CRC Report No. E-135

TIER 3 GDI VEHICLE TECHNOLOGY EFFECTS ON PARTICLE EMISSIONS OPERATING WITH DIFFERENT FUELS

Final Report

March 2024

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Final Report

Tier 3 GDI Vehicle Technology Effects on Particle Emissions Operating with Different Fuels

Project E-135

Submitted to:

Coordinating Research Council
5755 North Point Parkway, Suite 265
Alpharetta, GA 30022
Attention: Amber Leland

March 2024

POWERTRAIN ENGINEERING DIVISION

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Southwest Research Institute® Final Report
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FOREWORD

This report covers development and testing conducted by Southwest Research Institute (SwRI) for the Coordinating Research Council (CRC). The project, performed under CRC contract E-135, was conducted between November of 2021 and July of 2022. The internal SwRI project number is 03.27093. The SwRI project manager was Matt Blanks, assisted in testing and development by Chaz Ginger. Laboratory emissions testing was overseen by David Zamarripa. Tim Martinez was the driver for all tests and Kevin Hohn operated the chassis dynamometer and laboratory emissions equipment. All fuel-related and mileage accumulation tasks were managed by Kevin Brunner. Statistical analysis and design of experiments were conducted by Travis Kostan.

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1.0 EXECUTIVE SUMMARY

This report documents a project conducted by SwRI on behalf of the Coordinating Research Council (CRC). The goal of the project was to improve understanding of fuel injection pressure impact, as well as other technologies present in Tier 3 certified vehicles, on tailpipe emissions from gasoline direct injected vehicles. This scoping project evaluated exhaust emissions from two light-duty vehicles using seven test fuels.

Four (4) of the test fuels were commercially available E10 market gasolines, consisting of two (2) summer-grade and two (2) winter-grade fuels. Each seasonal grade was represented by one (1) high and one (1) low Particulate Matter Index (PMI) fuel. For this project, a PMI level of 1.0 was considered low and a level of 2.0 was considered high. Because the project focused on PM effects of high and low PMI fuels, the matrix had a gap in PMI level between approximately 1.1 and 1.7. This gap includes the median market fuel PMI of near 1.6 (EPA NPRM[1]). Ethanol was splash-blended into each of the two summer-grade market gasolines to produce a high PMI E15 and low PMI E15 fuel. The seventh fuel was an EPA Tier 3 emissions-grade certification gasoline. Each vehicle-fuel combination was evaluated over a minimum of three tests, based on a Design of Experiments (DOE). SwRI oversaw procurement and blending of the fuels with guidance and direction provided by CRC committee members.

The two (2) test vehicles were selected by CRC for their high-pressure gasoline direct injection (GDI) systems and set of technologies. Typical 2021 model year GDI systems produce peak fuel pressures of 150 bar while the selected test vehicles were marketed to produce up to 350 bar. Both vehicles were procured by SwRI from dealerships in the San Antonio area. One (1) vehicle was purchased new and the other with 1,992 miles on the odometer. Both vehicles were driven on mileage accumulation dynamometers (MADs) to an odometer reading of 4,000 miles. Oil and oil filters were changed, and 500 miles were accumulated to degreen the new oil before emission tests were conducted. Results in this report are blinded to vehicle identifications.

Triplicate cold-start LA92 drive cycles were used to evaluate each vehicle-fuel combination. A fourth test was conducted if repeatability of the first three tests did not meet predetermined criteria. Approximately 53 cold-start chassis dynamometer emission tests were conducted for this project. For each test criteria gaseous emissions were measured along with exhaust soot, particulate mass, particulate number, and particulate size.

Statistical analysis was conducted to determine whether any of the emissions generated by these high fuel injection pressure vehicles were significantly impacted by the differences in fuel PMI, Reid Vapor Pressure (RVP), or ethanol content. The emissions data used for the analysis were generated over the LA92 cycle and phase-weighted using the FTP composite weight factors (see Section 4.3). Regression models were run to determine the statistical significance (based on a 5% level of significance) of PMI, RVP, and ethanol content as predictors in the emissions models. Due to the limited number of fuels and the large number of fuel properties, some strong correlations existed between the fuel properties being studied and other fuel properties, including, for example, back-end distillation (T70 and higher) and density with PMI, front-end distillation

[1] U.S. Environmental Protection Agency, "Proposed Rule: Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles," EPA-HQ-OAR-2022-0829, May 5, 2023.

