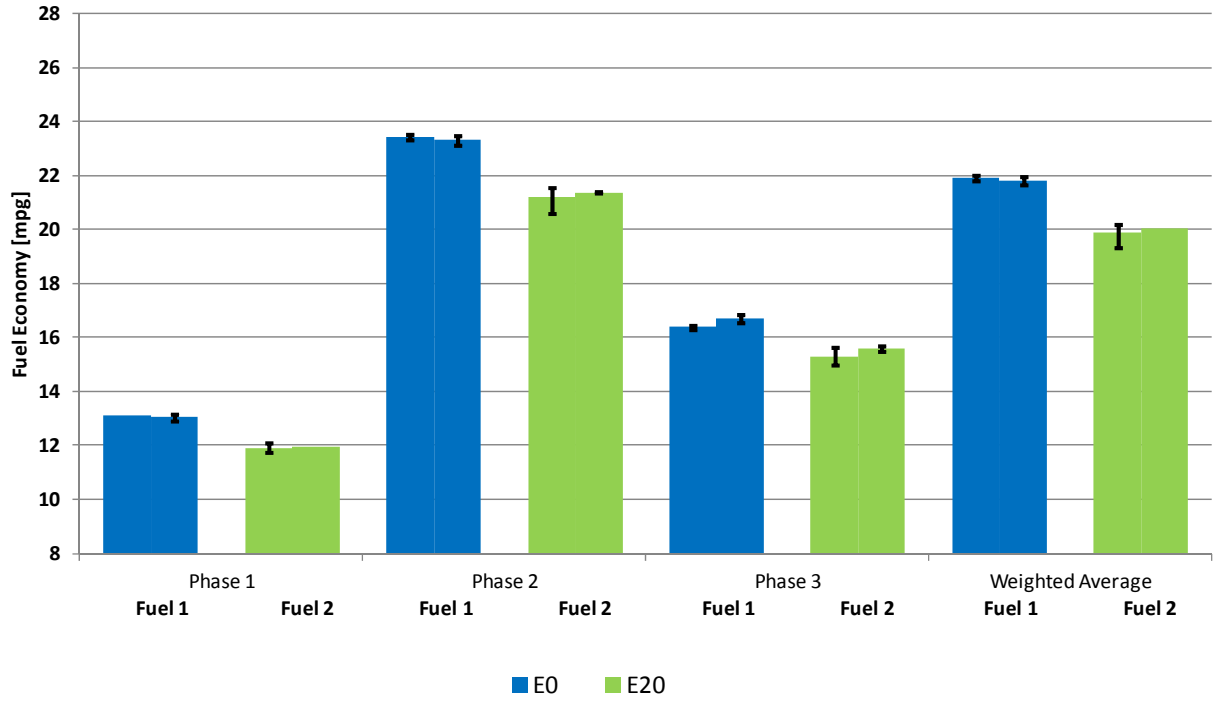



**FIGURE D-22. VEHICLE 1 FUEL ECONOMY**

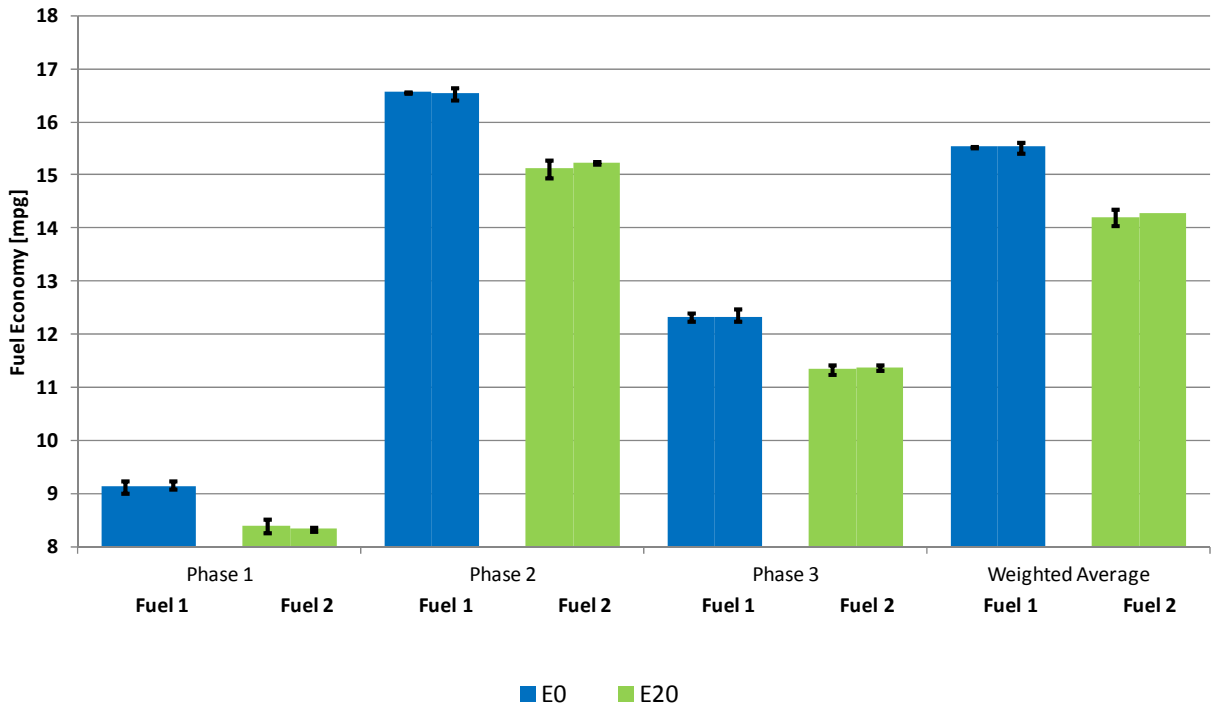



**FIGURE D-23. VEHICLE 2 FUEL ECONOMY**

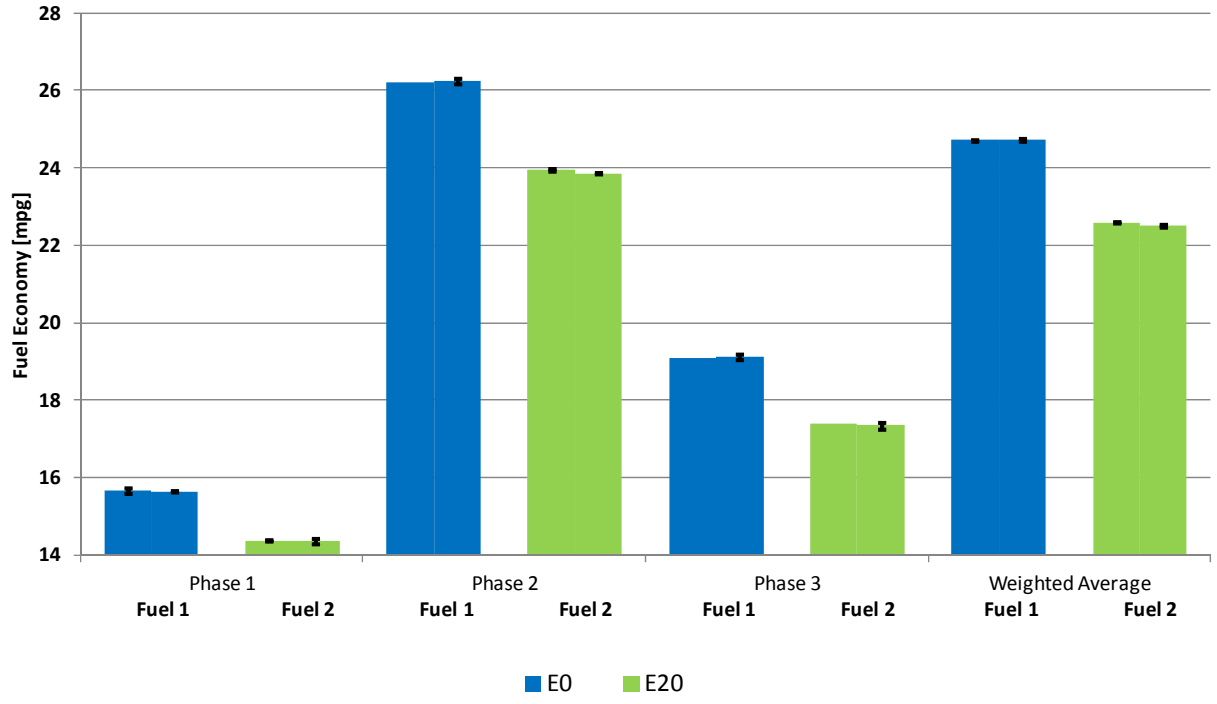



