CRC Report No. E-94-3

IMPACTS OF SPLASH-BLENDING ON PARTICULATE EMISSIONS FOR SIDI ENGINES

June 26, 2018

COORDINATING RESEARCH COUNCIL, INC.
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CRC Project E-94-3

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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, Principal Engineer, Light Duty Vehicle Technology. Technical staff members who contributed to this work were Mr. Peter Lobato, Light Duty Vehicle Technology; Mr. Kevin Whitney, Manager, Light Duty Vehicle Technology; 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. Kevin Brunner, Staff Engineer, Fuels and Driveline Lubricants Research. The statistical analysis was conducted by Mr. Robert Crawford of Rincon Ranch Consulting under an independent CRC contract. Mr. Jacob Bell from Ford and Mr. Paul Loeper from Chevron served as the CRC technical contacts for this project, and Amber Leland and Dr. Christopher J. Tennant represented the project sponsor, CRC.

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AKI	Anti Knock Index
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CH_4	Methane
CLD	Chemiluminescence Detector
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPC	Condensation Particle Counter
CRC	Coordinating Research Council
CVS	Constant Volume Sampling
CVT	Continuously Variable Transmission
DBE	Double Bond Equivalent
DHA	Detailed Hydrocarbon Analysis
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
EtOH	Ethanol Content
FID	Flame Ionization Detector
GC	Gas Chromatograph
GHG	Greenhouse Gas
MON	Motor Octane Number
MSS	Microsoot Sensor
NA	Naturally Aspirated
NMHC	Non-Methane Hydrocarbon
NO_x	Oxides of Nitrogen
N_2O	Nitrous Oxide
OC	Organic Carbon
OEM	Original Equipment Manufacturer
PAH	Polycyclic Aromatic Hydrocarbon
PM	Particulate Matter
PMI	Particulate Matter 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 CAFE and GHG emissions standards for model year 2017-2025 light-duty vehicles are significantly more stringent than past vehicles. 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 E10 certification fuel. Europe has implemented, for the first time, a particle number (PN) standard starting with the introduction of EURO 6 emissions regulations. There is an interest in investigating the impact of fuel properties on gaseous, PM and PN emissions for in-use SIDI vehicles.

This project, Coordinating Research Council (CRC) E-94-3, was conducted by Southwest Research Institute (SwRI) to perform a scoping study to investigate the impacts of splash-blending ethanol (EtOH) with gasoline on regulated gaseous, PM and PN emissions from vehicles equipped with SIDI engines. Project E-94-3 is a continuation of work completed in CRC Projects E-94-1[1], E-94-1a[2] and E-94-2[3]. The results from this study are compared to E-94-2, where ethanol-containing fuels were match-blended.

Denatured ethanol was splash-blended into E0 fuels from the E-94-2 program to create four gasoline-ethanol blends containing 9.4 to 9.8% ethanol by volume. The test fuels matrix was selected to represent high and low values for Particulate Matter Index (PMI) and Octane Rating (as determined by the anti-knock index, or AKI). The AKI of the splash-blended fuels ranged from 91.1 to 96.4, and the PMI ranged from 1.17 to 2.45. Fuel properties and test order can be seen in Table ES-1 and Figure ES-1.

TABLE ES-1: FUEL AKI, PMI AND ETOH CONTENT

AKI	Ethanol (EtOH), vol%	PMI	Fuel Letter	Fuel Test Order
91.5	9.44	1.28	C-E10	1
96.0	9.88	2.32	H-E10	2
96.4	9.75	1.17	G-E10	3
91.1	9.71	2.45	D-E10	4

[1] Morgan, P. (2014 June). CRC E-94-1, https://crcao.org/reports/recentstudies2014/E-94-1%20Evaluation%20and%20Investigation%20of%20Gaseous%20and%20Particulate%20Emissions%20on%20SIDI%20In-Use%20Vehicles%20with%20Higher%20Ethanol%20Blends/03-17589_CRC-E94-1_Final-Report_6-2-2014_Lobato_Morgan.pdf

[2] Morgan, P. (2014 December). CRC E-94-1a, https://crcao.org/reports/recentstudies2014/E-94-1a%20Evaluation%20of%20New%20Prep%20Cycle%20for%20Emissions%20of%20SIDI%20Vehicles/03-19840_CRC-E-94-1a_Final_4-6-2015.pdf

[3] Morgan, P. (2017 March). CRC E-94-2, https://crcao.org/reports/recentstudies2017/E-94-2/CRC_2017-3-21_03-20955_E94-2FinalReport%20Rev1b.pdf

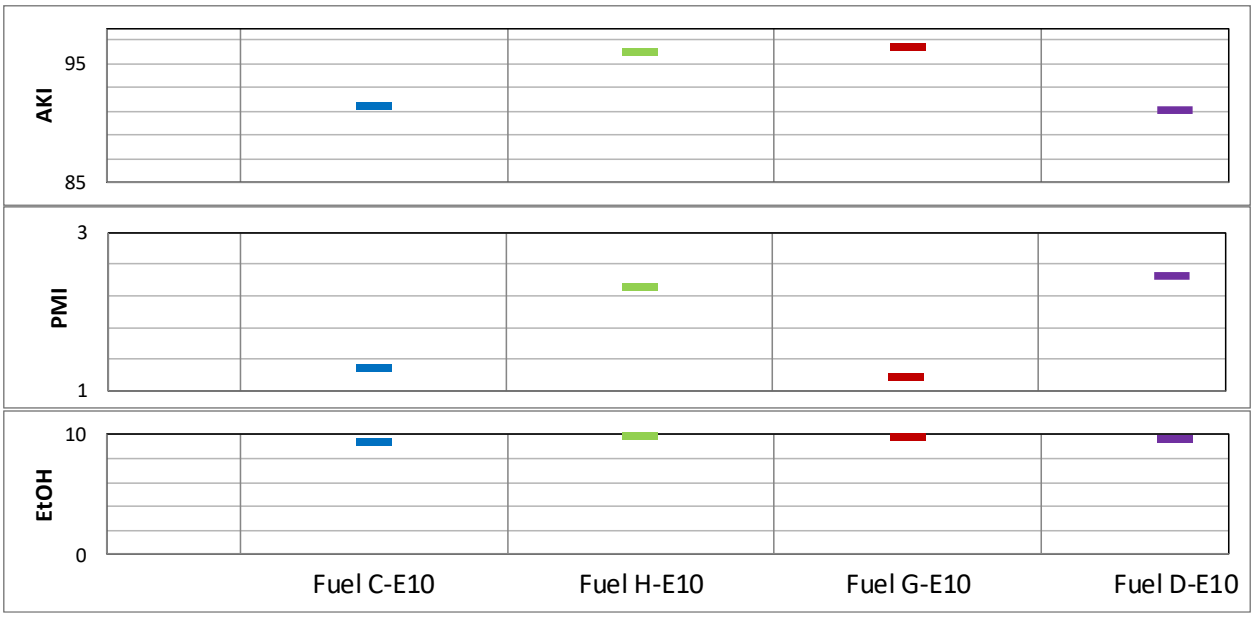


FIGURE ES-1: GRAPHICAL REPRESENTATION OF AKI, PMI, AND ETOH CONTENT FOR EACH FUEL

The test fleet of four modern vehicles equipped with SIDI engines was selected from the fleet of 12 vehicles used in the E-94-2 program to cover a range of particulate matter emissions from that study. Table ES-2 shows an overview of the four vehicles used in this program. Model names of these vehicles have been blinded in the report with the randomly generated assignment of the following letter codes: A, B, C and D.

TABLE ES-2: VEHICLES USED IN E-94-3 PROGRAM

Vehicle	Engine Type	Certification Group
2011 Nissan Juke	1.6L Turbocharged, I4	EPA Tier 2 Bin 5
2013 Chevrolet Malibu	2.5L Naturally Aspirated, I4	EPA Tier 2 Bin 4
2015 Lexus NX200t	2.0L Turbocharged, I4	EPA Tier 2 Bin 5 LDT2; California LEVIII-ULEV125-LDT2
2013 Mercedes-Benz GLK350	3.5L Naturally Aspirated, V6	EPA Tier 2 Bin 4

Each vehicle was tested twice over the LA92 drive cycle. During this drive cycle, non-methane hydrocarbons (NMHC), carbon monoxide (CO), oxides of nitrogen (NO_X) and nitrous oxide (N_2O), particulate matter (PM), soot mass, particle size, and fuel economy were measured. Upon completion of two tests, a repeatability check was run on total hydrocarbons (THC), CO and NO_X, with the following criteria: less than a 30% difference in THC (g/mi), and less than a 50% difference in CO (g/mi) and NO_X (g/mi). If any of these criteria failed, then the vehicle was tested a third time and the results reported.

A statistical analysis of the emissions results was performed by Rincon Ranch Consulting under separate contract with CRC. The objectives were to understand how the presence of ethanol in the fuels influenced particulate emissions. Both LA92 Phase 1 and LA92 weighted-average PN and PM emissions were examined. Two specific questions were posed:

1. Does the addition of ethanol to E0 fuels through splash-blending change particulate emissions?

2. How do emissions from splash-blended E10 fuels compare to the emissions of corresponding match-blended E10 fuels from E-94-2?

A chief conclusion of the analysis is that the addition of ethanol to E0 fuels through splash-blending increases particulate emissions in terms of both total number (PN) and total mass (PM). This effect is seen most easily during Phase 1 of the LA92 driving cycle as the large majority of emitted particulates are formed during cold-start vehicle operations.

The analysis conducted parallel studies of the entire dataset (four vehicles) and of a subset of three vehicles that were generally similar in response to fuels and, as a group, different than the forth vehicle. Figure ES-2 shows the effect of splash-blending on Phase 1 PM emissions of the 3-vehicle subset of the test fleet that proved to be similar in response. In this figure, the emissions measured for the splash-blended E10 fuels (the E10-S fuels) are compared to the emissions from the E0 fuels that were created and tested in E-94-2 and used as the base fuels for the splash-blending. The percent changes shown reflect the average vehicle in the test fleet and thus refer to changes in the average emission levels between the fuels.

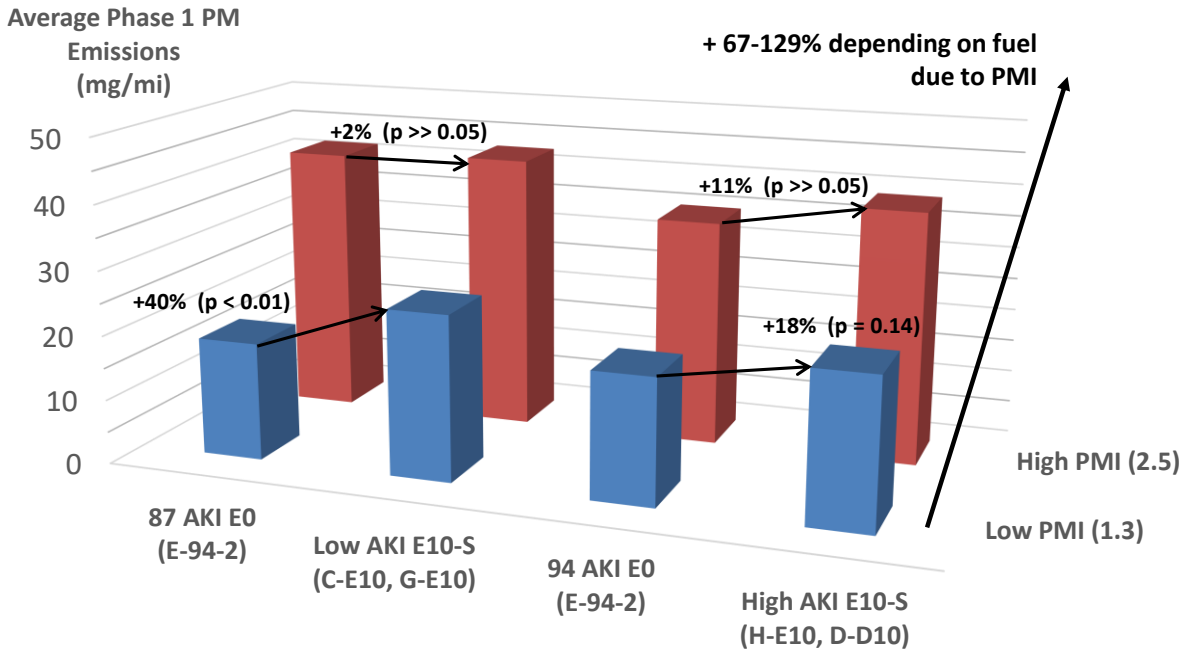


FIGURE ES-2: EFFECT OF E10 SPLASH-BLENDING ON PHASE 1 PM EMISSIONS (AVERAGE OF THREE VEHICLES)

As shown, the PMI index of the fuel has a strong effect on Phase 1 PM emissions, increasing emissions by 67-129% depending on the fuel. However, the addition of ethanol to the E0 fuels leads to consistently higher PM emissions. However, only one of the ethanol-related emission changes is statistically significant on its own (indicated parenthetically[4]), while the other changes fail to achieve statistical significance.

Table ES-3 looks more broadly at the effect of ethanol splash-blending on particulate emissions; in this, only the conclusions that can be drawn with statistical confidence are shown. The change in ethanol content from E0 to E10 by splash-blending is found to increase Phase 1 PN and PM emissions for all fuels on average and in the group of Low PMI fuels specifically, with statistical significance. Similarly, the change in ethanol content from E0 to E10 by splash-blending is found to increase LA92 PN and PM emissions for all fuels on average and in the group of Low PMI fuels, with acceptable and good statistical confidence, respectively. The emission changes observed in the group of High PMI fuels were too small to be statistically significant.

TABLE ES-3: FINDINGS ON THE EFFECT OF E0 TO E10 SPLASH-BLENDING ON PARTICULATE EMISSIONS (AVERAGE OF THREE VEHICLES)

	LA92 Phase 1	**LA92 Cycle**
PN Emissions (10^{12} per mi)	E0→E10 found to ↑ PN by +12%, for all fuels on average and in the group of Low PMI fuels. (with statistical significance)	E0→E10 found to ↑ PN by +17%, for all fuels on average and in the group of Low PMI fuels. (with statistical significance)
PM Emissions (mg/mi)	E0→E10 found to ↑ PM by +13%, for all fuels on average and in the group of Low PMI fuels. (good statistical significance)	E0→E10 found to ↑ PM by +24% for all fuels on average and in the group of Low PMI fuels. (good statistical significance)
Notes: Statistical significance refers to findings that achieve the accepted p = 0.05 level. Good statistical significance refers to findings that achieve the p ≤0.01 level.		

Splash-blending involves the simple dilution of an E0 base fuel with a specified volume of ethanol. Because the presence of ethanol is the only difference between the E0 and the splash-blended E10 fuels, these findings mean that ethanol itself must be the factor responsible for the increased particulate emissions. Such ethanol-caused emission increases are in addition to the effects attributable to variation in the PMI of the fuels, which remains the most important fuel determinant of the total variability in particulate emissions.

The study also compared particulate emissions of the vehicles on the match-blended E10 fuels to those on the splash-blended E10 fuels tested here. The match-blending practiced in the E-94-2 study involved the selection of an alternative E0 base fuel for blending such that the final E10 fuel would meet desired values of AKI, RVP, and other characteristics once ethanol was added.

[4] A parenthetical value of $p \leq 0.05$ indicates that the result achieves the conventionally accepted level of statistical significance. A value of $p >> 0.05$ indicates the result carries no statistical significance.

Particulate emissions on the match-blended E10 fuels are observed to be generally higher than on the corresponding splash-blended fuels. This should be no surprise as the E10-M fuels had PMI values that corresponded closely to the E0 fuels because of the match-blending, while the E10-S fuels had lower PMI values by as much as -0.2 due to the dilution of the gasoline hydrocarbons by ethanol. The emission differences are small (a few to several percent) in most cases and did not reach the accepted level for statistical significance. For one fuel, the differences were larger (up to as much as +20%) and statistically significant.

With respect to the influence of splash- versus match-blending on particulate emissions, this study reaches two primary conclusions:

1. It is not possible to conclude generally that particulate emissions from match-blended E10 fuels will be significantly higher than emissions from splash-blended E10 fuels. The effect on emissions depends more on the E0 base fuel than on the fact that match-blending versus splash-blending has been performed. Where significant PM emission increases occurred in this study, they were best interpreted as characteristic of the specific fuel involved.

2. The particulate emission increases attributed in the E-94-2 program to the presence of ethanol at the E10 level *largely* reflect the influence of ethanol itself on emissions. These particulate increases are not primarily the result of the match-blended fuel characteristics, although a modest amount of the PM emissions increase due to the match-blended ethanol may have been influenced by these characteristics. The influence also depends on the composition of the test fleet, as the particulate emission response was found to vary among the vehicles.

1.0 BACKGROUND

The Corporate Average Fuel Economy (CAFE) and Greenhouse Gas (GHG) emissions standards for 2017-2025 model year light-duty vehicles are significantly more stringent than the previous 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 10% ethanol (E10) certification fuel. Europe has implemented, for the first time, a particle number (PN) standard starting with the EURO 6 emissions regulations. The California Air Resources Board (CARB) is also investigating using a PN standard.

There has been interest in studying the emissions response of SIDI-equipped vehicles to changes in the particulate matter index (PMI) of a fuel. This index, developed by Aikawa, Sakurai and Jetter[5], 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 a continuation of E-94-1, E-94-1a and E-94-2, in which the octane number and ethanol content were also varied to study their effects on the performance and emissions of SIDI-equipped vehicles. E-94-2 studied the comparison between match-blended E10 fuels and E0 fuels. For a given PMI and AKI, E0 and E10 fuels were blended in a manner that maintained similar PMI and AKI. E-94-3 studied how PM emissions are impacted when E0 fuels with high or low AKI and PMI have ethanol splash-blended. This work generates data to support an assessment of a different method of developing gasoline test fuels containing 10 percent ethanol by volume on the emissions responses of SIDI-equipped vehicles as determined in the CRC E-94-2 program.

[5]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

CRC was interested in investigating differences between match-blended and splash-blended E10 fuels used in naturally aspirated and turbocharged SIDI vehicles as measured by effects on particulate matter and particle number.

Four representative vehicles covering a range of particulate matter results from the E-94-2 program were selected from the test fleet used for that study. Gaseous, particulate matter, and particle number emissions data were collected while operating these four vehicles over the LA92 drive cycle.

Two fuel properties, AKI and PMI, were varied as either low or high to get a combination of each fuel property with the two properties held relatively constant. All four fuels were splash-blended with ethanol at a nominal volume concentration of 10%. Blendstock fuels used for blending were the remnant E0 fuels from the E-94-2 program. Match-blending in E-94-2 allowed these properties to be maintained between the E0 and E10 fuels, while splash-blending increased the AKI and lowered the PMI. Fuel properties and test order for E-94-3 can be seen in Figure 1. Results from E-94-2 will be used in comparison to results from E-94-3. Fuel properties for E-94-2 fuel can be seen in Figure 2

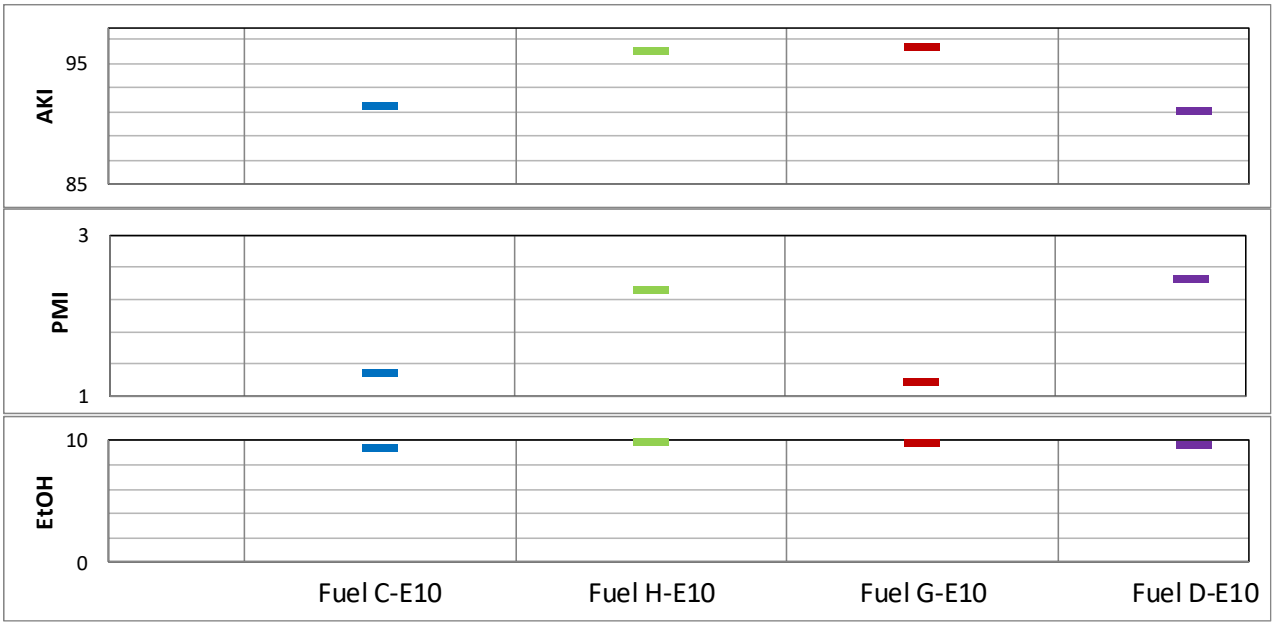


FIGURE 1: GRAPHICAL REPRESENTATION OF AKI, PMI, AND ETOH CONTENT FOR EACH FUEL IN E-94-3

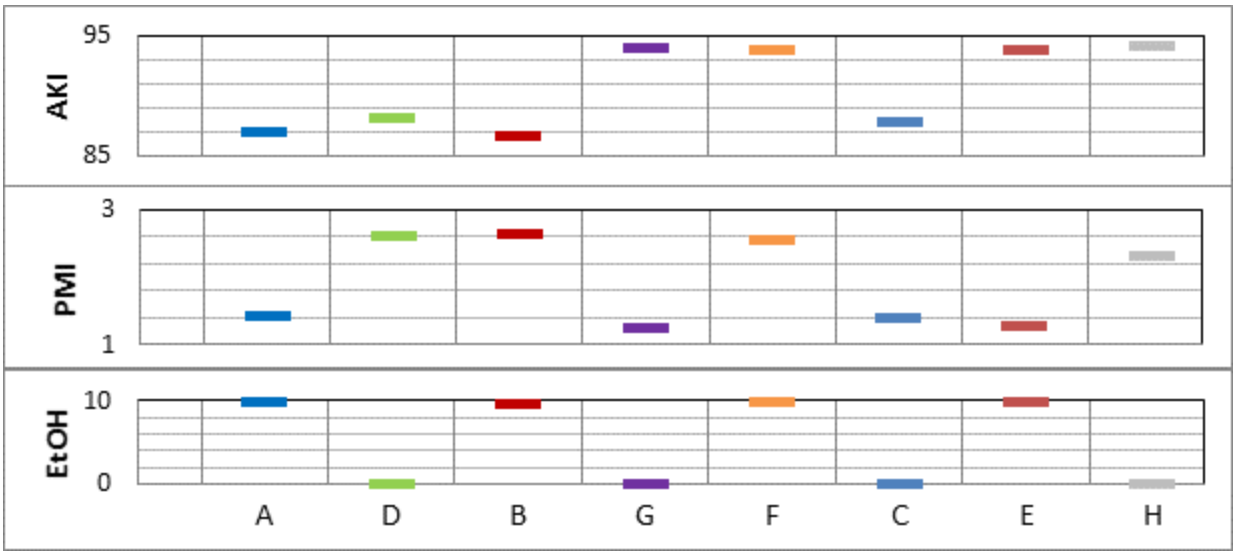


FIGURE 2: GRAPHICAL REPRESENTATION OF AKI, PMI, AND ETOH CONTENT FOR EACH FUEL IN E-94-2

Each vehicle was tested with each fuel consecutively, with one fuel being tested per week. Gaseous exhaust emissions, particulate matter, particle number and fuel economy were measured over two LA92 drive cycles conducted on consecutive days. The results of these two tests were then compared for repeatability: namely, the repeatability of measured THC, CO, and NO_X. Repeatability criteria of less than a 30% difference between for THC (g/mi), and less than a 50% difference for CO (g/mi) and NO_X (g/mi), evaluated on the weighted average results for the first and second tests, were required. If any of these repeatability criteria were not met, then a third test was conducted. The formula for percent difference can be seen below, where T_1 is the value of THC, CO or NO_X for the first test and T_2 is the value for the second test.

$$\% \text{ Difference} = \left(\frac{T_1 - T_2}{\frac{T_1 + T_2}{2}} \right) \times 100\%$$

3.0 TEST SETUP

3.1. Test Fuels

3.1.1. Types of Fuel Used

Four test fuels were blended for this program, using remaining E0 fuels from the E-94-2 program as blendstocks to create four splash-blended E10 fuels. The E0 base fuels used for blending were designed to meet a range of high and low targeted values for octane and PMI. The mid-range distillation and vapor pressure characteristics of all four E0 base fuels were matched, and other parameters (e.g., olefin, total aromatics and sulfur content) were also held within a narrow band of values in order to limit the number of properties that differed between the test fuels. Match-blending provides significantly more control over fuel properties than does splash blending. In match-blending, the base fuel is altered such that when ethanol is added the other fuel properties (e.g., effective octane rating, vapor pressure, etc.) more closely match the desired specifications. In splash-blending, ethanol is simply added to the base fuel. This study focused on splash-blending to compare differences in match-blended fuel results from E-94-2.

Honda collected a large set of data and compiled a histogram (Figure 3) showing the PMI of fuels found in the U.S. These data are used with permission from Honda R&D. The averages of the high and low PMI fuels used in this study are shown below. These averages fall within the typical PMI range for fuel found in the United States.

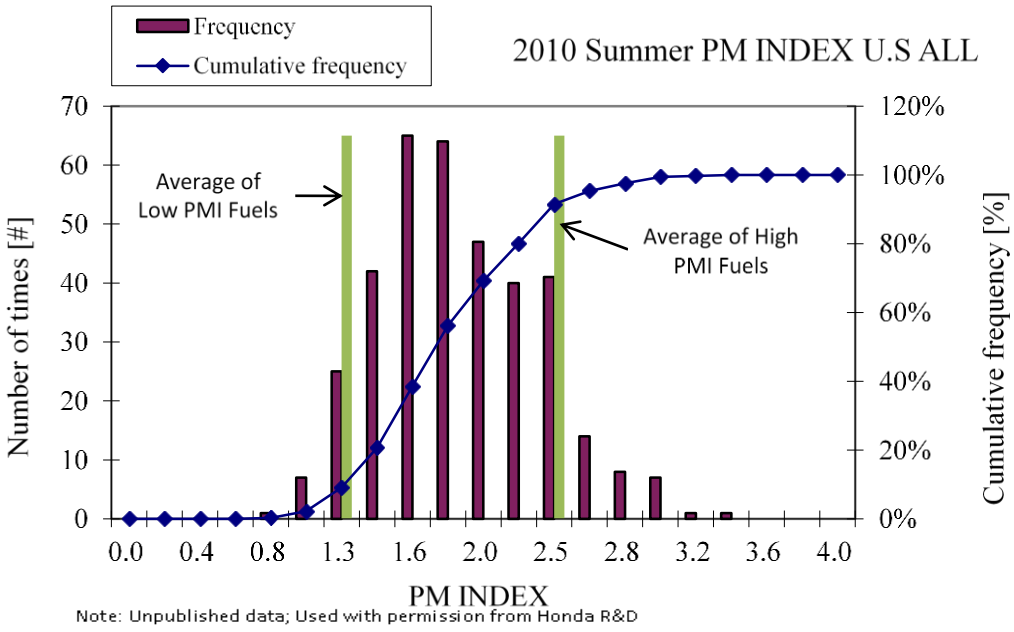


FIGURE 3: HISTOGRAM OF FUEL PMI IN THE UNITED STATES

To calculate a PMI number, the following equation was used, which takes into account the effects of molecular structure and volatility of the fuel.

$$PMI = \sum_{i=1}^{n} \frac{DBE_i + 1}{VP_{(443\ K)_i}} Wt_i$$

Here DBE represents the double bond equivalent, VP is the vapor pressure at 443°K, and Wt is the weight fraction of molecular species obtained from detailed hydrocarbon analysis (DHA) of the fuel. These properties are evaluated for each component within the fuel and then summed to give a PMI. It has been shown that more volatile gasoline results in lower PM and PN emissions; and that there is a strong correlation between aromatic carbon number and particulate emissions. This equation and index has shown good correlation with PM and PN emissions, with higher PMI resulting in higher PM and PN emissions[6].

3.1.2. Fuel Blending

Three 55-gallon drums of commercially available, fuel-grade denatured ethanol were purchased with the request that the ethanol in these drums originate from the same bulk tank prior to filling. Once the drums of ethanol were received, samples from each were obtained for analyses. One drum's sample was evaluated according to ASTM D 4806-15, excluding Silicon (ASTM D7757), while the other drum samples were checked only for density (ASTM D4052), water content (ASTM D6304) and ethanol concentration (ASTM D5501).

Prior to initiating any blending of base fuel and denatured ethanol in a tote, two drums of each base fuel were placed in a cold box and sampled. A one-pint sample was obtained from each drum and analyzed for RON, MON and ethanol concentration by PetroSpec and a Reid Vapor Pressure/DVPE (ASTM D5191) analysis to verify that the fuel in the respective drum was accurately labeled and had not weathered.

A stainless-steel blending tote was used to mix the base fuel and denatured ethanol on a weight basis. Prior to each blend, the tote was flushed with denatured ethanol. The empty tote was weighed before and after being used for flushing, and showed the same weight, 332kg. Therefore, the residual quantity of ethanol in the tote was within the resolution of the scale used for blending, or 0.5 kg, or 0.15% of measurement.

The base fuel alone was first comingled into the tote and a 1-gallon sample was obtained for analyses. This information verified the condition of the respective base fuel prior to the introduction of ethanol.

Ethanol was then added to the base fuel in the tote. Mixing of the two components was conducted in the tote with an air-powered stirrer that ensured thorough mixing of the ethanol and base fuel. A 1-gallon sample from each blend was analyzed and the complete fuel analysis results, including those from the match-blended fuels used in E-94-2 from the same measurement laboratory, are provided in Appendix A. One tote blend was prepared at a time until the four blends were completed. After analysis and approval, the blended fuels were transferred to drums. A comparison of the distillation properties of these fuels, those used in E-94-2 and market fuel samples is provided in Appendix B.

[6] 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.

The drums remained in a temperature-controlled facility until the morning of a fuel change procedure for a given test vehicle, 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 temperatures of the vehicle and fuel before the preconditioning procedure. Further details on this fuel change, preconditioning and testing procedure are provided in Appendix C.

3.2. Test Vehicles

Four vehicles were selected for this program, the details of which are shown in Table 1. These four vehicles were selected from the group used in E-94-2. The original group of vehicles was selected because they were available, widely used in the U.S., and equipped with engines using gasoline direct injection. Note that while all of these vehicles utilize direct injection, the Lexus NX200t utilizes both direct injection and port 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. The Nissan Juke was equipped with a continuously variable transmission (CVT). In order for the vehicle to drive properly on the dynamometer, the original equipment manufacturer (OEM) provided a new, replacement engine controller. The subset of vehicles used for this program was selected because it covers a range of PM emissions rates from the E-94-2 program.

TABLE 1: DESCRIPTION OF VEHICLES

Vehicle Make		Nissan	Chevrolet	Lexus	Mercedes
Vehicle Model		Juke	Malibu	NX200t	GLK350
Model Year		2011	2013	2015	2013
Engine Family		BNSXV01.6GDA	DGMXVO2.5001	FTYXT02.0KEM	DMBXV03.5BN4
Engine Evap. Code		BNSXR0090PBB	DGMXR0133810	FTYXR0132A22	DMBXR0155LNS
Engine Displacement		1.6L Turbocharged, I4	2.5L Naturally Aspirated, I4	2.0 L Turbocharged, I4	3.5L Naturally Aspirated, V6
Transmission		CVT	6-speed Automatic	6-speed Automatic	7-speed Automatic
Odometer, Miles (at start of E94-3)		54,233	25,101	5,365	23,787
Emissions Class		EPA Tier 2 Bin 5	EPA Tier 2 Bin 4	EPA Tier 2 Bin 5 LDT2; California LEVIII-ULEV125-LTD2	EPA Tier 2 Bin 4
Estimated Test Weight Class, lbs		3500	3750	4250	4500
EPA Tier 2 Certification Standard	NMOG, g/mi	0.075	0.07	0.075	0.07
	CO, g/mi	3.4	2.1	3.4	2.1
	NO_X, g/mi	0.05	0.04	0.05	0.04
	PM, g/mi	0.01	0.01	0.01	0.01
Note: 4,000 miles performed on mileage accumulation dynamometer (MAD) for vehicle break-in prior to testing.					

Used vehicles with an odometer reading between 4,000 and 10,000 miles were selected for the E-94-2 program so that the engines had already been broken in. However, the Lexus NX200t was purchased new. To break in the Lexus NX200t, the vehicle was operated on a mileage accumulation dynamometer (MAD) over the Standard Road Cycle (SRC) for 4,000 miles using commercially available Top Tier qualified gasoline.

3.2.1. Vehicle Check-In

Upon receipt of the test vehicles during E-94-2, 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 that included the items listed below.

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 and damage.
4. The exhaust systems were checked for leaks.
5. Fluid levels were checked and topped off as required. The manufacturer's recommended fluids were used for each vehicle.
6. The vehicles were checked for the presence of diagnostic trouble codes (DTCs).
7. A fuel change to EEE certification fuel was performed.

3.2.2. Vehicle Instrumentation and Preparation

Each vehicle was instrumented and prepared, prior to E-94-2, as described below.

- A Marmon flange was welded to the rear tailpipe for emissions testing.
- The engine oil was drained using two drains and fills of the crankcase with a Pennzoil GF-4 of the appropriate viscosity as recommended by the manufacturer.
- Each vehicle was operated on a MAD over the SRC for 250 miles to de-green the oil.

No further instrumentation was added for E-94-3.

3.2.3. Vehicle Emissions Check-Out Test

Prior to the testing of the splash-blended fuels, each vehicle received a single checkout emissions test over an LA-92 driving cycle using the same high octane, high PMI match-blended E10 fuel from the E-94-2 program (Fuel F). This verified that the four vehicles were operating the same as when they were tested in the E-94-2 program with the same fuel. 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. The preconditioning sequence for these checkout tests was the same as that used for testing in E-94-2. Vehicle C showed a "questionable" result which is addressed in Section 5.2.2 and Appendix G.

3.3. Vehicle Testing

Each vehicle/fuel combination was prepared, preconditioned, and tested as specified in the Fuel Change, Conditioning and Test Procedure (Appendix C) and the Catalyst Sulfur Purge Cycle (Appendix D). Two repeated emissions tests were conducted on consecutive days where possible; if a third test was required due to failing the repeatability criteria (given in Appendix C), it was conducted on the third consecutive day. The test protocol for each vehicle/fuel combination is shown in Figure 4.

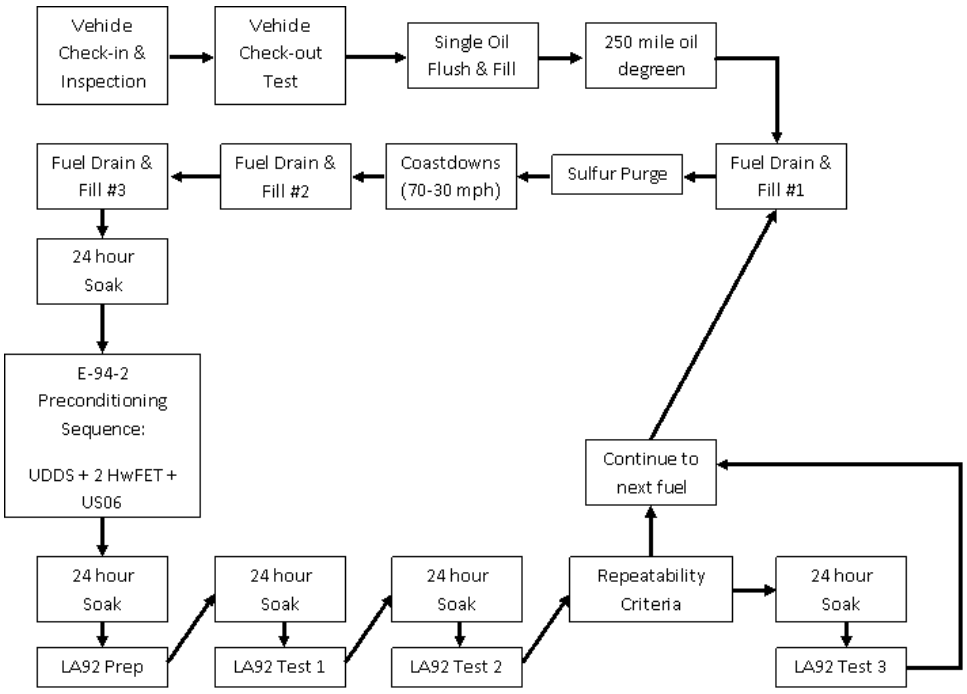


FIGURE 4: TEST PROTOCOL FOR VEHICLE/FUEL COMBINATIONS

The order in which the fuels were tested is shown in Table 2 and did not vary from vehicle to vehicle.

TABLE 2: TEST SEQUENCE

Fuel	Test Order
Fuel C – E10	1
Fuel H – E10	2
Fuel G – E10	3
Fuel D – E10	4

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 5.

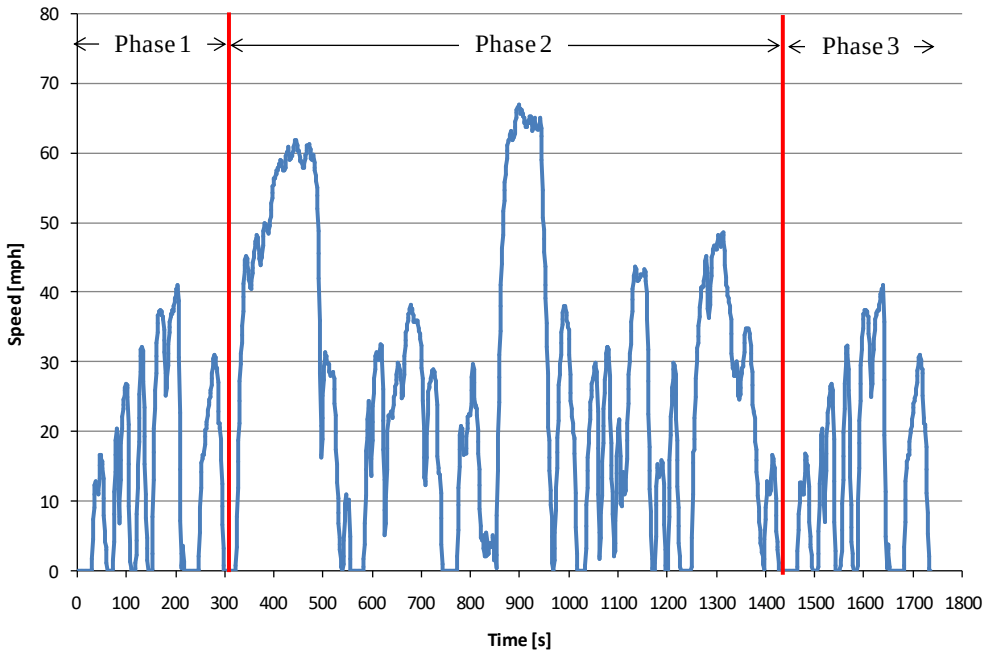


FIGURE 5: LA92 DRIVING CYCLE

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 first 300-seconds. Overall cycle emissions were calculated in the same manner as the weighted FTP-75 formula[7], 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 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. Road-load coefficients provided by engineers from Mercedes-Benz were used for the Mercedes-Benz GLK350. Published road-load coefficients from the EPA Test Car List were used for the remaining vehicles.

One dynamometer was used for all testing throughout this program. In order to minimize any effects on emissions that can be seen with different drivers, one of two drivers were assigned to each vehicle for the entire program. Testing utilized the same test site and drivers as the previous E-94-2 study. Each set of tests was conducted on consecutive days where possible. During the overnight soak periods, all vehicles were fitted with a trickle charger to maintain battery conditions. Prior to testing on the dynamometer each day, the vehicle's cold tire pressures were checked and, if needed, set to the manufacturer's specification.

[7] 40 CFR §86.144-94

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. Fuel economy was calculated by the carbon mass 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 3.

TABLE 3: DILUTE EXHAUST CONSTITUENT ANALYSIS METHODS

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

For the determination of PM mass emissions, a proportional sample of dilute exhaust was drawn through a 47 mm Whatman Teflon® membrane filter. The PM sampling method used 40 CFR Part 1066 protocols. The sample zone was maintained at 47°C ± 5°C. A $PM_{2.5}$ 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

Table 4 shows the analysis methods used for measuring the unregulated emissions. Multiple methods were used for analyzing the particulate emissions to obtain a more detailed characterization of the emissions as well as cross-check.

TABLE 4: UNREGULATED EMISSIONS ANALYSIS METHODS

Constituent	Analysis Method
Nitrous Oxide	Micro-electron Capture Detector (micro-ECD)
Particle Size Distribution	Spectrometer (EEPS and SPSS)
Particle Number	Condensation Particle Counter (CPC) 3790 – particles greater than 23 nm in diameter
	Condensation Particle Counter (CPC) 3025 – particles greater than 3 nm in diameter
PM	Photo-acoustic

3.3.3.1. 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.

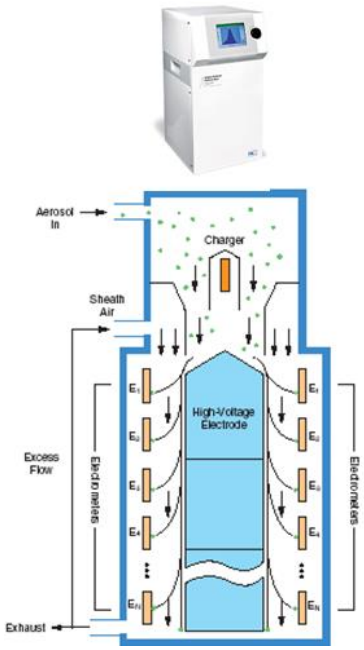


FIGURE 6: ENGINE EXHAUST PARTICLE SIZER (EEPS)

3.3.3.2. Solid Particle Sampling System (SPSS)

The SPSS, similar to the one 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. On average, the SPSS extracted sample from engine exhaust with a dilution ratio of ~ 5.50.

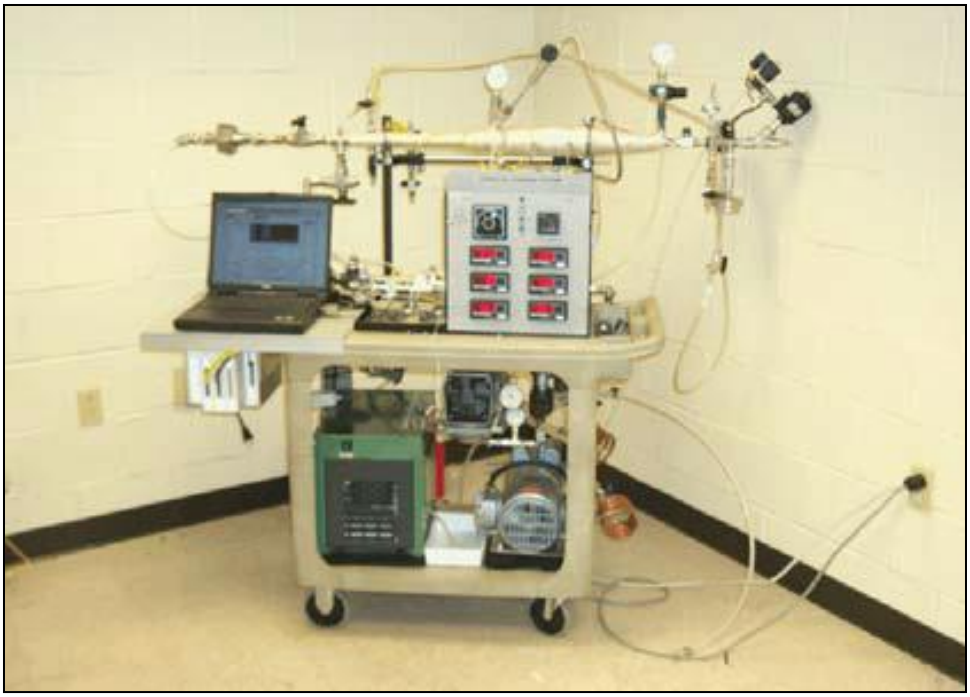


FIGURE 7: SOLID PARTICLE SAMPLING SYSTEM (SPSS)

3.3.3.3. 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. Particles greater than 23 nm in diameter are counted using a TSI model 3790 Condensation Particle Counter (CPC). The CPC 3790 has a 50% counting efficiency for particles less than 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 re-condensation of particles smaller than 23 nm. The catalytic stripper used in the SPNMS prevents re-nucleation / condensation by oxidizing the volatile material. 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 used for this work consists of the CPC 3790 (for particles greater than 23 nm) and the CPC 3025 (for particles greater than 3 nm); the system is shown in Figure 8. The CPC 3790 is located within the red case, and the CPC 3025 is the white instrument as pictured.