(T30 and lower) with RVP, lower heating value, atomic composition, and distillation recovery with ethanol. It should be noted that the correlations observed are not necessarily an indication that these fuel properties are intrinsically or typically related, but only that they share a relationship within the seven fuels tested in this study. With these correlations present, one cannot attribute changes in emissions to changes in PMI, RVP, or ethanol content independent of these other highly correlated properties. A targeted fuel property design of experiments would be needed to unconfound the effects of PMI, RVP, and ethanol from these other properties and quantify their effects independently. A summary of fuel property correlations identified in this work are presented in Section 4.1.

For the analysis, a regression model was run separately for each of the ten (10) types of criteria pollutant emissions measured. A backwards variable selection technique was used to reduce the model terms down to only statistically significant factors, based on a 5% level of significance. To help quantify the prediction strength of the variables deemed statistically significant, partial R-squared values are provided. These values represent the additional percentage of the variance explained by a variable relative to a reduced model with all variables except that one. For models with only a single variable this value is the same as the model R-squared. For statistically significant effects (enough evidence to say the coefficient of the predictor is non-zero), the strength of prediction was binned into groups based on the partial R-squared values to help separate stronger predictors from weaker predictors. Though the divisions here are subjective, a predictor was considered weak if less than 40%, moderate between 40%-70%, and strong if >70%. The summary tables are color-coded based on these groups, with yellow for weaker predictors, light green for moderate predictors, and dark green for strong predictors. Additionally, the regression equation was used to assess the estimated average change in emissions across the range tested for that fuel property. It is worth noting that since most emissions were modeled with data transformations, the predicted change will be non-linear in original measured units. It is also worth stating that these models are predicting an average emissions level based on each fuel property level, and therefore may not accurately capture the performance of each individual fuel.

As the primary interest in the study was to quantify the impact of fuel properties on soot and particulate matter (PM) emissions, these are summarized first in Table 1 for the LA92 weighted composite data. Gaseous emissions are discussed in Section 4 of the report. For soot and PM emissions, cold-start Phase 1 data was also analyzed on its own in addition to the weighted LA92 composite data, and these results are summarized in Table 2. Though Phase 1 represents the shortest phase distance in the LA92 cycle, it typically produces the highest particle emission levels and fuel impacts on particle emissions are more likely to appear. For this reason, Phase 1 particle emissions were also analyzed individually in CRC projects E-94-2 and E-94-3. In both the composite and Phase 1 only models of the current study, there was no statistical significance of RVP or ethanol for either vehicle. For Vehicle A, fuel PMI was statistically significant in both PM and Soot models for Phase 1 alone and in the weighted composite data. PMI was a moderate predictor, explaining approximately 60%-65% of the variability observed in this vehicle. Vehicle B, however, showed no impact of fuel PMI on the full weighted cycle results, but was statistically significant for PM and Soot when looking at Phase 1 alone. The prediction strength of PMI was weak for PM and moderate for MSS Soot. For these statistically significant factors, the summary tables below show the vehicle-specific regression model's predicted change in average PM and soot for each vehicle with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0. For the fuel property variables with coefficients determined to not be statistically different from zero, dashed lines (-) are shown for all table entries corresponding to that factor. A plot of the vehicle-specific model line predicting the mean PM emissions based on fuel PMI (with a 95% confidence interval for the mean) is provided in Figure 1 for the LA92 composite data, and in Figure 2 for the Phase 1 only data. In Figure 1 and Figure 2 it is important to note that the 95% confidence intervals represent the mean PM levels predicted by the model under the assumed relationship and are therefore not expected to capture all fuels individually. In addition, the relationship modeled is driven almost entirely by the observed PM at the highest and lowest PMI levels for the fuels in this study. The reader is therefore cautioned against relying on these models in the PMI range from about 1.0-1.5, for it is unknown if the assumed functional form is appropriate in this range, as evidenced by the Fuel B Vehicle A data which appears to not follow the same trend as the other fuels in this study.