**FIGURE D-24. VEHICLE 3 FUEL ECONOMY**

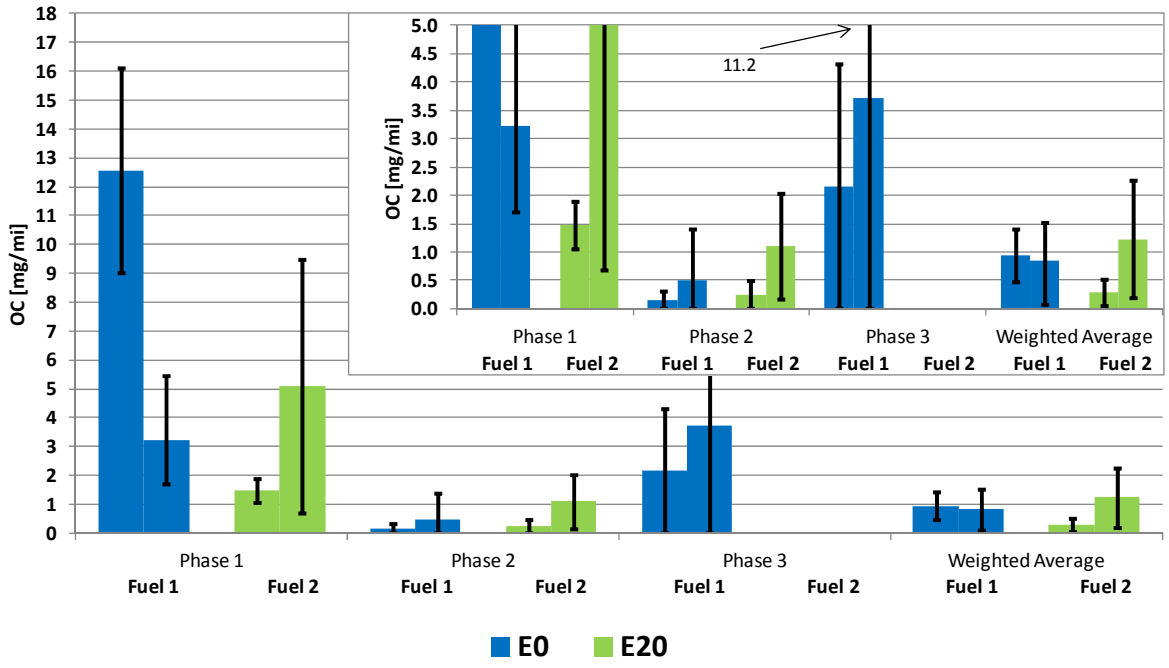



**FIGURE D-25. VEHICLE A ORGANIC CARBON**

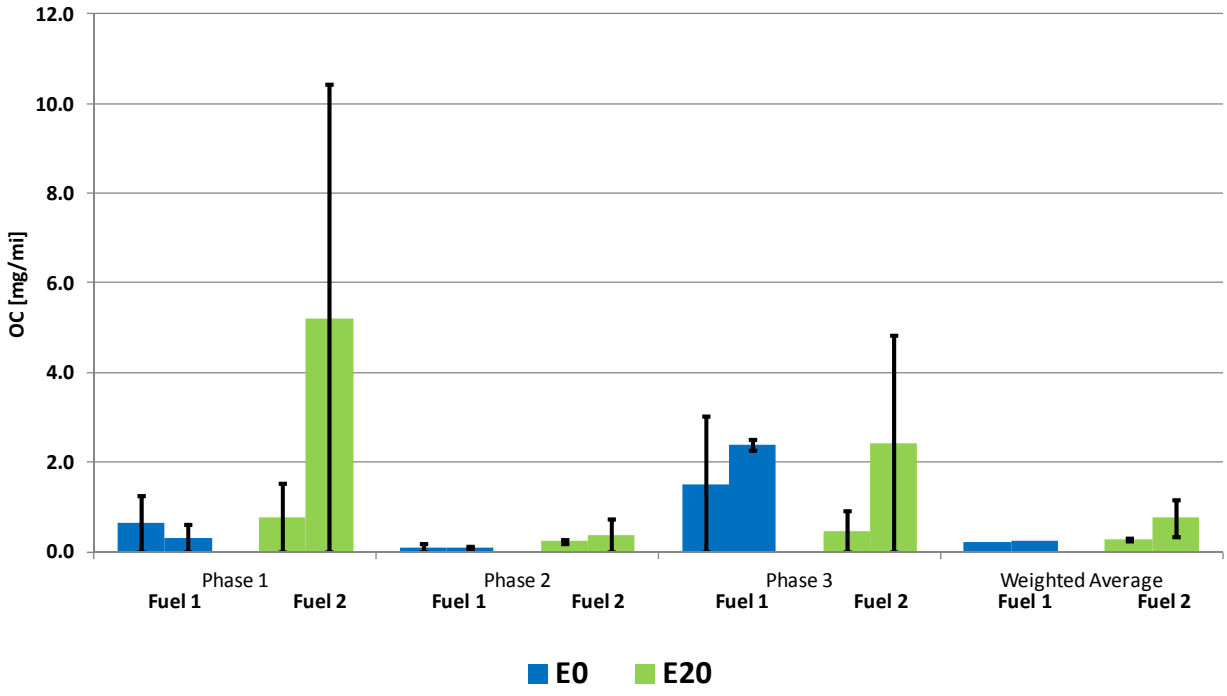



**FIGURE D-26. VEHICLE B ORGANIC CARBON**

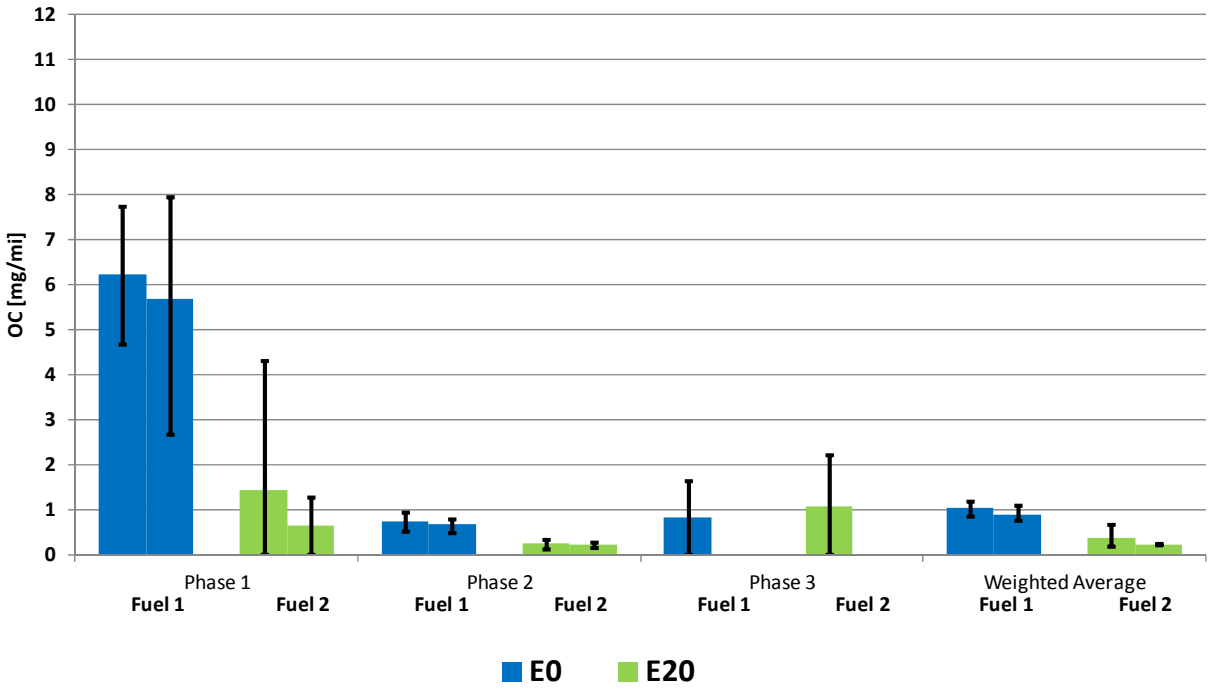