FIGURE 8: SWRI SOLID PARTICLE NUMBERING MEASUREMENT SYSTEM (SPNMS)

3.3.3.4. 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 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 the instrument's detector and sampling point, at the CVS.

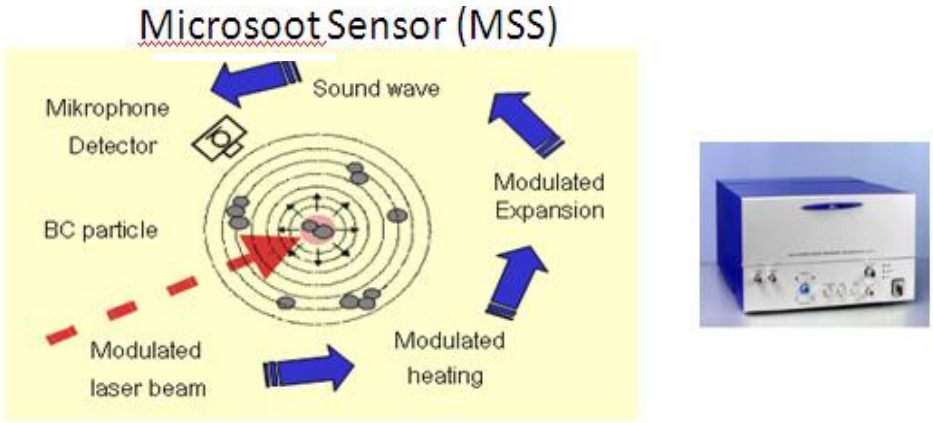


FIGURE 9: AVL MICROSOOT SENSOR (MSS)

3.3.3.5. On-Board Diagnostic Channels

Numerous OBD channels were recorded, if available, continuously throughout the LA92 tests. These channels included short-term fuel trim, long-term fuel trim, engine speed, vehicle speed, coolant temperature, ignition timing, mass air flow (when vehicle was outfitted with MAF sensor), manifold air pressure (when vehicle was outfitted with MAP sensor), throttle position, evaporative purge command percentage, and primary oxygen sensor voltage. These data were collected for quality control purposes and to help troubleshoot any potential problems with the vehicles.

4.0 TEST RESULTS

A summary of LA-92 weighted average gaseous emissions results from the four test vehicles is provided below in Table 5 through Table 8. Values shown are the weighted average emissions from multiple tests (either 2 or 3 depending on repeatability of the vehicle/fuel combination). Phase-level gaseous emissions results can be found in appendix Figures E-1 through E-16.

4.1. Regulated Gaseous Emissions

Table 5 through Table 8 show the weighted average regulated gaseous (THC, CO, NO_X, and NMHC) for Vehicles A, B, C and D for all fuels tested over the LA92 drive cycle. The fuel properties are also located on the left side of the table for reference. Phase-level and weighted average LA92 regulated gaseous emissions plots for these four vehicles can be found in appendix Figures E-1 through E-16. These figures also include the corresponding match-blended fuels results from E-94-2.

TABLE 5: VEHICLE A WEIGHTED AVERAGE OF REGULATED GASEOUS EMISSIONS SUMMARY

Fuel Letter	AKI, [-]	EtOH, [vol%]	PMI, [-]	THC, [g/mi]	CO, [g/mi]	NO_X, [g/mi]	NMHC, [g/mi]
C-E10	91.5	9.44	1.28	0.030	0.242	0.012	0.021
H-E10	96.0	9.88	2.32	0.029	0.225	0.010	0.020
G-E10	96.4	9.75	1.17	0.026	0.231	0.011	0.017
D-E10	91.1	9.71	2.45	0.037	0.272	0.014	0.026

TABLE 6: VEHICLE B WEIGHTED AVERAGE OF REGULATED GASEOUS EMISSIONS SUMMARY

Fuel Letter	AKI, [-]	EtOH, [vol%]	PMI, [-]	THC, [g/mi]	CO, [g/mi]	NO_X, [g/mi]	NMHC, [g/mi]
C-E10	91.5	9.44	1.28	0.022	0.144	0.017	0.017
H-E10	96.0	9.88	2.32	0.021	0.147	0.012	0.016
G-E10	96.4	9.75	1.17	0.019	0.162	0.008	0.015
D-E10	91.1	9.71	2.45	0.023	0.156	0.010	0.018

TABLE 7: VEHICLE C WEIGHTED AVERAGE OF REGULATED GASEOUS EMISSIONS SUMMARY

Fuel Letter	AKI, [-]	EtOH, [vol%]	PMI, [-]	THC, [g/mi]	CO, [g/mi]	NO_X, [g/mi]	NMHC, [g/mi]
C-E10	91.5	9.44	1.28	0.019	0.388	0.013	0.012
H-E10	96.0	9.88	2.32	0.017	0.456	0.010	0.012
G-E10	96.4	9.75	1.17	0.013	0.408	0.007	0.009
D-E10	91.1	9.71	2.45	0.024	0.503	0.019	0.016

TABLE 8: VEHICLE D WEIGHTED AVERAGE OF REGULATED GASEOUS EMISSIONS SUMMARY

Fuel Letter	AKI, [-]	EtOH, [vol%]	PMI, [-]	THC, [g/mi]	CO, [g/mi]	NO_X, [g/mi]	NMHC, [g/mi]
C-E10	91.5	9.44	1.28	0.012	0.527	0.008	0.007
H-E10	96.0	9.88	2.32	0.011	0.462	0.009	0.007
G-E10	96.4	9.75	1.17	0.013	0.548	0.009	0.008
D-E10	91.1	9.71	2.45	0.015	0.531	0.007	0.009

4.2. Particulate Emissions

A summary of weighted average particulate emissions results from the four test vehicles is provided below in Table 9 through Table 12. Values shown are the weighted average emissions from multiple tests (either 2 or 3 depending on repeatability of the vehicle/fuel combination). Here particulate mass (PM), soot mass (MSS), particle number greater than 3 nm (CPC 3025), and particle number greater than 23 nm (CPC 3790) are shown. For reference, the fuel properties have been included in each table on the left side.

TABLE 9: VEHICLE A WEIGHTED AVERAGE OF PARTICULATE EMISSIONS SUMMARY

Fuel Letter	AKI, [-]	EtOH, [vol%]	PMI, [-]	PM, [mg/mi]	MSS, [mg/mi]	CPC 3025, [particles/mi]	CPC 3790, [particles/mi]
C-E10	91.5	9.44	1.28	8.80	6.51	1.19E+13	1.09E+13
H-E10	96.0	9.88	2.32	11.90	9.32	1.49E+13	1.36E+13
G-E10	96.4	9.75	1.17	6.20	4.61	9.33E+12	8.24E+12
D-E10	91.1	9.71	2.45	12.73	10.36	1.59E+13	1.47E+13

TABLE 10: VEHICLE B WEIGHTED AVERAGE OF PARTICULATE EMISSIONS SUMMARY

Fuel Letter	AKI, [-]	EtOH, [vol%]	PMI, [-]	PM, [mg/mi]	MSS, [mg/mi]	CPC 3025, [particles/mi]	CPC 3790, [particles/mi]
C-E10	91.5	9.44	1.28	1.53	0.59	2.49E+12	1.83E+12
H-E10	96.0	9.88	2.32	1.87	1.16	4.56E+12	3.22E+12
G-E10	96.4	9.75	1.17	1.63	0.55	2.03E+12	1.49E+12
D-E10	91.1	9.71	2.45	2.39	1.33	4.43E+12	3.17E+12

TABLE 11: VEHICLE C WEIGHTED AVERAGE OF PARTICULATE EMISSIONS SUMMARY

Fuel Letter	AKI, [-]	EtOH, [vol%]	PMI, [-]	PM, [mg/mi]	MSS, [mg/mi]	CPC 3025, [particles/mi]	CPC 3790, [particles/mi]
C-E10	91.5	9.44	1.28	1.04	0.06	1.11E+12	6.62E+11
H-E10	96.0	9.88	2.32	0.79	0.15	2.07E+12	1.33E+12
G-E10	96.4	9.75	1.17	0.88	0.06	1.25E+12	7.56E+11
D-E10	91.1	9.71	2.45	0.71	0.21	2.71E+12	1.74E+12

TABLE 12: VEHICLE D WEIGHTED AVERAGE OF PARTICULATE EMISSIONS SUMMARY

Fuel Letter	AKI, [-]	EtOH, [vol%]	PMI, [-]	PM, [mg/mi]	MSS, [mg/mi]	CPC 3025, [particles/mi]	CPC 3790, [particles/mi]
C-E10	91.5	9.44	1.28	4.83	3.54	8.33E+12	7.37E+12
H-E10	96.0	9.88	2.32	9.39	7.26	1.55E+13	1.40E+13
G-E10	96.4	9.75	1.17	5.69	3.54	8.50E+12	7.42E+12
D-E10	91.1	9.71	2.45	12.73	10.55	1.94E+13	1.83E+13

4.2.1. Particulate Matter Emissions

Figure 10 shows phase-level and weighted average LA92 PM emissions for the first vehicle tested (Vehicle B). Because the objective of this study was to compare match-blended to splash-blended E10 fuels, results from E-94-2 are included for the same vehicles tested with match-blended fuels. Relationships between splash-blended and match-blended fuels are discussed further in Section 5.3. The PM emissions for Vehicle B as well as the remaining vehicles can be found in Appendix E, Figures E-17 through E-20. The error bars in the figures below represent the minimum and maximum values for the measured emission, with the colored bar representing the average value for all replicate tests (two or three) conducted for a given vehicle and fuel combination.

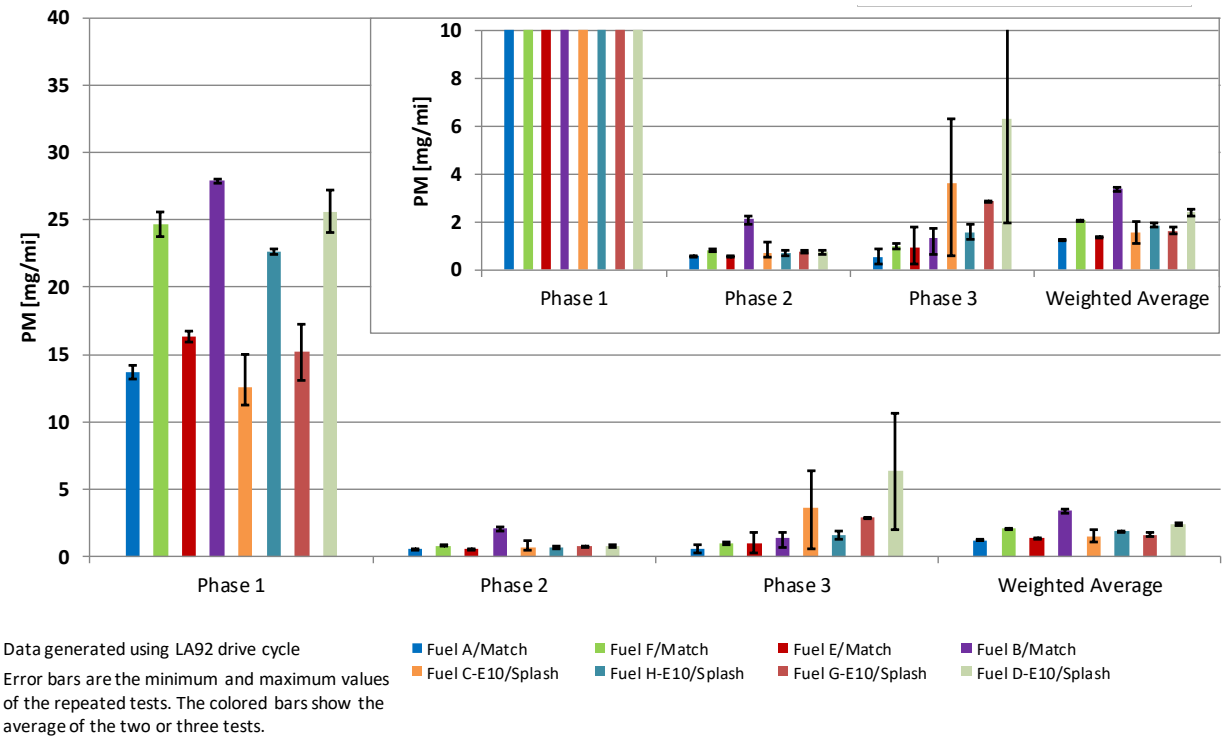


FIGURE 10: VEHICLE B PM EMISSIONS

4.2.2. 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). Phase-level and weighted average LA92 MSS results are shown in Appendix E, Figures E-21 through E-24 for all the vehicles.

Results show that soot mass correlates strongly to PM mass, contributing 50% to 80% of the mass fraction. Figure 11 shows the correlation between MSS and PM for all vehicles for all test phases. The correlation between MSS and PM is strongly linear with a coefficient of determination of 0.984.

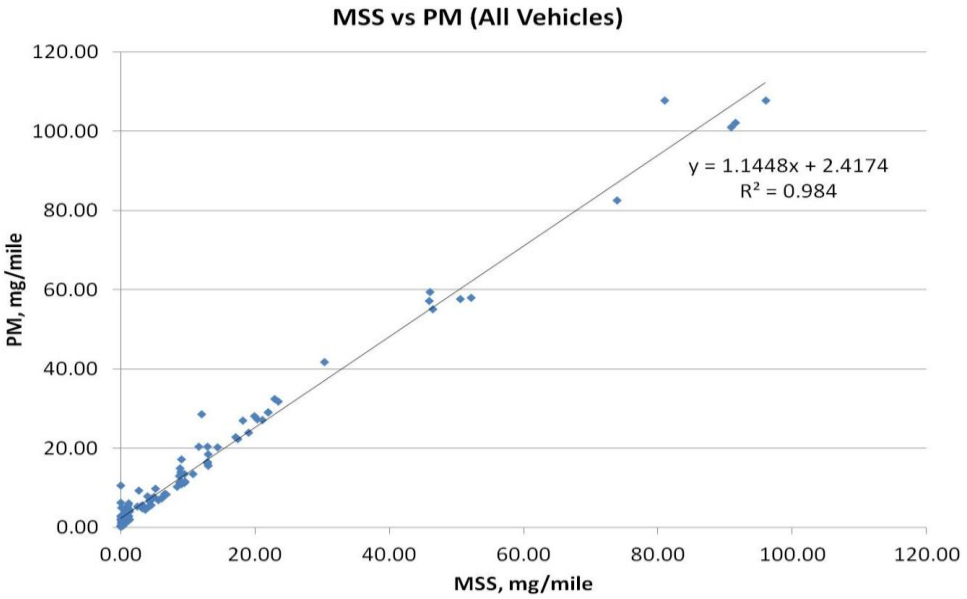


FIGURE 11: MSS VERSUS PM CORRELATION FOR ALL VEHICLES (VEHICLES A, B, C, D) AND PHASES

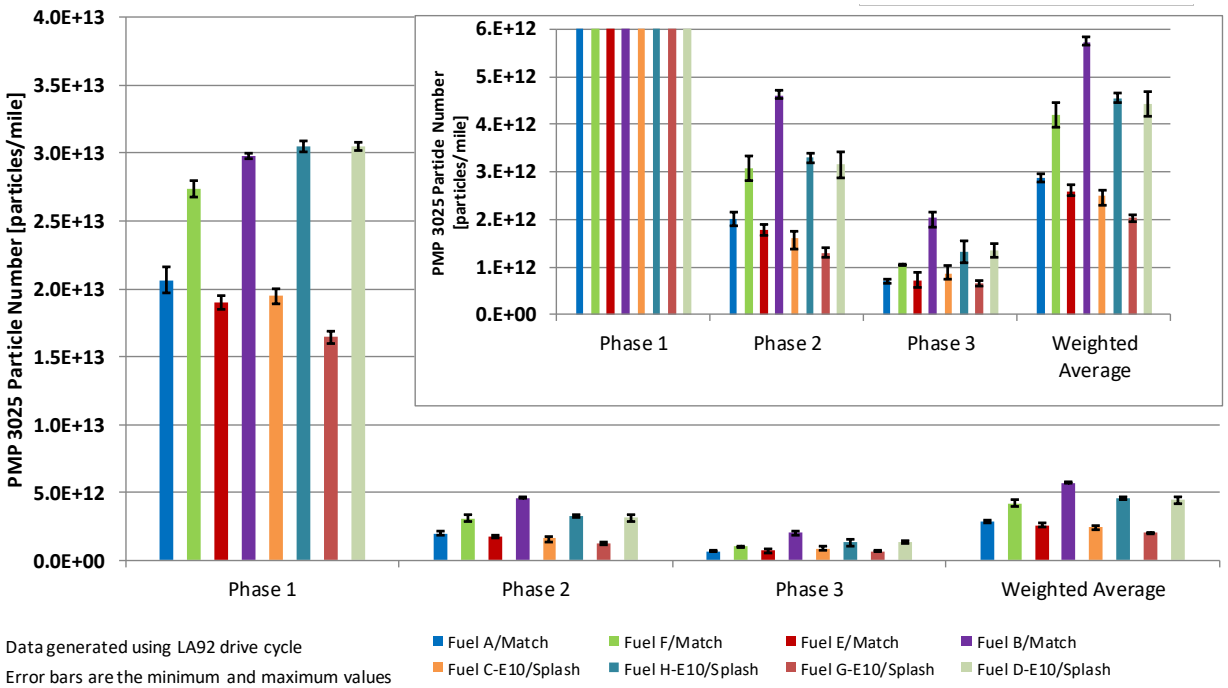
4.2.3. Particle Number (PN) Emissions

Particle number emissions measured with the CPC 3025 and CPC 3790 tracked each other well throughout the program in terms of trending on a phase-wise basis. Appendix Figures E-25 through E-32 present the phase-level and weighted average LA92 emissions for CPC 3025 and CPC 3790 particle count for all of the vehicles.

The average $\frac{\text{CPC 3025}}{\text{CPC 3790}}$ ratio was calculated for each phase for each vehicle (Table 13); a ratio greater than 1 indicates the presence of solid particles in the 3 nm to 23 nm size bin. Table 13 shows a sense of the amount of total particles that are in this smallest size bin. Phase-level particle size distributions provide further insight into these ratios. Particle size distributions are discussed in the following section, Section 4.2.4. Additionally, the trends observed in the PN measurements correlated well with soot mass observations (micro-soot sensor). PN emissions for Vehicle B for CPC 3025 and CPC 3790 are shown in Figure 12 and Figure 13, respectively.

TABLE 13: $\frac{CPC3025}{CPC3790}$ RATIO

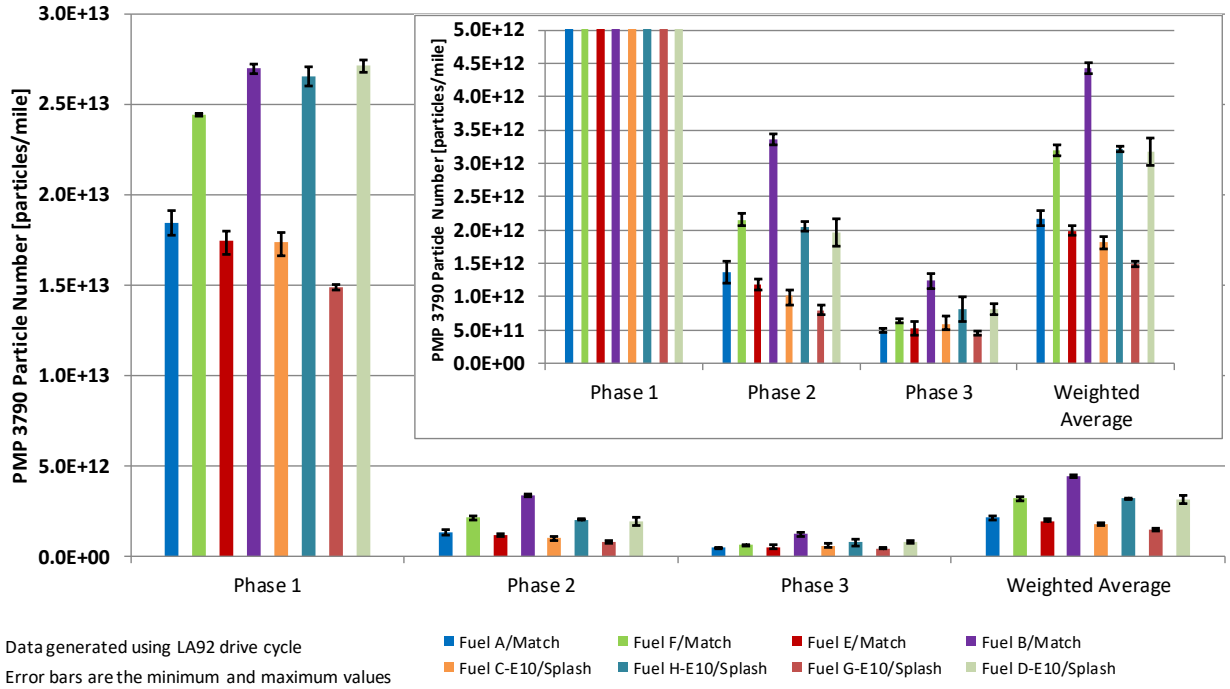
	Phase 1	Phase 2	Phase 3
Vehicle M	1.354	1.949	2.161
Vehicle O	1.171	1.602	1.562
Vehicle P	1.110	1.090	1.111
Vehicle N	0.984	1.198	1.485



Data generated using LA92 drive cycle

Error bars are the minimum and maximum values of the repeated tests. The colored bars show the average of the two or three tests.

FIGURE 12: CPC 3025 EMISSIONS FOR VEHICLE B



Data generated using LA92 drive cycle

Error bars are the minimum and maximum values of the repeated tests. The colored bars show the average of the two or three tests.

FIGURE 13: CPC 3790 EMISSIONS FOR VEHICLE B

4.2.4. 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 Vehicle D are shown in Figure 14. The peak of the size distribution for phase 1 was ~ 80 nm, phase 2 was ~ 52 nm and phase 3 was ~ 35 nm. Typical size distributions for the remaining vehicles are presented in Appendix F, Figures F-1 through F-4.

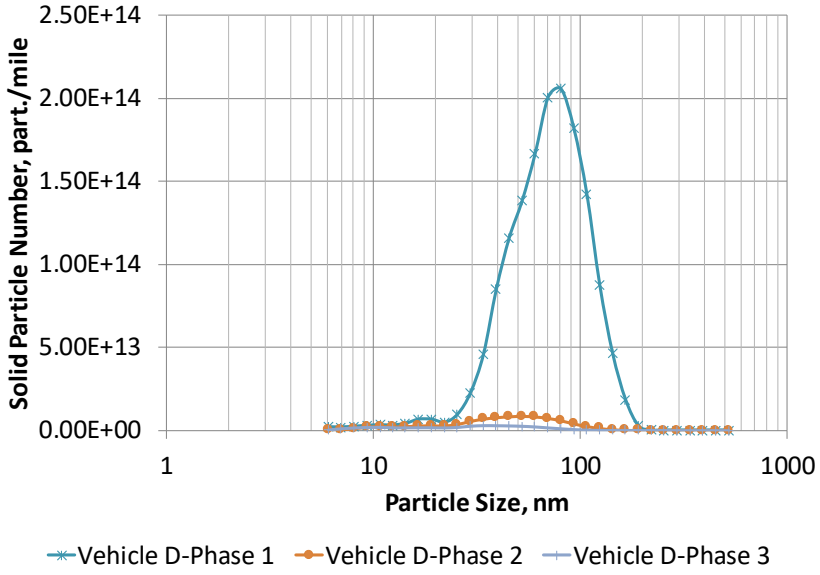


FIGURE 14: TYPICAL PARTICLE SIZE DISTRIBUTION FOR VEHICLE D

4.2.5. Real-Time Particle Emissions

Figure 15 and Figure 16 show typical real-time continuous traces of soot mass and solid particle number emissions for all four vehicles for Fuel C-E10. The vehicle speed trace is overlaid on these graphs. The graphs for the remaining fuels are presented in Appendix F, Figures F-5 through F-12. Typically, cold-start acceleration events in Phase 1 contribute significantly towards cumulative emissions. In the case of Vehicle A, a significant increase in both soot and number cumulative emissions were observed in phase 2 of the LA 92 test cycle approximately 400 seconds into the cycle. This observation was made for all fuels and was unique to Vehicle A. The same characteristic was observed previously for this vehicle. During phase 3, typically, a very minimal increase in cumulative emissions was observed for all vehicles. This observation was consistent for all fuels tested.

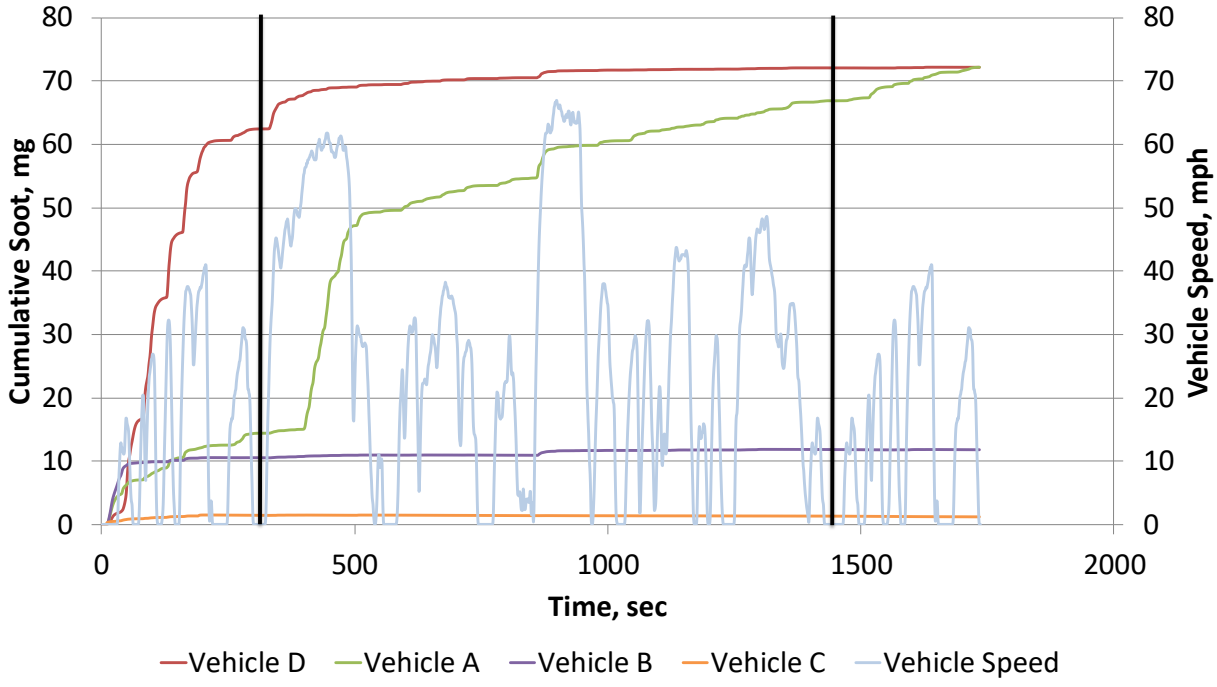


FIGURE 15: SOOT MASS CUMULATIVE EMISSIONS FOR ALL VEHICLES FOR FUEL C-E10

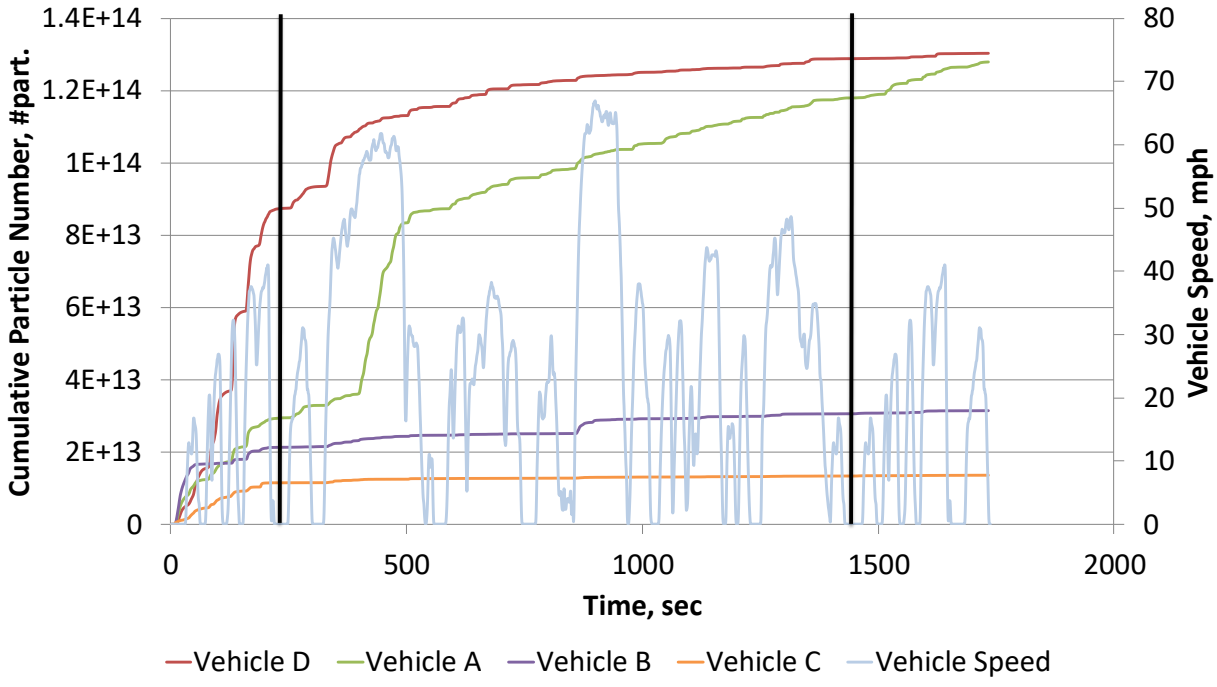


FIGURE 16: CPC 3790 SOLID PARTICLE NUMBER FOR CUMULATIVE EMISSIONS (>23NM) FOR FUEL C-E10

5.0 THE EFFECT OF ETHANOL BLENDING ON PARTICULATE EMISSIONS

5.1. Introduction

Following completion of the testing, a statistical analysis was conducted by Rincon Ranch Consulting under independent contract with CRC to understand the effect of fuels on the particulate emissions of the test fleet. The analysis was structured to address two chief questions:

- Does the splash-blending of ethanol with the gasoline hydrocarbons in E0 fuels at a 10% concentration by volume (E10) change particulate emissions?

- How do emissions from splash-blended E10 fuels compare to the emissions of the corresponding match-blended E10 fuels measured during the E-94-2 program?

Table 14 lists the pollutants that were examined in the statistical analysis. Particulate emissions are measured as PN emissions in units of 10^{12} particles per mi and PM emissions are measured in units of mg per mi.

TABLE 14: POLLUTANTS EXAMINED IN THE ANALYSIS

LA92 Phase 1	LA92 Weighted Average
Particle Number (PN)	Particle Number (PN)
Particulate Emissions (PM)	Particulate Emissions (PM)

Section 5.2 describes the data and the statistical methodology. The results of the analysis are then presented. Section 5.3 examines how ethanol splash-blending to the E10 level affects particulate emissions. Section 5.4 examines how the emissions from splash-blended E10 fuels compare to the emissions from corresponding match-blended fuels. Section 5.5 summarizes the findings of the analysis.

5.2. Statistical Methodology

5.2.1. Experimental Fuels

Four experimental fuels were created for this study by splash-blending ethanol into retained volumes of the E0 fuels created and tested in the E-94-2 program. To distinguish between the blending methods, the label E10-S is used to identify the E-94-3 splash-blended E10 fuels, while E10-M is used to identify the E-94-2 match-blended E10 fuels. Emissions measurements for the four test vehicles on the new E10-S fuels were combined with the prior results obtained for the same four vehicles on the E0 and E10-M fuels to produce the fuel matrix shown in Table 15. The values given for AKI, PMI, and Ethanol levels are the nominal values targeted in the blending; the actual values for individual fuels (shown in Appendix A) will vary from nominal.

TABLE 15: FUEL MATRIX

	CRC Program	Low PMI (1.3)	High PMI (2.5)
Low AKI (87)	E-94-2	E0 (0.0 vol %) E10-M (9.5 vol %)	E0 (0.0 vol %) E10-M (9.5 vol %)
	E-94-3	E10-S* (9.5 vol%)	E10-S* (9.5 vol%)
High AKI (94)	E-94-2	E0 (0.0 vol %) E10-M (9.5 vol %)	E0 (0.0 vol %) E10-M (9.5 vol %)
	E-94-3	E10-S* (9.5 vol%)	E10-S* (9.5 vol%)

* The E10-S are classified according to the AKI level of the E0 base fuel, but have AKI levels higher than the nominal target for the category.

The E10-S fuels are classified according to the AKI level of the E0 base fuel from which they were created. Unlike the match-blended fuels, for which selected properties were controlled to specified target values, the properties of splash-blended fuels, varied freely in response to the added ethanol and the resulting dilution of gasoline hydrocarbons. The AKI of the E10-S fuels was significantly increased by the ethanol splash-blending, such that the nominally low AKI E10-S fuels have AKI levels of ~91 and the nominally high AKI E10-S fuels have AKI levels of ~96.

In later parts of the analysis (Section 5.4.3), an effort was made to identify differences among the other properties of the E0, E10-S and E10-M fuels (i.e., other than AKI, PMI, and EtOH) that may help to explain the observed differences in the particulate emissions of the fuels. Four laboratories measured fuel properties for the E0 and E10-M fuels in the prior E-94-2 program, but only one of them (designated Lab C) measured the properties of the E10-S fuels blended for E-94-3. Where possible, the fuels used in the analysis were characterized using the properties determined by Lab C to minimize the potential for lab-to-lab differences in measurement and to maintain as much consistency as possible in the fuels data. As shown in Table 16, Lab C provided measurements for only 10 of the 14 selected fuel properties for the E0 and E10-M fuels used in E-94-2. Values for the octane numbers, RVP, and the distillation curve properties of the E0 and E10-M fuels in E-94-2 were represented by the average of the values measured by three other independent labs.

5.2.2. Emissions Data

The emissions data consist of PN and PM emission measurements for the E0 and E10-M fuels obtained for the four test fleet vehicles in the E-94-2 study and for the E10-S fuels in the new testing in this study. The measured values for PN and PM consist of two to four individual test runs for each vehicle/fuel combination, as all vehicle/fuel combinations were tested twice and the combinations displaying greater variability were allocated an additional third or fourth test. EC and OC emissions were not measured in the testing of E10-S fuels and are not considered here.

TABLE 16: LABORATORY DETERMINATION OF FUEL PROPERTIES FOR E0, E10-M AND E10-S FUELS

	E0, E10-M Fuels	E0 Fuels	E10-S Fuels
CRC Program	E-94-2	E-94-3	E-94-3
RON, MON, AKI, Sensitivity	Avg of Other Labs [a/]	Avg of Other Labs [a/]	Lab C
PMI	Lab C	Avg of Labs A, B, C	Lab C
EtOH	Lab C	Avg of Labs A, B, C	Lab C
RVP	Avg of Other Labs [a/]	Avg of Other Labs [a/]	Lab C
Aromatics	Lab C	Avg of Labs A, B, C	Lab C
C10+ Aromatics	Lab C	Avg of Labs A, C	Lab C
Benzene	Lab C	Avg of Labs A, B, C	Lab C
Olefins	Lab C	Avg of Labs A, B, C	Lab C
Sulfur	Lab C	Avg of Labs A, B, C	Lab C
IBP – FBP Distillation Temperatures	Avg of Other Labs [a/]	Avg of Other Labs [a/]	Lab C
Density, Specific Gravity, API Gravity	Lab C	Avg of Other Labs [a/]	Lab C
Gums, Existent and Washed	Lab C	Avg of Other Labs [a/]	Lab C
DI Index	Lab C	Avg of Other Labs [a/]	Lab C
[a/] Not measured by Lab C during the E-94-2 program.			

An initial step in the analysis was to screen the test run data for the presence of outliers, which are data points that lie sufficiently far (either high or low) from the other values in a dataset that they are unlikely outcomes of the experiment. Being an outlier in this sense does not automatically imply that the data point is invalid or should be excluded, but rather that it requires additional scrutiny. The methods used to identify and reject outliers are described in the report for the prior study[8].

In brief, two statistical tests were used to identify data points that fell at the extremes of the data distributions themselves (the Generalized ESD test) or of the residuals distribution from a comprehensive model of fuel effects (the Tukey test). For test runs flagged as candidate outliers, Student t-values for the variation of test runs around the average for each vehicle/fuel combination were used to select the data points to be classified as outliers and rejected. For the E-94-2 program, a total of eight test runs were rejected for the four particulate emissions and four gaseous emissions variables. Three of the rejected test runs involved one of the four vehicles tested in this study.

The same methods were applied to screen for outliers in the combined dataset assembled for this analysis. No evidence was found that additional test runs should be rejected as outliers for the four emission variables (Phase 1 and LA92 PN and PM emissions). The data were finalized to include those test runs for the four vehicles that were used in the analysis in the prior study plus the test runs newly obtained in this study.

Following removal of selected outliers, the dataset was reduced by averaging the emissions values across the test runs for each vehicle/fuel combination. This results in 32 data points representing the E0 and E10-M fuels from E-94-2 for the four vehicles and the 16 data points

[8] P. Morgan, I. Smith, V. Premnath, S. Kroll, R. Crawford, "Evaluation and Investigation of Fuel Effects on Gaseous and Particulate Emissions on SIDI In-Use Vehicles," Section 5.2.2, CRC Project E-94-2, Coordinating Research Council, Inc., March 2017.

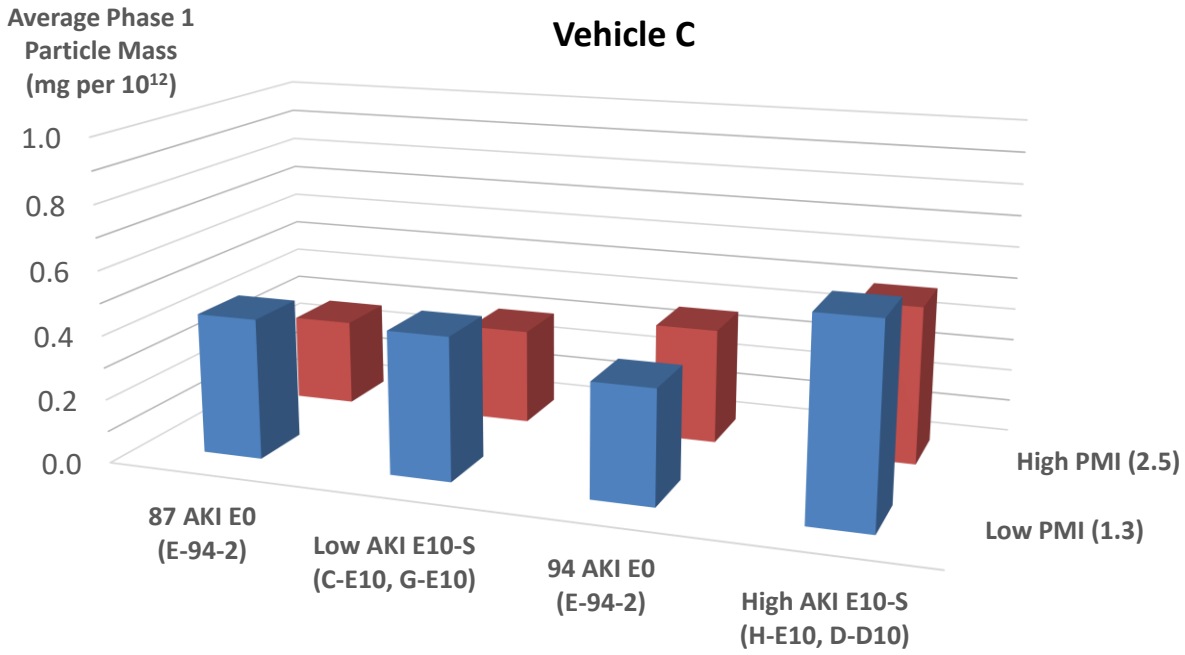
representing the E10-S fuels for the same vehicles in E-94-3. When a dataset varies in the amount of information underlying the data points, as is true here, the points are often weighted in proportion to their precision so that points based on more information are given greater weight. Recognizing that the vehicle/fuel combinations that were allocated additional testing were also the ones displaying greater variability, all 48 data points were given equal weight in the analysis.

The potential for emissions drift – a systematic change in emissions between two programs – is of concern because the analysis compares emissions of splash-blended E10 fuels determined in E-94-3 to emissions of E0 and match-blended E10 fuels determined in the prior study. The best defenses against drift are the procedures for test cell calibration, vehicle maintenance and fuels storage in the SwRI laboratory. The analysis in E-94-2 tested for systematic changes in emissions during the program and found no evidence of drift. In E-94-3, the test program included vehicle check-in inspection and check-out emissions testing using Fuel F as described in Section 3. A statistical analysis of the check-out testing was conducted to assess whether any evidence of emissions drift existed. As summarized in Appendix G, this assessment noted the possibility of emissions drift for one vehicle and supported the division of the test fleet into three- and four-vehicle groups (see below). Otherwise, the analysis found no conclusive evidence of emissions drift between the programs.

5.2.3. Organization of the Analysis

Based on a preliminary assessment of the data, a decision was made to conduct parallel studies of: (a) the entire dataset (the four-vehicle group); and (b) a narrowed dataset (the three-vehicle group) in which Vehicle C was removed. This approach was taken because of evidence in the data that the vehicle responded to fuels in a distinctive way. As discussed below, the other vehicles in the test fleet (A, B, and D) were generally similar in response and, as a group, differed from Vehicle C. Further, the pre-conditioning check for Vehicle C was questionable (see Appendix G), and it displayed relatively high variability in emissions during the testing.

With respect to PN emissions, Vehicle C is generally similar to the other three vehicles, although it emits fewer particulates in accord with its lower overall emission level. However, Vehicle C showed dissimilar responses for PM emissions to the E10 fuels of interest. Figure 17 shows the average mass of particles emitted in Phase 1 of the LA92 cycle for Vehicle C (at the top) and on average for Vehicles A, B, and D (at the bottom). Vehicle C emits much smaller particles on average than the other three. More importantly, its average particle mass *decreases* in response to *increased* PMI, while the average mass increases modestly with increased PMI for the other three vehicles. Vehicle C also has an exaggerated response in the High AKI fuels, where the average particle mass increases substantially in the E10-S fuels compared to their E0 counterparts. In contrast, particle mass for the other vehicles is relatively constant across the high PMI fuels and shows smaller responses to ethanol across the four AKI/PMI fuel groups.