TABLE 1: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE SOOT AND PARTICULATE MATTER EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	**Model Parameter**	**Partial R^2**	**PMI 2.0 → 1.5**	**PMI 2.0 → 1.0**	**Partial R^2**	**RVP 9 → 14**	**Partial R^2**	**E10 → E15**
A	**PM (mg/mi)**	63.3%	1.55→0.99 (-36%)	1.55→0.58 (-63%)	-	-	-	-
	MSS (mg/mi)	59.4%	1.29→0.58 (-55%)	1.29→0.26 (-80%)	-	-	-	-
B	**PM (mg/mi)**	-	-	-	-	-	-	-
	MSS (mg/mi)	-	-	-	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant for that emissions parameter.

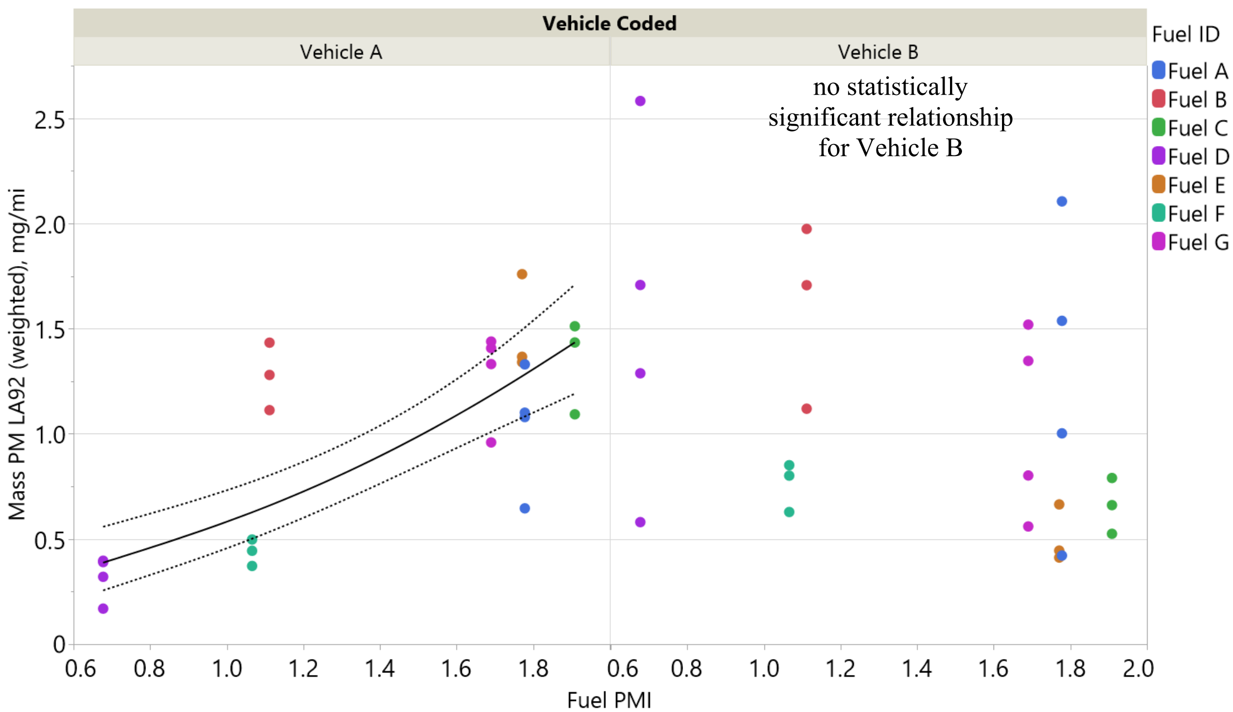

FIGURE 1: MODEL FITS PREDICTING MEAN PM EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS ON THE MEAN, LA92 WEIGHTED COMPOSITE DATA