**FIGURE D-27. VEHICLE C ORGANIC CARBON**

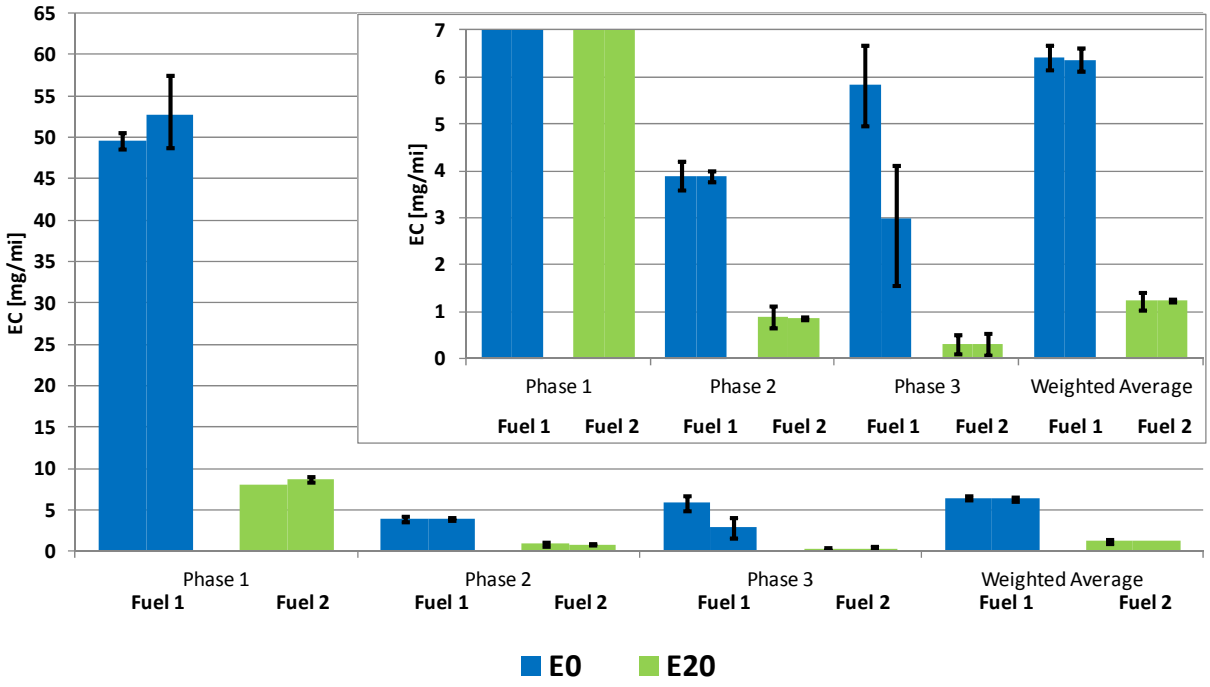



**FIGURE D-28. VEHICLE A ELEMENTAL CARBON**

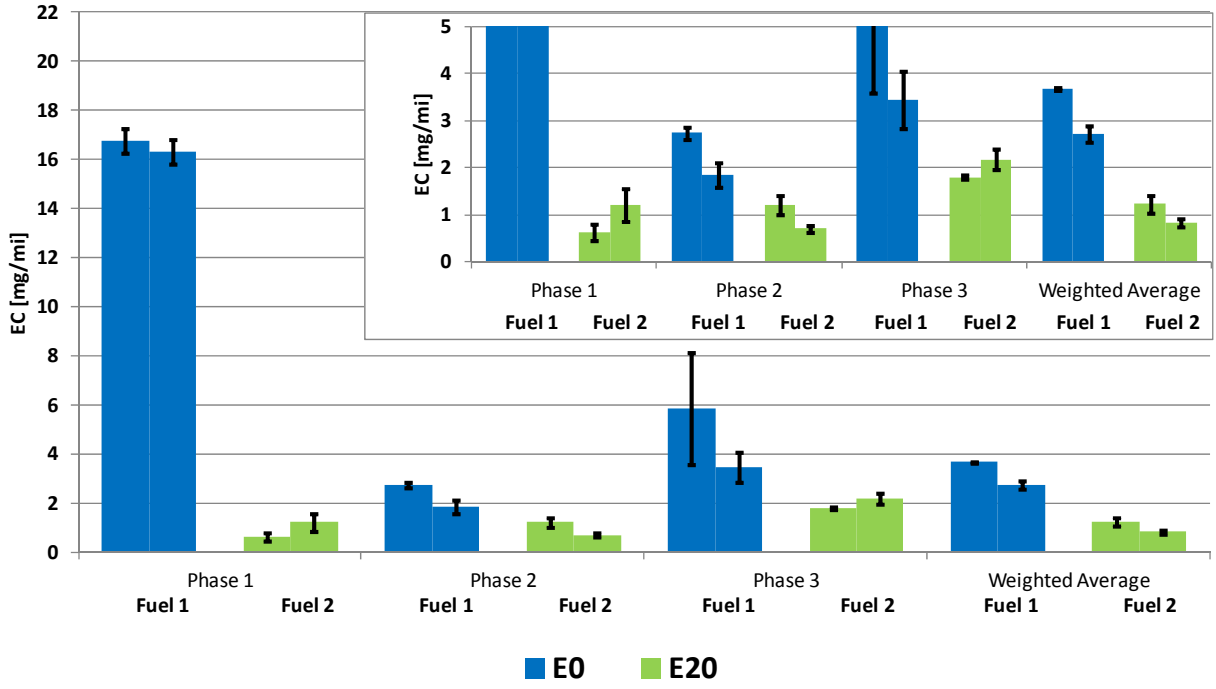



**FIGURE D-29. VEHICLE B ELEMENTAL CARBON**

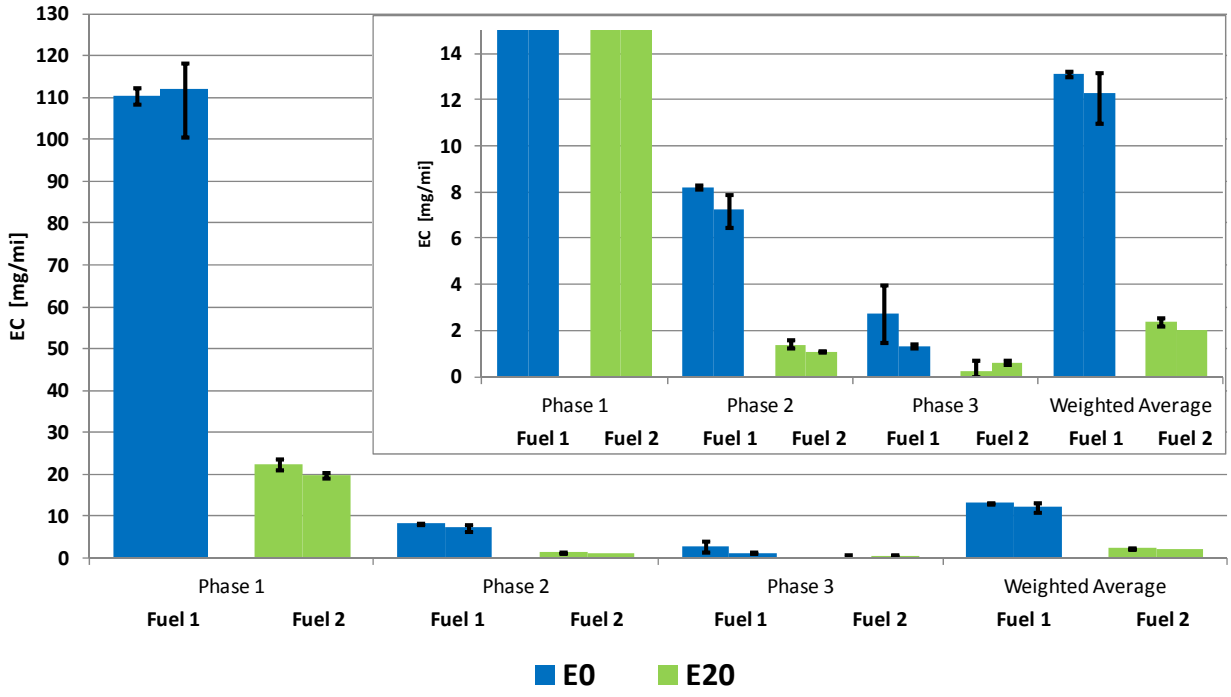