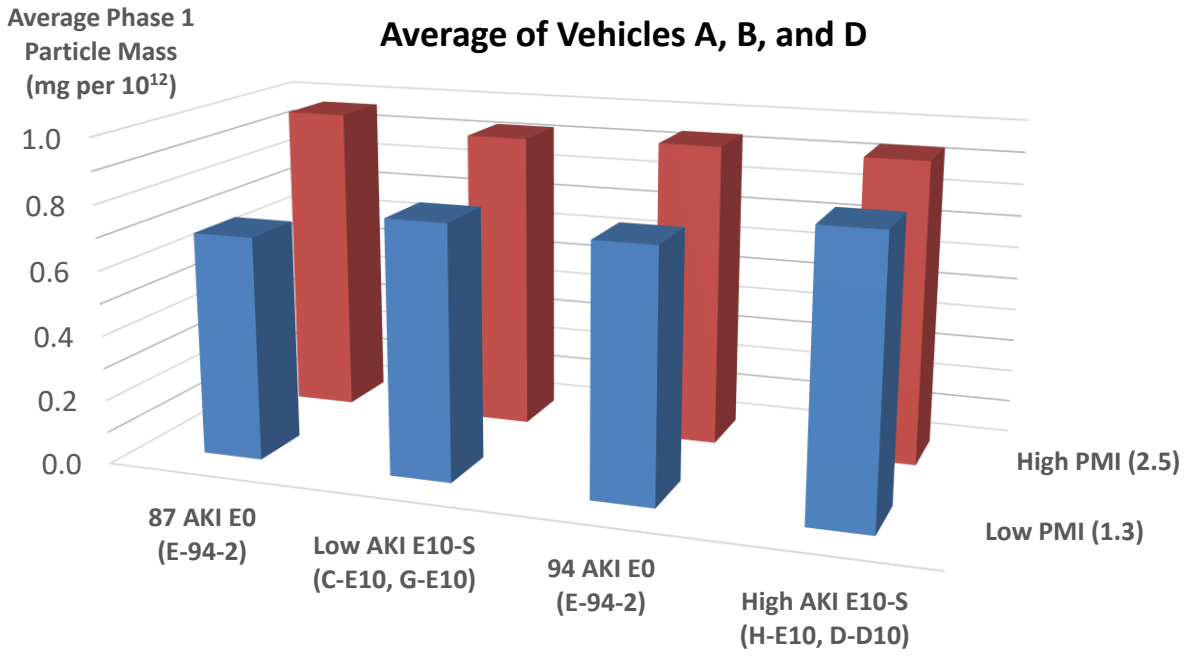


FIGURE 17: RESPONSE OF VEHICLE C TO FUELS COMPARED TO VEHICLES A, B, AND D

Given this evidence, the decision was made to view the data through two lenses: that of the three-vehicle group and that of the four-vehicle group. Results for the two vehicle groups are presented and discussed side-by-side in an effort to find consensus. Where differences exist between the groups, they must be taken as reminders that the emissions response to fuels and to ethanol is complex and can vary among vehicles.

5.2.4. Formulation of Statistical Models

5.2.4.1. Determination of Average Emissions and Emission Changes due to Fuels

The analysis used multiple linear regression to estimate the average emissions of the test fleet on each fuel. The test vehicles are considered to have individual average emission levels that are independent of (and constant across) the different fuels tested. The fuels are considered to have individual effects that will increase or decrease emissions relative to the average for each vehicle. The effects of ethanol splash-blending on emissions and the differing effects of splash- and match-blending on emissions are determined by the emission differences that are observed between corresponding pairs of fuels: the E0 and E10-S fuels in the first case, and the E10-S and E10-M fuels in the second case.

The dependent variable in the regression analysis is the natural logarithm of emissions. This choice, rather than the measured emissions value itself, is commonly used in vehicle emissions analysis because it recognizes that the variability of emissions tends to increase with the absolute level of emissions. Its use also leads to a mathematical form in which the emissions response to fuels is treated as being constant in percentage terms. The model can be described as a "discrete fuel" model because dummy variables are used to represent the emissions effect of each fuel. No effort was made to explain the emissions effect in terms of the individual properties of the fuels.

The mathematical form of the model is given by Equation 1 below. The nomenclature assigns the subscript f as a sequential index for the twelve E0, E10-M and E10-S fuels and the subscript i as a sequential index for the test vehicles. There is an overall mean emissions level μ for the average vehicle in the test fleet. Individual vehicles are considered as being drawn at random from the overall SIDI population, each with its own average emission level v_i and standard deviation σ_v. The fuel effects are represented by dummy variables d_f for the individual fuels, with one such term (the last) omitted by convention. The variable d_f takes on the value 1 for tests on the fuel denoted by subscript f and the value 0 in all other cases. The error term $\varepsilon_{f,i}$ represents the random variation of emissions unrelated to vehicles or fuels and is treated as having mean of zero and standard deviation of σ.

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

where:

μ = mean emissions for the average vehicle in the test fleet
f = 1, …, 12 for the twelve E0, E10-M and E10-S fuels
i = 1, …, 4 v_i: vehicles $v_i \sim N(0,\sigma_v)$
$\varepsilon_{f,i} \sim N(0,\sigma)$

A statistical model in the form of Equation 1 has been estimated for each dependent variable using both the three- and four-vehicle groups. The model is then used to predict emissions of the average vehicle in the group on each fuel by setting the v_i terms in Eq. 1 to zero. It is also used to estimate the effect of ethanol blending on emissions as described below.

Predictions for the effects of ethanol blending on emissions are obtained by having the statistical software evaluate specified changes in the independent variables to estimate the emissions change, and its uncertainty, when moving from one fuel to another. Different questions are examined by evaluating the emissions changes among different fuels. For example, the effect of ethanol splash-blending on emissions is examined by evaluating differences among the E0 and E10-S fuels, while the effect of splash- versus match-blending on emissions is examined by evaluating the differences among the E10-S and E10-M fuels.

The method of evaluation is one of computing differences between the emissions of specified starting and ending fuels. Because $Y_{f,i}$ is the logarithm of emissions, the percent change in emissions between two fuels f=1 and f=2 is equal to $\exp(\Delta Y_{1\rightarrow 2}) - 1$. The predicted log(emissions) change from f=1 to f=2 is given by Equation 2:

$$\Delta Y_{1\rightarrow 2} = c_{f=2} - c_{f=1} \qquad \text{(Eq. 2)}$$

where:

c_f is the coefficient for the dummy variable d_f
f = 1, …, 12 for the twelve E0, E10-M and E10-S fuels

For example, the percent change in emissions from the Low AKI / Low PMI E0 fuel (f = 1) to the corresponding E10-S fuel (f = 2) is given by $\exp(c_2 - c_1) - 1$; the percent change in emissions from the High AKI / Low PMI E0 fuel (f = 3) to the corresponding E10-S fuel (f = 4) is given by $\exp(c_4 - c_3) - 1$; and so forth.

The vehicle intercepts play no role in these calculations, as they are constants present for both fuels. In fact, this approach was taken to decouple uncertainty in the average emission levels of the vehicles from uncertainty in the emission changes between the fuels. Because of this, the statistical analysis is able to resolve smaller fuel effects than would be possible from simple comparisons of the observed average emissions on each fuel.

The approach described above is used to estimate one statistical model for each dependent variable for the three- and four-vehicle groups. The results of the model are then presented in two steps. For the effect of ethanol splash-blending on emissions, the average emissions on the E0 and E10-S fuels and the predicted emission changes between corresponding fuel pairs are determined using Equations 1 and 2 and the dummy variable coefficients c_f for the E0 and E10-S. These results are presented and discussed in Section 5.3. Then, for the effect of splash- versus match-blending on emissions, the average emissions on the E10-S and E10-M fuels and the predicted emission changes between corresponding fuel pairs are determined using Equations 1 and 2 and the dummy variable coefficients c_f for the splash- and match-blended E10 fuels. These results are presented and discussed in Section 5.4.

5.2.4.2. Examination of Fuel Property Effects on Emissions from Splash- versus Match-blending

The primary objectives of the analysis are to understand: (1) how ethanol affects emissions from splash-blended fuels; and (2) how emissions from E10 fuels are influenced by splash- versus match-blending. Once the latter determination is made, consideration is given to whether we can determine from the data which of the several physical and chemical properties of the E10-S and E10-M fuels are associated with the observed differences in splash- versus match-blended emissions. This secondary analysis was performed using *differential* formulations of the statistical model, in which the data themselves are differenced to compare corresponding fuels. The differenced emission values become the dependent variables and the differenced fuel properties are the independent variables. Two differencing methods were used and are described below.

Two caveats must be acknowledged. A fundamental assumption is that splash- and match-blending cannot lead to different levels of emissions for the fuels unless they also lead to different values for the physical and chemical properties of the fuels. Furthermore, the approach assumes that the set of physical and chemical properties listed in Table 16 contain the fuel characteristics that are responsible the observed differences in emissions or are related to the causes. It remains possible that the differences in emissions are driven by differences in the composition or combustion of gasoline hydrocarbons that are not adequately described by the available property measurements.

Method 1: E10-S and E10-M differences from E0

The first method differences the log(emissions) and fuel property values of the E10-S and E10-M fuels from the corresponding E0 fuels. The approach is to directly calculate how splash- and match-blending at the E10 level changes particulate emissions compared to the baseline of E0 fuels. Corresponding differences are taken for the physical and chemical properties of the fuels. The observed emission differences are then tested against the observed fuel property differences.

If $Y_{f=E10\text{-}S,i}$ denotes the log(emissions) values for the set of four E10-S fuels for the i^{th} vehicle and $Y_{f=E0,i}$ denotes the log(emissions) values for the set of four E0 fuels, then the splash-blended E10-S fuels appear in the dataset as the values:

$$\Delta Y_{f=E10\text{-}S,i} = Y_{f=E10\text{-}S,i} - Y_{f=E0,i} \qquad \text{(Eq. 3)}$$

If $X_{f=E10\text{-}S,j}$ denotes the values of the j^{th} fuel property for the E10-S fuels in the list of properties given in Table 16, then the independent variables appear in the dataset as:

$$\Delta X_{f=E10\text{-}S,j} = X_{f=E10\text{-}S,j} - X_{f=E0,j} \qquad \text{(Eq. 4)}$$

The same is true for the match-blended E10-M fuels, which appear in the dataset as:

$$\Delta Y_{f=E10\text{-}M,i} = Y_{f=E10\text{-}M,i} - Y_{f=E0,i} \qquad \text{(Eq. 5)}$$

$$\Delta X_{f=E10\text{-}M,j} = X_{f=E10\text{-}M,j} - X_{f=E0,j}$$

The E0 fuels do not appear in the dataset as their differenced dependent and independent variables would be identically zero. Therefore, the dataset consists of observations for the eight E10-S and E10-M fuels for the four vehicles that were tested, for a total of 32 data points.

The effects of the fuel properties are then estimated using conventional linear regression models of the form given in Eq. 6. Stepwise selection techniques look for associations between differences in the fuel properties and the observed differences in emissions.

$$\Delta Y_{f,i,j} = \mu + \Delta X_{f=1,j=1} + \ldots + \Delta X_{f=n,j=n} + \varepsilon_{hijk} \qquad \text{(Eq. 6)}$$

where:

$\mu = 0$	i.e., the intercept is suppressed	
$f = 1, \ldots, 8$	differential fuel pairs	
$j = 1, \ldots, n$	fuel properties listed in Table 16	
$i = 1, \ldots, 4$	v_i: vehicles	$v_i \sim N(0,\sigma_v)$
		$\varepsilon_{f,i} \sim N(0,\sigma)$

As discussed below, a second method was used in the effort to identify the causes for difference between splash- and match-blended fuels. It did not identify meaningful associations with fuel properties, so that Method 1 became the primary basis to test for associations.

Method 2: E10-M differences from E10-S

The second method narrows the comparison by differencing the log(emissions) and fuel property values of the E10-M fuels from the corresponding E10-S fuels. The formulation and mathematics of Method 2 are essentially the same for Method 1 except that the E0 fuels play no role. In the notation used above, the match-blended E10-M fuels appear in the dataset as:

$$\Delta Y_{f=E10\text{-}M,i} = Y_{f=E10\text{-}M,i} - Y_{f=E10\text{-}S,i} \qquad \text{(Eq. 7)}$$

$$\Delta X_{f=E10\text{-}M,j} = X_{f=E10\text{-}M,j} - X_{f=E10\text{-}S,j}$$

The E10-S fuels do not appear in the dataset as their differenced dependent and independent variables would be identically zero. The dataset consists of observations for the four E10-M fuels for the four vehicles that were tested, for a total of 16 data points.

Method 2 was considered because it most closely isolates the emissions difference (between E10-S and E10-M fuels) that is relevant to understanding how the method of ethanol blending influences particulate emissions. By doing so, the method was thought to give the best chance of determining which of the measured physical and chemical properties were associated with the emission differences. In the end, the particulate emission differences between splash- and match-blended E10 fuels proved to be relatively small, and the analysis based on Method 2 did not identify meaningful associations with the fuel properties.

5.3. The Effect of E10 Splash-Blending on Particulate Emissions

As has been described, a discrete-fuel statistical model was used to estimate emissions of the test fleet on each of the 12 fuels including E0, the match-blended E10-M fuels, and the splash-blended E10-S fuels. This section examines the results for eight of the fuels to identify how ethanol splash-blending at the E10 level influences particulate emissions of the test fleet. The eight fuels consist of the E0 and E10-S fuels in each of four fuel groups defined by low and high levels of AKI and PMI. Both the three-vehicle and four-vehicle groups are examined to account for the distinctive performance of Vehicle C.

The results for each emissions variable are presented in the following sections using paired figures for the three- and four-vehicle groups and one table. Eight bars are shown in each figure, representing the average emissions of the test fleet on the E0 and E10-S fuels in the four AKI/PMI fuel groups. The estimated emission changes between the fuels are indicated by arrows with the percent values given in text and statistical significance indicated parenthetically[9]. The impacts of fuel PMI are shown in each figure to provide context for the size of the E0 to E10-S emission changes. The corresponding table summarizes the emissions changes between E0 and E10-S fuels for the two vehicle groups at a hierarchy of levels, beginning with the average of all fuels and progressing to the averages for Low and High PMI fuels as groups and for the individual experimental fuels.

5.3.1. Phase 1 Emissions

The majority of emitted particles are formed during Phase 1 of the LA92 cycle. Thus, the effects of fuels on emissions are most easily seen in this phase and will flow through to influence overall LA92 emissions on a weighted-average basis.

5.3.1.1. Phase 1 PN Emissions

PN emissions were determined by the CPC 3790 instrument that counts the number of solid particle emitted greater than 23 nm in diameter. Emissions are reported in units of 10^{12} particles/mile. These trends are presented in Figure 18 and Figure 19 and are summarized in Table 17.

Figure 18 reports the estimated Phase 1 PN emissions of the three-vehicle group. For these vehicles, ethanol splash-blending at the E10 level is observed to increase PN emissions in all four fuel groups. In three, the observed changes range from +6% to +12% and are too small to be statistically significant (see Table 17). In the fourth, the +24% change observed for Low AKI / Low PMI fuels is significant at the $p = 0.014$ level, meaning that it has only a 1-in-71 chance of occurring in the data simply by chance. When the fuels are combined, we observe that E10 splash-blending significantly increases PN emission by 15% ($p = 0.027$) in the group of Low PMI fuels and by 12% ($p = 0.011$) for all fuels on average.

[9] A parenthetical value of $p \leq 0.05$ indicates that the result achieves the conventionally-accepted level of statistical significance. A value of $p \leq 0.01$ indicates that the result carries good statistical significance. Actual p values may be cited in tables and figures and can be interpreted qualitatively as described above. A value of $p >> 0.05$ indicates that the result is far from the threshold p=0.05 value and carries no statistical significance. Actual p values may be cited when a result, while failing to achieve statistical significance, is not so far from the threshold p value as to labeled $p >> 0.05$. This may be done for p values falling in the range $0.05 < p < 0.15$.

Similar trends occur in the four-vehicle group, as shown in Figure 19. Ethanol splash-blending is observed to increase Phase 1 PN emissions in all cases by amounts that are generally similar to the three-vehicle group. The emission changes for two of the fuels are large enough to be statistically significant, but are not significant in the other cases. As the Table 17 shows, ethanol splash-blending significantly increases emissions in the Low AKI / Low PMI and the High AKI / High PMI fuels individually, in both the Low PMI and High PMI fuels as groups and for all fuels on average.

TABLE 17: MODEL-ESTIMATED PHASE 1 PN EMISSIONS CHANGE FOR E0 → E10-S

	Three-vehicle group		Four-vehicle group	
	Emissions Change	**Statistical Significance**	**Emissions Change**	**Statistical Significance**
Average of All Fuels	+12%	p = 0.011	***+13%***	p = 0.002
Avg Low PMI	+15%	p = 0.027	+12%	p = 0.031
Low AKI / Low PMI	+24%	p = 0.014	+19%	p = 0.017
High AKI / Low PMI	+ 6%	p = 0.49	+ 5%	p = 0.51
Avg High PMI	+ 9%	p = 0.13	+14%	p = 0.013
Low AKI / High PMI	+ 7%	p = 0.41	+12%	p = 0.11
High AKI / High PMI	+12%	p = 0.18	+15%	p = 0.049

Note: Underlining indicates that the estimated change is statistically significant at the $p \leq 0.05$ level. Underlining with bold italicized text indicates the change is statistically significant at the $p \leq 0.01$ level.

Considering both vehicle groups, the following conclusions can be drawn from the data:

- Ethanol splash-blending increases Phase 1 PN emissions by 12 to 13% for all fuels on average compared to E0 fuels.
- Ethanol splash-blending increases Phase 1 PN emissions by 12 to 15% in the group of Low PMI fuels compared to E0 fuels.
- Ethanol splash-blending increases Phase 1 PN emissions in some individual fuels by 14 to 24% compared to E0 fuels.

These conclusions generally achieve a $p = 0.03$ level of confidence or better and carry a good level of statistical significance ($p \leq 0.01$) for all fuels on average in the four-vehicle group. Taken together, the data strongly support the conclusion that ethanol splash-blending at the E10 level increases Phase 1 PN emissions compared to E0 fuels.

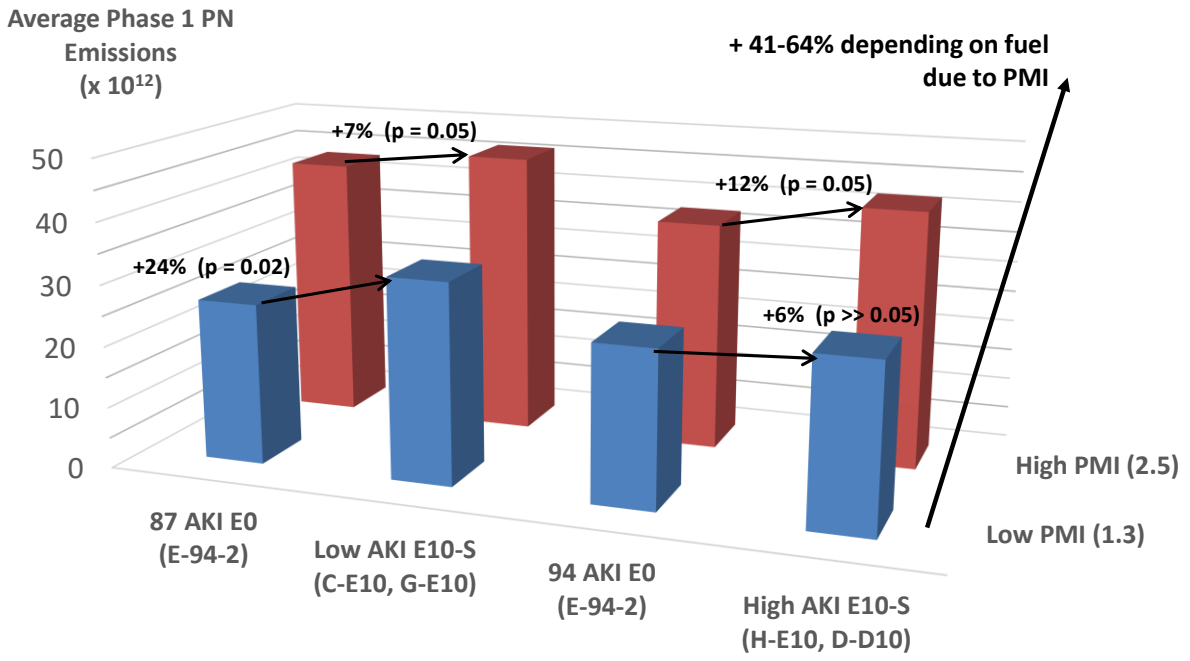


FIGURE 18: EFFECT OF E10 SPLASH-BLENDING ON PHASE 1 PN EMISSIONS (AVERAGE OF THREE-VEHICLE GROUP)

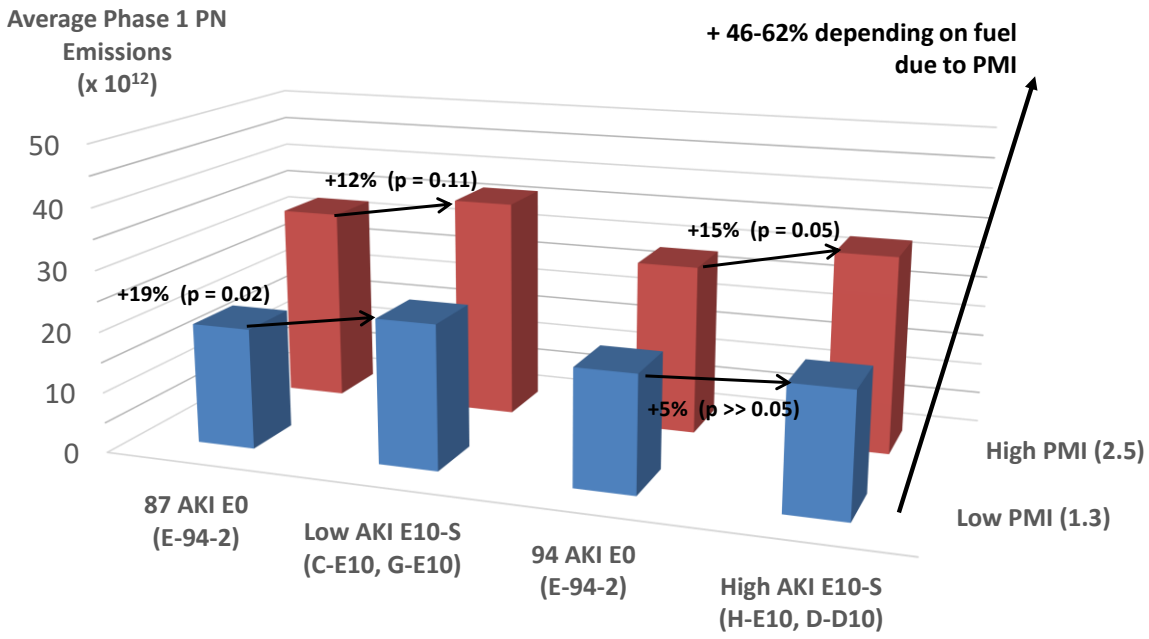


FIGURE 19: EFFECT OF E10 SPLASH-BLENDING ON PHASE 1 PN EMISSIONS (AVERAGE OF FOUR-VEHICLE GROUP)

5.3.1.2. Phase 1 PM Emissions

Phase 1 PM emissions were determined in the testing by a gravimetric method that measures the particle mass emitted in units of mg/mi. These trends are presented in Figure 20 and Figure 21 and are summarized in Table 18.

As seen in both figures and in the table, ethanol splash-blending increases Phase 1 PM emissions in all four of the fuel groups in both the three- and four-vehicle groups. In the three-vehicle group, ethanol splash-blending is observed to increase emissions most strongly in the Low PMI fuels (+18% to +40%), by a smaller amount (+11%) for the High AKI / High PMI fuel, and by only 2% for the Low AKI / High PMI fuel. The +40% emissions change observed for the Low AKI / Low PMI fuel is statistically significant ($p < 0.01$), as are the changes for the groups that contain the fuel (Low PMI Fuels and all fuels on average).

TABLE 18: MODEL-ESTIMATED PHASE 1 PM EMISSIONS CHANGEFOR E0 → E10-S

	Three-Vehicle Group		Four-Vehicle Group	
	Emissions Change	**Statistical Significance**	**Emissions Change**	**Statistical Significance**
Average of All Fuels	***+17%***	p = 0.008	***+24%***	p = 0.002
Avg Low PMI	***+29%***	p = 0.004	***+31%***	p = 0.006
Low AKI / Low PMI	***+40%***	p = 0.005	+31%	p = 0.043
High AKI / Low PMI	+18%	p = 0.14	+31%	p = 0.046
Avg High PMI	+ 7%	p = 0.41	+17%	p = 0.086
Low AKI / High PMI	+ 2%	p = 0.83	+11%	p = 0.41
High AKI / High PMI	+11%	p = 0.34	+24%	p = 0.10

Note: Underlining indicates that the estimated change is statistically significant at the $p \leq 0.05$ level. Underlining with bold italicized text indicates the change is statistically significant at the $p \leq 0.01$ level.

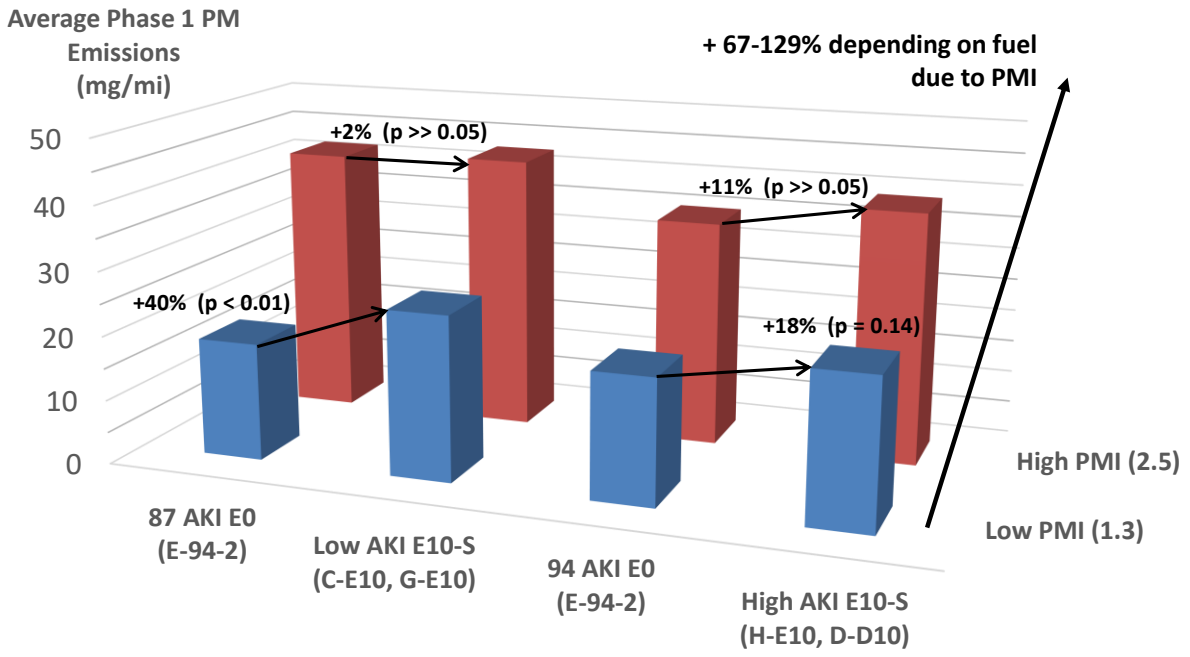


FIGURE 20: EFFECT OF E10 SPLASH-BLENDING ON PHASE 1 PM EMISSIONS (AVERAGE OF THREE-VEHICLE GROUP)

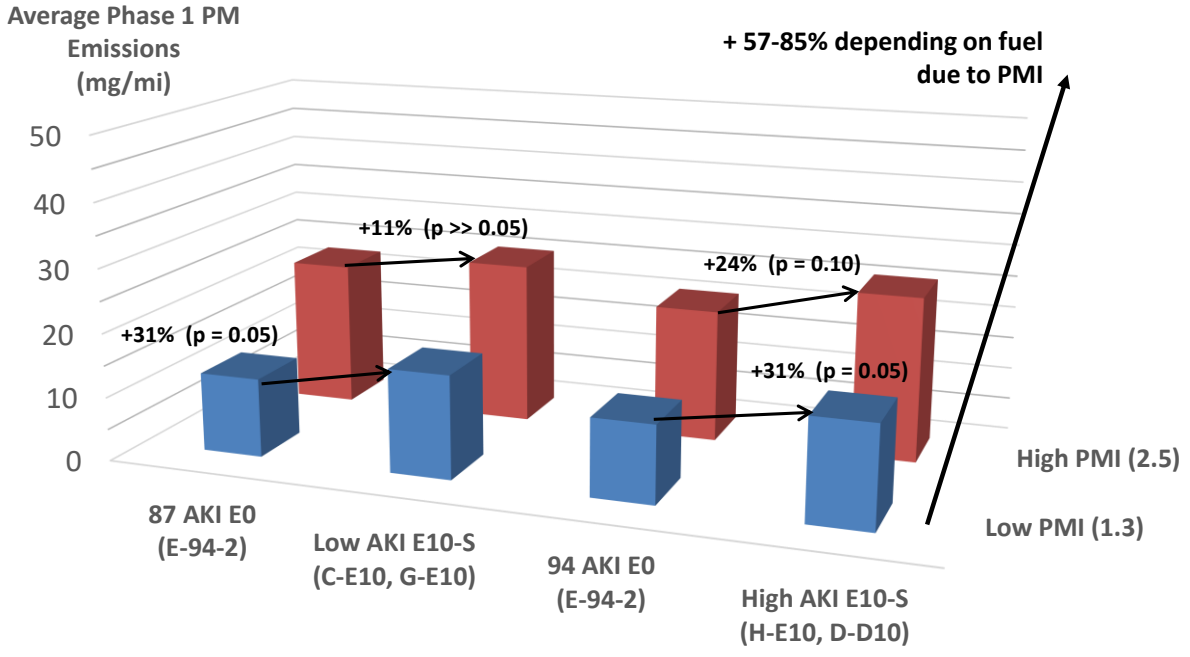


FIGURE 21: EFFECT OF E10 SPLASH-BLENDING ON PHASE 1 PM EMISSIONS (AVERAGE OF FOUR-VEHICLE GROUP)

In the four-vehicle group, the pattern of emissions changes among the fuels is generally similar to that seen in the three-vehicle group but the changes are larger. Ethanol splash-blending is observed to increase Phase 1 PM emissions in all four fuel groups and most strongly in the Low PMI fuels. The observed emission changes are statistically significant for the two Low PMI fuels individually, for the Low PMI fuels as a group, and for all fuels on average.

Considering both vehicle groups, the following conclusions can be drawn from the data:

- Ethanol splash-blending increases Phase 1 PM emissions by 17% to 24% for all fuels on average compared to E0 fuels.

- Ethanol splash-blending increases Phase 1 PM emissions by 29% to 31% in the group of Low PMI fuels compared to E0 fuels.

- Ethanol splash-blending increases Phase 1 PM emissions by 31% to 40% in the Low AKI / PMI fuel compared to E0 fuels.

These conclusions achieve a $p \leq 0.01$ level of confidence in all cases except one, where a $p \leq 0.05$ level of confidence is achieved. Taken together, the data strongly support the conclusion that ethanol splash-blending at the E10 level increases Phase 1 PN emissions compared to E0 fuels.

5.3.2. LA92 Emissions

This section examines the effect of ethanol splash-blending on particulate emissions over the LA92 cycle. The LA92 emission trends by fuel are a composite of the Phase 1 trends presented in the prior section, weighted appropriately for the Phase 1 contribution to the overall cycle, net of countervailing trends (if any) that occur in Phases 2 and 3. Because particle emission levels are lower on the LA92 cycle than in Phase 1, one should expect the data to provide less resolution of fuel effects than was seen in the Phase 1 data.

5.3.2.1. LA92 PN Emissions

The trends by fuel for LA92 PN emissions are presented in Figure 22 and Figure 23 and are summarized in Table 19. As was true for Phase 1 PN emissions, there is generally similarity between the three- and four-vehicle groups. Ethanol splash-blending increases PN emissions most strongly in two fuels – the Low AKI / Low PMI fuel and the High AKI / High PMI fuel – by amounts that range from 19% to 22% in the three-vehicle group and from 14% to 15% in the four-vehicle group. Emission changes are much smaller (+5% to +6%) in the other two fuels.

As the table shows, none of the emission changes observed for the individual fuels are large enough to achieve statistical significance on their own. They begin to approach significance when grouped into Low and High PMI fuels, but achieve the conventionally accepted $p = 0.05$ level of significance only for all fuels on averages combined.

Considering both vehicle groups, we can conclude that ethanol splash-blending increases LA92 PN emissions by 10% to 12% for all fuels on average compared to E0 fuels. These conclusions achieve the conventional $p \leq 0.05$ level of statistical significance.

TABLE 19: MODEL-ESTIMATED LA92 PN EMISSIONS CHANGE FOR E0 → E10-S

	Three-Vehicle Group		Four-Vehicle Group	
	Emissions Change	**Statistical Significance**	**Emissions Change**	**Statistical Significance**
Average of All Fuels	<u>+12%</u>	p = 0.031	<u>+10%</u>	p = 0.039
Avg Low PMI	+13%	p = 0.10	+ 9%	p = 0.15
Low AKI / Low PMI	+22%	p = 0.075	+14%	p = 0.16
High AKI / Low PMI	+6%	p = 0.59	+5%	p = 0.55
Avg High PMI	+12%	p = 0.14	+10%	p = 0.13
Low AKI / High PMI	+6%	p = 0.57	+6%	p = 0.52
High AKI / High PMI	+19%	p = 0.12	+15%	p = 0.13
Note: Underlining indicates that the estimated change is statistically significant at the $p \leq 0.05$ level.				

5.3.2.2. LA92 PM Emissions

The trends by fuel for LA92 PM emissions are presented in Figure 24 and Figure 25 and are summarized in Table 20. In both vehicle groups, splash-blending is observed to increase LA92 PM emissions in all of fuels compared to E0 fuels, with the largest increases occurring in the Low PMI fuels.

In the three-vehicle group, ethanol splash-blending increases LA92 PM emissions by 30% in both Low PMI fuels and by much a smaller amount (+3% to +9%) in the High PMI fuels compared to E0 fuels. The observed emissions changes are statistically significant for both Low PMI fuels ($p = 0.029$ and $p = 0.030$), as are the changes for the groups that contain these fuels (Low PMI Fuels and the average of all fuels).

In the four-vehicle group, LA92 PM emissions are noticeably lower as a consequence of the much lower particulate emission level of Vehicle C. However, the pattern of emissions among the fuels is similar to that seen in the three-vehicle fleet. Compared to E0 fuels, ethanol splash-blending increases LA92 PM emissions in all four fuel groups and most strongly in the Low PMI fuels. The observed emission change approaches statistical significance ($p = 0.058$) for the Low AKI / Low PMI fuel individually, but is significant for the Low PMI fuels as a group, and for all fuels on average.

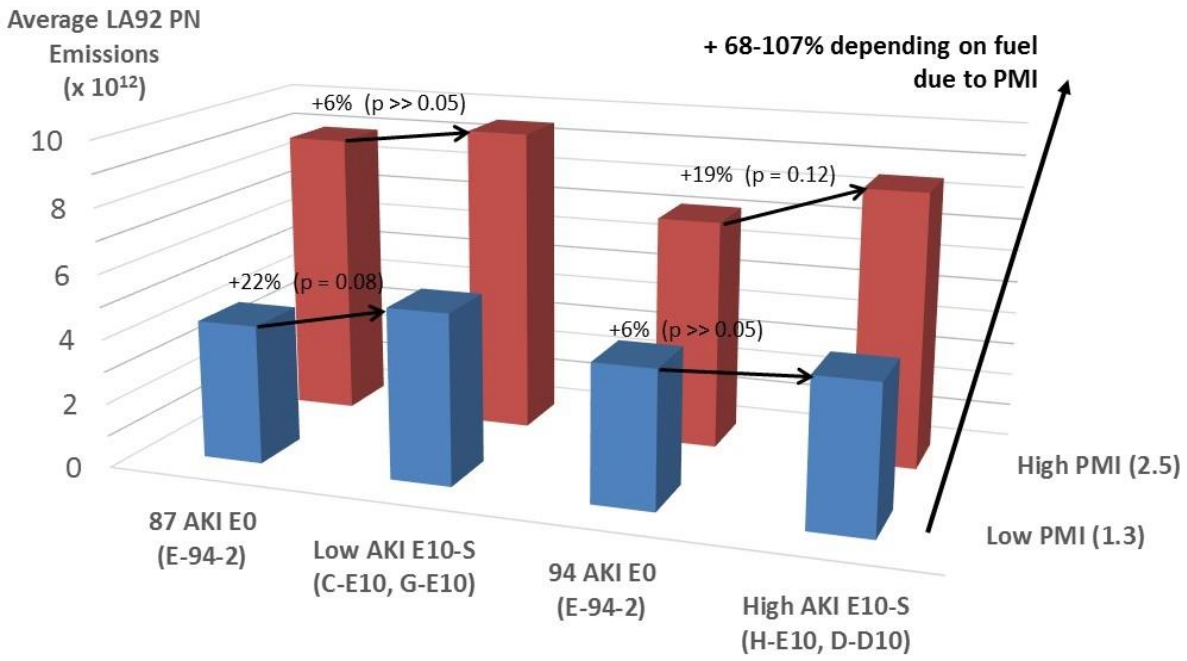


FIGURE 22: EFFECT OF E10 SPLASH-BLENDING ON LA92 PN EMISSIONS (AVERAGE OF THREE-VEHICLE GROUP)

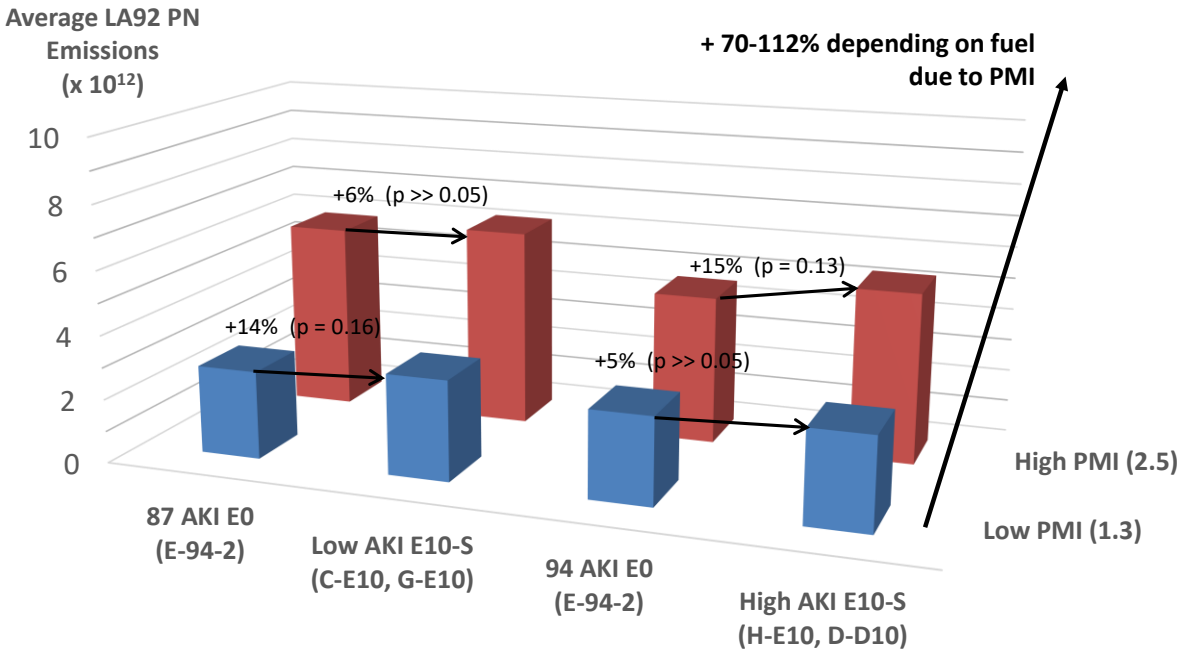


FIGURE 23: EFFECT OF E10 SPLASH-BLENDING ON LA92 PN EMISSIONS (AVERAGE OF FOUR-VEHICLE GROUP)

TABLE 20: MODEL-ESTIMATED LA92 PM EMISSIONS CHANGEFOR E0 → E10-S

	Three-Vehicle Group		Four-Vehicle Group	
	Emissions Change	**Statistical Significance**	**Emissions Change**	**Statistical Significance**
Average of All Fuels	***+17%***	p = 0.010	+21%	p = 0.036
Avg Low PMI	***+30%***	p = 0.003	+34%	p = 0.022
Low AKI / Low PMI	+30%	p = 0.029	+41%	p = 0.058
High AKI / Low PMI	+30%	p = 0.032	+28%	p = 0.16
Avg High PMI	+ 6%	p = 0.47	+ 9%	p = 0.50
Low AKI / High PMI	+ 3%	p = 0.79	+ 7%	p = 0.71
High AKI / High PMI	+ 9%	p = 0.45	+11%	p = 0.56

Note: Underlining indicates that the estimated change is statistically significant at the $p \leq 0.05$ level. Underlining with bold italicized text indicates the change is statistically significant at the $p \leq 0.01$ level.

Considering both vehicle groups, the following conclusions can be drawn from the data:

- Ethanol splash-blending increases LA92 PM emissions in all fuels by 17% to 21% on average compared to E0 fuels.

- Ethanol splash-blending increases LA92 PM emissions in the group of Low PMI fuels by 30 to 34% compared to E0 fuels.

- In the three-vehicle group, ethanol splash-blending increases LA92 PM emissions by 30% in the two Low PMI fuels individually compared to E0 fuels.

These conclusions achieve the $p \leq 0.05$ level of confidence in both vehicle groups. In the three-vehicle group, the conclusions that ethanol splash-blending increases LA92 PM emissions in the group of Low AKI fuels and for all fuels on average achieve the $p \leq 0.01$ level for good statistical confidence. Taken together, the data support the conclusion that ethanol splash-blending at the E10 level increases LA92 PM emissions compared to E0 fuels

5.4. Emission Differences between E10 Splash- and Match-Blended Fuels

This section examines the emissions of all 12 fuels to identify whether ethanol splash- and match-blending affect particulate emissions in different ways. The 12 fuels consist of the E0, E10-M, and E10-S fuels in each of four fuel groups defined by the low and high levels of AKI and PMI. Both three- and four-vehicle groups are examined to account for the distinctive performance of Vehicle C. As in the prior section, the results for each emissions variable are presented using paired figures and one table to display the emission values and summarize the emission differences between the splash- and match-blended fuels.