TABLE 2: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED PHASE 1 SOOT AND PARTICULATE MATTER EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	PM (mg/mi)	64.0%	5.96→3.56 (-40%)	5.96→1.91 (-68%)	-	-	-	-
	MSS (mg/mi)	65.2%	6.10→2.27 (-63%)	6.10→0.84 (-86%)	-	-	-	-
B	PM (mg/mi)	23.4%	1.62→1.29 (-20%)	1.62→1.02 (-37%)	-	-	-	-
	MSS (mg/mi)	50.9%	0.44→0.29 (-33%)	0.44→0.19 (-55%)	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant for that emissions parameter.

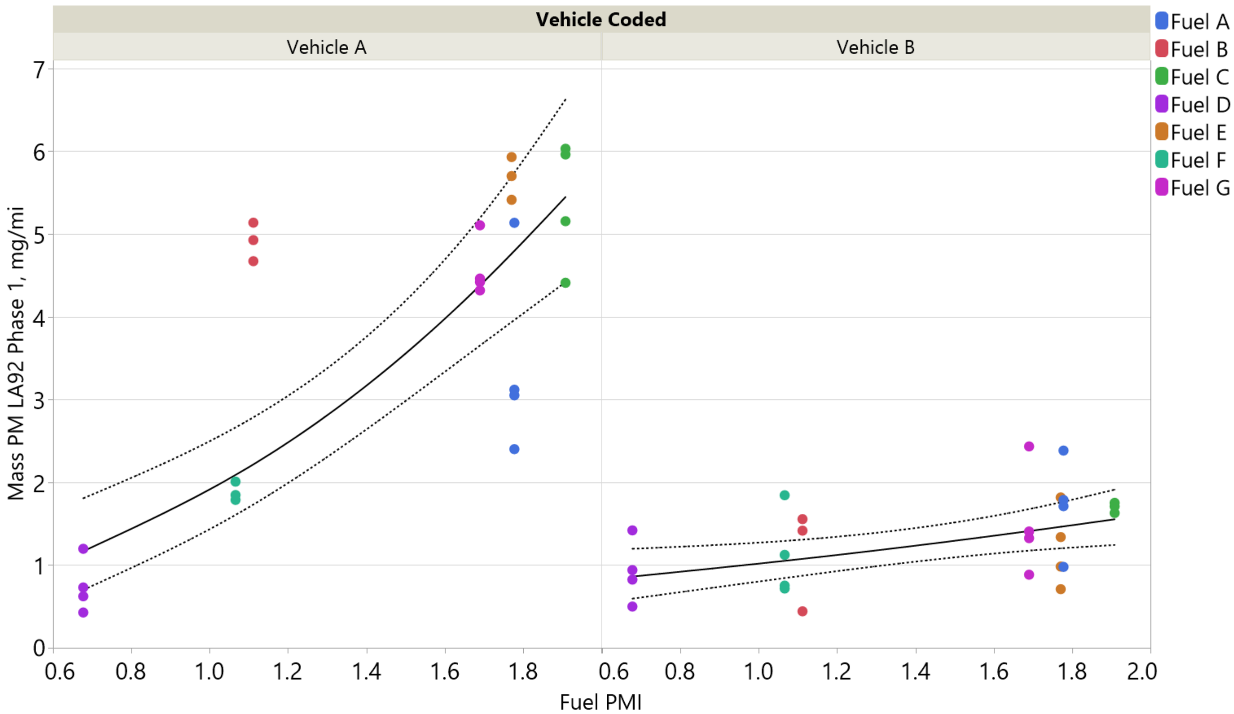

FIGURE 2: MODEL FITS PREDICTING MEAN PM EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS ON THE MEAN, LA92 PHASE 1 DATA