**FIGURE D-30. VEHICLE C ELEMENTAL CARBON**

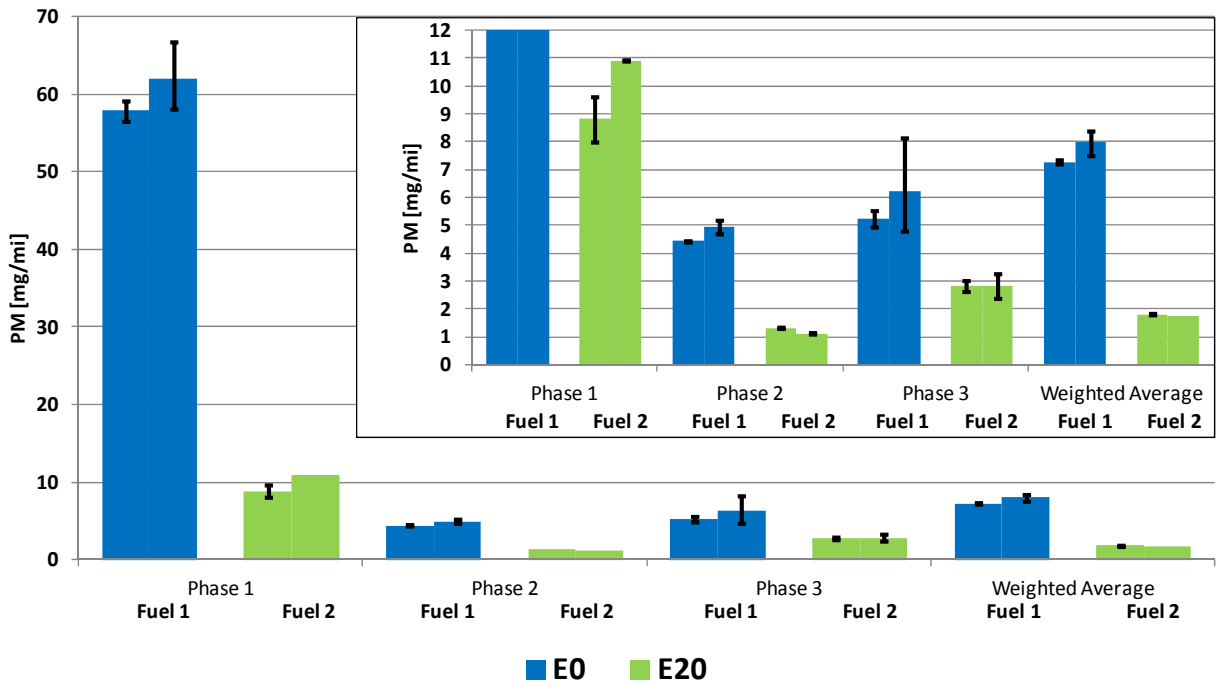



FIGURE D-31. VEHICLE A PARTICULATE MASS

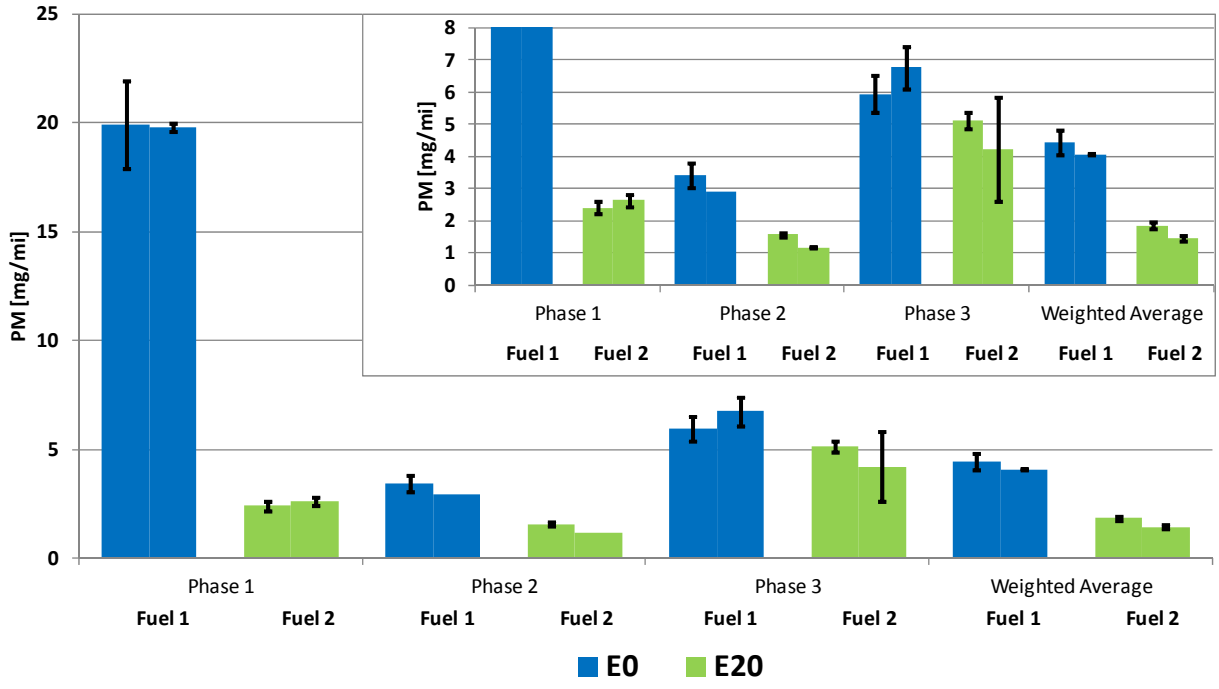



FIGURE D-32. VEHICLE B PARTICULATE MASS