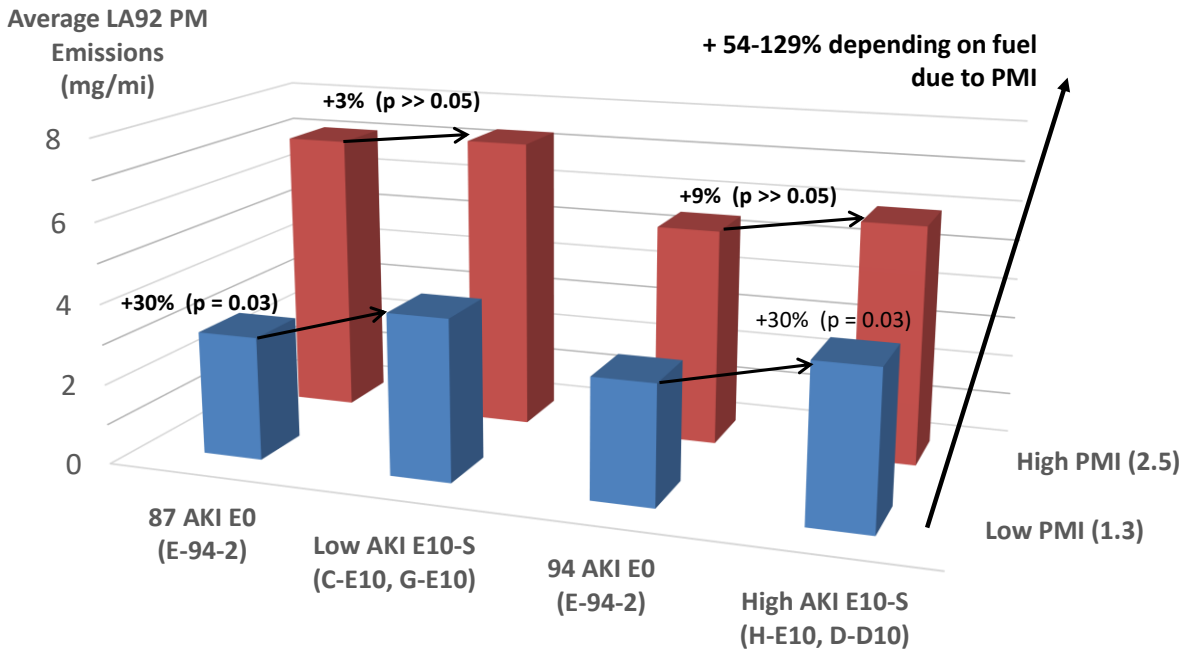


FIGURE 24: EFFECT OF E10 SPLASH-BLENDING ON LA92 PM EMISSIONS (AVERAGE OF THREE-VEHICLE GROUP)

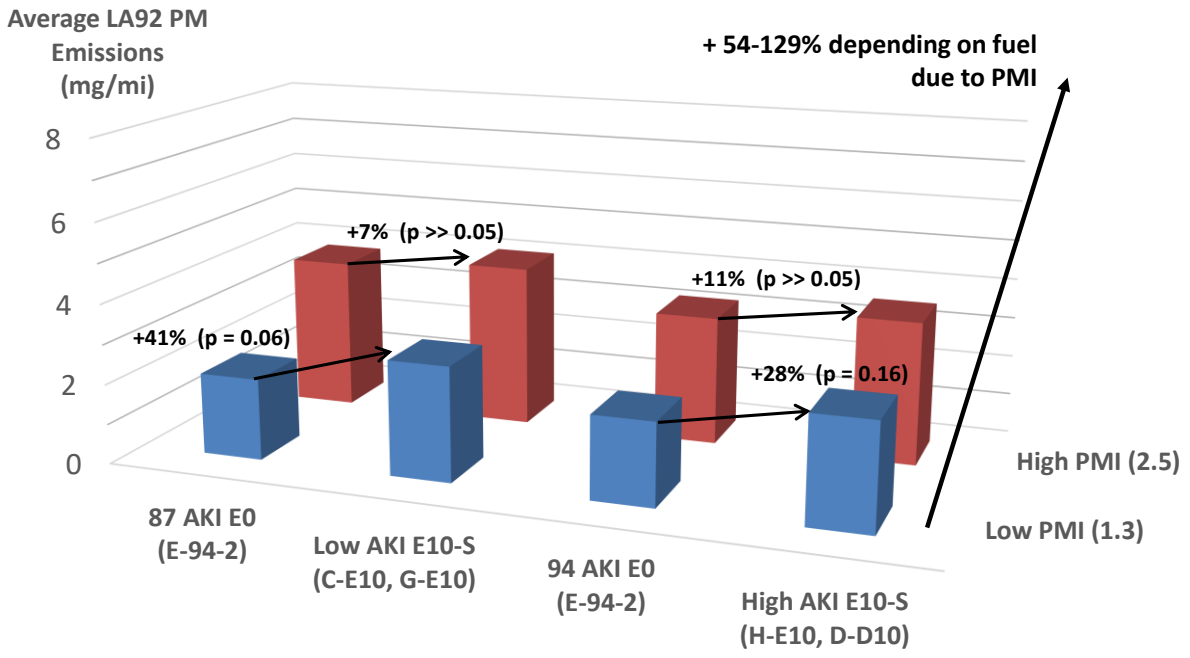


FIGURE 25: EFFECT OF E10 SPLASH-BLENDING ON LA92 PM EMISSIONS (AVERAGE OF FOUR-VEHICLE GROUP)

Twelve bars are shown in each figure, representing the E0, E10-S, and E10-M fuels for each of the four AKI/PMI fuel groups. As emissions differences between the E10-S and E10-M Bars, are the primary interest, these changes are highlighted using bold arrows and boxed values citing the percent changes. Smaller arrows and unboxed values are given for the E0 and E10-S fuels for context. The tables summarize the emissions changes for the two vehicle groups at varying levels of aggregation, beginning with the average for all fuels and progressing to the averages for the Low and High PMI fuels as groups and for the individual fuels.

5.4.1. Phase 1 Emissions

5.4.1.1. Phase 1 PN Emissions

Figure 26 shows the estimated emissions of the three-vehicle group. For these vehicles, match-blended E10-M emissions are observed to be greater than splash-blended E10-S emissions in all cases, but the differences are very small (2 to 4%) for three of the fuels. Only the increase for the High AKI / Low PMI fuel is large. As Table 21 shows, the 23% increase for that fuel is statistically significant at the p = 0.020 level, meaning that it has only a 1 in 50 chance of occurring in the data simply by chance. The other emission changes between E10-S and E10-M fuels are well within the variability present in the data and are not statistically significant.

Similar trends occur in the four-vehicle group, as shown in Figure 27. Emissions are observed to be greater for the E10-M fuels in all cases, but again, the difference is large only for the High AKI / Low PMI fuel. For three of the fuels the emission changes are small enough to have no statistical significance, while the +26% change for the four-vehicle group achieves a high level of significance (p = 0.003 or 3 chances in 1,000 of occurring by chance).

TABLE 21: MODEL-ESTIMATED PHASE 1 PN EMISSIONS CHANGE FOR E10-S → E10-M

	Three-Vehicle Group		Four-Vehicle Group	
	Emissions Change	**Statistical Significance**	**Emissions Change**	**Statistical Significance**
Average of All Fuels	+ 8%	p = 0.088	+10%	p = 0.013
Avg Low PMI	+ 3%	p = 0.052	***+15%***	p = 0.007
Low AKI / Low PMI	+ 3%	p = 0.69	+ 6%	p = 0.43
High AKI / Low PMI	+23%	p = 0.020	***+26%***	p = 0.003
Avg High PMI	+ 3%	p = 0.65	+ 4%	p = 0.40
Low AKI / High PMI	+ 2%	p = 0.83	+ 2%	p = 0.80
High AKI / High PMI	+ 4%	p = 0.66	+ 7%	p = 0.35

Note: Underlining indicates that the estimated change is statistically significant at the $p \leq 0.05$ level. Underlining with bold italicized text indicates the change is statistically significant at the $p \leq 0.01$ level.

Considering both vehicle groups, the following conclusions can be drawn from the data:

- Phase 1 PN emissions are greater on E10-M fuels compared to E10-S fuels for all fuels on averages (four-vehicle group).

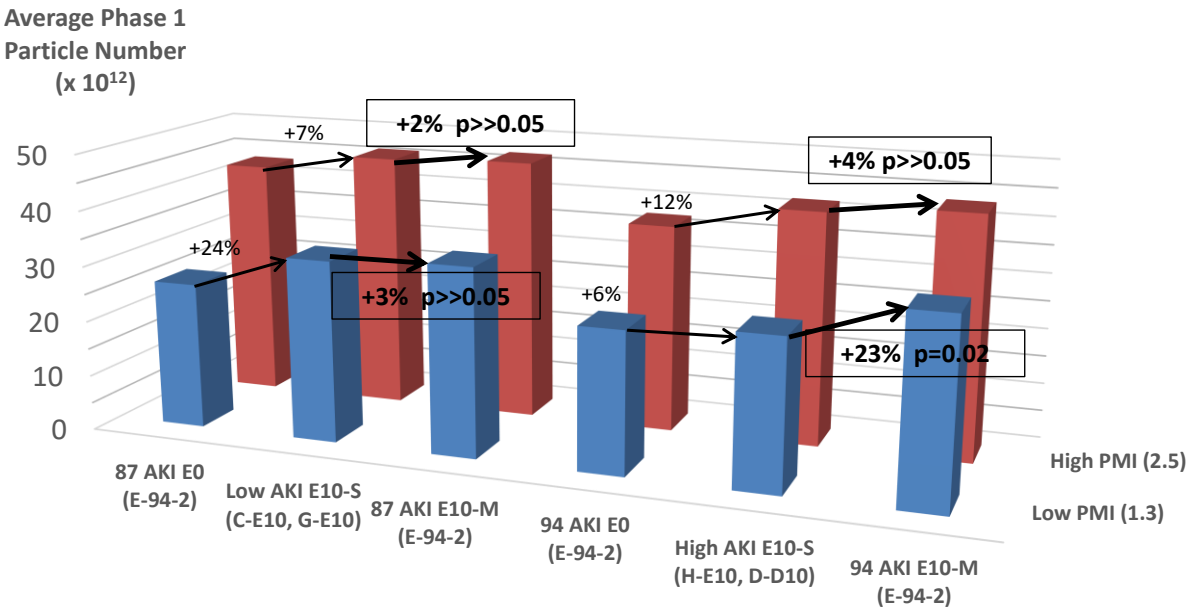


FIGURE 26: EFFECTS OF E10 SPLASH- AND MATCH-BLENDING ON PHASE 1 PN EMISSIONS (AVERAGE OF THREE-VEHICLE GROUP)

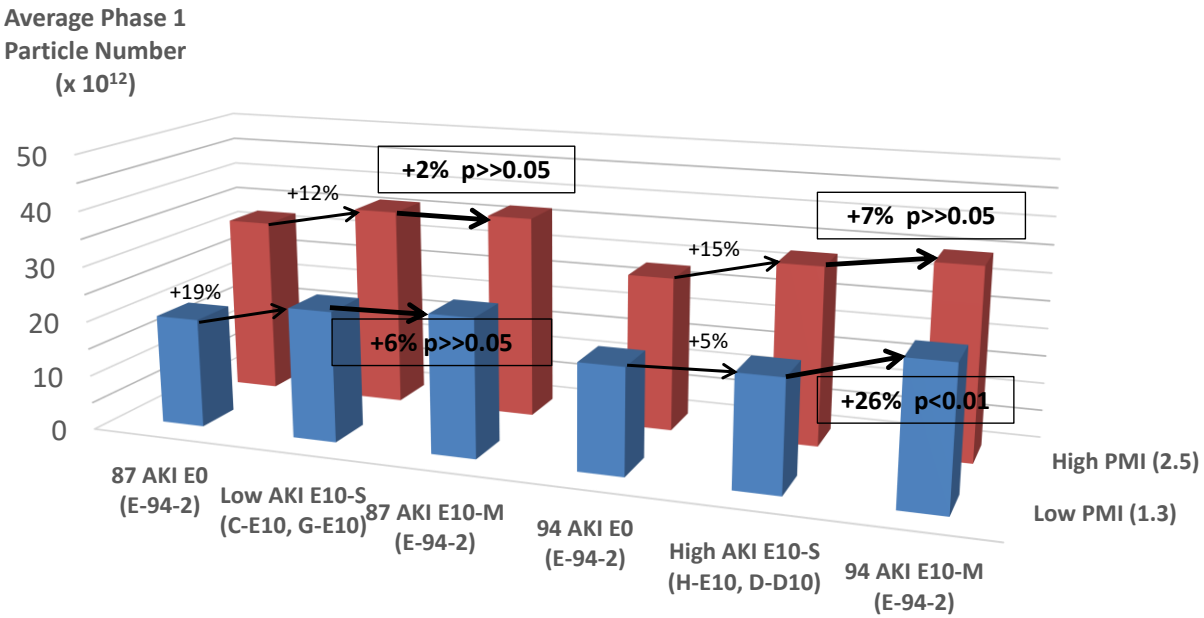


FIGURE 27: EFFECTS OF E10 SPLASH- AND MATCH-BLENDING ON PHASE 1 PN EMISSIONS (AVERAGE OF FOUR-VEHICLE GROUP)

- Phase 1 PN emissions are greater on E10-M fuels compared to E10-S fuels for the group of Low PMI fuels on average (four-vehicle group).

- Phase 1 PN emissions are greater on E10-M fuels compared to E10-S fuels for the High AKI / Low PMI fuel individually (both vehicle groups).

In the four vehicle group, these conclusions achieve a good level of statistical significance ($p \leq 0.01$) for the Low PMI fuel group and for the one High AKI / Low PMI fuel. In the three vehicle group, the conclusion for the High AKI / Low PMI fuel is significant at the $p \leq 0.05$ level.

However, as the figures and the table make clear, all of these conclusions are driven by the large increase observed for the High AKI / Low PMI fuel. A simpler interpretation of the data is that only the High AKI / Low PMI fuel exhibits a significant emissions difference due to the match-blending of ethanol. Thus, the increase in Phase 1 PN emissions that is observed may be limited to the specific E10-M fuel that was created for the cell in the E-94-2 experiment design.

5.4.1.2. Phase 1 PM Emissions

For the three-vehicle group, Phase 1 PM emissions are observed to increase in all of the match-blended E10-M fuels compared to their splash-blended E10-S counterparts, but the differences are relatively small (8-13%) in three of the four cases, while the increased observed for High AKI / Low PMI fuel (32%) is much larger (see Figure 28). Yet, in all of the cases, the emissions changes are comparable to or larger than the emissions changes observed between the E0 to E10-S fuels, suggesting the possibility that match-blending has a material effect on Phase 1 PM emissions overall.

The statistical significance reported in Table 22 provides context for interpretation of the observed differences. The +32% emissions change for the High AKI / Low PMI fuel is statistically significant ($p = 0.018$, or less than 2 chances in 100 of occurring by chance), while the other changes are not. While the data will support conclusions that Phase 1 PM emissions are higher on the match-blended E10-M fuels for all fuels on average and for the group of Low PMI fuels, these aggregate changes are actually driven by the specific result for the High AKI / Low PMI fuel.

For the four-vehicle group, we see more variability among the fuels (see Figure 29). Phase 1 PM emissions are observed to increase in the match-blended E10-M fuels for two of the fuels (by +10 to +11%) but show essentially no change for the other two fuels (+1% and -3%) compared to E10-S fuels. As the table shows, none of the emission differences are statistically significant, whether individually or when grouped.

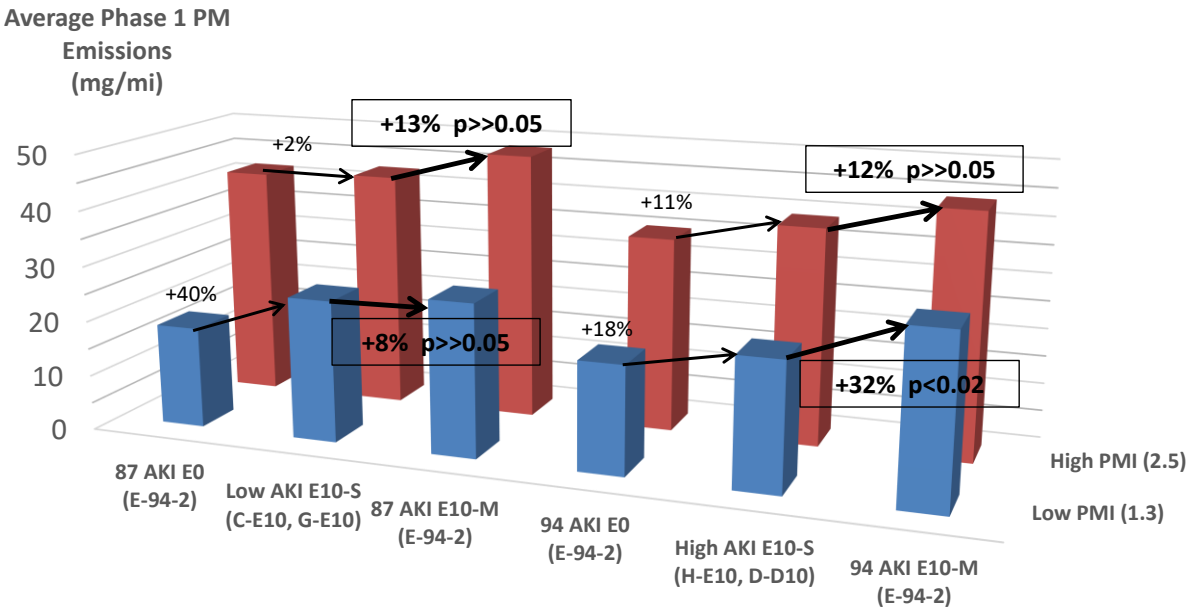


FIGURE 28: EFFECTS OF E10 SPLASH- AND MATCH-BLENDING ON PHASE 1 PM EMISSIONS (AVERAGE OF THREE-VEHICLE GROUP)

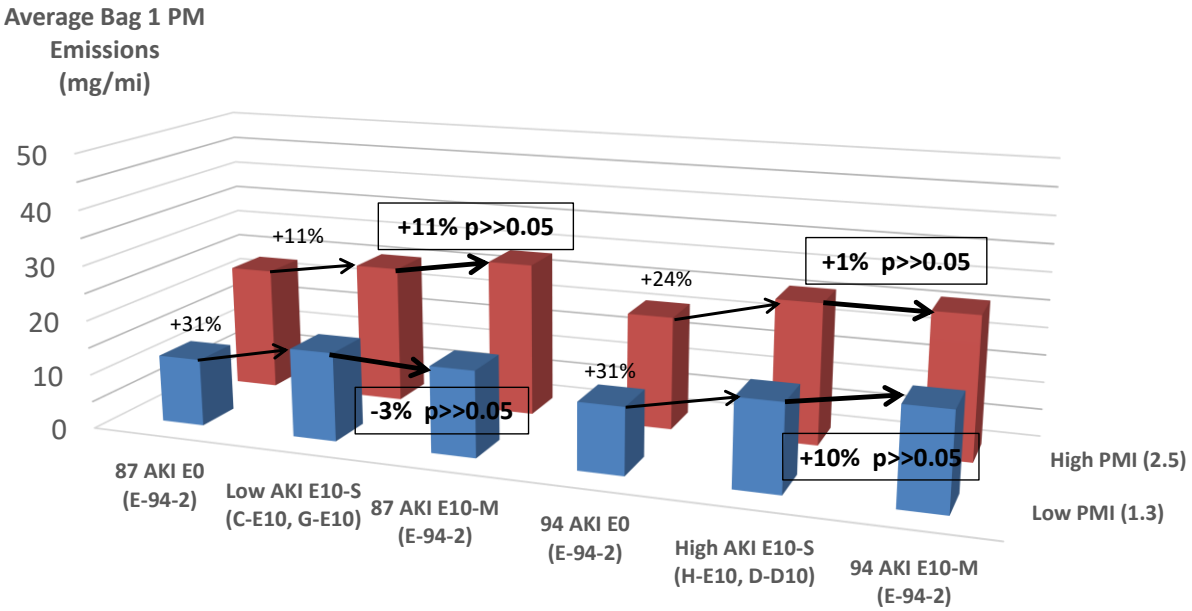


FIGURE 29: EFFECTS OF E10 SPLASH- AND MATCH-BLENDING ON PHASE 1 PM EMISSIONS (AVERAGE OF FOUR-VEHICLE GROUP)

TABLE 22: MODEL-ESTIMATED PHASE 1 PM EMISSIONS CHANGE FOR E10-S → E10-M

	Three-vehicle group		Four-vehicle group	
	Emissions Change	**Statistical Significance**	**Emissions Change**	**Statistical Significance**
Average of All Fuels	+16%	p = 0.013	+ 5%	p = 0.48
Avg Low PMI	+19%	p = 0.033	+ 3%	p = 0.71
Low AKI / Low PMI	+ 8%	p = 0.51	- 3%	p = 0.81
High AKI / Low PMI	+32%	p = 0.018	+10%	p = 0.45
Avg High PMI	+13%	p = 0.14	+ 6%	p = 0.53
Low AKI / High PMI	+13%	p = 0.28	+11%	p = 0.42
High AKI / High PMI	+12%	p = 0.30	+ 1%	p = 0.94

Note: Underlining indicates that the estimated change is statistically significant at the $p \leq 0.05$ level.

Considering the three-vehicle group, the following conclusions can be drawn from the data:

- Phase 1 PN emissions are greater on E10-M fuels compared to E10-S fuels for all fuels on averages.

- Phase 1 PN emissions are greater on E10-M fuels compared to E10-S fuels for the group of Low PMI fuels on average.

- Phase 1 PN emissions are greater on E10-M fuels compared to E10-S fuels for the High AKI / Low PMI fuel individually.

As for Phase 1 PN emissions, the simplest interpretation is that Phase 1 PM emissions are significantly increased by the match-blended High AKI / Low PMI E10-M fuel compared to its splash-blended E10-S counterpart. While the data show consistent increases for the other match-blended E10 fuels, the observed changes fall within the variability of the data. The absence of statistically significant trends in the four-vehicle group emphasizes the distinctive performance of the vehicle excluded from the group.

5.4.2. LA92 Emissions

This section examines the effect of splash- and match-blending on weighted-average particulate emissions over the LA92 cycle. The LA92 emission trends by fuel are a composite of the Phase 1 trends presented in the prior section plus the trends (if any) that occur in Phases 2 and 3. Because particulate emission levels are lower on the LA92 cycle than in Phase 1, one should expect the LA92 data to provide less resolution of fuel effects than was seen in the Phase 1 data.

5.4.2.1. LA92 PN Emissions

The trends by fuel for LA92 PN emissions are presented in Figure 30 and Figure 31 and are summarized in Table 23. For the three-vehicle group, LA92 PN emissions are observed to be higher on the match-blended E10-M fuels compared to their E10-S counterparts, with the observed increases ranging from 7% to 25% depending on fuel. As in Phase 1, the largest emissions increase occurs for the match-blended High AKI / Low PMI fuel E10-M. For the other fuels, where the

increases are smaller, we see that the differences between E10-S and E10-M fuels are comparable to (or even larger than) the emissions change from E0 to E10-S fuels.

The statistical significance reported in the table provides the context for understanding these differences. The 25% increase in the High AKI / Low PMI fuel just fails to achieve the p = 0.05 level of significance (and so is not marked as significant in the table). Such an outcome can occur by chance even when an effect is actually present because of a chance deviation to lower emissions in one or more of the vehicles. When this fuel is aggregated with the others, LA92 PN emissions are found to be significantly increased for the group of Low PMI fuels (+18%, p = 0.039) and for all fuels on average (+14%, p = 0.027). However, these results are driven by the large increase in emissions that is observed for the match-blended High AKI / Low PMI E10 fuel compared to the splash-blended fuels.

TABLE 23: MODEL-ESTIMATED LA92 PN EMISSIONS CHANGE FOR E10-S → E10-M

	Three-vehicle group		Four-vehicle group	
	Emissions Change	**Statistical Significance**	**Emissions Change**	**Statistical Significance**
Average of All Fuels	+14%	p = 0.027	***+20%***	p < 0.001
Avg Low PMI	+18%	p = 0.039	***+27%***	p = 0.001
Low AKI / Low PMI	+12%	p = 0.30	+23%	p = 0.024
High AKI / Low PMI	+25%	p = 0.053	***+31%***	p = 0.005
Avg High PMI	+9%	p = 0.26	+13%	p = 0.065
Low AKI / High PMI	+11%	p = 0.34	+12%	p = 0.23
High AKI / High PMI	+7%	p = 0.53	+14%	p = 0.15

Note: Underlining indicates that the estimated change is statistically significant at the $p \leq 0.05$ level. Underlining with bold italicized text indicates the change is statistically significant at the $p \leq 0.01$ level.

LA92 PN emissions for the four-vehicle group are noticeably lower overall due to the very low particulate emission levels of Vehicle C. Emissions on the E10-M fuels are observed to be higher in all cases, with the differences from E10-S fuels again being greatest for the High AKI / Low PMI fuel. The emission changes reach a good level of statistical significance ($p \leq 0.01$) for that fuel, for the group of Low PMI fuels, and for all fuels on averages. The change for the Low AKI / Low PMI reaches the conventionally-accepted level of statistical significance ($p \leq 0.05$).

Considering both vehicle groups, the following conclusions can be drawn from the data:

- Phase 1 PN emissions are greater on E10-M fuels compared to E10-S fuels for all fuels on average.

- Phase 1 PN emissions are greater on E10-M fuels compared to E10-S fuels for the group of Low PMI fuels on average.

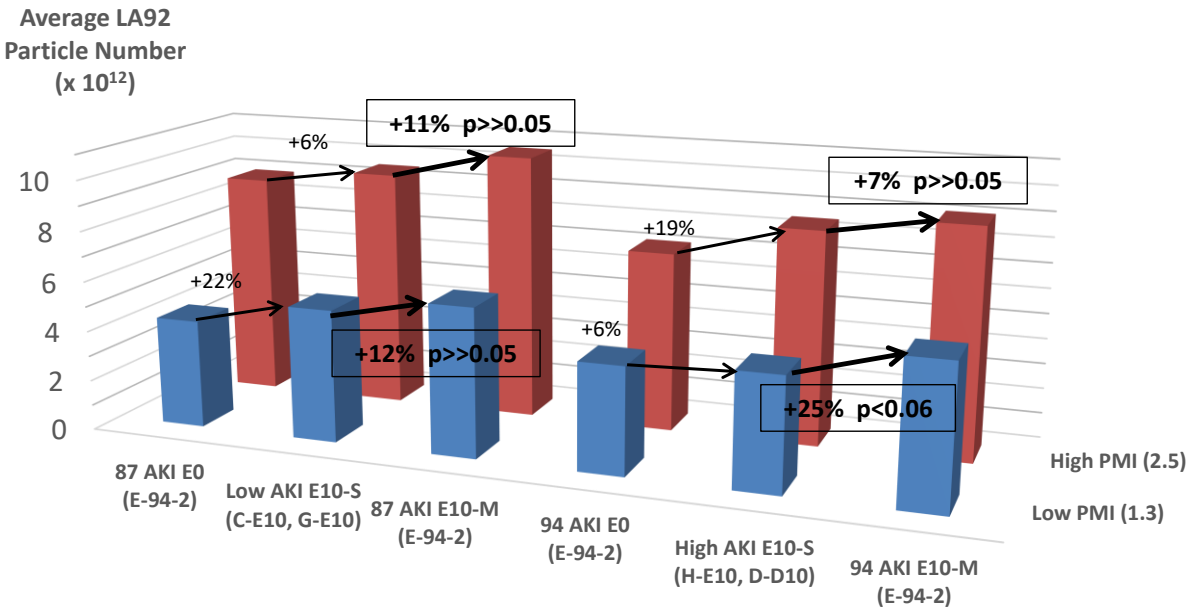


FIGURE 30: EFFECTS OF E10 SPLASH- AND MATCH-BLENDING ON LA92 PN EMISSIONS (AVERAGE OF THREE-VEHICLE GROUP)

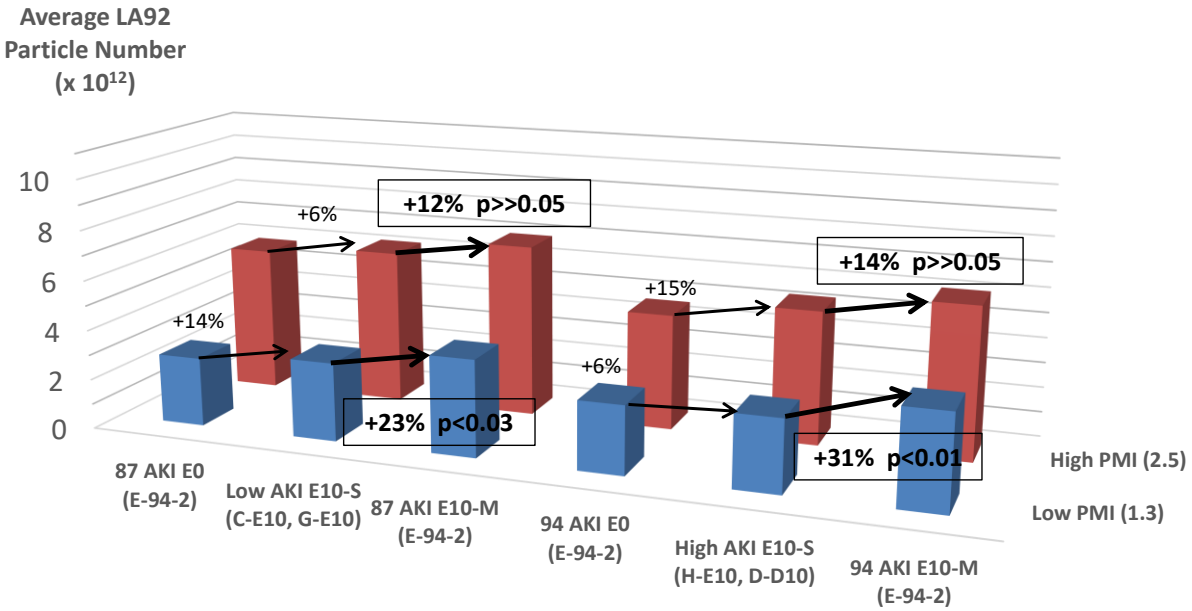


FIGURE 31: EFFECTS OF E10 SPLASH- AND MATCH-BLENDING ON LA92 PN EMISSIONS (AVERAGE OF FOUR-VEHICLE GROUP)

- Phase 1 PN emissions are greater on E10-M fuels compared to E10-S fuels for the High AKI / Low PMI fuel individually (four-vehicle group). In the three-vehicle group, the conclusion just fails to achieve statistical significance.

Again, the simplest interpretation is that LA92 PM emissions are significantly increased in the match-blended High AKI / Low PMI E10-M fuel compared to its splash-blended E10-S counterpart. The consistency with which higher emissions are observed for the E10-M fuels suggests the possibility that match-blending has a material effect on LA92 PN emissions overall.

5.4.2.2. LA92 PM Emissions

The trends by fuel for LA92 PM emissions are presented in Figure 32 and Figure 33 and are summarized in Table 24.

For the three-vehicle group, LA92 PM emissions on the E10-M fuels are greater than on the E10-S fuels in three of four cases, while essentially unchanged in one case. As the table shows, none of the changes for the individual fuels are statistically significant. However, the 18% increase in the group of High PMI fuels just achieves significance ($p = 0.047$) as does the 13% increase for the average of all fuels ($p = 0.040$). The data indicate that LA92 PM emissions *may* be higher in the match-blended E10-M fuels than in the splash-blended E10-S fuels.

LA92 PM emissions are again much lower in the four-vehicle group. Emissions on the E10-M fuels are observed to be greater than on the E10-S fuels in two of four cases, while emissions are decreased in the other cases. None of the changes reach the level of statistical significance.

TABLE 24: MODEL-ESTIMATED LA92 PM EMISSIONS CHANGE FOR E10-S → E10-M

	Three-vehicle group		Four-vehicle group	
	Emissions Change	**Statistical Significance**	**Emissions Change**	**Statistical Significance**
Average of All Fuels	<u>+13%</u>	p = 0.040	- 2%	p = 0.79
Avg Low PMI	+ 8%	p = 0.34	-13%	p = 0.26
Low AKI / Low PMI	+ 2%	p = 0.88	-21%	p = 0.19
High AKI / Low PMI	+15%	p = 0.23	- 5%	p = 0.78
Avg High PMI	<u>+18%</u>	p = 0.047	+10%	p = 0.45
Low AKI / High PMI	+20%	p = 0.12	+12%	p = 0.52
High AKI / High PMI	+16%	p = 0.19	+ 8%	p = 0.67

Note: Underlining indicates that the estimated change is statistically significant at the $p \leq 0.05$ level.

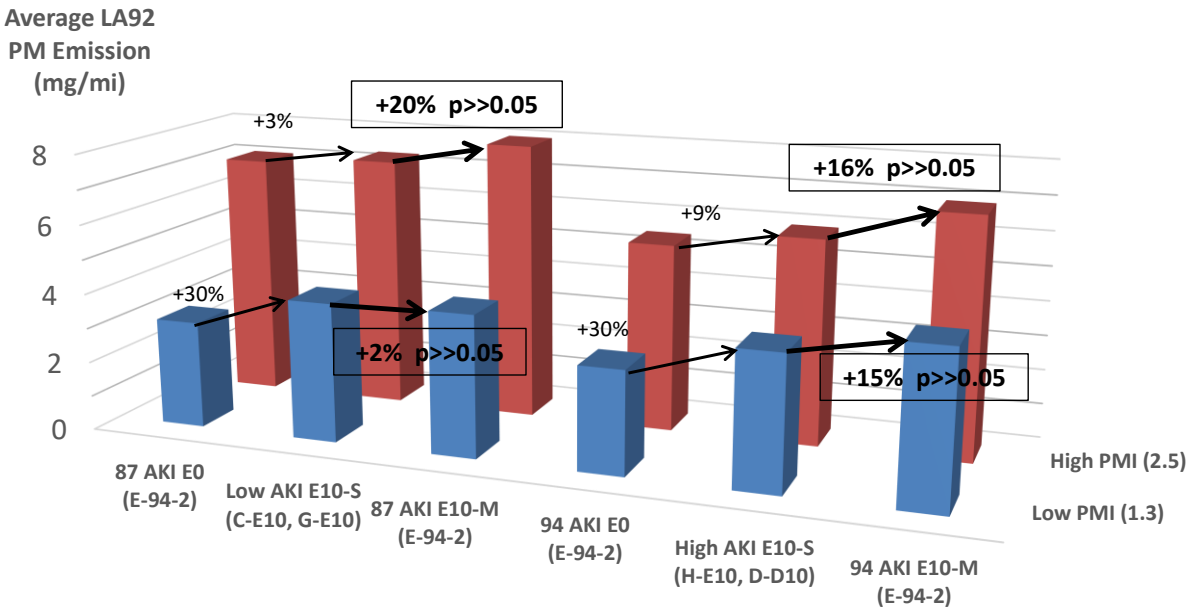


FIGURE 32: EFFECTS OF E10 SPLASH- AND MATCH-BLENDING ON LA92 PM EMISSIONS (AVERAGE OF THREE-VEHICLE GROUP)

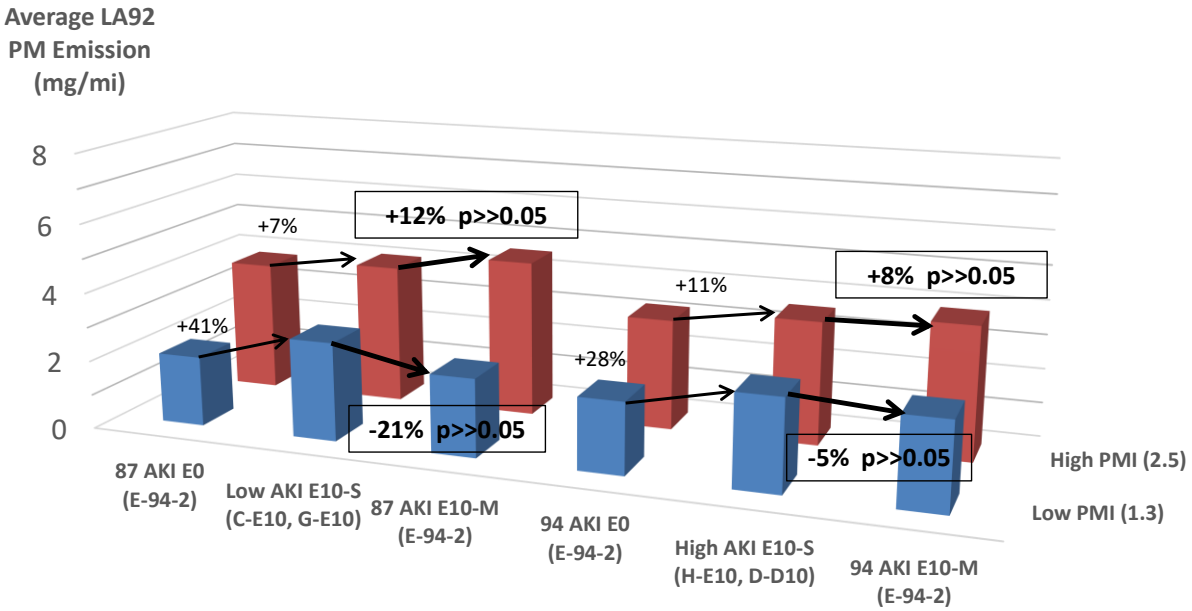


FIGURE 33: EFFECTS OF E10 SPLASH- AND MATCH-BLENDING ON LA92 PM EMISSIONS (AVERAGE OF FOUR-VEHICLE GROUP)

For the three-vehicle group, the data support the conclusion that the match-blended E10 fuels have higher LA92 PM emissions on average and in the group of High PMI fuels compared to the splash-blended E10 fuels; this conclusion just barely achieves statistical significance. There are no statistically significant trends in the four-vehicle group.

5.4.3. Fuel Properties Differences Associated with the Observed Splash- versus Match-blending Differences in Emissions

Given the determination that particulate emissions are significantly different between splash- and match-blended fuels *in at least some cases*, this section examines whether we can identify the physical and chemical properties of the E10-S and E10-M fuels that are responsible. This is a secondary analysis performed using two different formulations of the statistical model, in which the data themselves are differenced to compare corresponding fuels. Method 1 compares the E10-S and E10-M fuels to the E0 fuels as a baseline. Method 2 compares the E10-M fuels to the E10-S fuels as a baseline. The approach was described previously in Section 5.2.4.

As summarized in the following sections, Method 1 identifies ethanol content and the T90 distillation temperature as the variables most strongly associated with emission differences between the splash- and match-blended E10 fuels. This outcome is plausible, given that the E-94-2 program identified ethanol content as having a significant effect on particulate emissions, although secondary to the effect of PMI. The T90, T95, and FBP temperatures at the end of the distillation curve were also shown to be so highly correlated to PMI as to be synonymous. Thus, the outcome of Method 1 is to say that splash- and match-blended fuels are likely to show significant differences in emissions when their ethanol contents and PMI values differ sufficiently as a result of the blending.

Method 2 was not successful in identifying fuel properties that aid the understanding of the observed differences in emissions between the E10-S and E10-M fuels. This null result is due, at least in part, to the fact that the observed emission differences are small and difficult to resolve.

5.4.3.1. Fuel Properties Associated with Emission Changes: Method 1

Method 1 compares the E10-S and E10-M fuels to the corresponding E0 fuels. When all available fuel properties are tested against the observed differences in emissions, only two variables – ΔEtOH and ΔT90 – are found to carry explanatory power. Table 25 summarizes the explanatory variables selected in each case.

The T90 temperature on the distillation curve is highly correlated with PMI itself, as are the T95 and FBP temperatures. The selection of T90 as an explanatory variable for the differences in emissions among the E10 fuels simply recognizes that the blending of individual fuels did not (and could not) control the PMI value exactly to the same levels. Thus, differences in PMI among the fuels will induce differences in particulate emissions among the fuels.

TABLE 25: FUEL PROPERTIES ASSOCIATED WITH EMISSION CHANGES DUE TO BLENDING METHOD. E10-S AND E10-M FUELS COMPARED TO E0 FUELS

	Phase 1	LA92 Cycle
Three-vehicle group		
PN Emissions	ΔEtOH ($p < 0.001$) ΔT90 ($p = 0.010$)	ΔEtOH ($p < 0.001$) ΔT90 ($p = 0.010$)
PM Emissions	ΔEtOH ($p < 0.001$) ΔT90 ($p = 0.002$)	ΔEtOH ($p < 0.001$)
Four-vehicle group		
PN Emissions	ΔEtOH ($p < 0.001$) ΔT90 ($p = 0.025$)	ΔEtOH ($p < 0.001$) ΔT90 ($p = 0.025$)
PM Emissions	ΔEtOH ($p < 0.001$)	ΔEtOH ($p < 0.001$) ΔT90 ($p = 0.002$)

In general, the E10-S fuels had lower PMI values (by as much as -0.2) than the E0 base fuels from which they were blended due to the dilution of the gasoline hydrocarbons with ethanol. In contrast, the E10-M fuels had higher PMI values that corresponded more closely (range -0.2 to +0.2) to those of the E0 fuels because of the match-blending to meet the PMI (and other) targets of the E0 fuels. Directionally, the differences in PMI (and thus the T90 temperatures) mean that the particulate emissions of the E10-S fuels should be lower than for the E10-M fuels, as observed in the data.

The E-94-2 study found that fuel ethanol content also influences particulate emissions. The ethanol levels of the splash-blended E10-S fuels were slightly, but consistently higher (range 9.4 to 9.9 vol %), than those in the E10-M fuels (range 9.51 to 9.56 vol %). Directionally, the differences in ethanol content should increase particulate emissions of the E10-S fuels compared to the E10-M fuels. This directional difference offsets that resulting from the differences in T90, thus narrowing the difference between the E10-S and E10-M fuels.

5.4.3.2. Fuel Properties Associated with Emission Changes: Method 2

Method 2 compares the E10-M fuels to the corresponding E10-S fuels as a baseline. When all available fuel properties are tested against the observed differences in emissions, no set of variables is consistently identified. Table 26 summarizes the explanatory variables selected in each case.

The variable ΔBenzene is found to be associated with PN emission differences in Phase 1 and the LA92 cycle for the three- and four-vehicle groups. Benzene is present in the fuels in only small quantities, and the differences among the fuels are difficult to measure with accuracy. Absent a clear basis to connect benzene content to particulate emissions, the identification of benzene as an explanatory variable is probably best interpreted as a chance marker for specific fuels for which emission differences are observed.

Overall, the Method 2 analysis does not add to the understanding gained from Method 1. This outcome is likely due, at least in part, to the fact that the observed emission differences are small and difficult to resolve using the available data.

TABLE 26: FUEL PROPERTIES ASSOCIATED WITH EMISSION CHANGES DUE TO BLENDING METHOD. E10-M FUELS COMPARED TO E10-S FUELS

	Phase 1	LA92 Cycle
Three-vehicle group		
PN Emissions	ΔBenzene ($p = 0.01$)	ΔBenzene ($p = 0.02$)
PM Emissions	ΔT80 ($p < 0.01$)	ΔT05 ($p < 0.002$)
Four-vehicle group		
PN Emissions	ΔBenzene ($p < 0.01$)	ΔBenzene ($p < 0.01$)
PM Emissions	None at $p \leq 0.10$	None at $p \leq 0.10$

5.5. Conclusions Regarding the Effect of Ethanol on Particulate Emissions

5.5.1. Effect of E10 Splash-Blending on Particulate Emissions

Taken in their entirety, the E-94-3 data support the conclusion that ethanol splash-blending significantly increases particulate emissions compared to E0 fuels, both in LA92 Phase 1 and the overall LA92 cycle, whether measured as PN or PM emissions. Table 27 compiles a summary of the findings reached in the preceding sections, which are itemized below.

LA92 Phase 1 Emissions

1. Ethanol splash-blending increases Phase 1 PN emissions for all fuels on average and in the group of Low PMI fuels with acceptable statistical significance ($p \leq 0.05$) compared to E0 fuels. The data demonstrate that emissions are significantly increased in some of the experimental fuels individually, most consistently the Low AKI / Low PMI fuel.

2. Ethanol splash-blending increases Phase 1 PM emissions for all fuels on average and in the group of Low PMI fuels with good statistical confidence ($p \leq 0.01$) compared to E0 fuels. The data again demonstrate that emissions are increased in some of the experimental fuels individually, most consistently the Low AKI / Low PMI fuel.

Overall, the data support the theory that ethanol splash-blending increases Phase 1 particulate emissions in all of the fuels, compared to E0 fuels, with the largest increases occurring in the Low PMI fuels.

Despite these findings with respect to ethanol, PMI remains the primary influence on Phase 1 particulate emissions. The data presented in this section show that the PMI change from 1.3 (Low) to 2.6 (High) results in a 41% to 64% increase in Phase 1 PN emissions and a 57% to 129% increase in Phase 1 PM emissions, depending on fuel and vehicle group. Thus, the PMI effect is far larger than the effect of ethanol.

TABLE 27: SUMMARY OF STATISTICALLY SIGNIFICANT EMISSION INCREASES FOR E0 → E10-S

	LA92 Phase 1		LA92 Cycle	
	Three-vehicle group	**Four-Vehicle group**	**Three-vehicle group**	**Four-vehicle group**
PN	On Average Low PMI Fuels Low AKI / Low PMI fuel	***On Average*** Low PMI Fuels Low AKI / Low PMI fuel High AKI Fuels High AKI / High PMI fuel	On Average	On Average
PM	***On Average*** ***Low PMI Fuels*** ***Low AKI / Low PMI fuel***	***On Average*** ***Low PMI Fuels*** Low AKI / Low PMI fuel High AKI / Low PMI fuel	***On Average*** ***Low PMI Fuels*** Low AKI / Low PMI fuel High AKI / Low PMI fuel	On Average Low PMI Fuels

Note: Statistical significance requires $p \leq 0.05$. ***Bold and italicized*** font indicate $p \leq 0.01$.

LA92 Emissions

1. Ethanol splash-blending increases LA92 PN emissions for all fuels on average with acceptable statistical confidence ($p \leq 0.05$) compared to E0 fuels.

2. Ethanol splash-blending increases LA92 PM emissions for all fuels on average and for the group of Low PMI fuels, with good statistical confidence ($p \leq 0.01$) in the three-vehicle group and with acceptable confidence ($p \leq 0.05$) in the four-vehicle group, compared to E0 fuels. In the three-vehicle fleet, the data demonstrate that emissions are increased in the two Low PM fuels individually.

Overall, the data support the theory that ethanol splash-blending increases LA92 particulate emissions in all the fuels, compared to E0 fuels, with the largest increases occurring in the Low PMI fuels.