Vehicle B exhibited an interesting particle emissions signature. Results for this vehicle were consistently low for Phase 1, while Phases 2 and 3 were highly variable and had an increased rate of emissions. Additionally, although both vehicles were marketed to have the same maximum fuel injection pressure, the injection control strategies were very different. Vehicle B produced a fuel injection pressure of 350 bar just after the engine was cranked, compared to 170 bar from Vehicle A. Vehicle B also maintained a higher minimum fuel pressure of 130 bar, compared to the minimum pressure of 80 bar from Vehicle A. The higher injection pressure for Phase 1, discussed in Section 3.2, may play a role in why Vehicle B generally produced lower PM through the range of low and high PMI fuels. Vehicle technology is further discussed in Section 3.2.4. These vehicles were selected to understand how PMI, ethanol, and RVP could impact emissions for vehicles operating at 350 bar fuel injection pressure. However, these results were inconclusive, due to the injection control strategies which reduced injection pressures to a level lower than the pressure of interest. Nonetheless, this Phase 1 data shows when comparing Vehicle A to Vehicle B that there was a decreased relationship between PM emissions and Fuel PMI due to differences in vehicle technology that include increased fuel injection pressure, combustion chamber geometry, injector location, engine operational differences (e.g., stop/ start), etc. Further work should be performed to evaluate injection pressure sensitivity of tailpipe PM to PMI.

2.0 INTRODUCTION

New vehicle technologies geared towards Tier 3 compliance, such as increasing fuel injection pressure and atomization, have shown potential significant benefits to reduce particle emissions from gasoline direct injection engines. As emissions regulations become more stringent, deployment of these technologies is expected to increase. Furthermore, fuels containing a high proportion of heavy aromatics (C9+) compared to market average and certification fuels, characterized with a high particulate matter index (PMI), have been found to generate higher particle emissions. CRC projects E-94-2 and E-94-3 have indicated a potential link between an increase in particulate matter index (PMI) and ethanol content with increased PM emissions. Understanding this interaction with new vehicle technologies is of interest for future vehicle/fuel co-optimization to comply with upcoming emission regulations.

This project evaluated a matrix of fuels with low and high PMI, different ethanol contents, and different vapor pressures. The fuels matrix was tested using two (2) vehicles equipped with high-pressure gasoline GDI fuel systems. Triplicate LA92 cold-start transient tests were used for each evaluation. The project was initiated in November of 2021 and official testing began in February of 2022. Testing was completed in April 2022.

3.0 PROJECT SETUP

All tests were conducted in SwRI's light-duty vehicle laboratory. The following sections detail test fuels, test vehicles, and the test procedure used to measure exhaust emissions.

3.1 Test Fuels

A total of seven (7) fuels were used in this project. Five (5) of the fuels were located and procured under CRC Project E-122-2. Four (4) of the E-122-2 fuels were market fuels, comprised of summer and winter grades, each having a low and high Particulate Matter Index (PMI). Tier 3 emissions-grade certification fuel was also procured from Haltermann Solutions under that project. All market fuels were 87 AKI E10 regular unleaded gasoline (RUL) except for the winter-grade, high PMI fuel. A 93 AKI E10 premium unleaded gasoline (PUL) was chosen for the winter-grade high PMI fuel because a suitable RUL could not be located. The PUL fuel was supplied unadditized by a CRC committee sponsor but was subsequently additized with a commercial additive package at the minimum TOP TIER® treat rate before use. A portion of the two (2) summer-grade E10 market fuels were then splash blended to produce high and low PMI, E15 fuels. Acquisition of the market fuels occurred between May of 2020 and June of 2021. The E15 fuels were blended in March of 2022.

Key properties from each test fuel are shown in Table 3, and all analysis results are given in Appendix A. Appendix A also includes a detailed description of the fuel procurement process for the market fuels and the supplier's certificate of analysis for the certification fuel. The certification fuel was shipped from the supplier in drums.