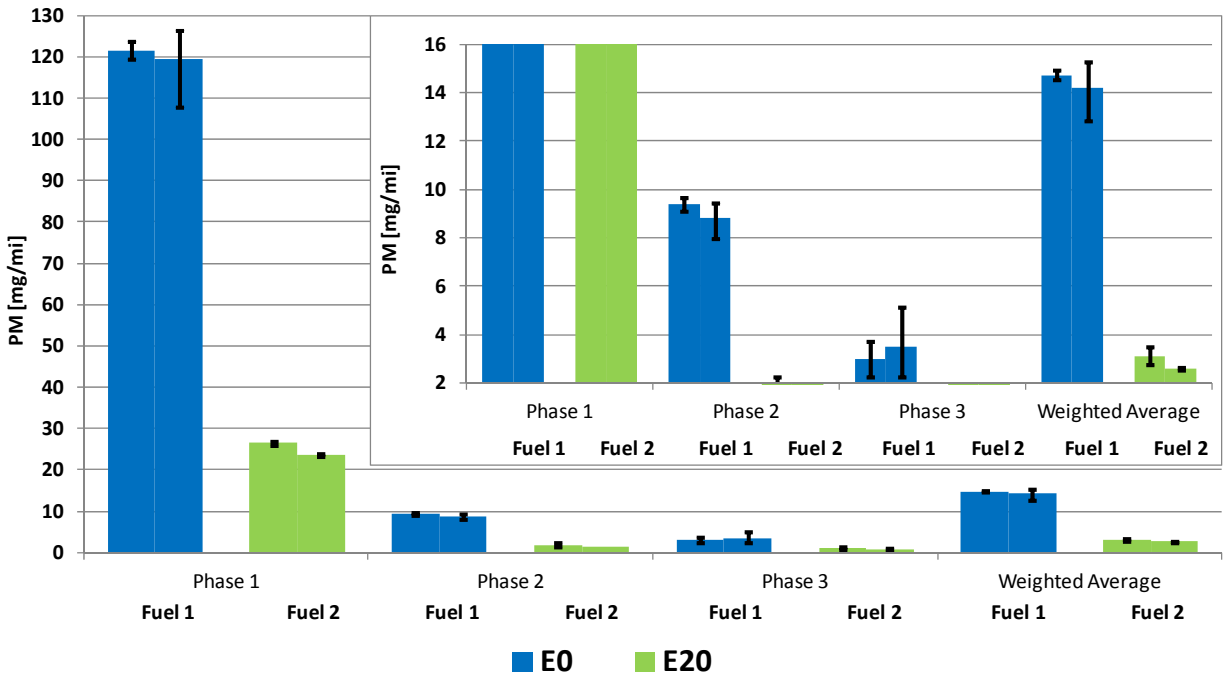



FIGURE D-33. VEHICLE C PARTICULATE MASS

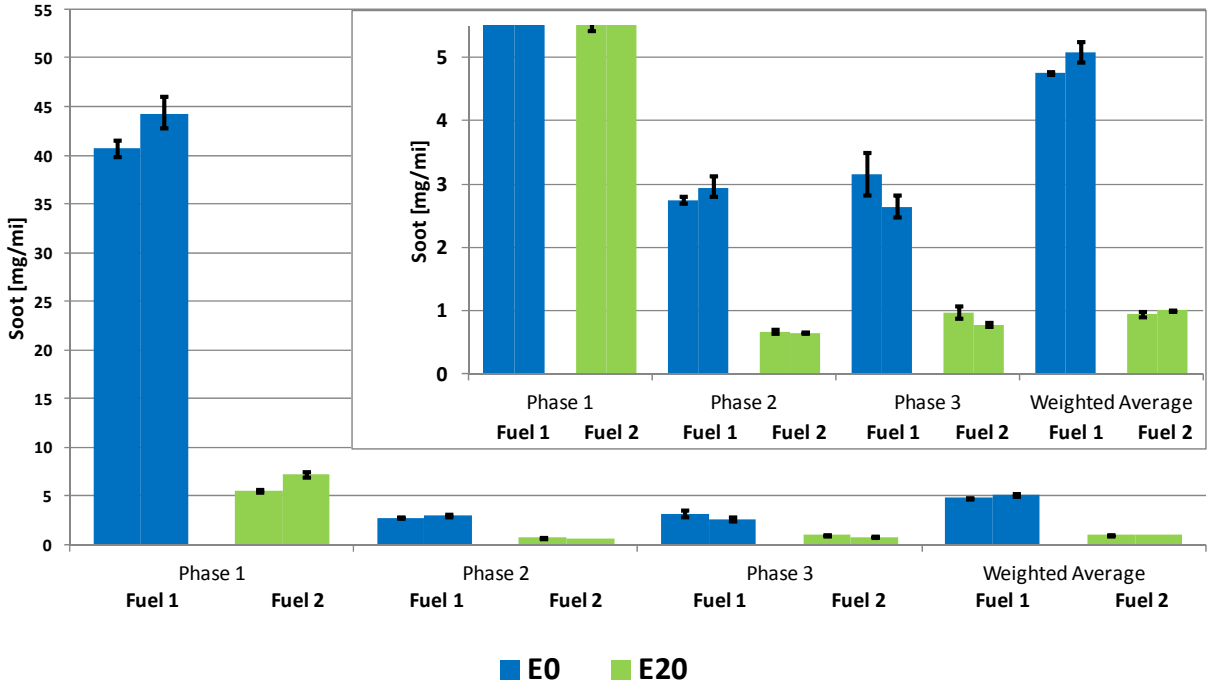



FIGURE D-34. VEHICLE A AVL MICROSOOT SENSOR

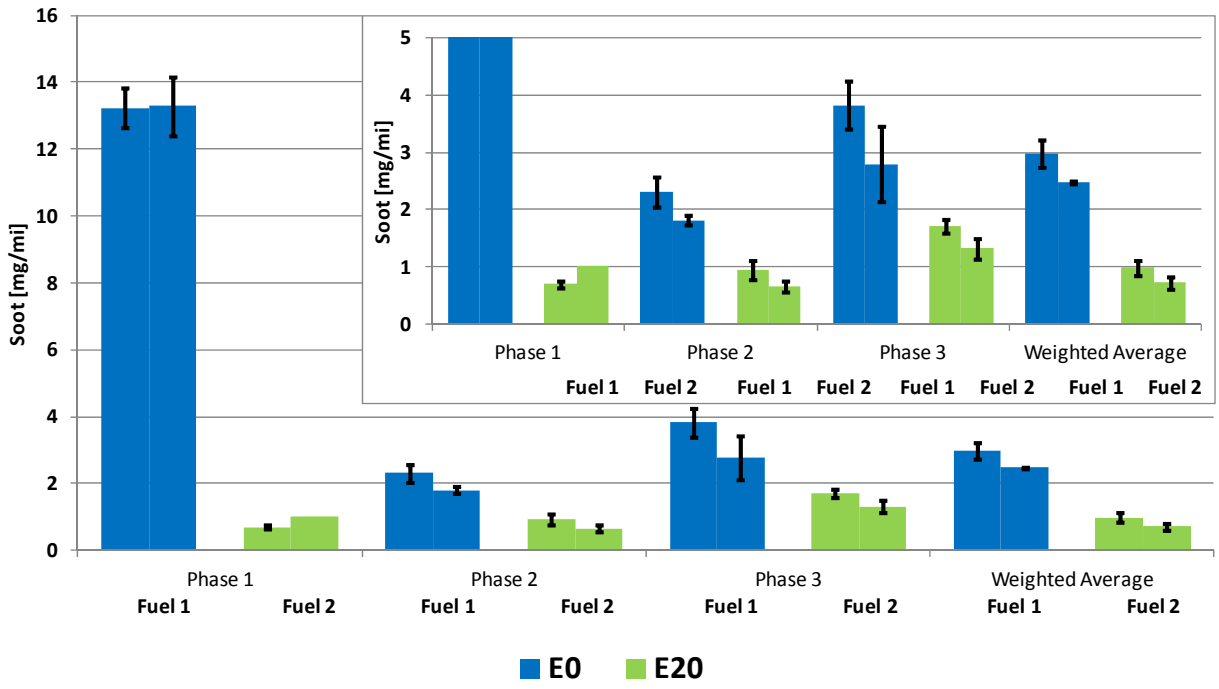