PMI remains the primary influence on LA92 particulate emissions. The data presented above show that the PMI change from 1.3 (Low) to 2.6 (High) results in a 68% to 112% increase in LA92 PN emissions and a 57% to 129% increase in LA92 PM emissions, depending on fuel and vehicle group. The PMI effect is far larger than the effect of ethanol.

5.5.2. Effect of Splash- and Match-Blending on Particulate Emissions

The results presented in Section 5.4 for the effect of splash- and match-blending on emissions are difficult to summarize in simple terms, because they vary among the emission variables and the phases and they are often different in the two vehicle groups. To aid

understanding, Table 28 summarizes the statistically significant[10] emission changes that are observed between E10-S and E10-M fuels; comments on the directional consistency of results among fuels are offered in brackets. The conclusions are itemized below:

1. Throughout the data, PN emissions are observed to be higher on the match-blended E10 fuels than on the splash-blended E10 fuels (but not necessarily by statistically significant amounts). This should be no surprise, as the E10-M fuels had PMI values that corresponded closely to the E0 fuels because of the match-blending in E-94-2. In contrast, the E10-S fuels had lower PMI values (by as much as -0.2) than the E0 base fuels from which they were blended due to the dilution of the gasoline hydrocarbons with ethanol. Ethanol contents of the E10-M fuels were also somewhat different than the E10-S fuels. Splash- and match-blended fuels are likely to show significant differences in emissions when their PMI values and ethanol contents differ sufficiently as a result of the blending.

2. The PN emissions increase is greatest by far in the match-blended High AKI / Low PMI fuel, being statistically significant in 3 of the 4 cases and just failing to reach significance in the other. The simplest and most direct interpretation of the data is that only the High AKI / Low PMI fuel exhibits a significant emissions difference due to the match-blending. The increase in PN emissions caused by match-blending may be limited to the specific E10-M fuel that was created for the cell in the E-94-2 experiment design.

3. For PM emissions, the greatest difference is between the three- and four-vehicle groups. For the three-vehicle group, the data support a finding PM emissions are significantly increased for all match-blended fuels on average compared to their splash-blended counterparts. In contrast, there is no evidence in the four-vehicle group that match- and splash-blended fuels have different effects on PM emissions.

4. For both PN and PM emissions, the observed emission differences do not support a general conclusion that match-blending leads to higher emissions than splash-blending. Where statistically significant emission increases do occur, they may be best interpreted as characteristic of the match-blended High AKI / Low PMI E10 fuel itself.

[10] Two levels of statistical significance ($p \leq 0.05$ and $p \leq 0.01$) are recognized in the table. Many statistical comparisons were made in the course of the analysis. False positives (a finding of significance by chance when no effect is actually present) will occur occasionally at the $p \leq 0.05$ significance level and are difficult to distinguish from real effects. The consistency of observing similar effects elsewhere in the data, either for other variables or for other fuels, is one way of gaining confidence in conclusions based on the $p \leq 0.05$ level. Conclusions that are based on $p \leq 0.01$ are stronger and less likely to be false positives

TABLE 28: SUMMARY OF STATISTICALLY SIGNIFICANT EMISSION INCREASES FOR E10-S → E10-M

	LA92 Phase 1		LA92 Cycle	
	Three-vehicle group	**Four-vehicle group**	**Three-vehicle group**	**Four-vehicle group**
PN	High AKI /Low PMI fuel [Increases observed in all cases]	On Average ***Low PMI fuels*** ***High AKI / Low PMI fuel*** [Increases observed in all cases]	On average Low PMI fuels [Increases observed in all cases]	**On Average** ***Low PMI fuels*** Low AKI / Low PMI fuel ***High AKI / Low PMI fuel*** [Increases observed in all cases]
PM	On Average Low PMI fuels High AKI / Low PMI fuel [Increases observed in all cases]	No evidence for change in PM emissions.	On Average High PMI fuels [Increases observed in all cases]	No evidence for change in PM emissions.

Note: Statistical significance requires $p \leq 0.05$. ***Bold and italicized*** font indicates $p \leq 0.01$.

The E-94-2 study examined emissions from a 12-vehicle test fleet operated on the eight E0 and match-blended E10 fuels. It concluded that PMI was the most important fuel characteristic influencing vehicular particulate emissions. A near-doubling of the PMI index from 1.3 to 2.6 was estimated to approximately double the average LA92 PM emissions of the test fleet. It also concluded that ethanol at the E10 level led to increased LA92 PM emissions, over and above the increase that would be expected from the PMI of the fuels, by amounts ranging from 18% to 46% depending on the fuel.

The E-94-3 findings support the conclusion that the particulate emission increases attributed in the E-94-2 program to ethanol *largely* reflect the influence of ethanol itself on emissions and are *not primarily* the result of the choices of alternative E0 base fuels in the match-blending. The emissions increase on E10-M fuels may be influenced by the base fuel choices made in match-blending, but by modest amounts in most cases. The effect also depends on the composition of the test fleet, as the response of particulate emissions to fuels was found to vary among the vehicles.

5.6. Recommendations for Future Work

The analysis performed here demonstrates that the addition of ethanol to gasoline hydrocarbons by splash-blending increases particulate emissions of the in-use SIDI vehicles tested to levels that are greater than that of corresponding E0 fuels. In E-94-2, the analysis demonstrated that ethanol increased particulate emissions over and above the level that would be expected from the PMI values of the match-blended fuels.

The effect of ethanol on particulate emissions of oxygenated fuels is complex and may be related to the specific hydrocarbon composition of the fuels and to the combustion characteristics of the species. Further, ethanol's emissions effect is measured relative to the emissions level that would be expected for an E0 fuel with the same PMI value. Thus, the magnitude of the ethanol effect that is inferred may be different when different PM indices are used to estimate emissions.

These observations indicate that a fuller understanding is needed of the performance of the various PM indices that have been published. CRC has recently begun work under Project RW-107: Assessment of the Relative Accuracy of the PM Index and Related Methods to determine the relative performance of the indices and assess whether an improved index might be developed.

The Honda PMI used here is computed from a detailed hydrocarbon analysis (DHA), in which the set of hydrocarbon species making up each of the twelve experimental fuels is determined with high resolution. Further analysis of the E-94-2 and E-94-3 data should be performed to relate the particulate emissions increases observed in the data to the hydrocarbon composition of the fuels in a manner that does not require use of a PM index value. Such work can provide further insight on the extent to which ethanol increases particulate emissions by removing the need to reference the increase to an expected emissions level. Further, it can add to the understanding of which hydrocarbon species (or groups) are the causal factors for particulate emission increases.

APPENDIX A

COMPLETE FUEL PROPERTIES ANALYSIS

TABLE A-1: FUEL PROPERTIES

		Fuel A	Fuel B	Fuel C	Fuel C-E10	Fuel D	Fuel D-E10	Fuel E	Fuel F	Fuel G	Fuel G-E10	Fuel H	Fuel H-E10
		CGA-9208	CGA-9209	CGA-9210	CGB-9458	CGA-9211	CGB-9473	CGA-9212	CGA-9213	CGA-9214	CGB-9467	CGA-9215	CGB-9463
	Blend Method	Match	Match		Splash		Splash	Match	Match		Splash		Splash
RON	D2699	91.2	91.3	91.3	95.7	91.8	95.9	99.0	99.0	98.4	102.1	98.8	102.0
MON	D2700	83.3	82.9	84.5	87.3	84.6	86.3	88.1	88.3	89.1	90.7	89.4	89.9
AKI	(R+M)/2	87.3	87.1	87.9	91.5	88.2	91.1	93.6	93.7	93.8	96.4	94.1	96.0
Sensitivity	R-M	8.0	8.1	6.7	8.4	7.2	9.6	11.0	10.7	9.3	11.4	9.4	12.1
Aromatic, vol%	D6729	29.2	29.4	26.1	22.8	27.6	23.8	30.1	31.4	27.3	24.4	28.5	24.9
PMI Honda Eq†	PMI Tool	1.400	2.607	1.377	1.280	2.560	2.454	1.293	2.420	1.250	1.174	2.367	2.320
RVP @ 100˚F, psi	D5191	7.22	7.31	7.29	8.21	6.81	8.03	6.99	7.16	7.35	8.42	7.23	8.37
Ethanol, vol%	D4815	9.62	9.61	0.00	9.44	0.00	9.71	9.62	9.62	0.00	9.75	0.00	9.88
	D5599				9.5		9.8				9.8		10.0
	D5599 (rerun)				9.6		--				--		--
Oxygen, wt%	D5599				3.5		3.6				3.7		3.7
Sulfur, ppm w/w	D5453	8.9	9.3	8.7	8.1	9.7	9.2	0.9	1.0	1.2	1.3	1.2	0.8
Benzene, vol%	D6729	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.5	0.5	0.5	0.5
Olefins, vol%		5.500	5.133	5.767	5.260	5.800	4.900	5.667	5.733	5.300	5.131	4.933	5.154

† PMI values for E0 & E10-M fuels are average of Labs A, B, C. Lab C used updated methodology in D6729 DHA
PMI values for E10-S fuels are results of Lab C. Lab C used updated methodology in D6729 DHA

TABLE A-1: FUEL PROPERTIES (CONTINUED)

		Fuel A	Fuel B	Fuel C	Fuel C-E10	Fuel D	Fuel D-E10	Fuel E	Fuel F	Fuel G	Fuel G-E10	Fuel H	Fuel H-E10
		CGA-9208	CGA-9209	CGA-9210	CGB-9458	CGA-9211	CGB-9473	CGA-9212	CGA-9213	CGA-9214	CGB-9467	CGA-9215	CGB-9463
	Blend Method	Match	Match		Splash		Splash	Match	Match		Splash		Splash
Distillation, IBP °F	D86	104.8	106.3	90.1	99.4	97.4	97.8	99.9	104.5	91.6	95.3	91.2	96.0
Distillation, 5% °F		131.0	128.7	131.0	129.8	132.1	125.5	130.6	129.2	124.1	121.6	123.7	123.7
Distillation, 10% °F		137.6	134.8	151.5	139.4	145.8	133.4	137.2	135.6	139.0	130.6	139.1	132.2
Distillation, 20% °F		146.4	144.0	180.2	150.3	166.3	142.3	146.6	145.1	162.3	142.0	163.9	143.7
Distillation, 30% °F		152.9	150.9	201.4	157.4	185.8	149.8	154.8	153.5	188.0	151.8	190.5	152.6
Distillation, 40% °F		175.5	165.7	216.1	193.5	203.8	157.8	189.7	176.5	211.0	162.4	213.8	166.0
Distillation, 50% °F		218.4	220.7	227.5	223.2	221.1	207.7	228.9	223.9	225.1	217.5	227.5	220.4
Distillation, 60% °F		236.7	248.5	237.9	233.3	239.0	230.1	241.4	235.9	235.1	231.4	238.8	235.1
Distillation, 70% °F		254.1	277.6	250.2	242.2	261.4	252.1	256.6	252.7	246.0	241.9	253.4	245.1
Distillation, 80% °F		275.1	308.6	268.7	265.6	299.6	288.2	277.8	288.3	264.9	259.8	282.6	274.9
Distillation, 90% °F		305.7	341.9	302.5	299.6	345.5	339.5	311.0	339.7	309.7	304.8	343.7	337.4
Distillation, 95% °F		332.7	368.2	332.3	329.1	373.5	370.9	332.5	373.3	336.9	333.0	374.8	370.1
Distillation, DP °F		389.7	426.1	386.4	386.5	430.0	420.6	367.3	429.9	377.9	377.5	431.6	427.3
Recovery, vol %		97.9	97.9	97.7	98.4	98.1	98.0	98.1	97.9	98.0	98.2	98.0	98.5
Residue, vol %		1.0	0.9	1.1	1.0	1.0	1.1	1.0	1.0	1.0	0.8	1.0	0.9
Loss, vol%		1.1	1.3	1.3	0.6	0.9	0.9	0.9	1.1	1.0	1.0	1.0	0.6

TABLE A-1: FUEL PROPERTIES (CONTINUED)

		Fuel A	Fuel B	Fuel C	Fuel C-E10	Fuel D	Fuel D-E10	Fuel E	Fuel F	Fuel G	Fuel G-E10	Fuel H	Fuel H-E10
		CGA-9208	CGA-9209	CGA-9210	CGB-9458	CGA-9211	CGB-9473	CGA-9212	CGA-9213	CGA-9214	CGB-9467	CGA-9215	CGB-9463
	Blend Method	Match	Match		Splash		Splash	Match	Match		Splash		Splash
DI Index	D4814	1182.9	1221.7	1212.2	1178.3	1227.4	1162.7	1219.1	1230.2	1193.6	1153.2	1235.0	1196.9
C10+ Aromatics, vol%	D6729	3.050	7.400	3.000	2.786	8.000	6.800	2.900	8.300	2.950	2.716	8.150	6.942
Existent Gums washed, mg/100 ml	D381	0.9	1	1.0	<0.5	1.0	<0.5				<0.5		<0.5
Unwashed Gums, mg/100 ml		11.2	11.4	10.5	9.5	12.2	8.5	10.1	11.6	11.7	7.5	11.6	9.5
Specific Gravity @ 60°F	D4052	0.7506	0.7535	0.7376	0.7437	0.7379	0.7437	0.7528	0.7525	0.7346	0.7404	0.7408	0.7461
Density @ 60°F, g/ml		0.7624	0.7647	0.7277	0.7435	0.7374	0.7435	0.7640	0.7639	0.7255	0.7402	0.7300	0.7459
API Gravtiy		56.84	56.15	60.08	58.80	60.20	58.80	56.33	56.49	60.99	59.60	59.34	58.20

APPENDIX B

E-94-2 AND E-94-3 DISTILLATION PROPERTY COMPARION TO AVERAGE MARKET FUEL SAMPLES

The distillation properties of all CRC E-94-2 Match-Blended and E-94-3 Splash-Blended fuels were compared to average market fuel distillation properties for both E0 and E10 gasoline. "Summer-time" vapor pressure gasoline from 2016 from the ABC gasoline survey conducted by Southwest Research Institute is used for the E0 market data, and 2016 Summer (July) Alliance of Automobile Manufacturers North American Fuel Survey© (USA data only) was used for the E10 data.

The comparisons of the E0 test fuels and average E0 market fuel for both regular and premium octane grades are displayed in Figure B-1. It should be noted that the E0 fuels from the ABC Survey were obtained from PADDS 2 and 3 during the summer and shoulder months of 2016 (April through October) with a vapor pressure range of 8.3 to 9.3 psi, while the E-94-2 and E-94-3 E0 fuels had nominal 7 psi vapor pressures. No ABC fuels had lower than 8.3 psi vapor pressure, and 9.3 psi was selected as the maximum allowable from the shoulder months to be representative of "compliant" vapor pressure for summer gasoline.

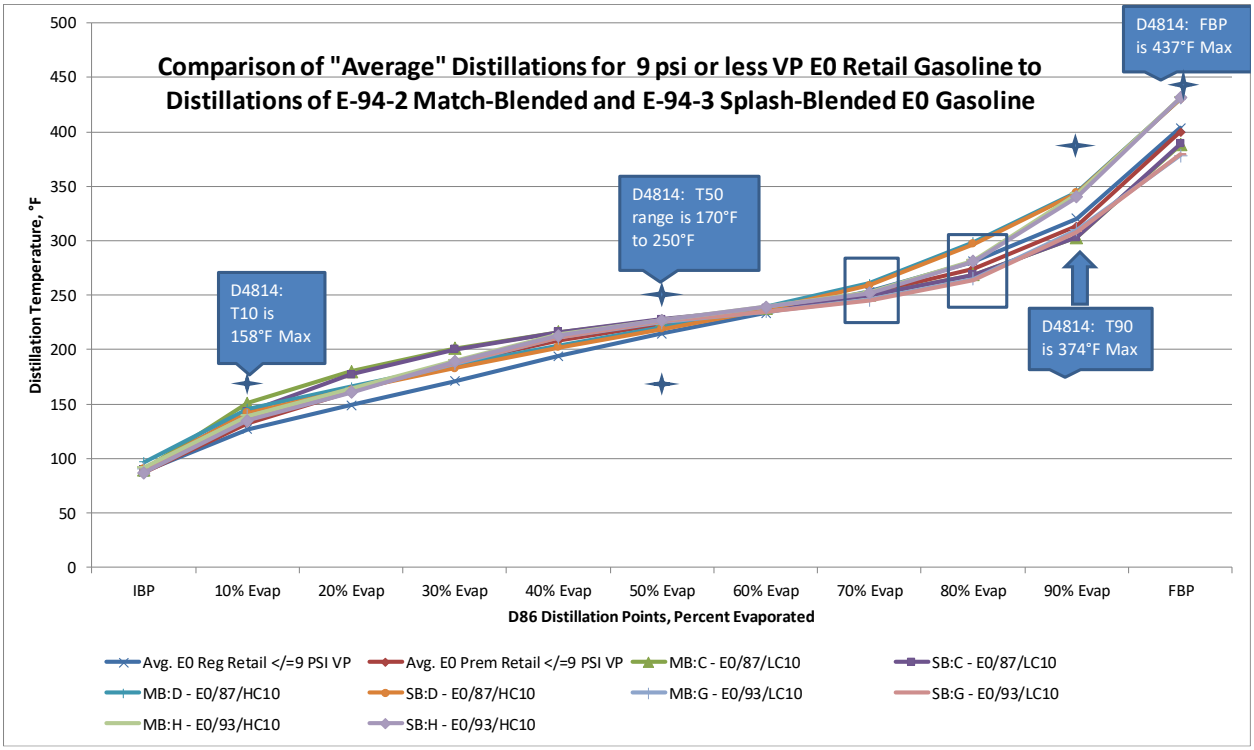


FIGURE B-1: 2016 ABC RETAIL SURVEY "AVERAGE" DISTILLATION CURVES FOR E0 FUELS COMPARED TO E-94-2 AND E-94-3 BLENDS

The rectangular shaped regions represent the range of temperatures for two particular distillation points, T70 and T80, within the fuels sampled for the ABC retail survey. The regions are a combination of both regular and premium with the regular retail E0 gasoline T70 ranging from 245°F to 260°F and the premium retail T70 ranging from 227°F to 271°F. The retail E0 T80 ranges from 270°F to 290°F for regular and 239°F to 301°F for premium. The blue stars and comment boxes on the chart show the ASTM D4814 limits for Class A/AA gasoline for the T10, T50, T90, and FBP. It should be noted that all of the match-blended and splash-blended fuels have distillation curves consistent with those in the retail sample set and fall within the ASTM D4814 distillation limits for gasoline in this vapor pressure range.

The Alliance of Automobile Manufacturers fuel survey data was used for comparison in the range of 6.7 PSI to 7.5 PSI Reid Vapor Pressure (RVP) for the regular octane grade and premium fuel sets. The regular fuel survey T70 ranged from 233°F -266°F. Fuel A and B measured at 254°F and 277°F respectfully. The T80 market range was 261°F to 298°F and fuels A and B were measured to be 275°F and 308°F. Fuel B was slightly higher from T60 to T90 compared to market fuels in the (6.7 to 7.5) PSI range. However, if you look at all of the market fuels that range up to15PSI RVP the maximum T70 and T80 values were found to be 280°F and 307°F. This indicates that Fuel B was in line with other regular fuels found in the market.

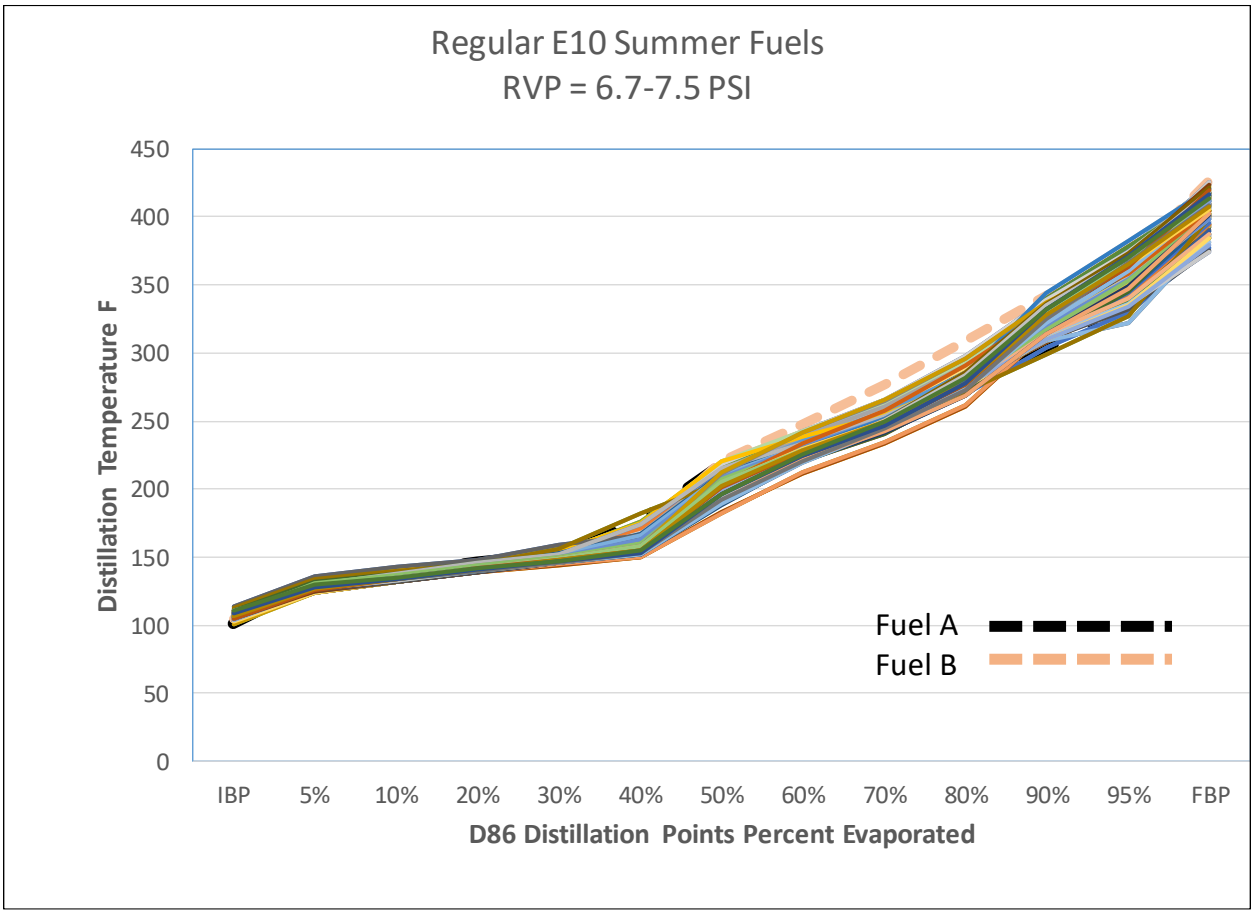


FIGURE B-2: AAM FUEL SURVEY FOR REGULAR E10 SUMMER FUELS

Analyzing the premium data set in the same manner, the T70 range for market fuels was 233°F to 265°F. Fuels E and F resulted in 256°F and 250°F. The T80 range was 249°F to 289°F with fuels E and F measured at 278°F and 288°F respectfully. Fuels E and F fall within the premium market fuels only using the 6.7 to 7.5 RVP criteria.

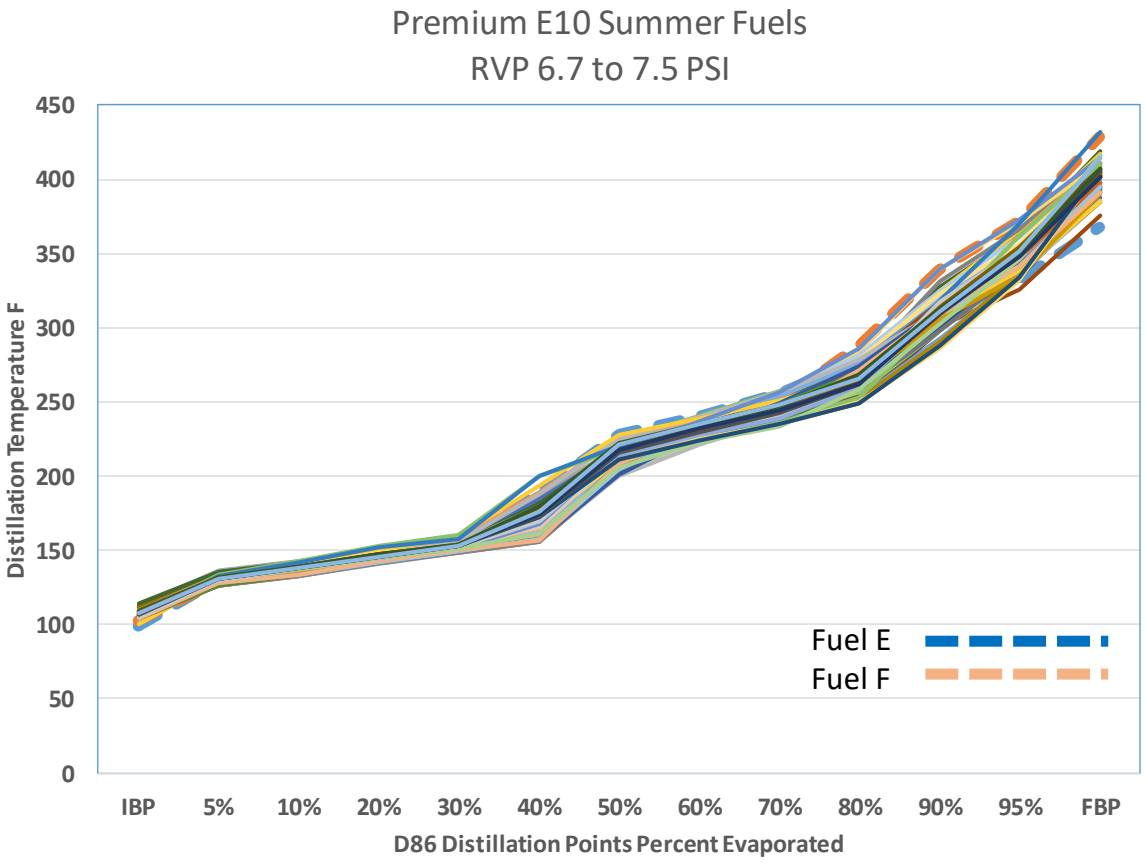


FIGURE B-3: AAM FUEL SURVEY FOR PREMIUM E10 SUMMER FUELS

*NOTE: Data Used with Permission from the Alliance of Automobile Manufacturers. 1. The Alliance of Automobile Manufacturers North American Fuel Survey© data reflect single sample "snapshots" of market fuel properties from retail stations sampled in various cities.
2. The number of stations varies from city to city, and cities and stations can vary from survey to survey.
3. The cities and stations sampled are not selected to meet statistical criteria, or on the basis of market share.
4. Surveys are taken in January (Winter) and July (Summer) of each calendar year.
5. Reports are available through www.autoalliance.org.

APPENDIX C

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.
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 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 40% 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.
9. 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.
10. Move vehicle to test area without starting engine.
11. Perform cold prep cycle (UDDS + HwFET + HwFET + US06). During the prep cycle, apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system.
12. Check vehicle for diagnostic trouble codes (DTC). If new codes are detected the CRC Program Manager will be contacted.
13. 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.
14. Move vehicle to test area without starting engine.
15. Start vehicle and perform LA92 prep cycle.
16. Move vehicle to soak area without starting the engine.
17. Park vehicle in soak area at proper temperature (75 °F) for at least 12 hours and no more than 36 hours. During the soak period, maintain the nominal charge of the vehicle's battery using an appropriate charging device.
18. Move vehicle to test area without starting engine.
19. Perform LA92 cycle emissions test.
20. Move vehicle to soak area without starting the engine.

21. Park vehicle in soak area of proper temperature for 12-36 hours. During the soak period, maintain the nominal charge of the vehicle's battery using an appropriate charging device.
22. Move vehicle to test area without starting the engine.
23. Perform LA92 emissions test.
24. Move vehicle to soak area without starting the engine.
25. Determine whether third replicate is necessary, based on repeatability criteria in Table C-1.
26. 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.

TABLE C-1: REPEATABILITY CRITERIA

	Criteria
THC, g/mi	30%
CO, g/mi	50%
NOx, g/mi	50%

APPENDIX D

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. It is required to demonstrate that the catalyst inlet temperature must exceed 700°C during the wide-open throttle (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).

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 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 five (5) WOT excursions.
6. One sulfur removal cycle has been completed.
7. Repeat steps 1 to 5 for the second sulfur removal cycle.

APPENDIX E

COMPLETE EMISSIONS RESULTS

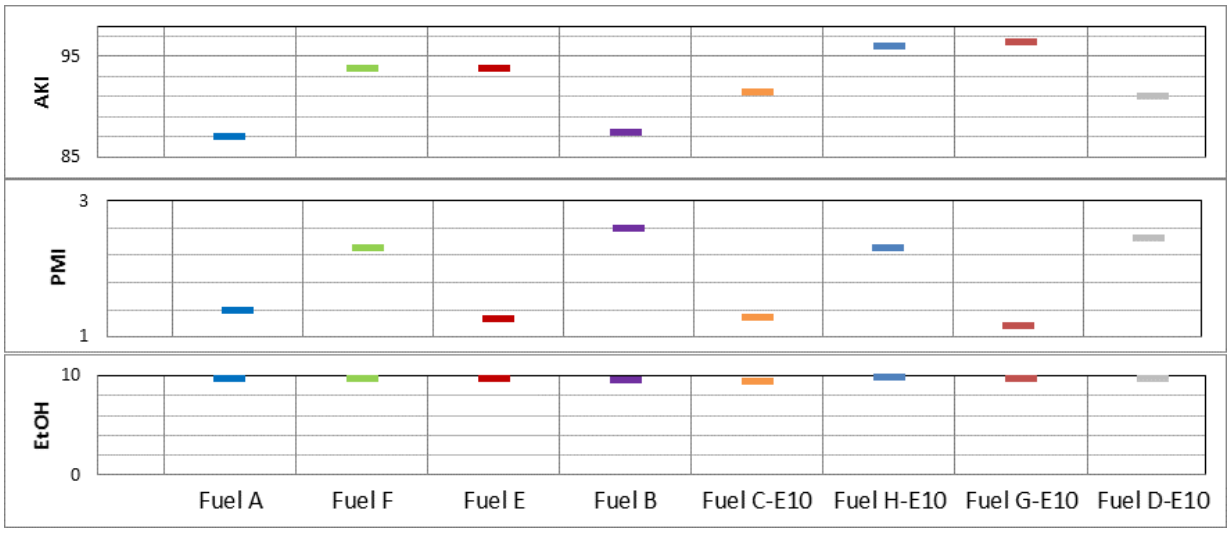


FIGURE E-1: FUEL LEDGEND

Gaseous Emissions

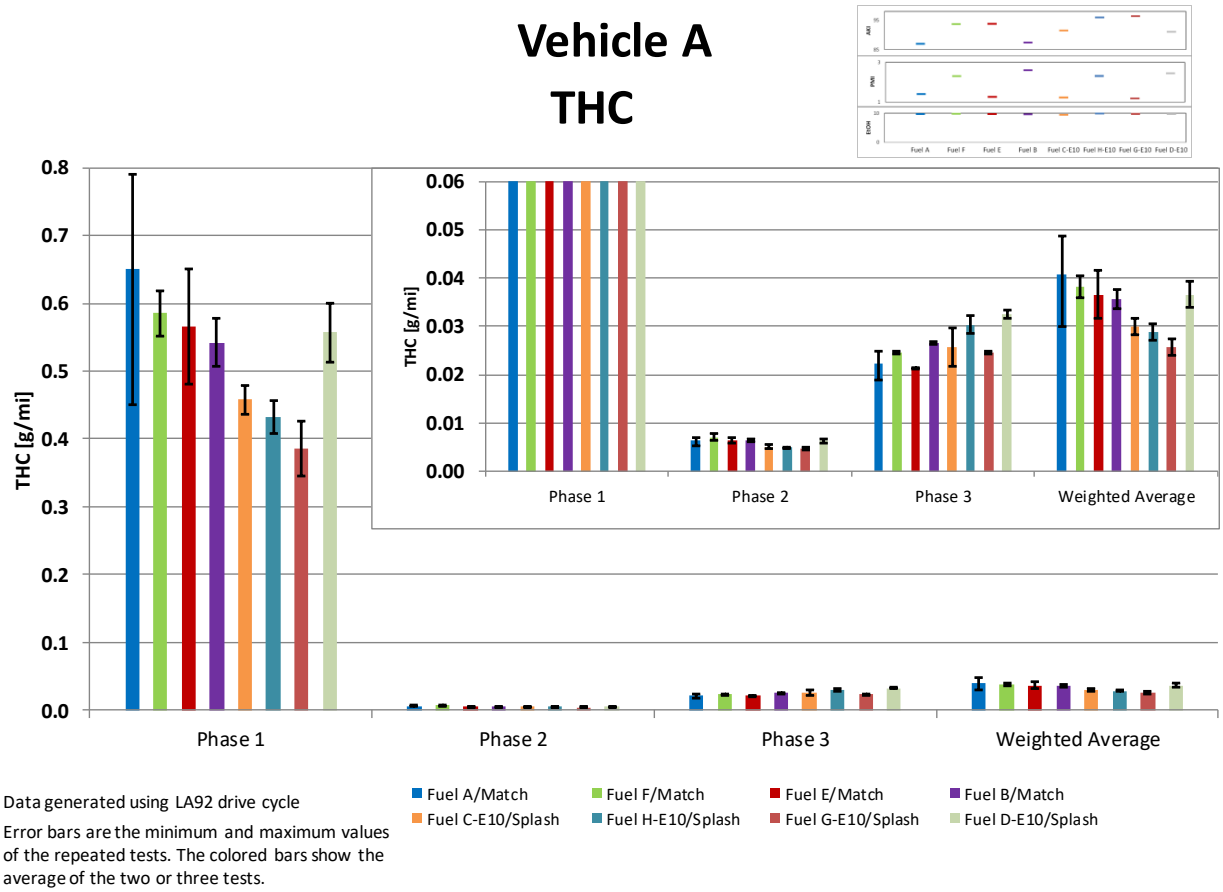
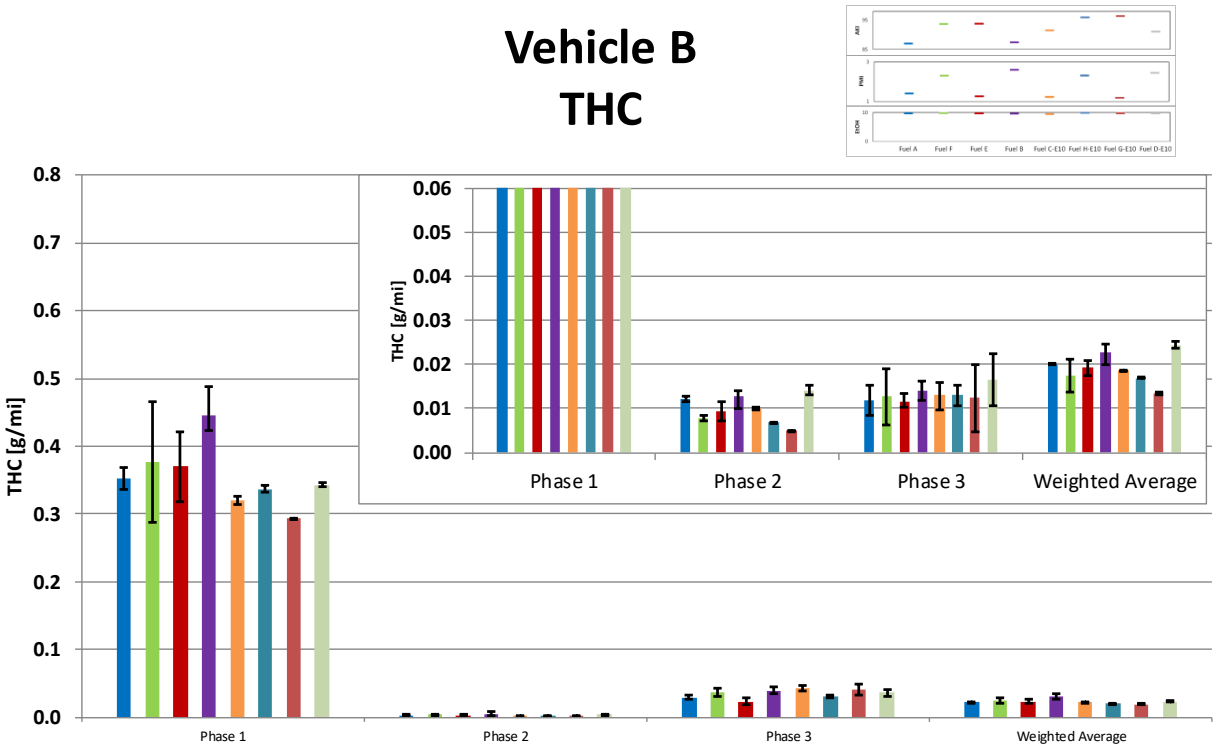


FIGURE E-1: THC EMISSIONS FOR VEHICLE A



Data generated using LA92 drive cycle

Error bars are the minimum and maximum values of the repeated tests. The colored bars show the average of the two or three tests.

Fuel A/Match
Fuel F/Match
Fuel E/Match
Fuel B/Match
Fuel C-E10/Splash
Fuel H-E10/Splash
Fuel G-E10/Splash
Fuel D-E10/Splash