**FIGURE D-35. VEHICLE B AVL MICROSOOT SENSOR**

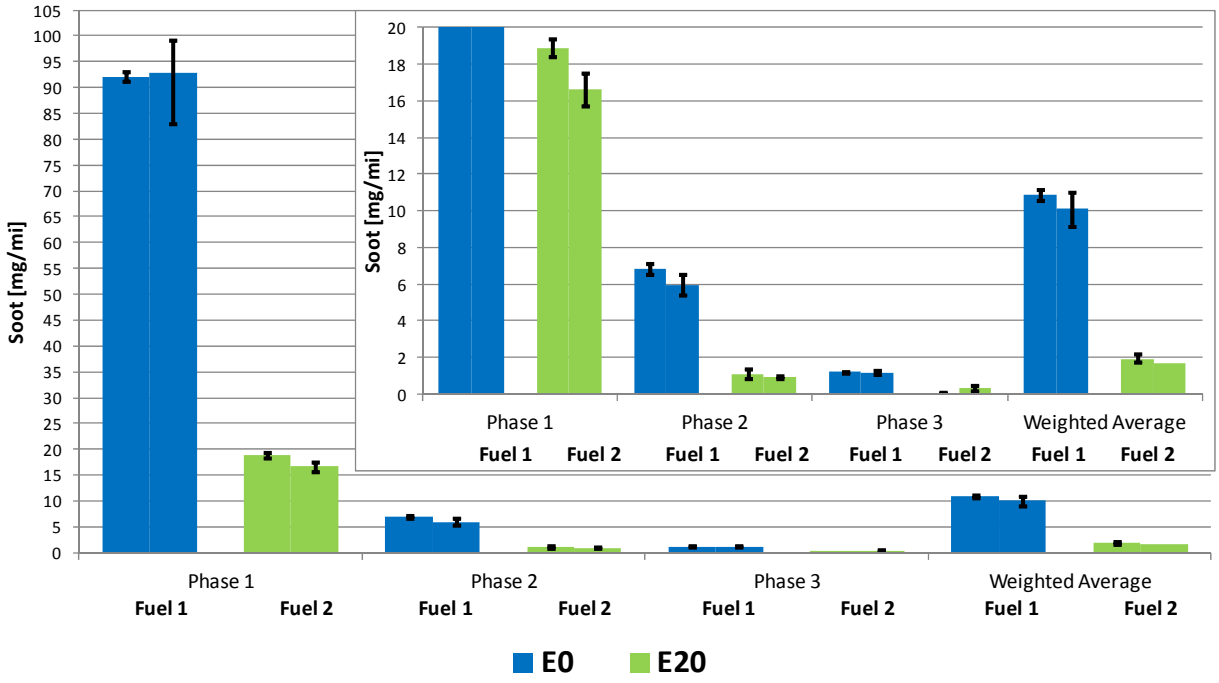



**FIGURE D-36. VEHICLE C AVL MICROSOOT SENSOR**

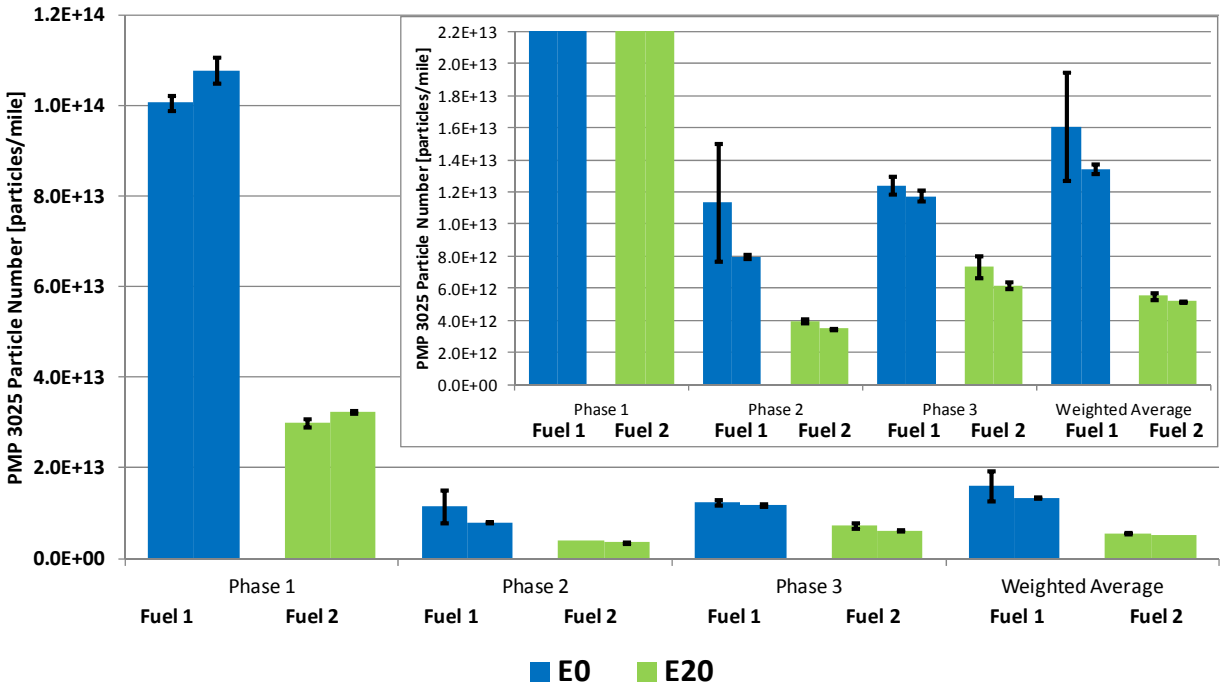



**FIGURE D-37. VEHICLE A PARTICLE NUMBER CPC3025**

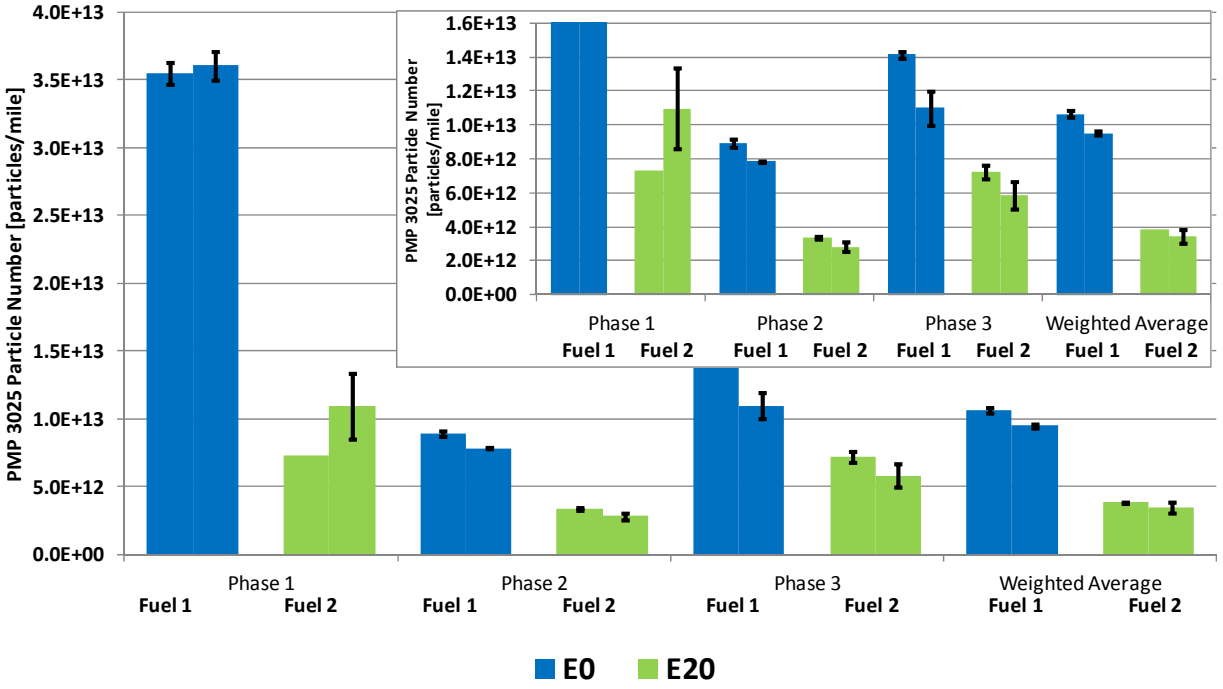



**FIGURE D-38. VEHICLE B PARTICLE NUMBER CPC3025**

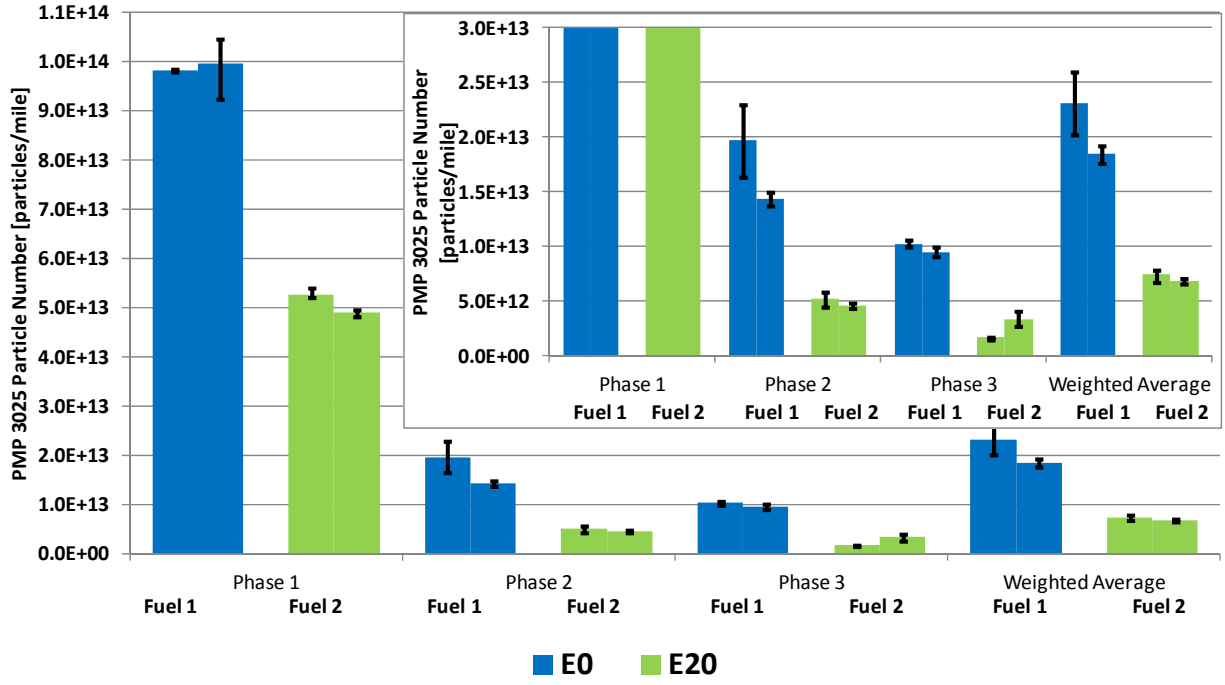



**FIGURE D-39. VEHICLE C PARTICLE NUMBER CPC3025**

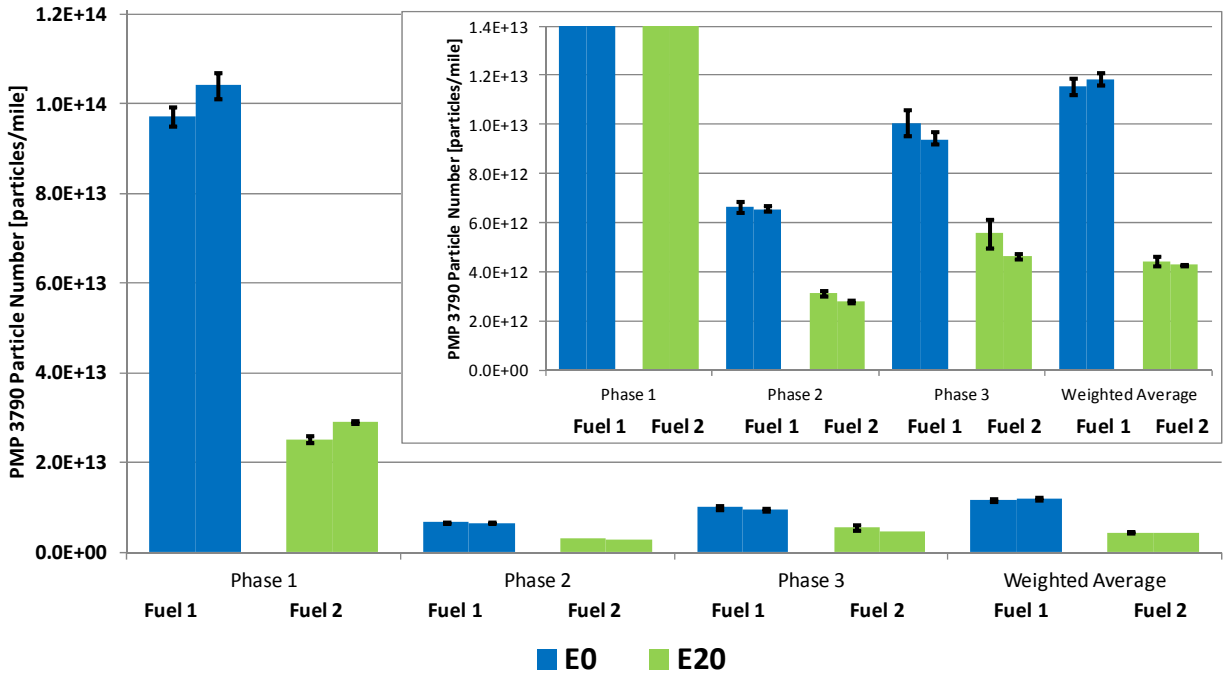