FIGURE E-2: THC EMISSIONS FOR VEHICLE B

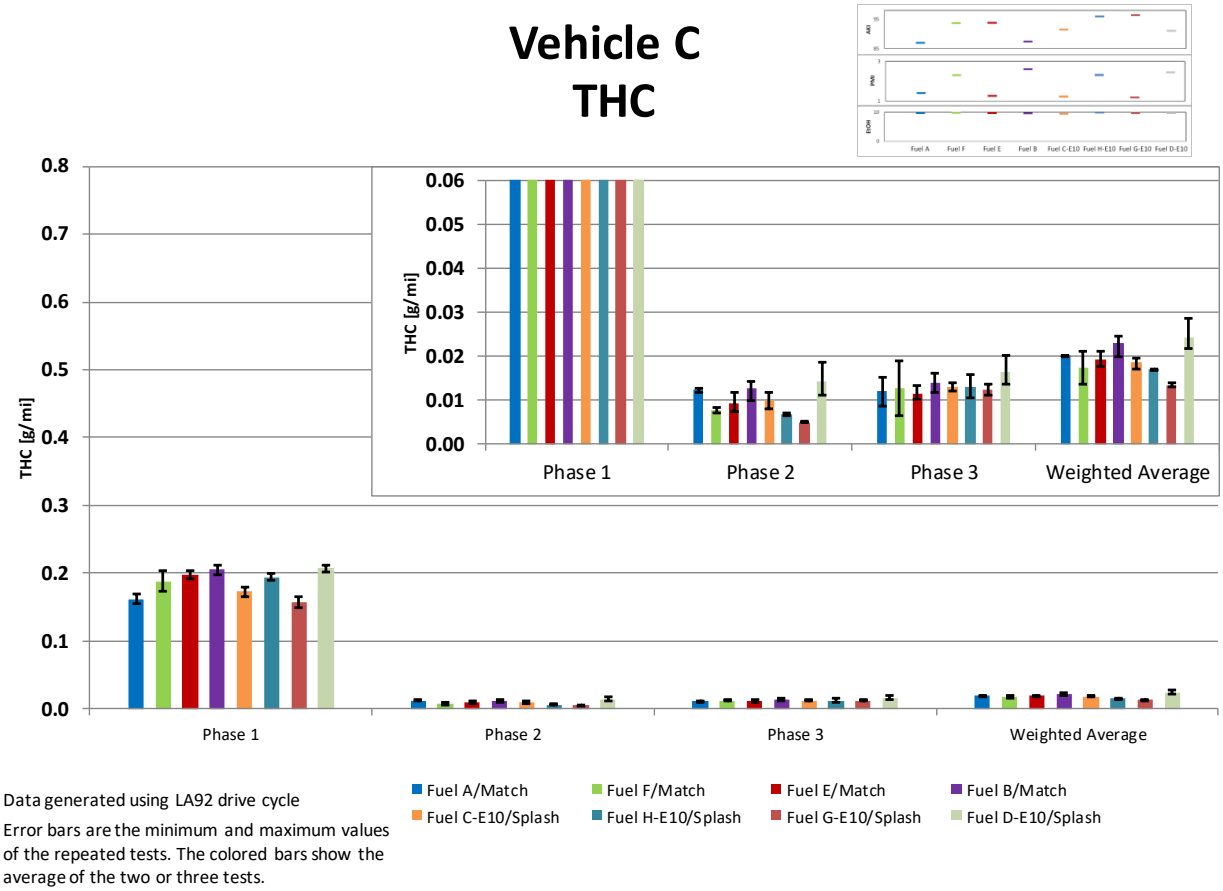


FIGURE E-3: THC EMISSIONS FOR VEHICLE C

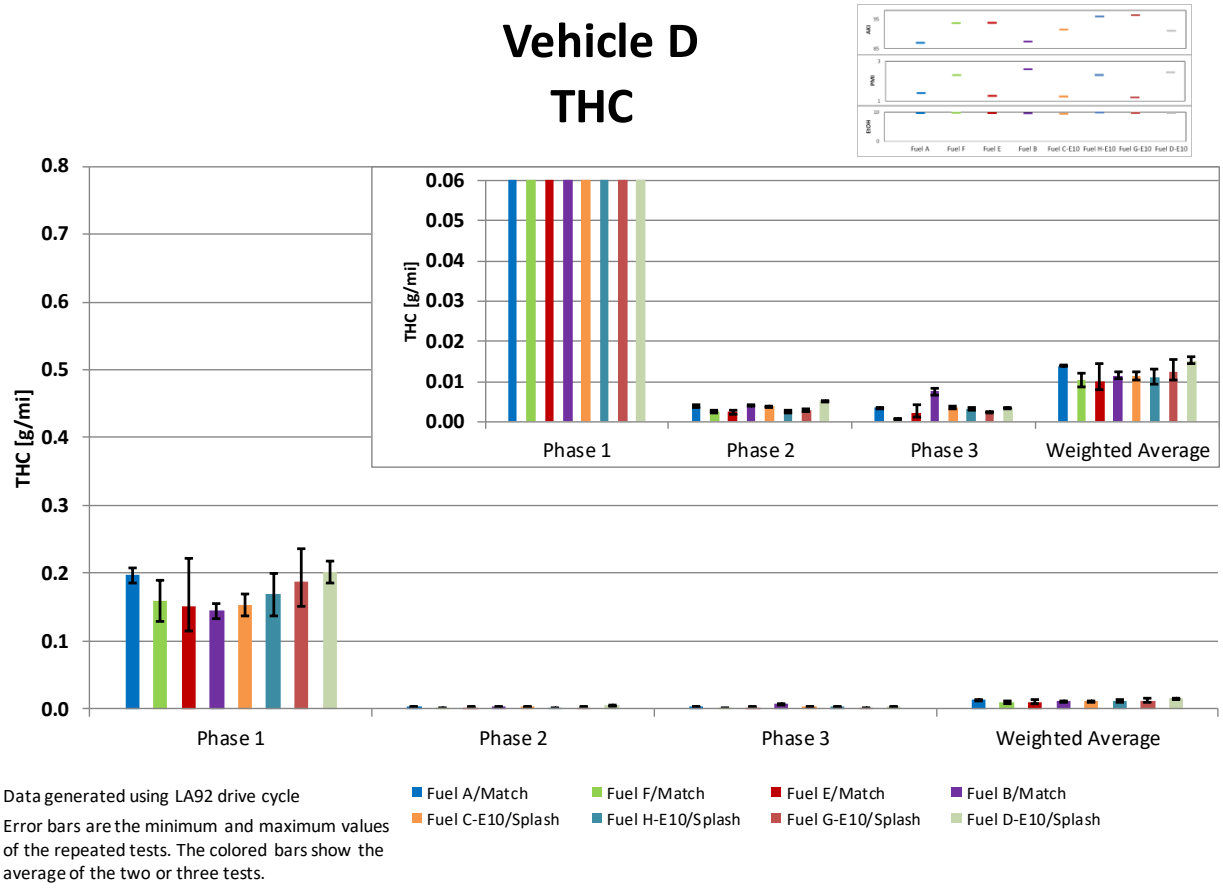


FIGURE E-4: THC EMISSIONS FOR VEHICLE D

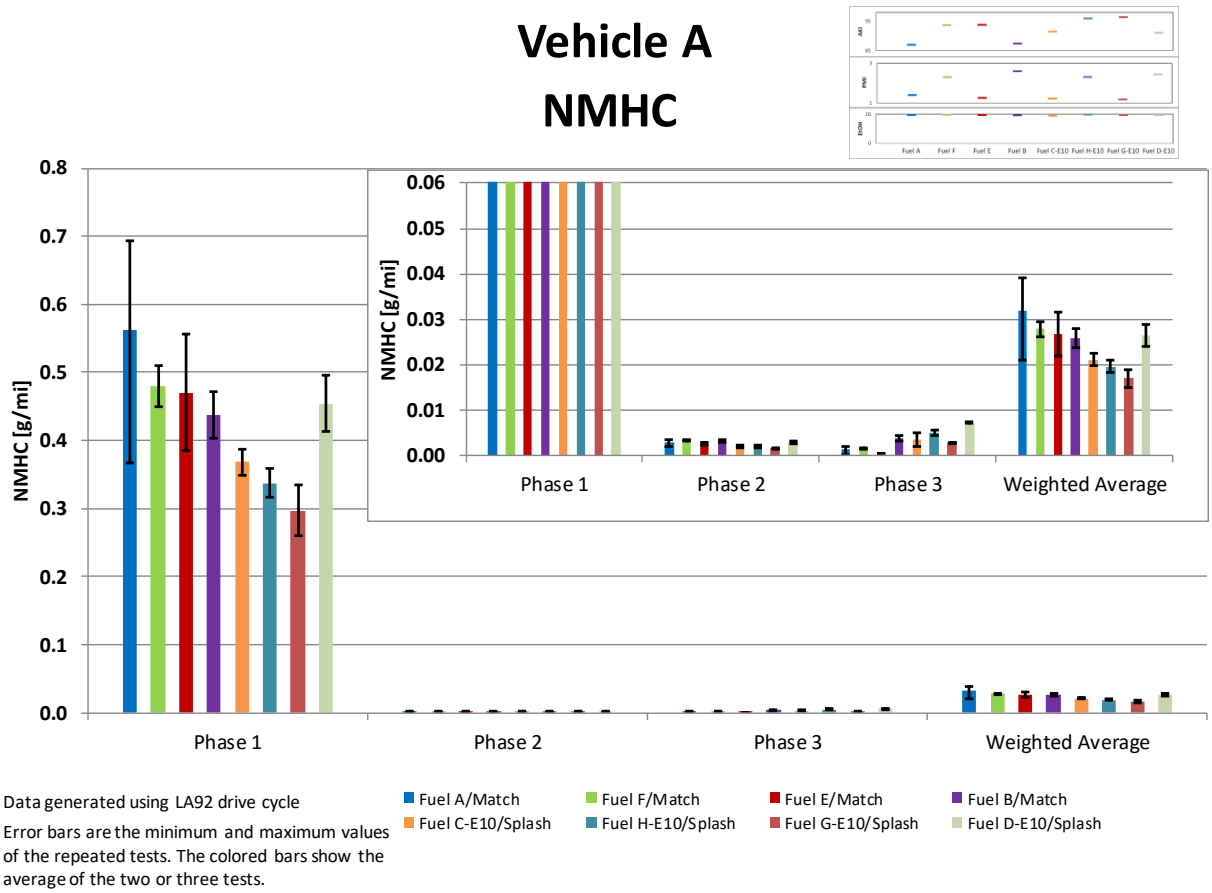


FIGURE E-5: NMHC EMISSIONS FOR VEHICLE A

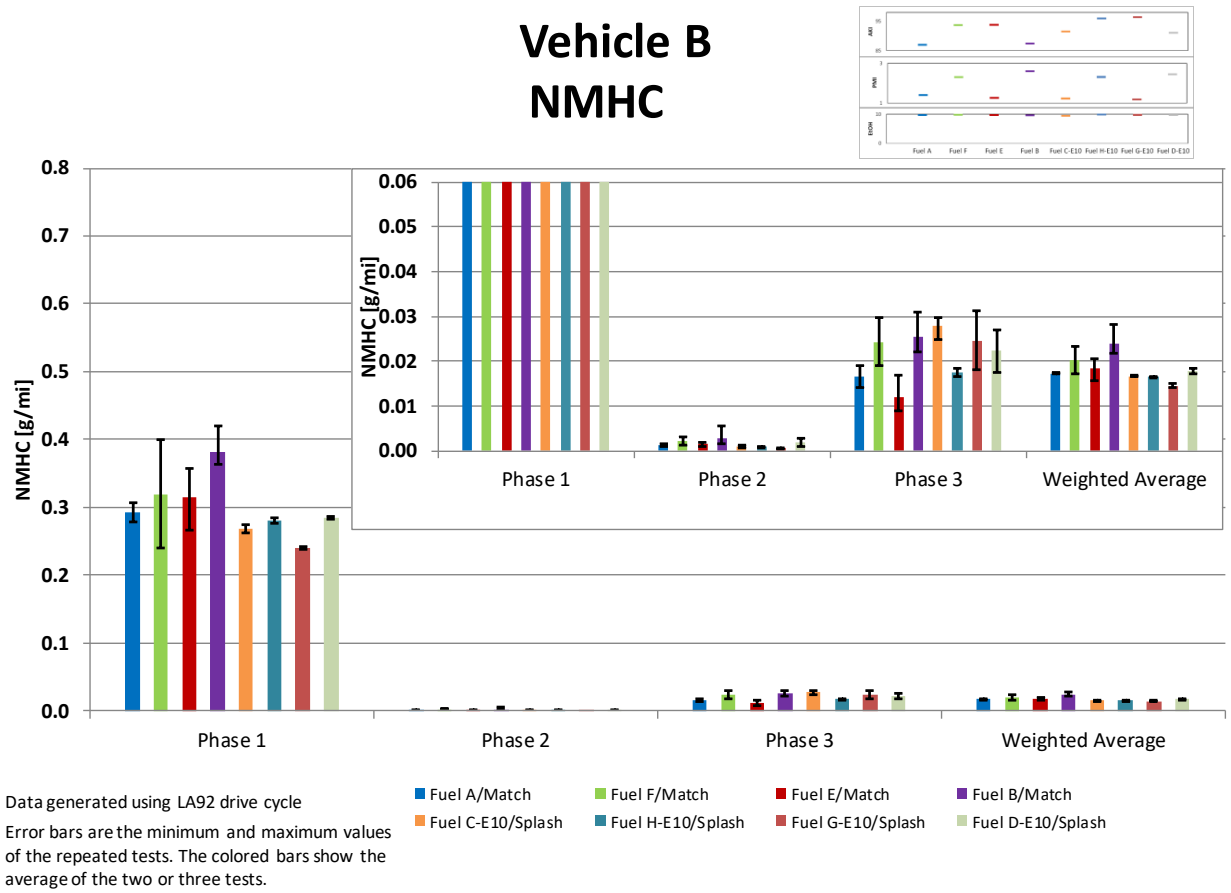


FIGURE E-6: NMHC EMISSIONS FOR VEHICLE B

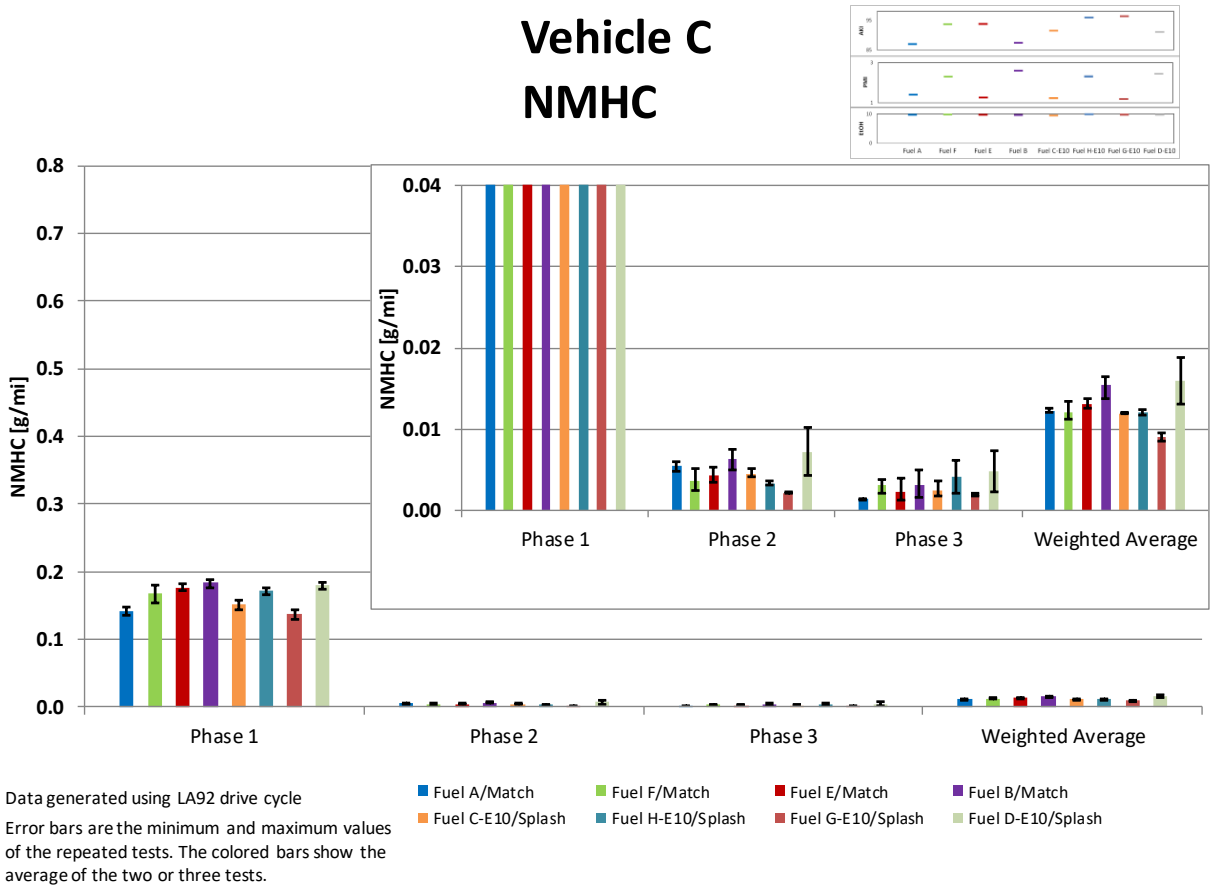


FIGURE E-7: NMHC EMISSIONS FOR VEHICLE C

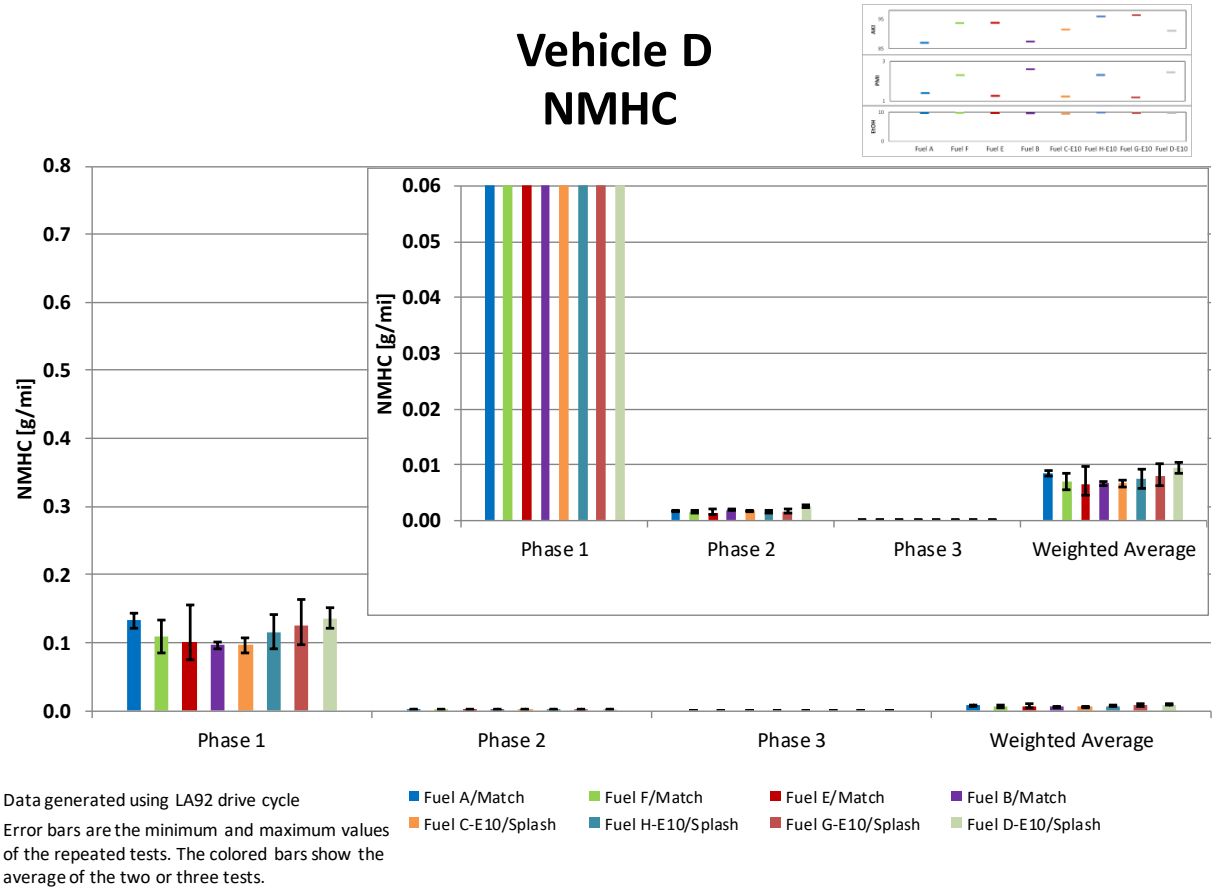


FIGURE E-8: NMHC EMISSIONS FOR VEHICLE D

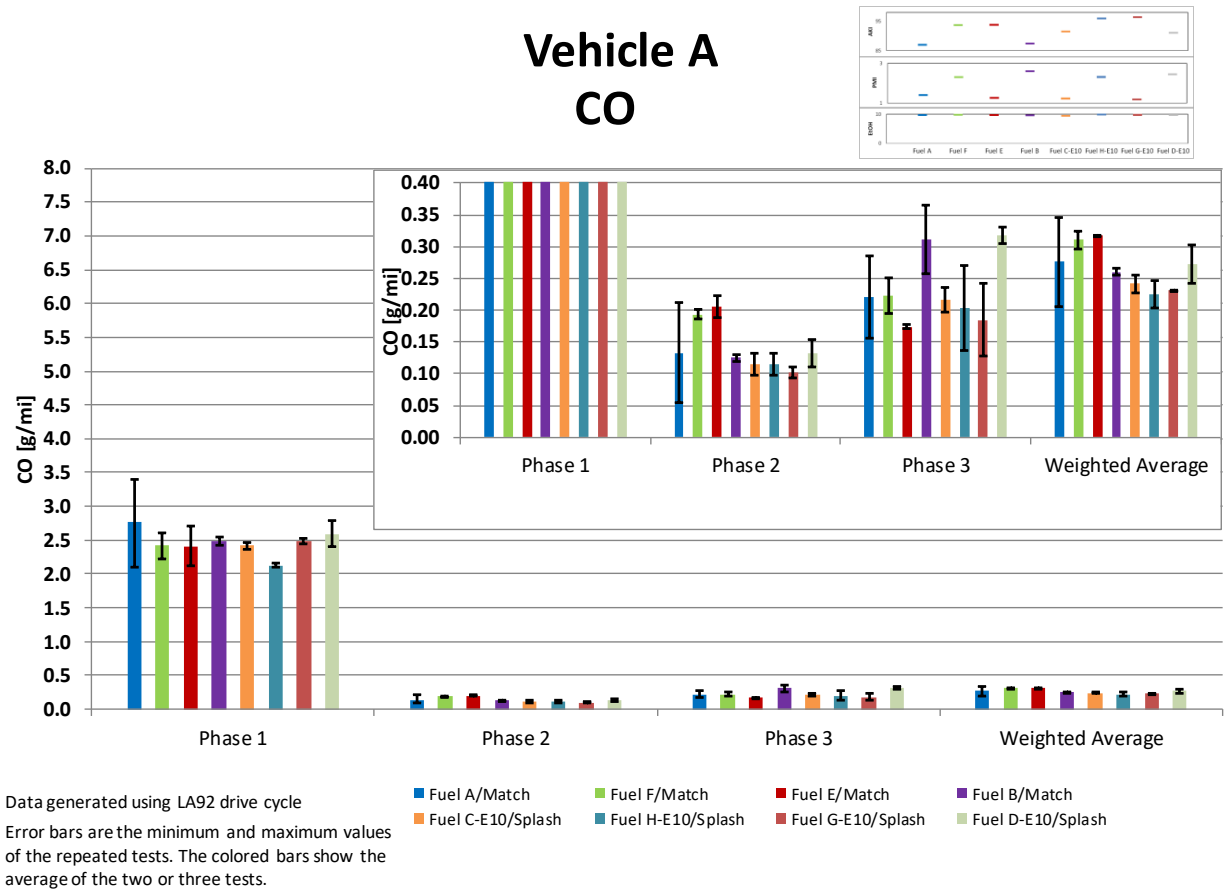


FIGURE E-9: CO EMISSIONS FOR VEHICLE A

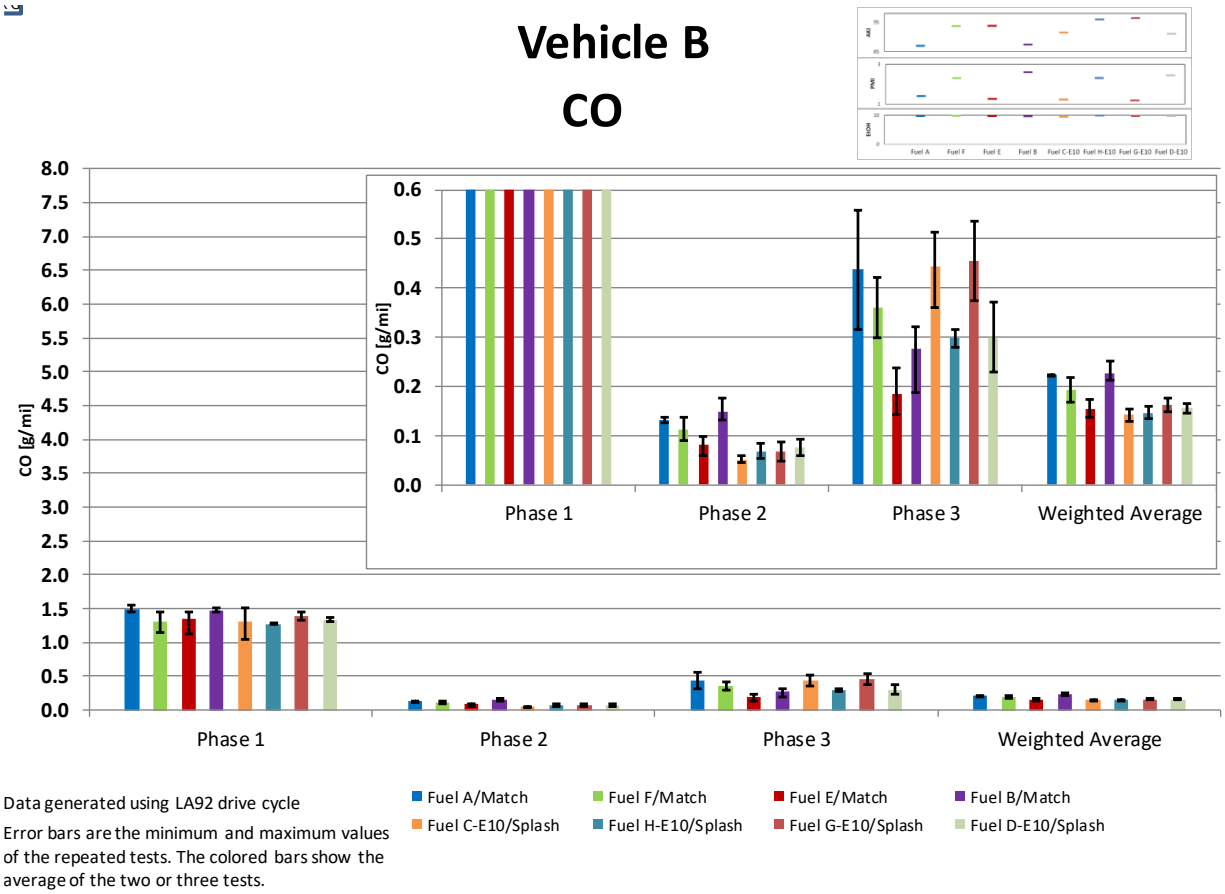


FIGURE E-10: CO EMISSIONS FOR VEHICLE B

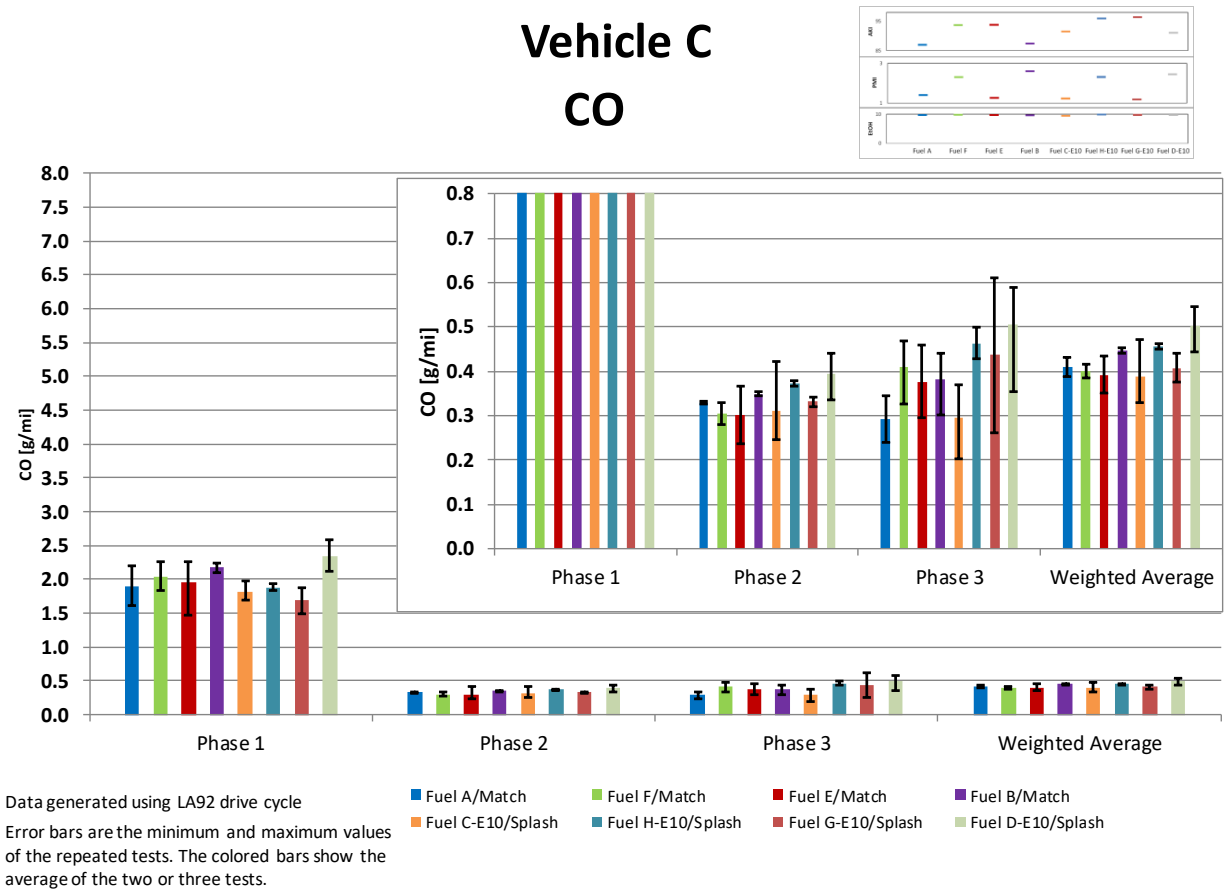


FIGURE E-11: CO EMISSIONS FOR VEHICLE C

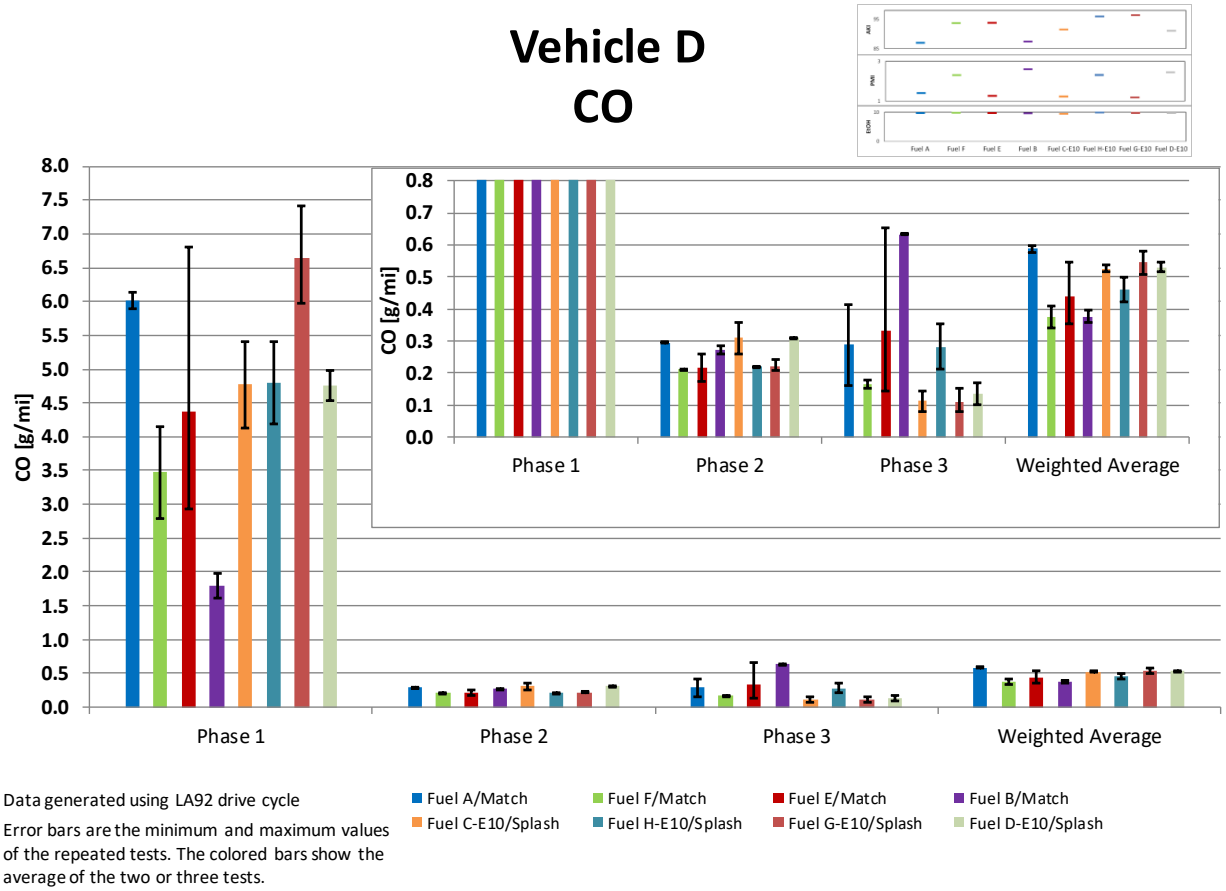


FIGURE E-12: CO EMISSIONS FOR VEHICLE D

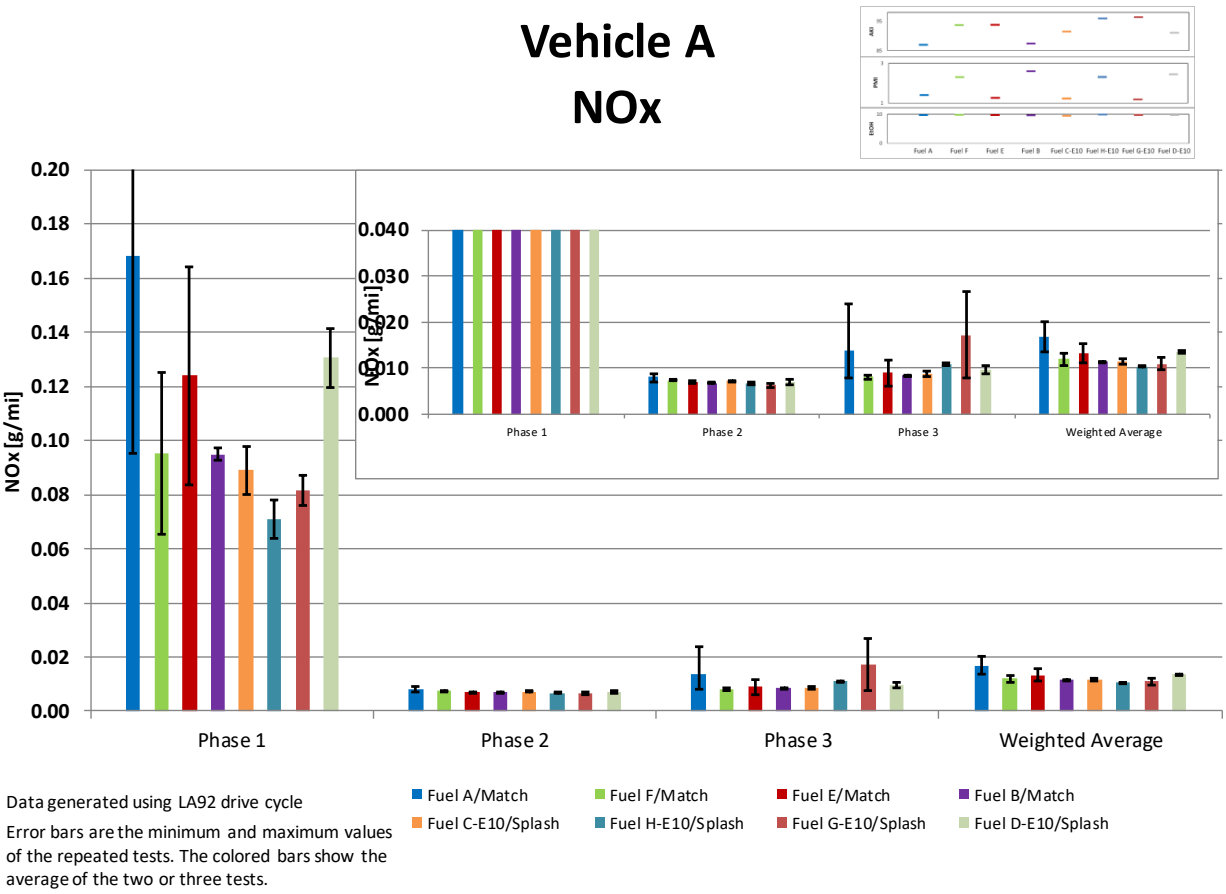


FIGURE E-13: NO_X EMISSIONS FOR VEHICLE A

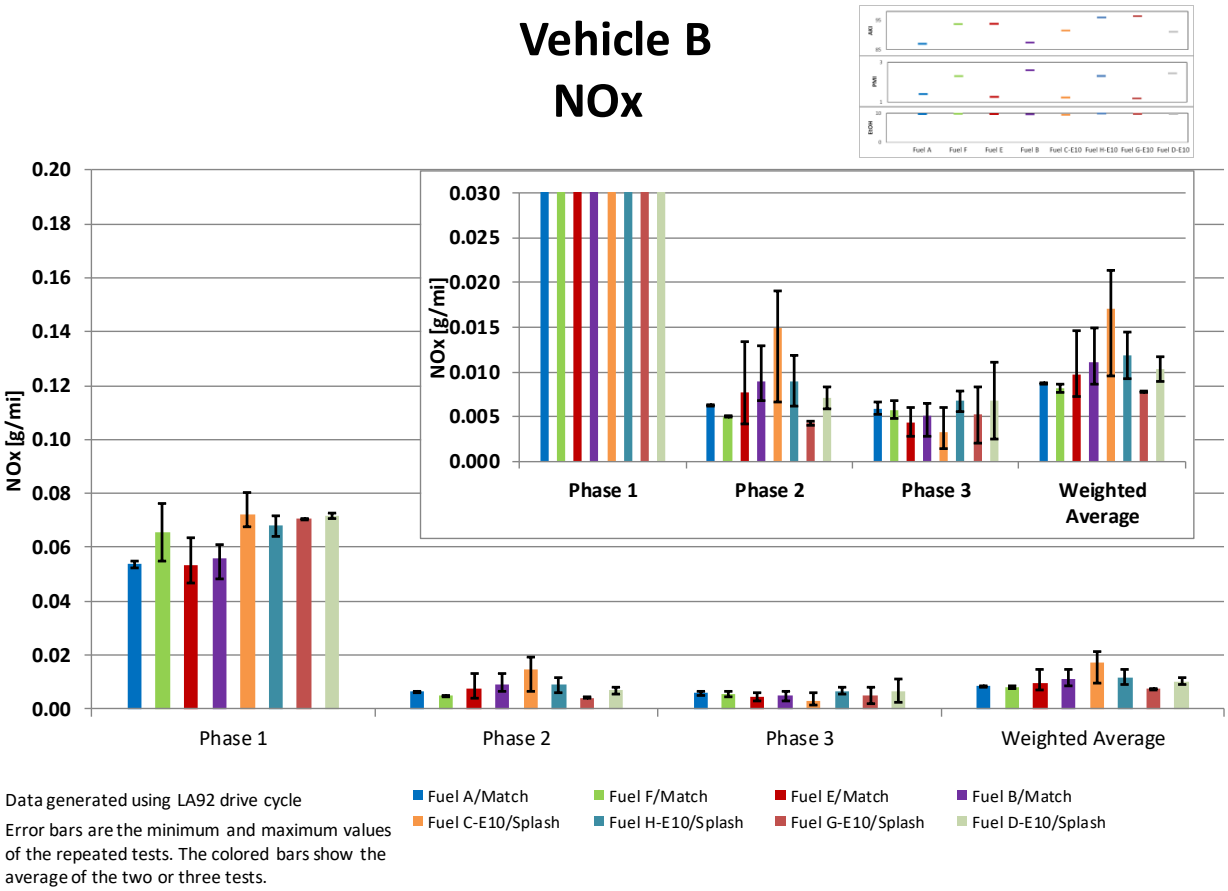


FIGURE E-14: NO_X EMISSIONS FOR VEHICLE B

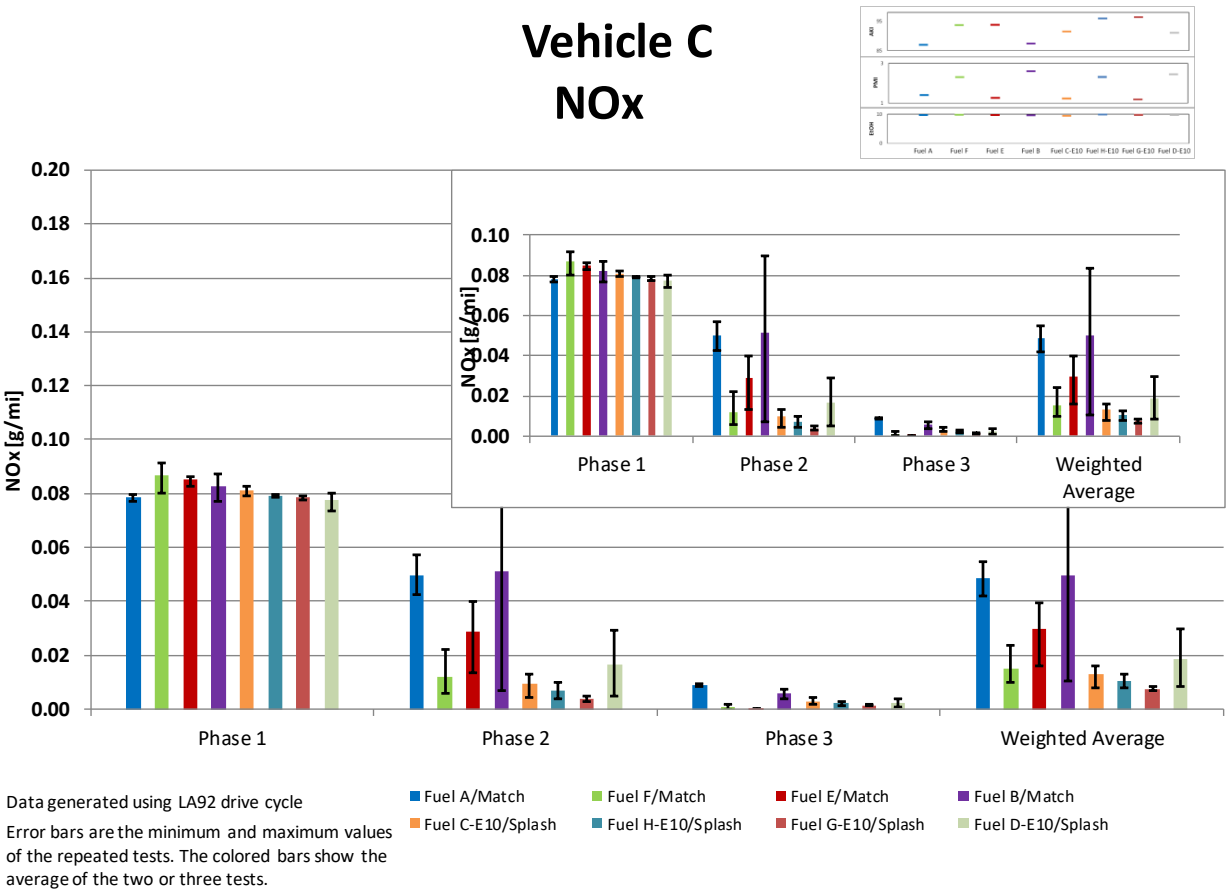


FIGURE E-15: NO_X EMISSIONS FOR VEHICLE C

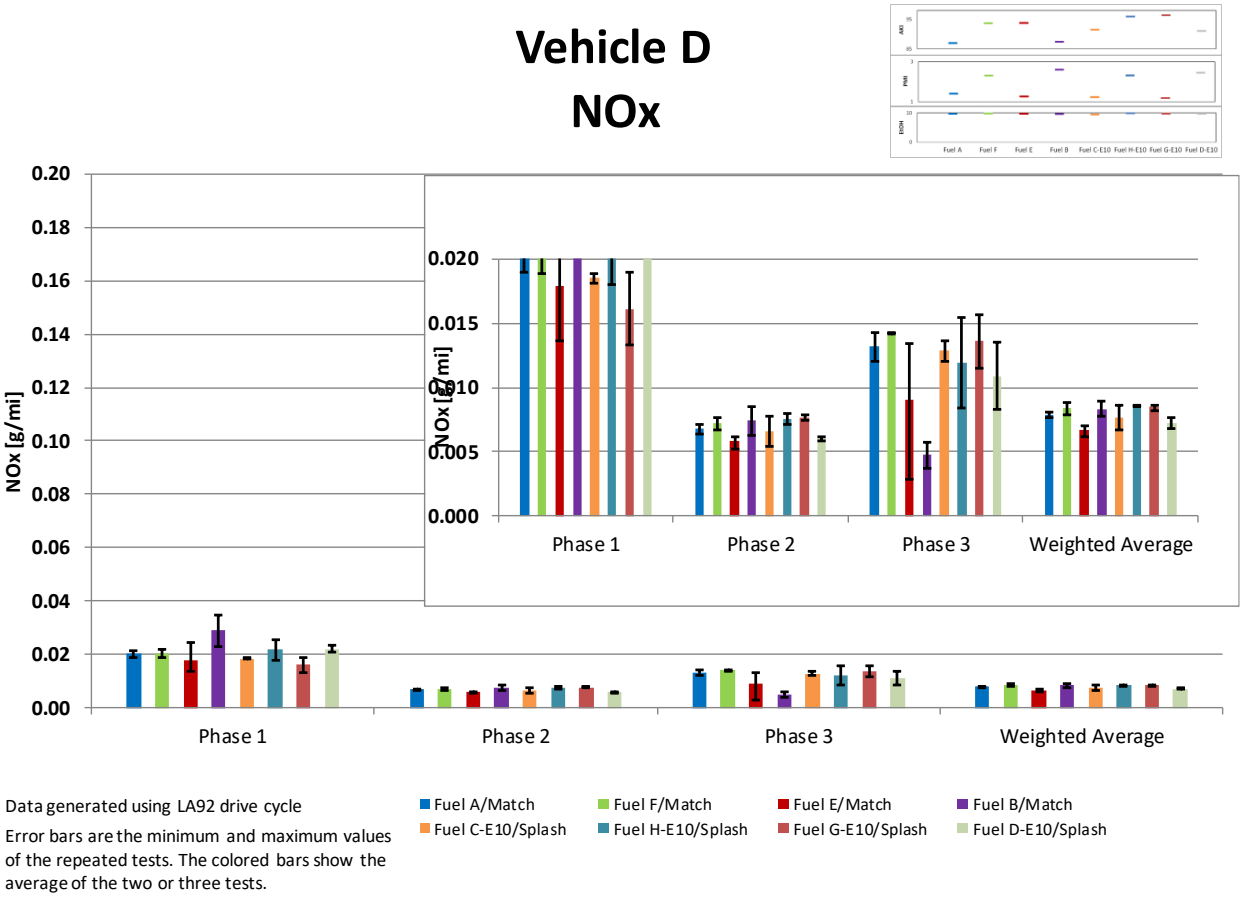


FIGURE E-16: NO_X EMISSIONS FOR VEHICLE D

Particle Emissions

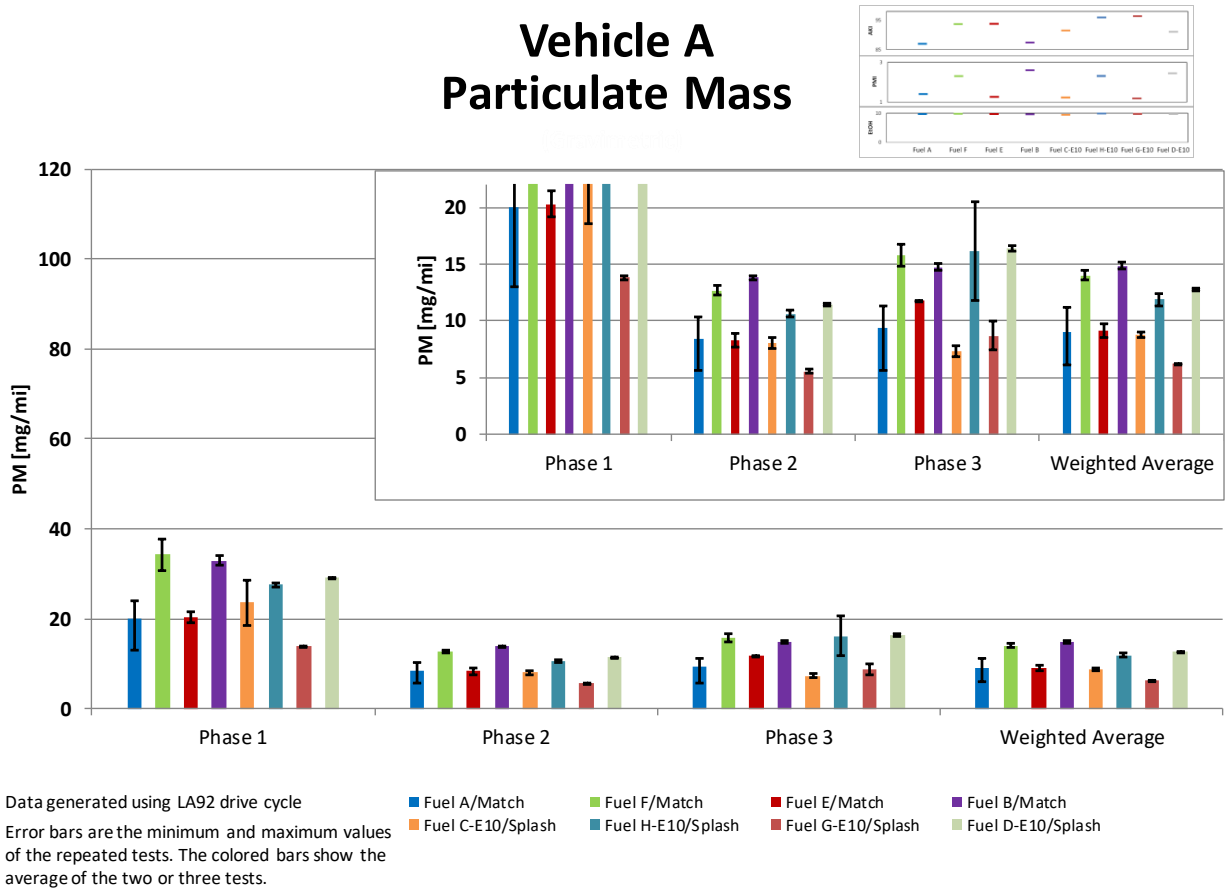


FIGURE E-17: PM EMISSIONS FOR VEHICLE A

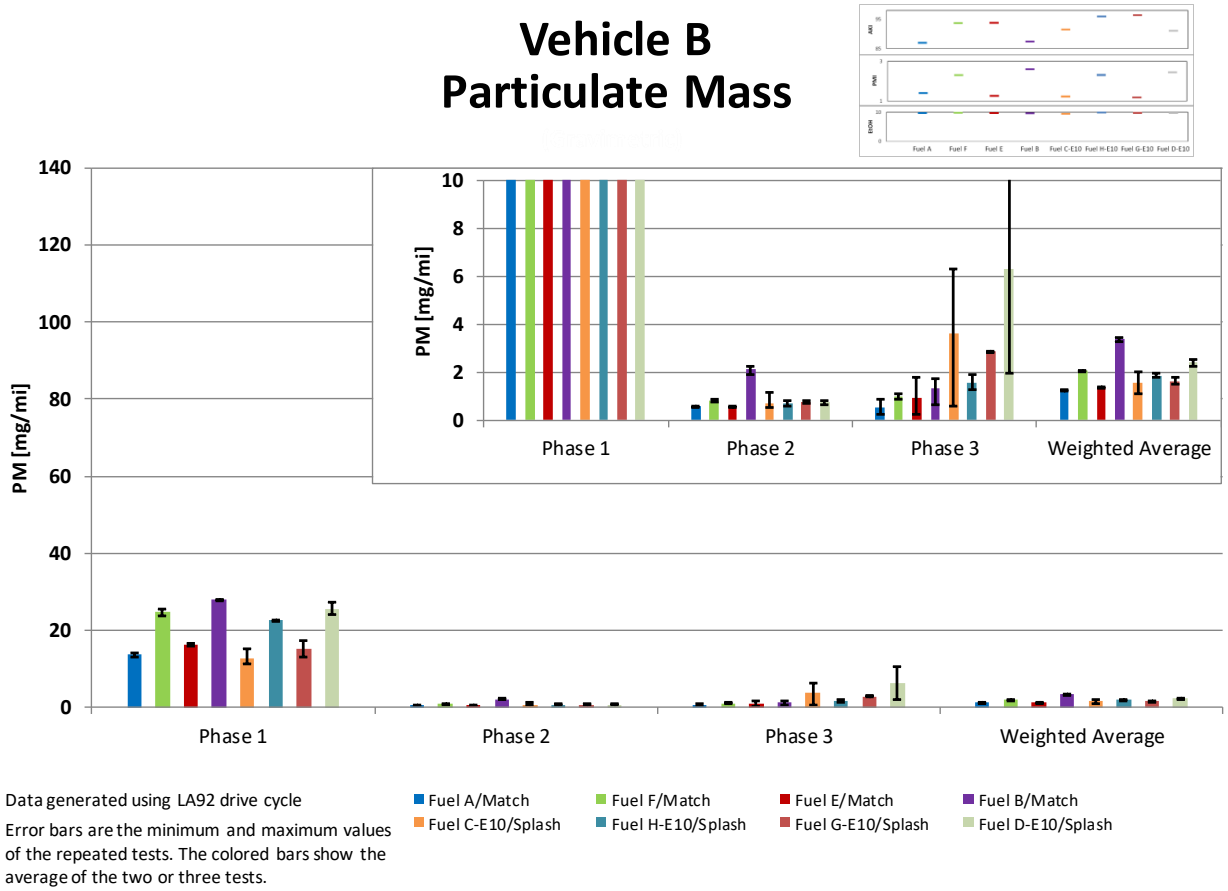


FIGURE E-18: PM EMISSIONS FOR VEHICLE B

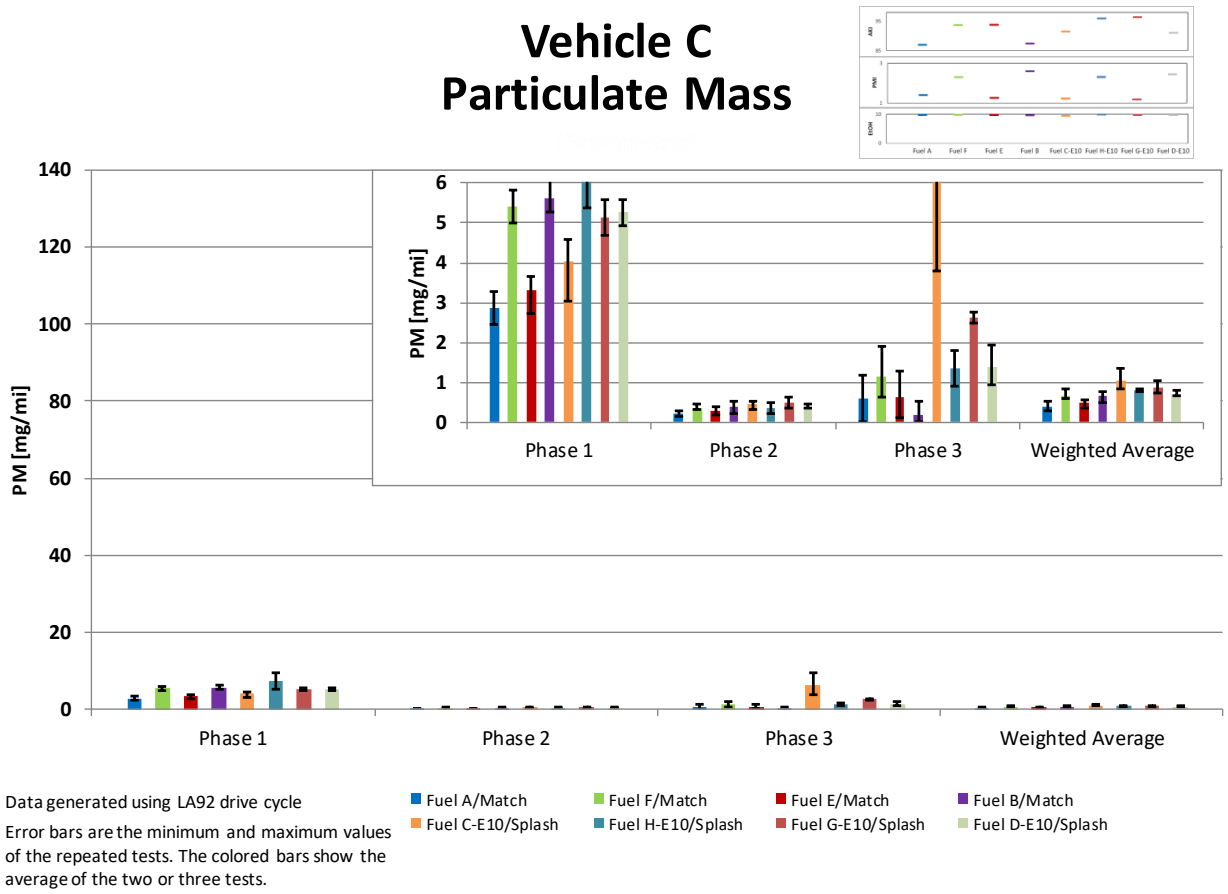


FIGURE E-19: PM EMISSIONS FOR VEHICLE C

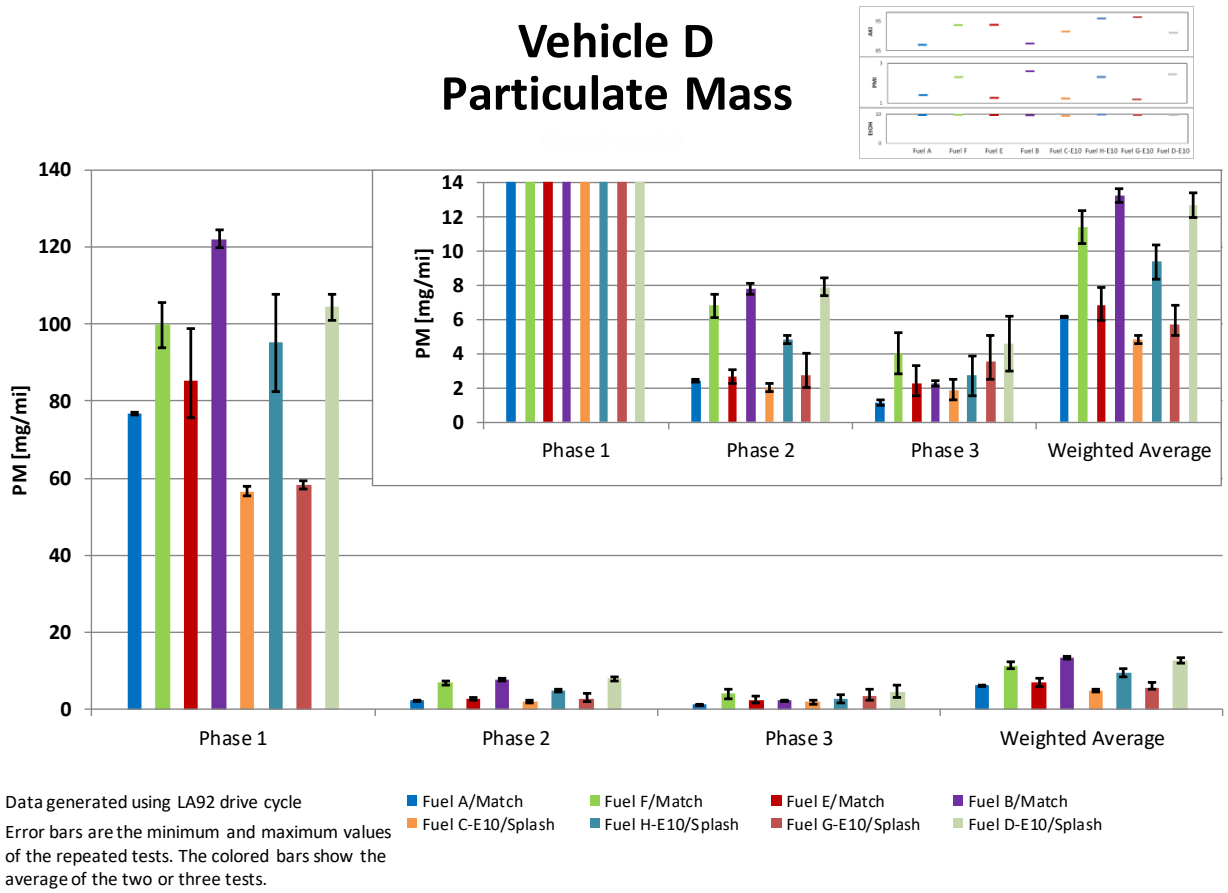


FIGURE E-20: PM EMISSIONS FOR VEHICLE D

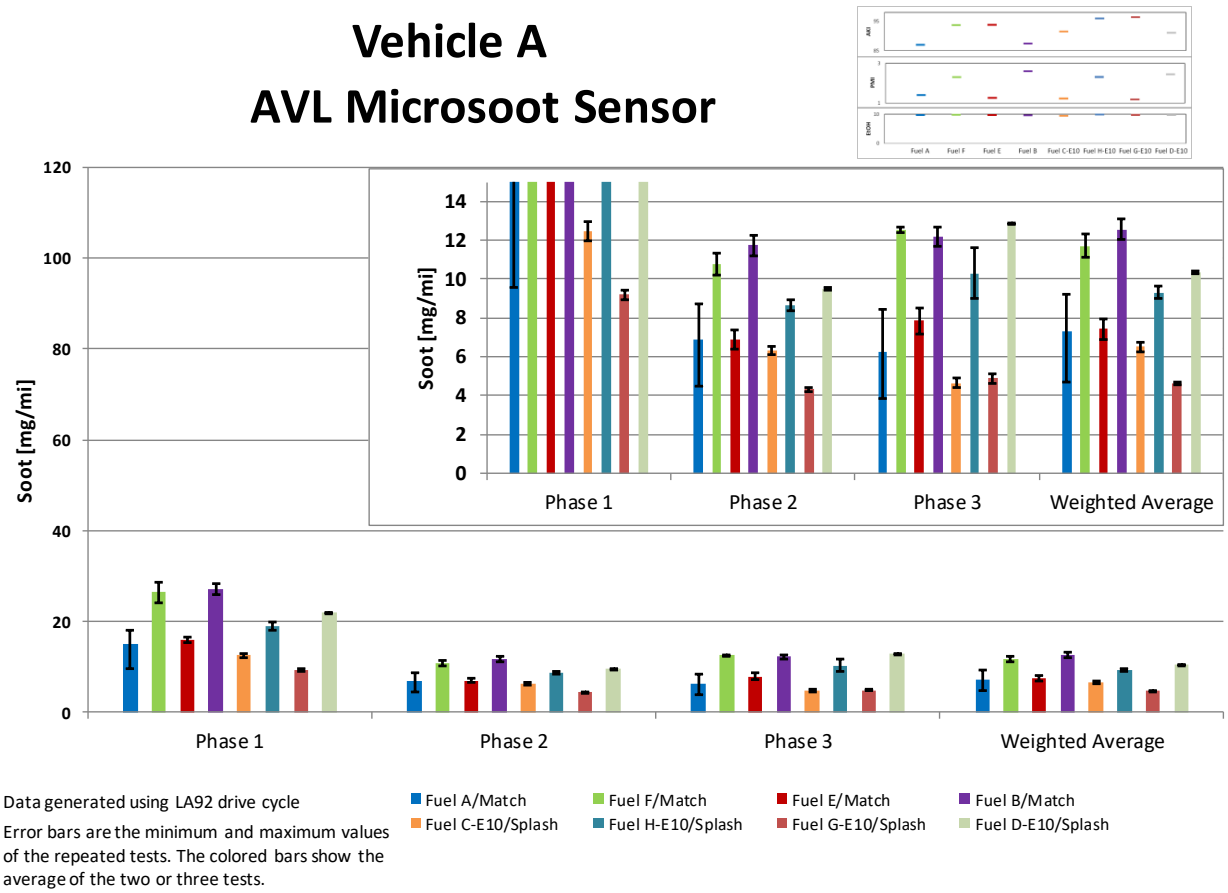


FIGURE E-21: MSS EMISSIONS FOR VEHICLE A

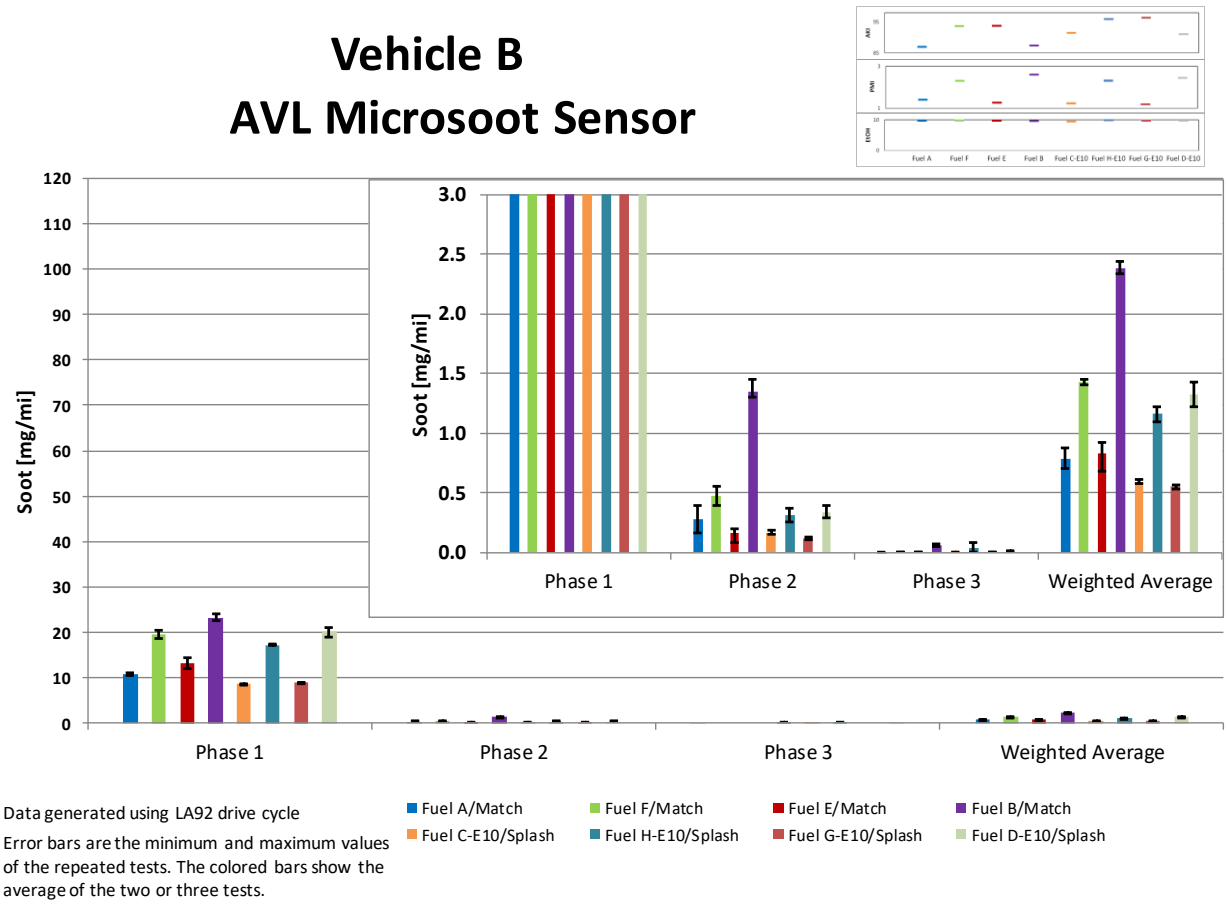


FIGURE E-22: MSS EMISSIONS FOR VEHICLE B

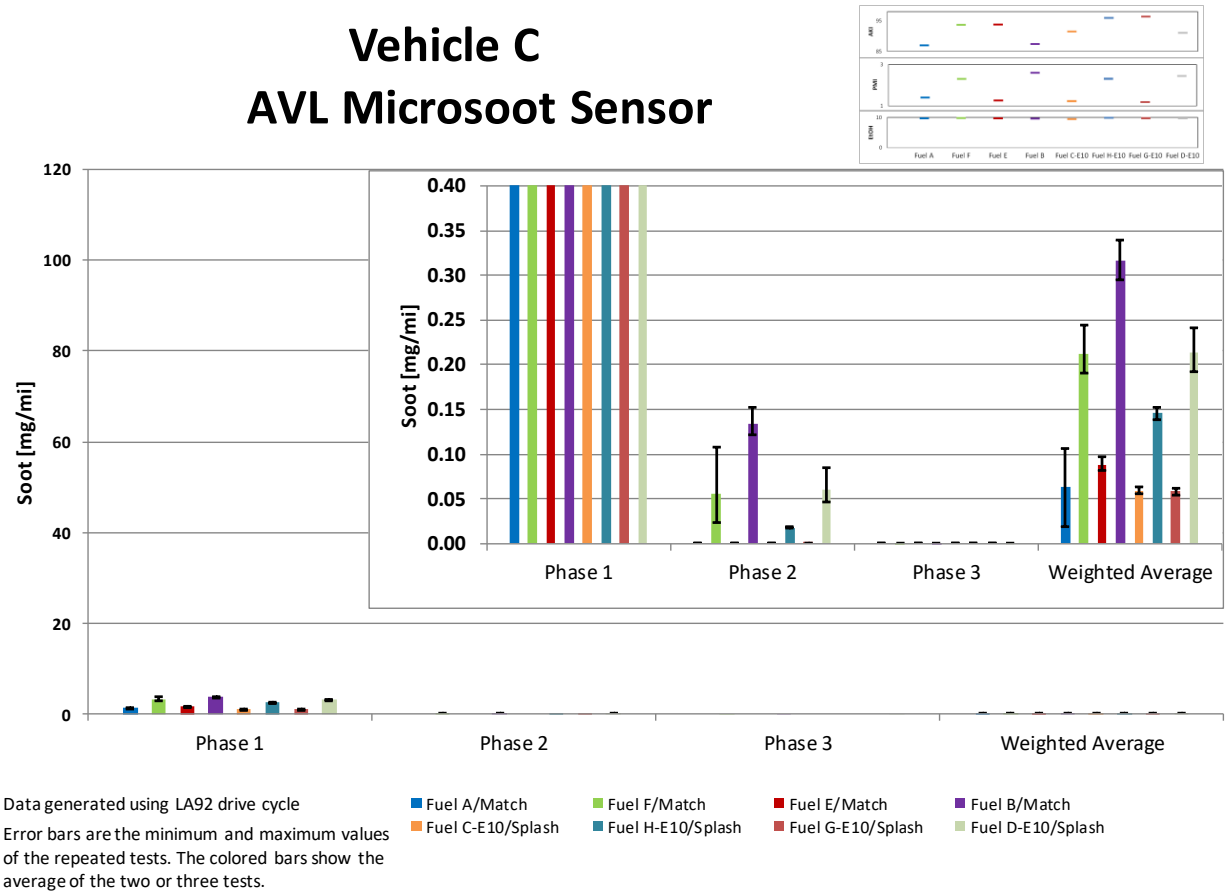


FIGURE E-23: MSS EMISSIONS FOR VEHICLE C

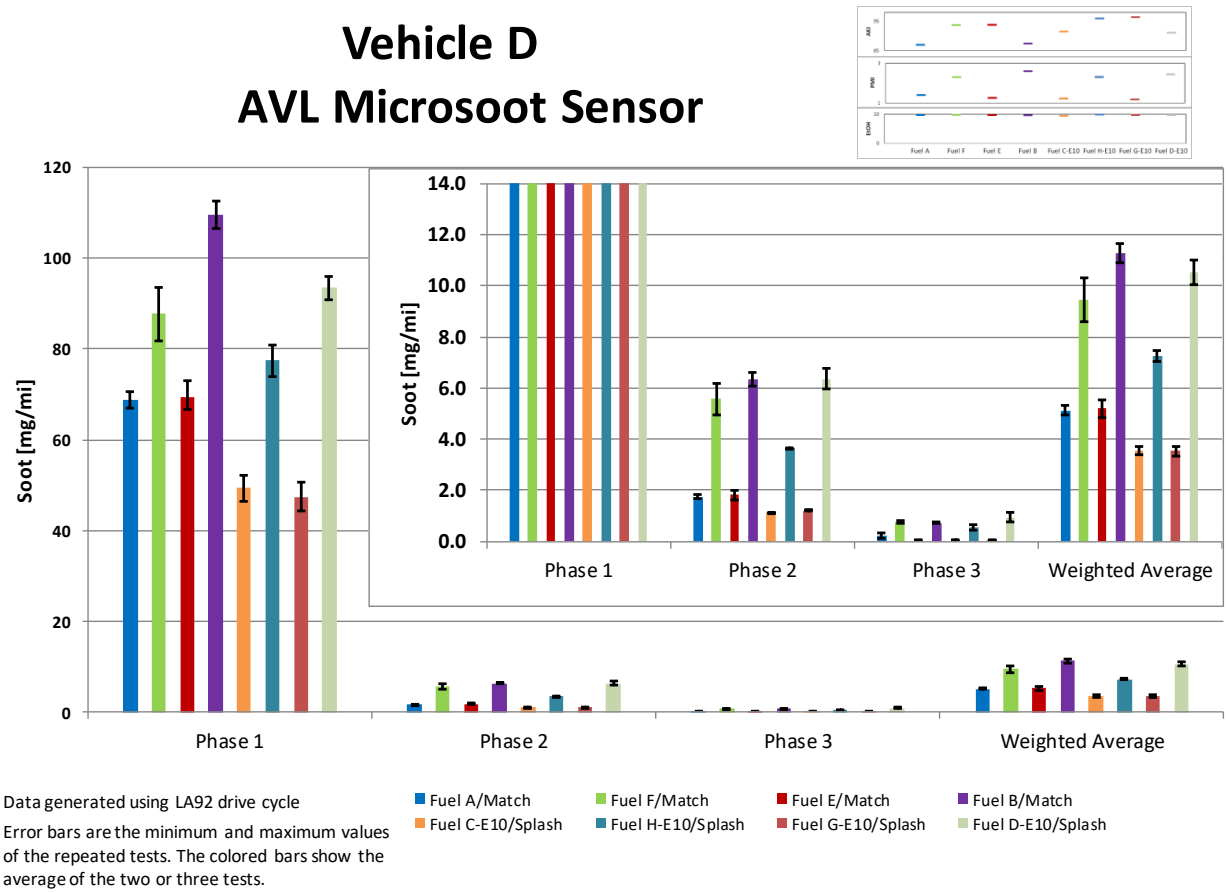


FIGURE E-24: MSS EMISSIONS FOR VEHICLE D

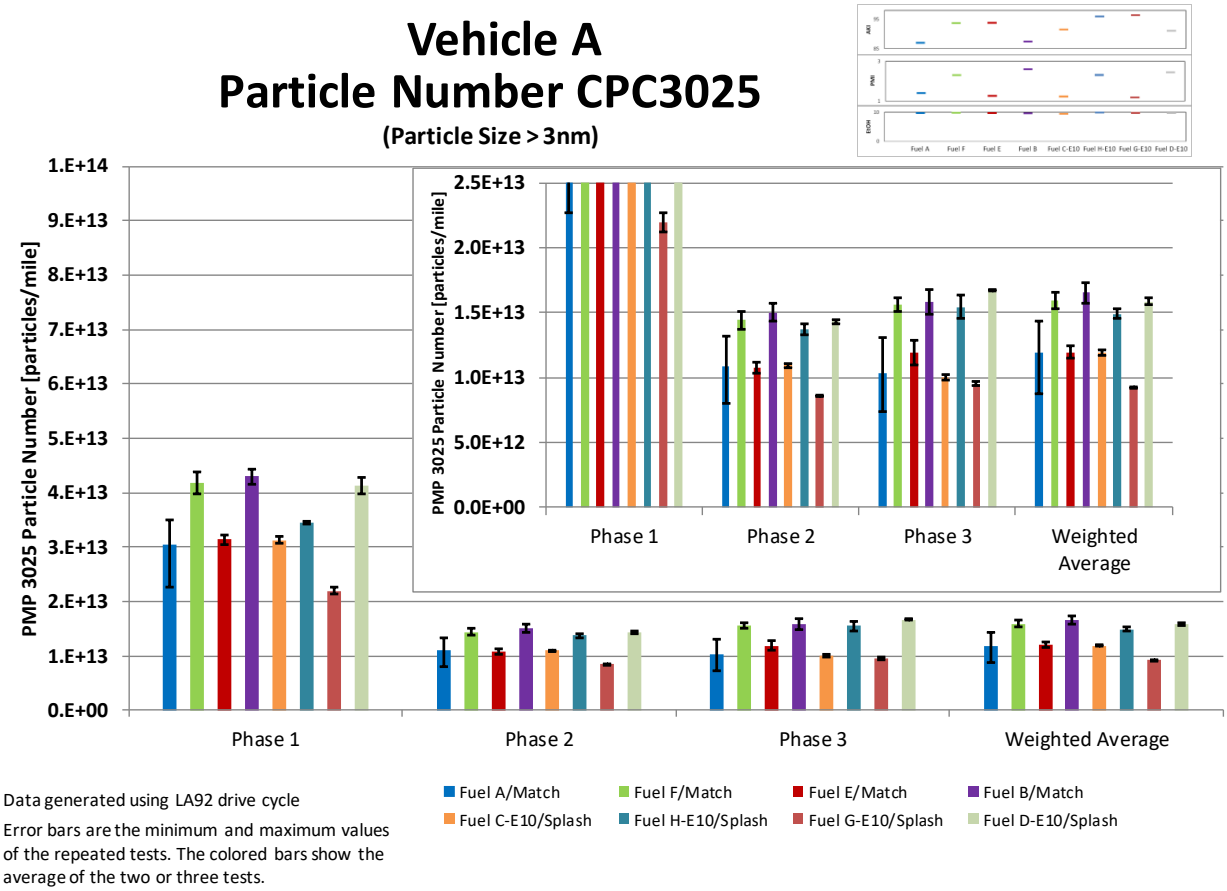


FIGURE E-25: CPC 3025 EMISSIONS FOR VEHICLE A

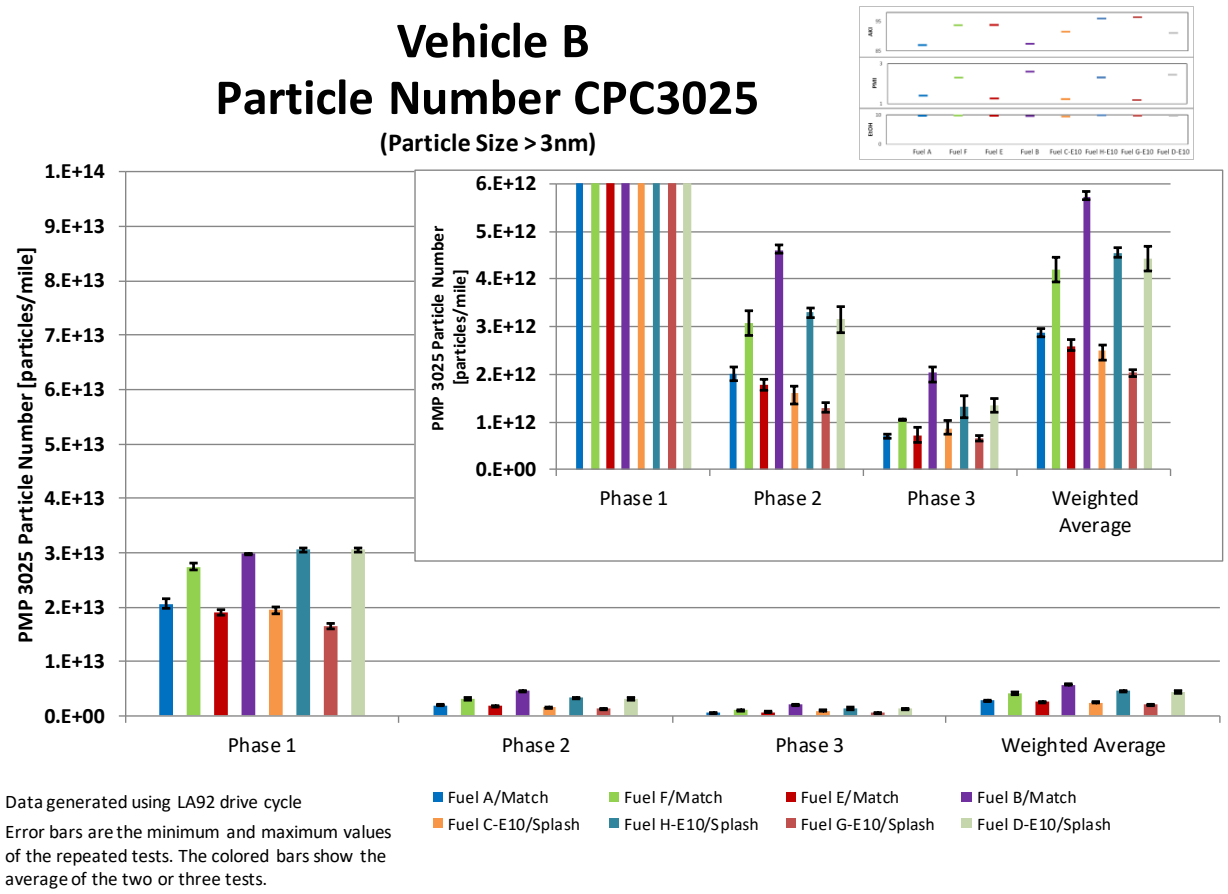


FIGURE E-26: CPC 3025 EMISSIONS FOR VEHICLE B

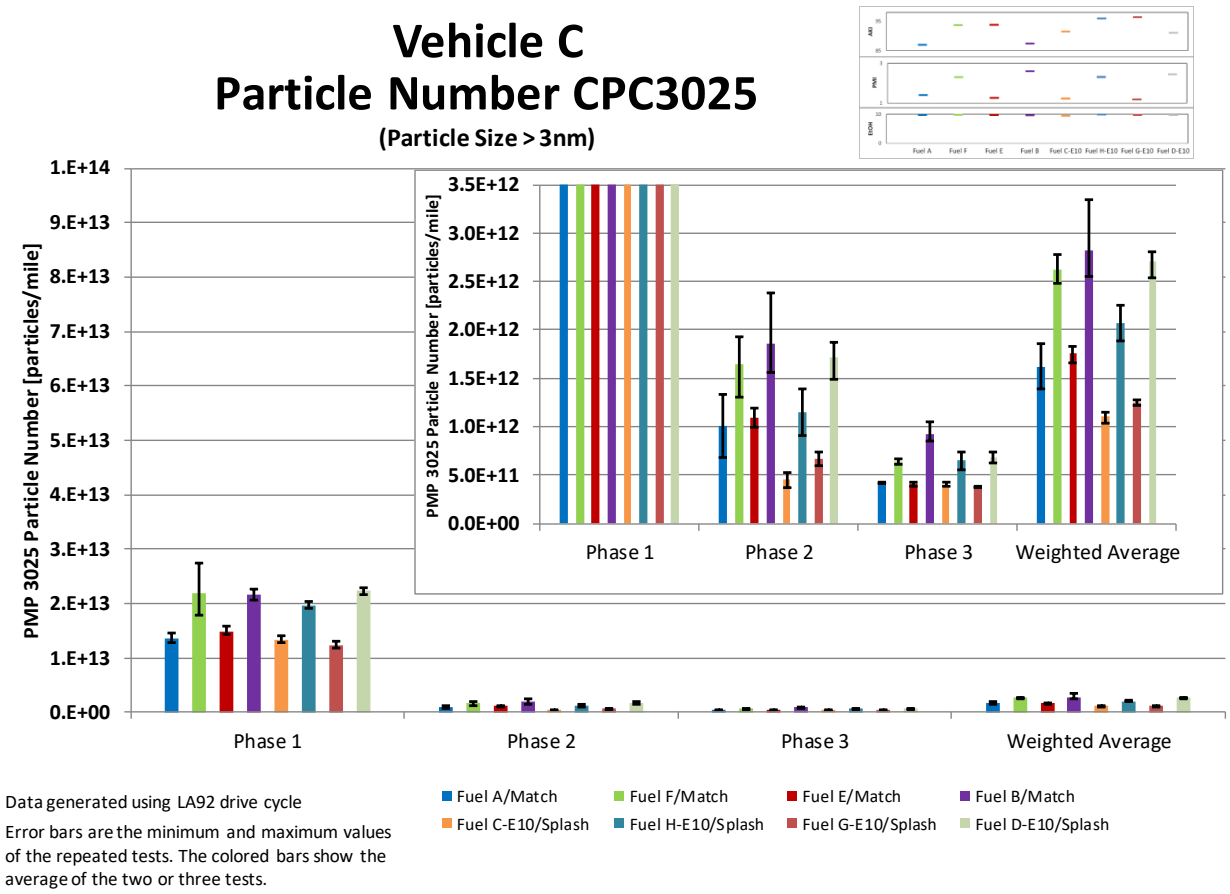


FIGURE E-27: CPC 3025 EMISSIONS FOR VEHICLE C

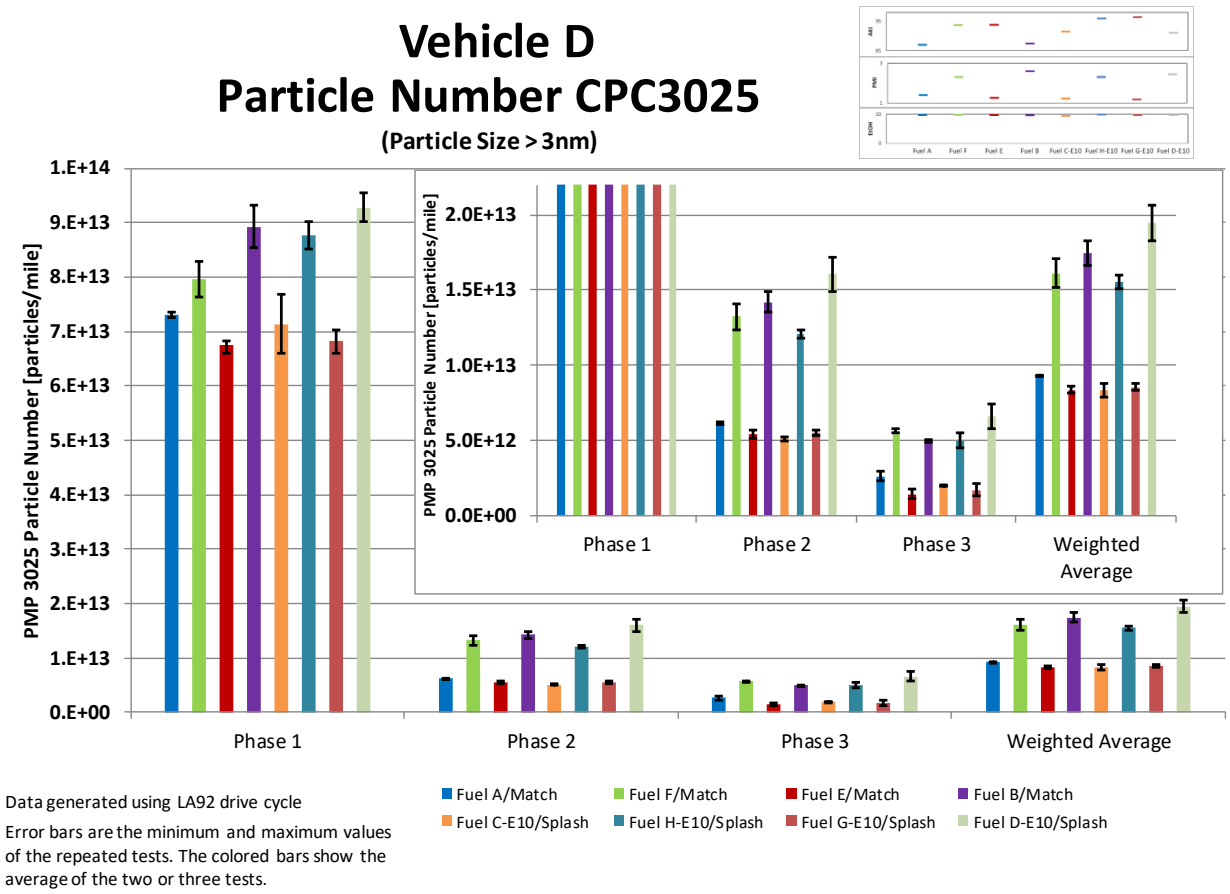


FIGURE E-28: CPC 3025 EMISSIONS FOR VEHICLE D

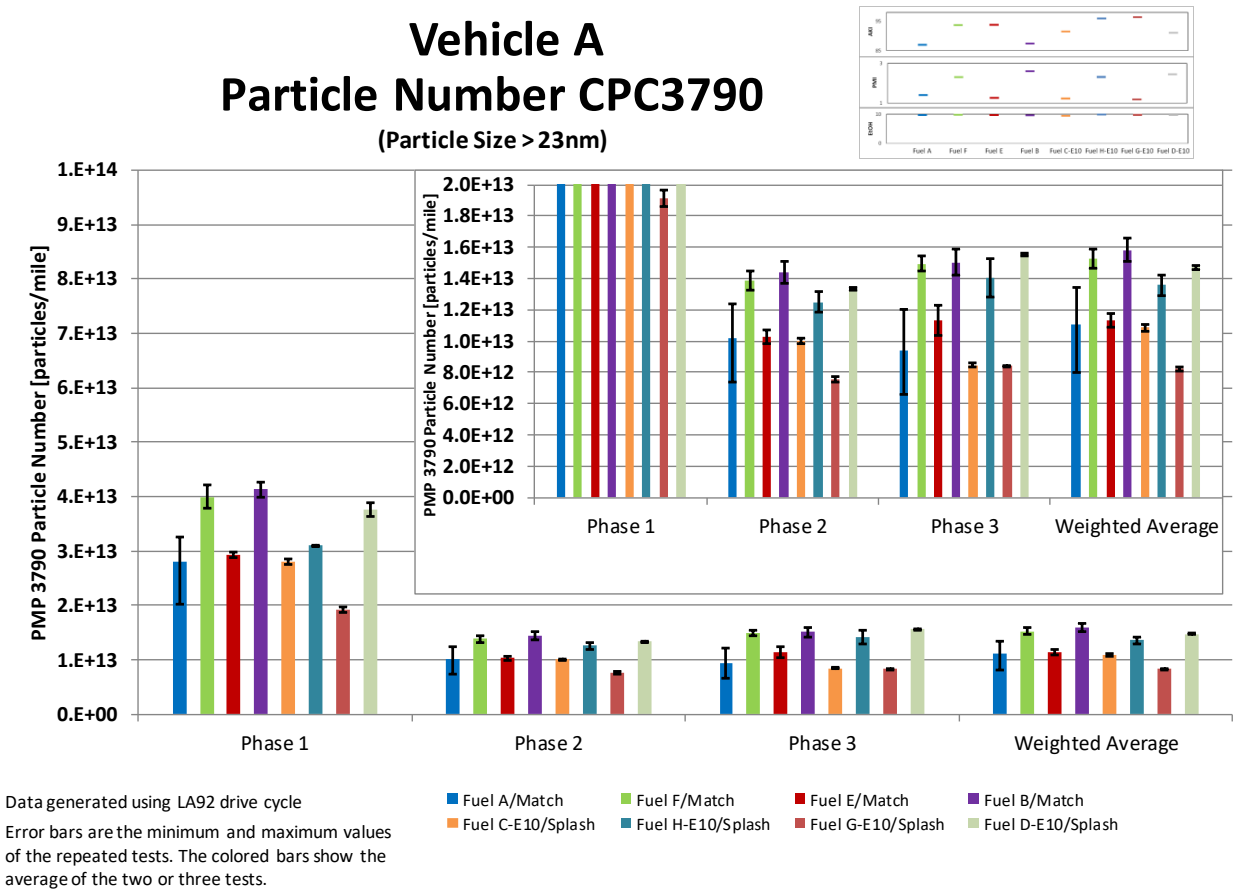


FIGURE E-29: CPC 3790 EMISSIONS FOR VEHICLE A

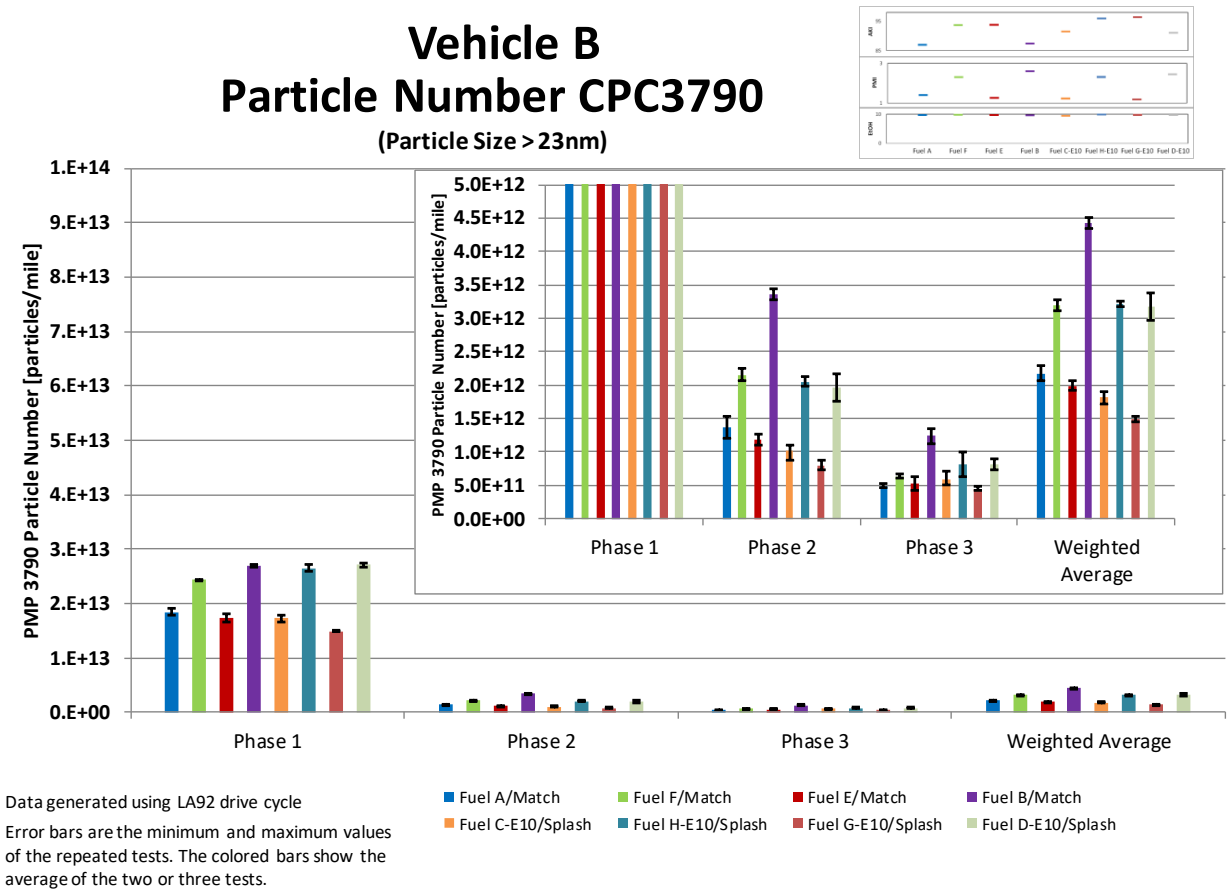


FIGURE E-30: CPC 3790 EMISSIONS FOR VEHICLE B

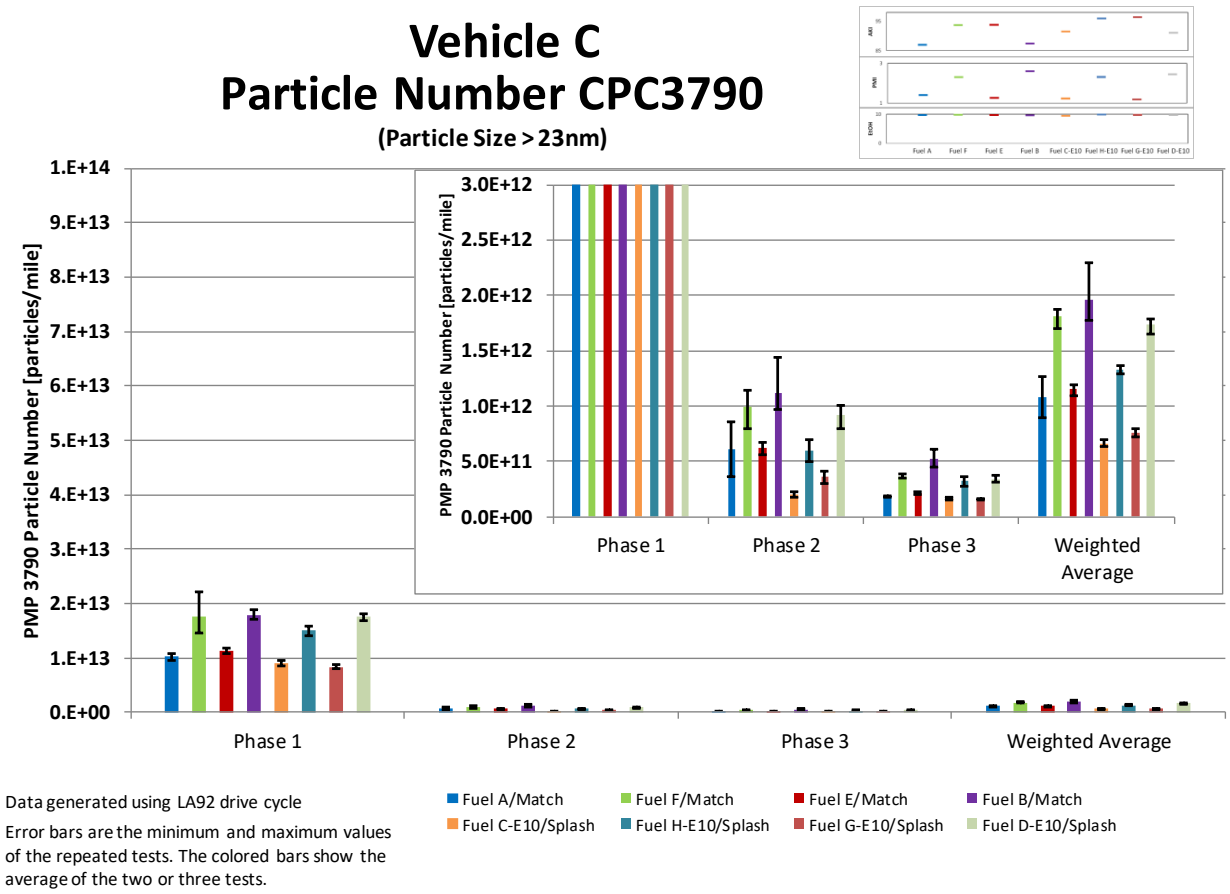


FIGURE E-31: CPC 3790 EMISSIONS FOR VEHICLE C

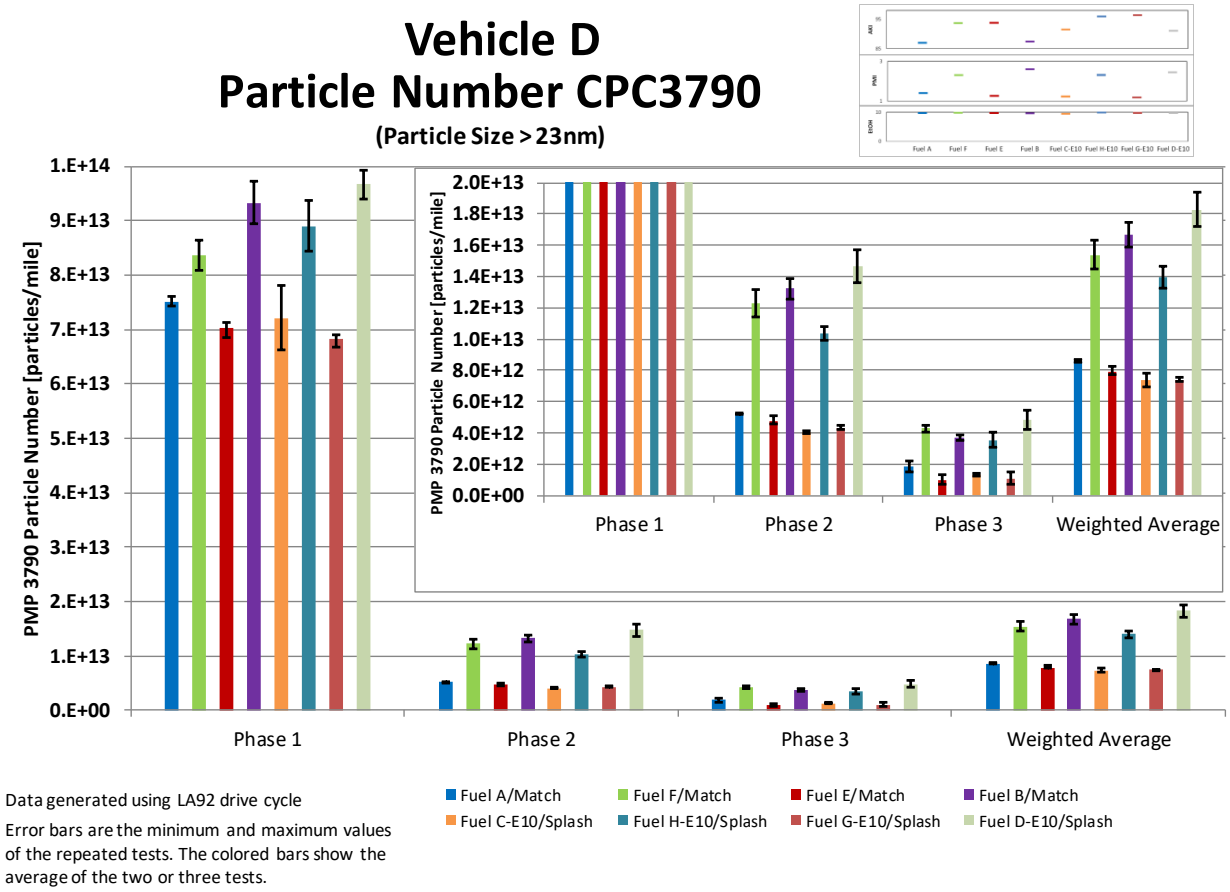


FIGURE E-32: CPC 3790 EMISSIONS FOR VEHICLE D

APPENDIX F

PHASE-LEVEL PARTICLE NUMBER SIZE DISTRIBUTION
REAL-TIME CUMULATIVE PARTICLE NUMBER EMISSIONS
REAL-TIME CUMULATIVE PARTICLE SOOT MASS EMISSIONS

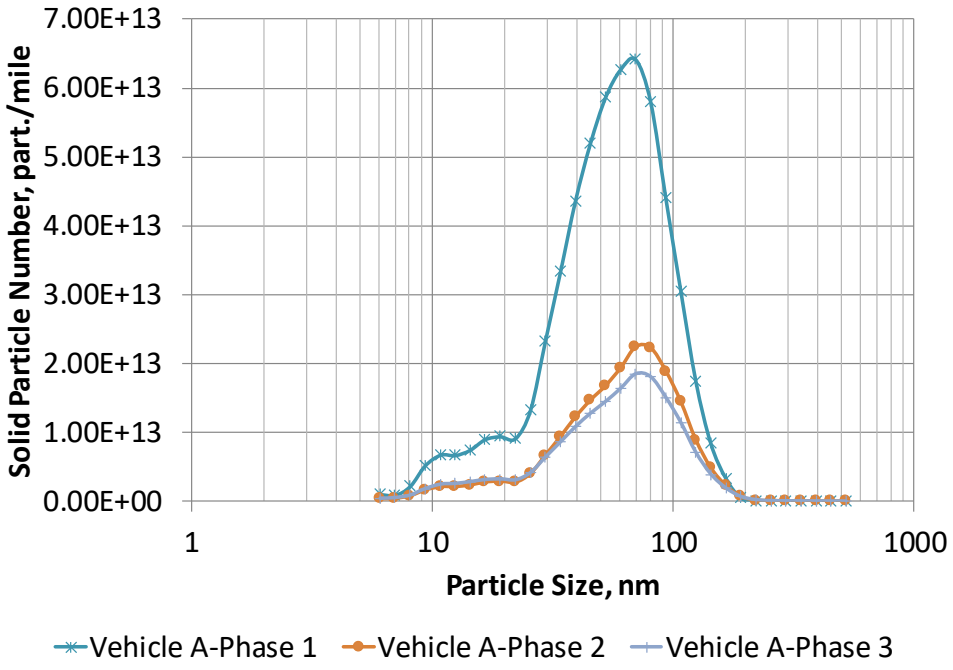


FIGURE F-1: PHASE-LEVEL PARTICLE NUMBER SIZE DISTRIBUTION FOR VEHICLE A

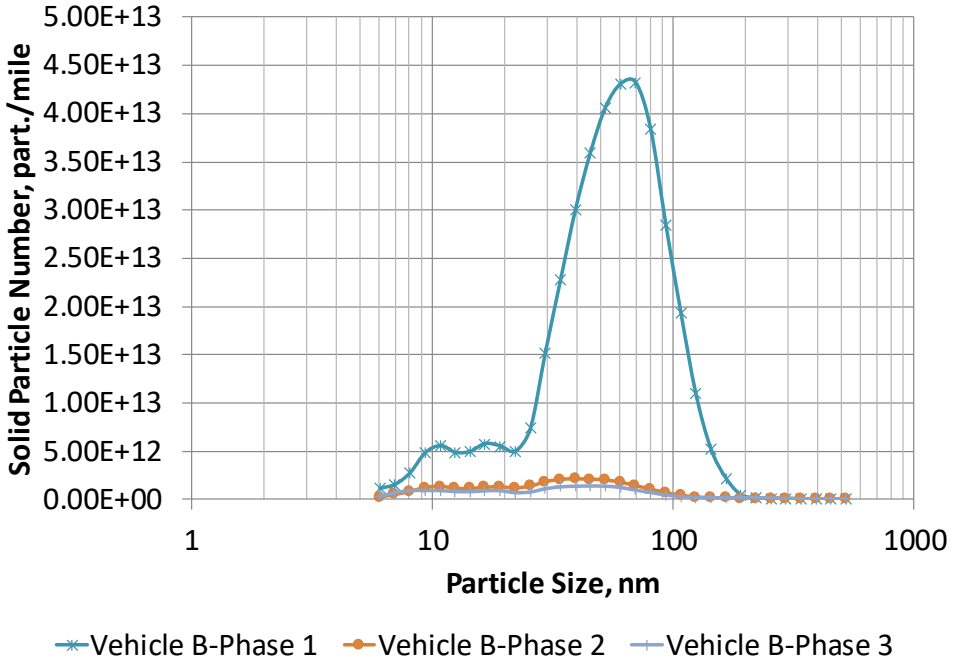


FIGURE F-2: PHASE-LEVEL PARTICLE NUMBER SIZE DISTRIBUTION FOR VEHICLE B

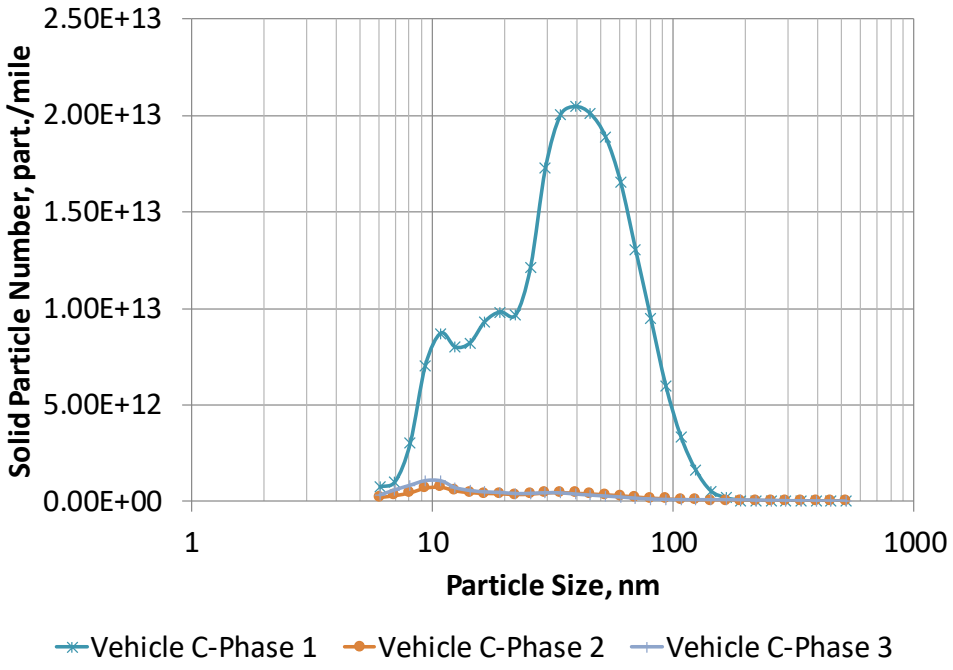


FIGURE F-3: PHASE-LEVEL PARTICLE NUMBER SIZE DISTRIBUTION FOR VEHICLE C