**FIGURE D-40. VEHICLE A PARTICLE NUMBER SPNMS**

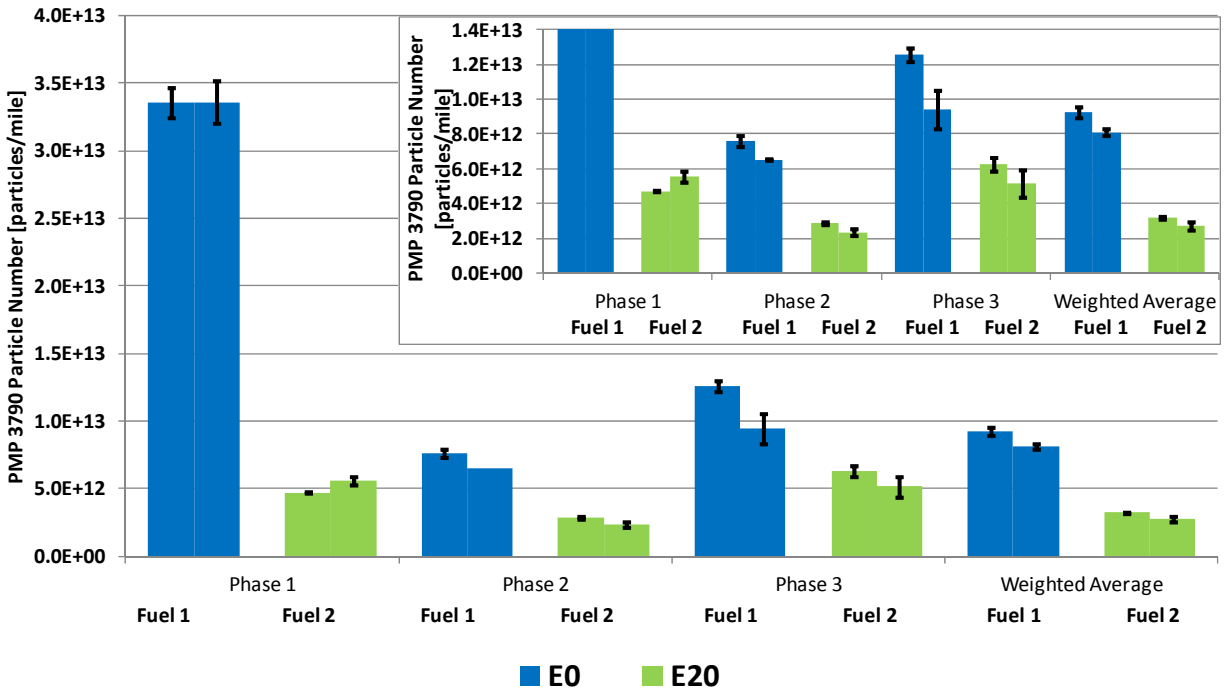



**FIGURE D-41. VEHICLE B PARTICLE NUMBER SPNMS**

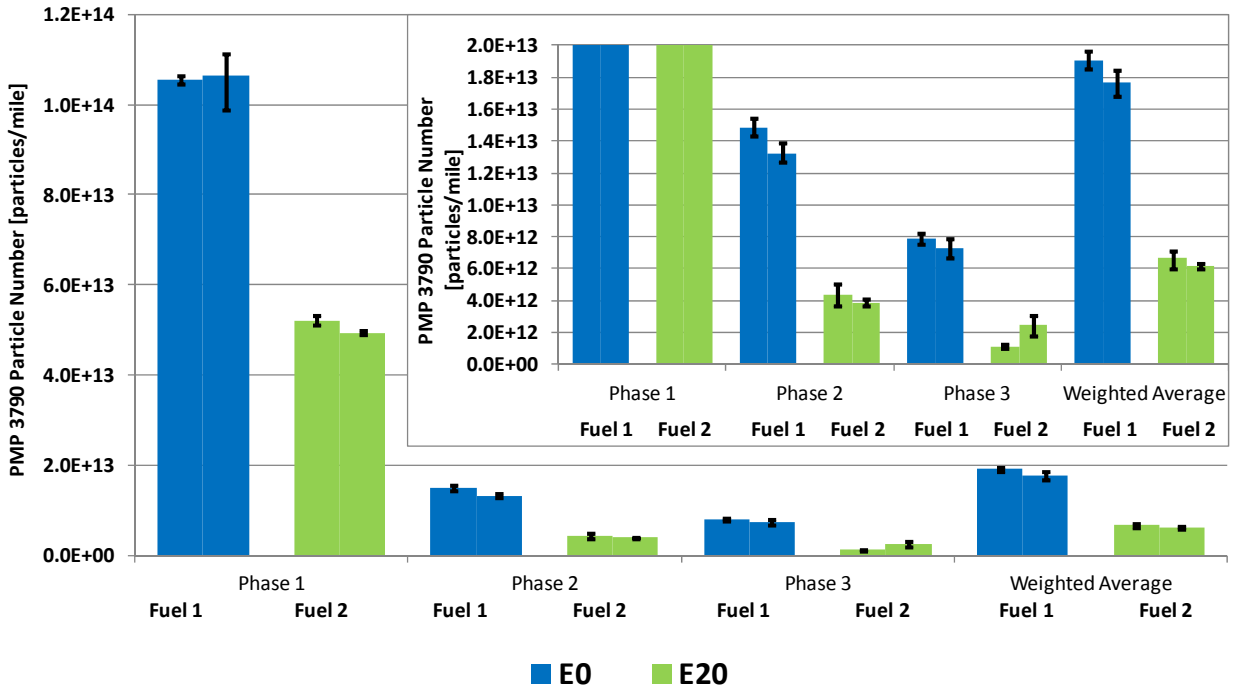



**FIGURE D-42. VEHICLE C PARTICLE NUMBER SPNMS**