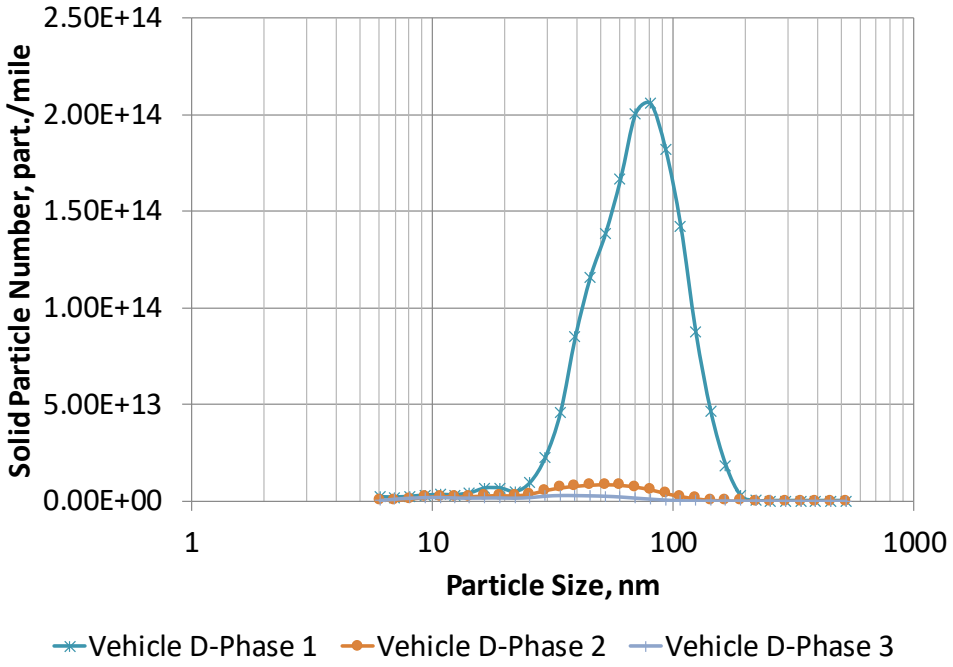


FIGURE F-4: PHASE-LEVEL PARTICLE NUMBER SIZE DISTRIBUTION FOR VEHICLE D

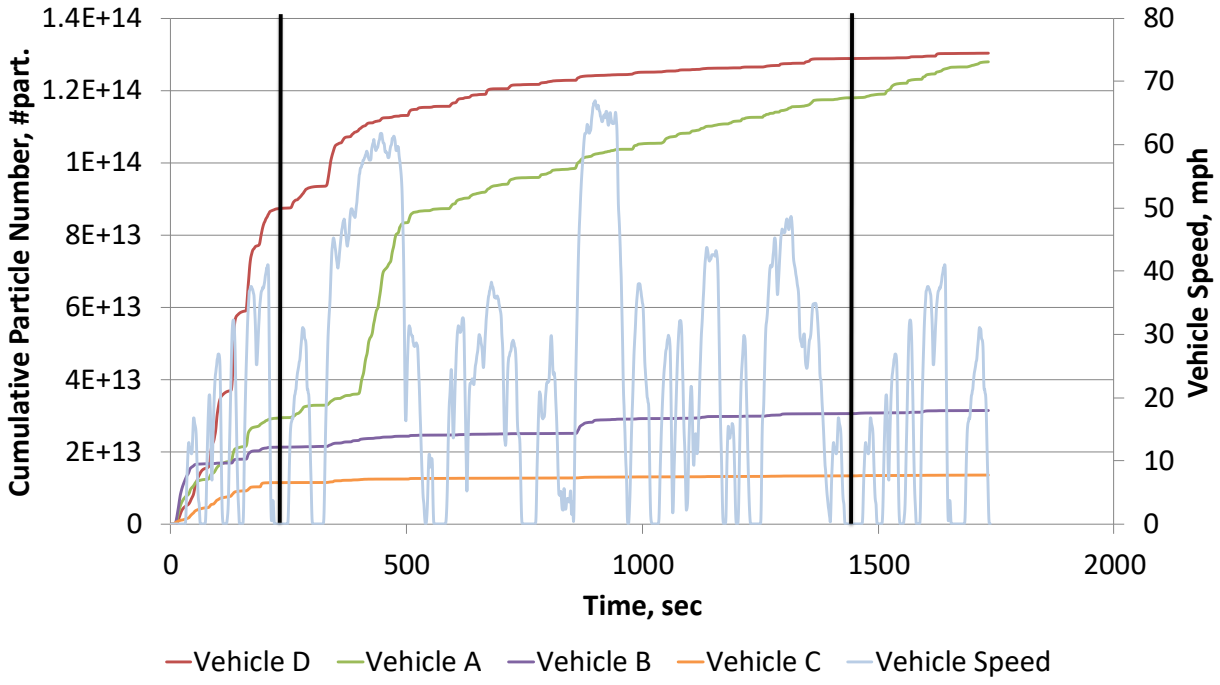


FIGURE F-5: REAL-TIME CUMULATIVE PARTICLE NUMBER EMISSIONS FOR ALL VEHICLES - FUEL C-E10

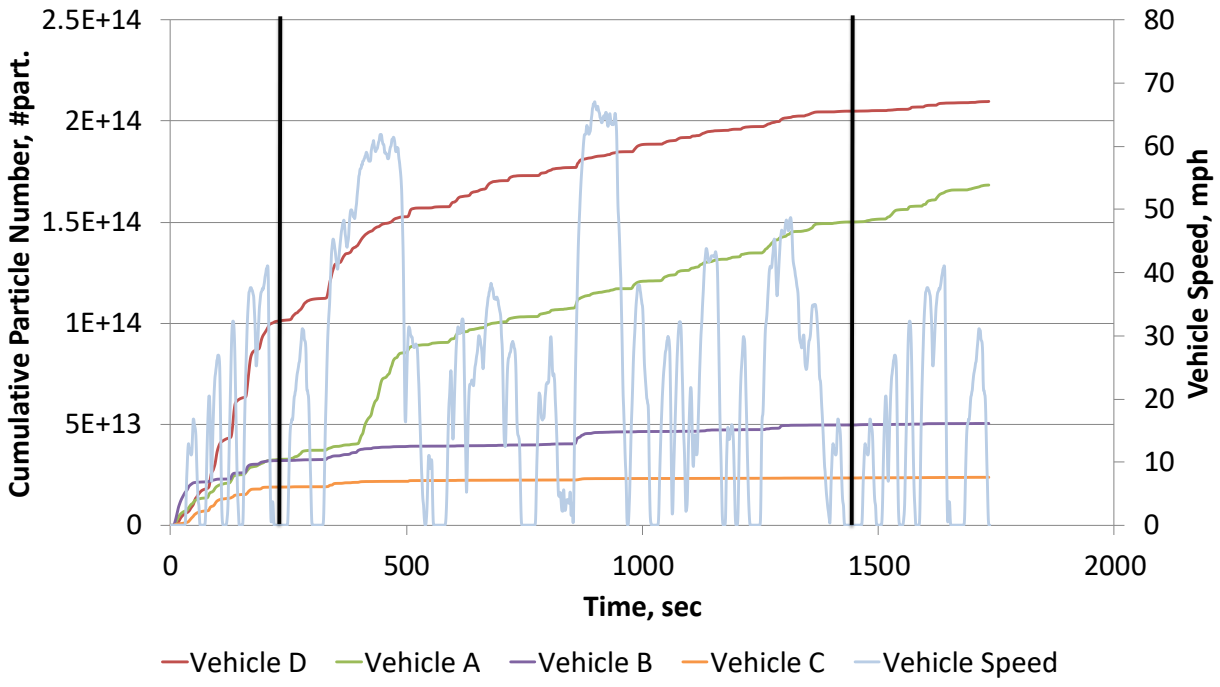


FIGURE F-6: REAL-TIME CUMULATIVE PARTICLE NUMBER EMISSIONS FOR ALL VEHICLES - FUEL H-E10

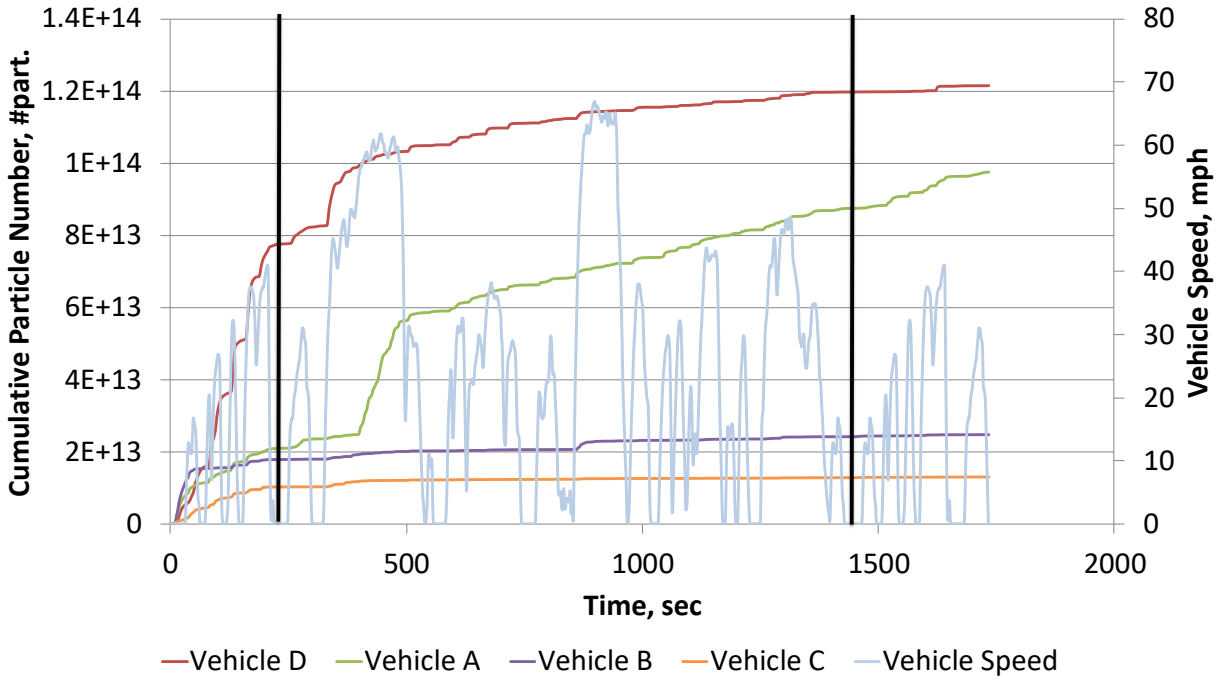


FIGURE F-7: REAL-TIME CUMULATIVE PARTICLE NUMBER EMISSIONS FOR ALL VEHICLES - FUEL G-E10

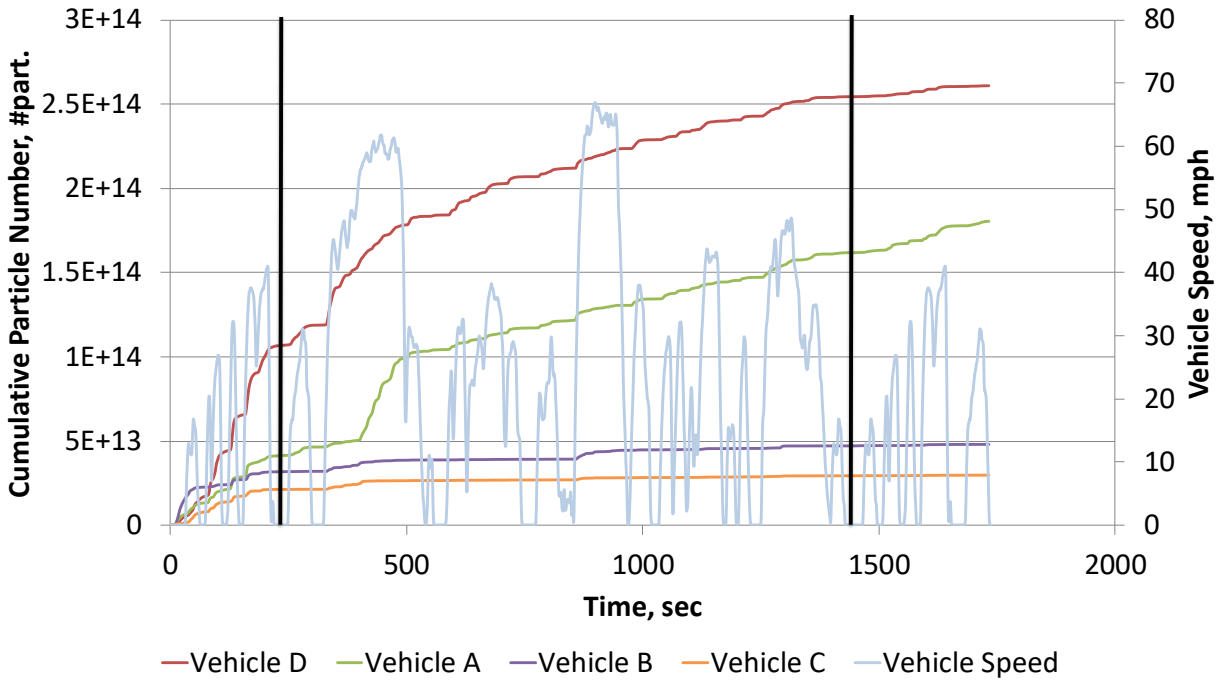


FIGURE F-8: REAL-TIME CUMULATIVE PARTICLE NUMBER EMISSIONS FOR ALL VEHICLES - FUEL D-E10

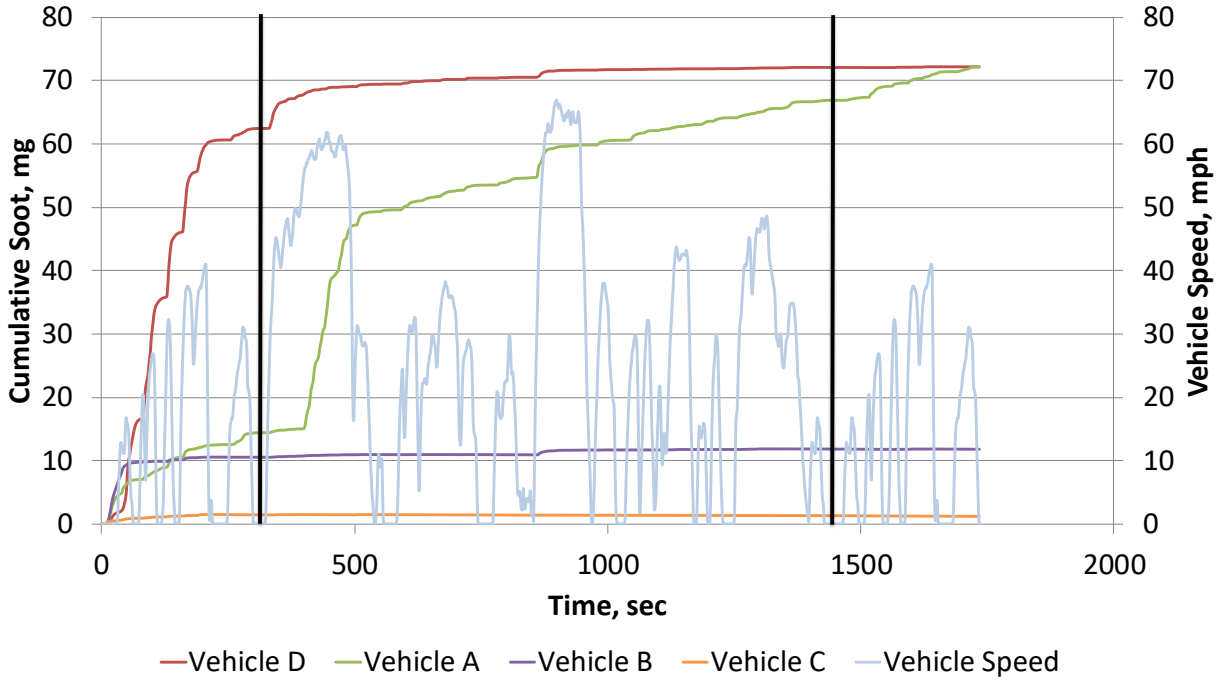


FIGURE F-9: REAL-TIME CUMULATIVE PARTICLE SOOT MASS EMISSIONS FOR ALL VEHICLES – FUEL C-E10

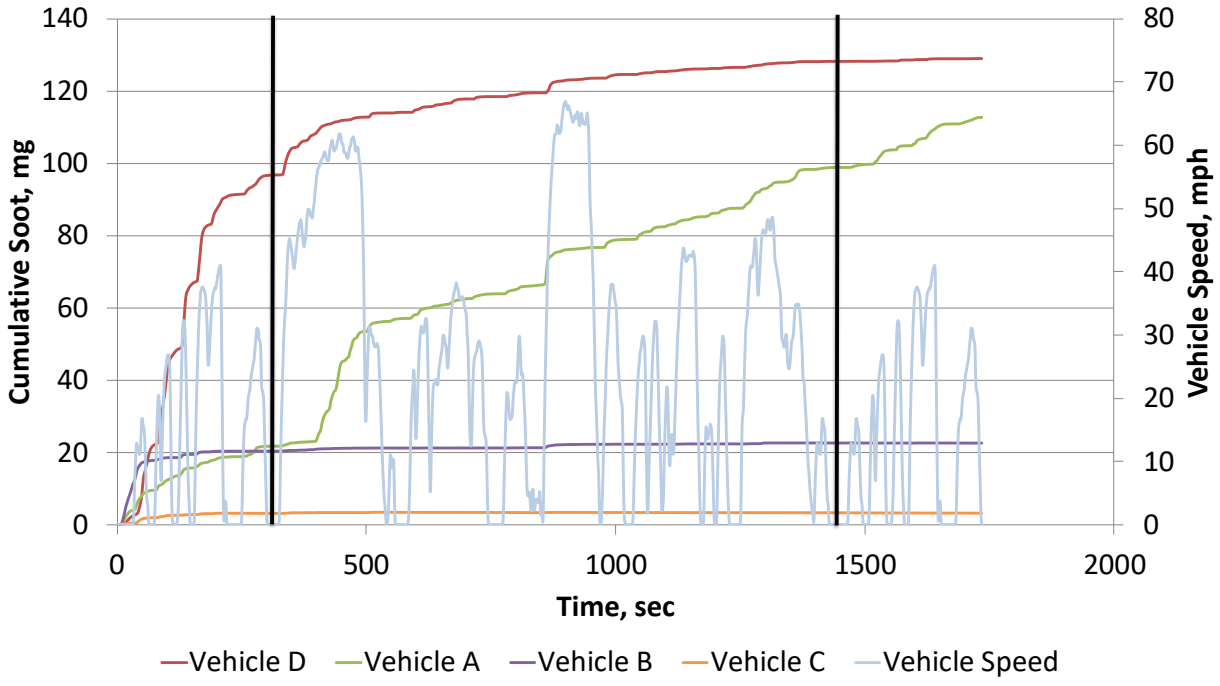


FIGURE F-10: REAL-TIME CUMULATIVE PARTICLE SOOT MASS EMISSIONS FOR ALL VEHICLES – FUEL H-E10

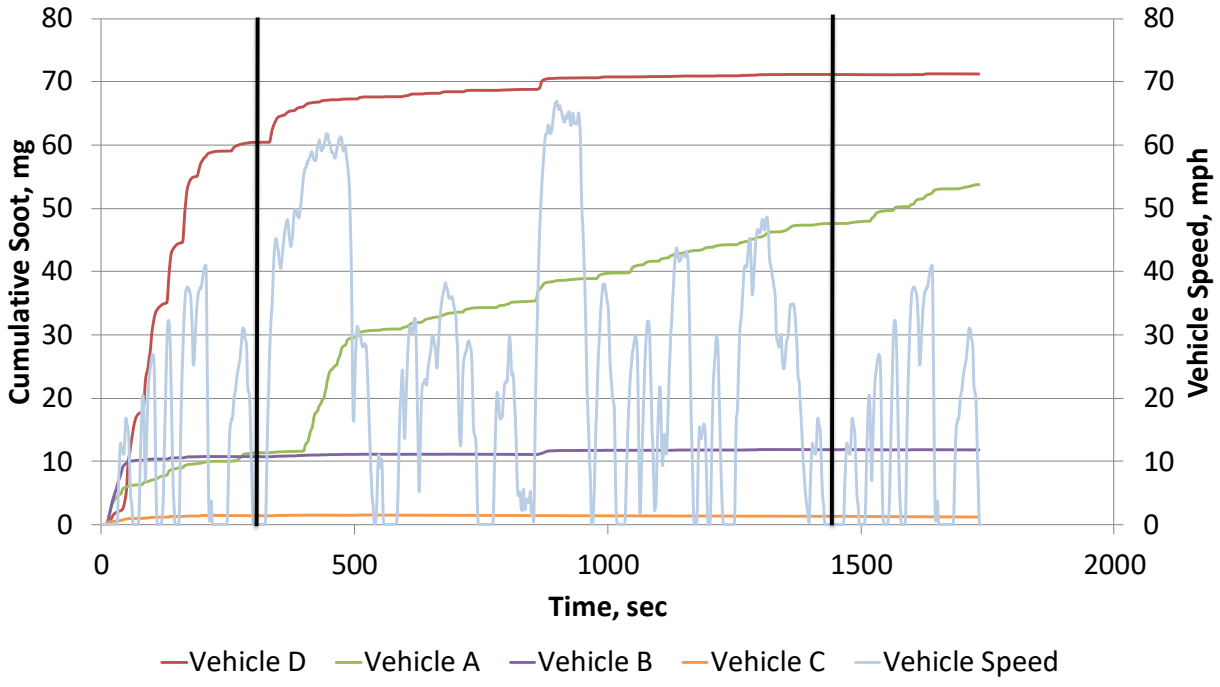


FIGURE F-11: REAL-TIME CUMULATIVE PARTICLE SOOT MASS EMISSIONS FOR ALL VEHICLES – FUEL G-E10

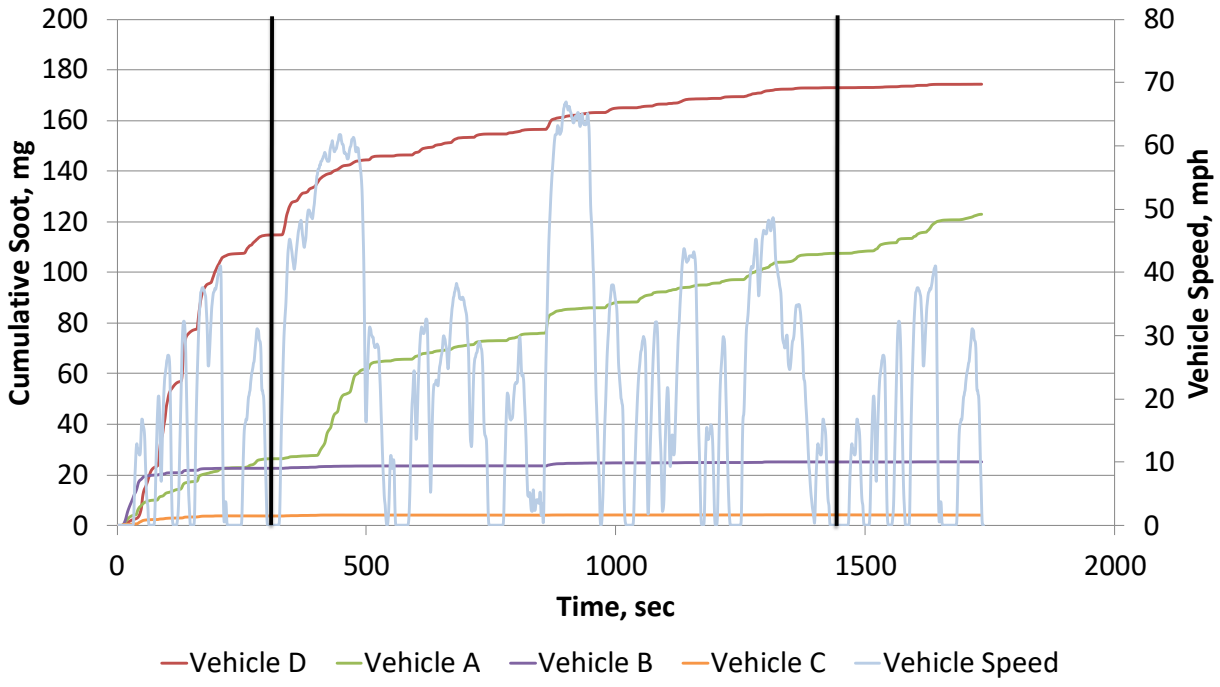


FIGURE F-12: REAL-TIME CUMULATIVE PARTICLE SOOT MASS EMISSIONS FOR ALL VEHICLES – FUEL D-E10

APPENDIX G

ASSESSMENT OF EMISSIONS DRIFT

ASSESSMENT OF EMISSIONS DRIFT

The E-94-3 program was conducted as a successor to E-94-2, using four of the vehicles (A, B, C and D) and five of the fuels (F, C, D, G, H) from that program. Fuel F (High AKI / High PMI, E10) was a remnant fuel used for initial check-out tests to ensure that the vehicles had emissions and fuel economy results comparable to E-94-2. The other four fuels were E0 fuels used as the base fuels for ethanol splash-blending. This appendix reviews data on the particulate emissions of the four vehicles on Fuel F to assess whether there is evidence for a drift or change in emissions due to changes in the fuels or vehicles between the programs.

As described in Section 3, check-out testing was performed using Fuel F. For THC, CO, and NO_X, check-out emissions were sometimes above and sometimes below those measured in the prior program as would be expected when no difference in emissions is present. For PM, check-out emissions were greater than measured in the prior program for each of the four vehicles. Although this may appear to indicate a problem, such an event actually has a 25 percent chance of occurring for one of the pollutants even when no emissions difference is present. The CRC-appointed program manager approved the test results and use of the vehicles in further testing.

Because particulate emissions are the focus of this study, a statistical analysis of the check-out test was conducted for Phase 1 and LA92 PM emissions. The Student t-test is one method used to test for differences on average between two groups. This test, with the assumption of equal variance in the groups, was used for Vehicle C for which three test runs were conducted in each program. The remaining vehicles (A, B and D) had fewer test runs in each program and the t-test was not used. A second analysis was performed in which emission averages for the vehicles were pooled and used to estimate a statistical model of the kind presented in Section 5. The form of the model is given in Eq. G-1 below:

$$\log(Y_{f,i}) = \mu + v_i + dE943_{f,i} + \varepsilon_{f,i} \qquad \text{(Eq. G-1)}$$

where:

μ = mean emissions for the average vehicle in the test fleet
f = Fuel F
i = 1, …, 4 v_i: vehicles $v_i \sim N(0,\sigma_v)$
$\varepsilon_{f,i} \sim N(0,\sigma)$

In this equation, the dummy variable dE943 tests for emission differences between the two programs on average. If dE943 is found to be statistically significant, one can conclude that emissions differ between the programs. If dE943 is not statistically significant, one can conclude that there is no evidence of an emissions difference or "drift". The analysis was performed for both three- and four-vehicle groups of the data.

Table G-1 summarizes the results of these tests for emissions drift between the programs by reporting the p value for statistical significance of the comparisons conducted. A value $p \leq 0.05$ is conventionally required for a finding of significance. When multiple comparisons are made, this value gives a weak demonstration of significance due to the risk of false positives. The analysis in Section 5 of this report used a value $p \leq 0.01$ as an indicator of good statistical significance that is

less subject to the risk. As can be seen, none on the comparisons achieve the conventional $p \leq 0.05$ level of significance, much less a good level of significance.

TABLE G-1. STATISTICAL SIGNIFICANCE OF OBSERVED EMISSIONS DIFFERENCE BETWEEN PROGRAMS

Vehicle Group	Method	Phase 1 PM	LA92 PM
Vehicle C	Student t-test	p = 0.08	p = 0.19
All Four Vehicles	Statistical model	p = 0.10	p = 0.14
Vehicles A, B and D	Statistical model	p = 0.17	P = 0.12

For LA92 emissions, none of the comparisons report a statistically significant difference. For Phase 1 PM, the t-test (p=0.08) for Vehicle C approaches, but does not reach statistical significance. For the group of four vehicles, which includes Vehicle C, the test based on the statistical model results in a value (p = 0.10) that fails to achieve statistical significance, but is not much weaker than the t-test result for Vehicle C itself. In the group of three vehicles, which excludes Vehicle C, the result of the Phase 1 PM comparison falls well short of significance. Based on these results, one can conclude that there is no evidence for a significant difference in emissions between the programs, but there may be reason to suspect such a difference for Vehicle C.

Section 5.2.3 discusses the reasons for organizing the analysis into parallel tracks for a group of all four vehicles and for a group of three vehicles that excluded Vehicle C. In brief, Vehicle C proved to be distinctive with respect to its particulate emissions and response to fuels in the two CRC programs. The assessment of check-out emissions for Vehicle C raises the possibility that its PM emissions, specifically Phase 1 PM emissions, may have drifted between the programs. This is a further reason supporting the decision to conduct parallel emissions analyses.