TABLE 3: ANALYSIS RESULTS OF SELECTED FUEL PROPERTIES

ID	Code	Name	Ethanol, vol% (ASTM D4815 / D5599)	PMI (ASTM D6729)	RVP, PSI (ASTM D5191)	FBP, °F (ASTM D86)	Total Aromatics, wt% (ASTM D6729)	Notes
A	EM-10967	Certification E10	9.7	1.8	9.2	388	27.6	EPA Tier 3 EEE
B	GA-10940	Summer Low PMI E10	9.7	1.1	9.0	367	24.4	
C	GA-10920	Summer High PMI E10	9.5	1.9	7.7	408	33.2	
D	GA-11027	Winter Low PMI E10	9.6	0.7	15.3	344	25.8	
E	CGB-11093	Winter High PMI E10	10.2	1.8	13.6	392	32.7	PUL
F	CGB-11285	Summer Low PMI E15	15.1	1.1	8.8	375	24.2	Fuel B + Ethanol Splash Blend
G	CGB-11286	Summer High PMI E15	15.2	1.7	7.6	399	32.2	Fuel C + Ethanol Splash Blend

3.2 Test Vehicles

Two (2) test vehicles were selected by CRC for their high-pressure gasoline direct injection fuel systems and set of technologies. Both vehicles were marketed to produce a maximum of 350 bar injection pressure, which is higher than most GDI vehicles produced during or before 2021 for the US market. The vehicles were procured by SwRI from dealerships in the San Antonio area with one (1) being purchased new and the other preowned with 1,992 miles. Both vehicles were driven on milage accumulation dynamometers (MADS) to an odometer reading of 4,000 miles before changing the oil and oil filters. An additional 500 miles were accumulated to degreen the new oil before emission tests were conducted. Table 4 gives a description of each vehicle listing key properties.

Along with vehicle descriptions, this section discusses vehicle-specific topics that include:

- Tasks performed with each vehicle after purchase
- Checkout tests and results
- Problems encountered with individual vehicles
- Engine fuel pressure discussion

TABLE 4: TEST VEHICLE AND ENGINE PROPERTIES

Vehicle ID	A	B
Model Year	2021	2021
Displacement [L]	1.6	3
Bore [mm]	75.6	82
Stroke [mm]	89	94.6
GDI Pressure [bar]	350	350
Power [hp]	180	335
Torque [lb-ft]	195	368
Turbocharged?	Yes	Yes
Turbocharger details	Twin-scroll	Single-Scroll
Cylinder Deactivation?	No	No
EGR	Yes	No
Valves per Cylinder	4	4
Valvetrain Configuration	Dual Overhead Cam	Dual Overhead Cam
Emission Cert Level	Tier 3 Bin 70	Tier 3 Bin 70
Equivalent Test Weight (lbs)	3625	4250
Compression Ratio	10.5:1	10.2:1
Fuel Grade Recommended in Owner's Manual	AKI 87 Minimum	AKI 89 Minimum AKI 91 Recommended
Start / Stop	No	Yes
Hybrid? (BSG)	No	Yes
Aftertreatment Configuration	2 Three-way Catalysts (CC and UF)	1 Three-way Catalysts (CC)
Fuel system specifics (injector design)	Direct, Side-mounted, multi-hole solenoid Injection	Direct, Top-mounted, multi-hole solenoid Injection
Transmission Pump	electric oil pump	chain driven oil pump

After purchase, the following tasks were performed with each vehicle:

- Add to SwRI's test vehicle insurance policy
- Drive to a 4,000-mile odometer reading on a chassis dynamometer using the US EPA Standard Road Cycle (SRC) and E10 RUL gasoline
- Change engine oil and oil filter
- Accumulate 500 miles over the Standard Road Cycle (SRC) to degreen fresh oil using RUL E10 gasoline
- Run reports to check for powertrain recalls, technical service bulletins (TSB), diagnostic trouble codes (DTC), or required vehicle software updates
- Check coolant level and freeze-point
- Inspect tires

3.2.1 Emissions Verification Test

Prior to the start of testing, each vehicle was flushed with certification-grade fuel and tested over a single FTP-75 cycle to determine if the vehicle's emission control system was working properly. Regulated emissions (NMHC, CO, CO_2, NO_X, and PM) were measured and provided to the CRC technical contact for final approval of the vehicles. Both vehicles produced emissions well below their certification level, but Vehicle B produced much lower particulate mass (PM) emissions compared to Vehicle A. Table 5 gives the results for all measured pollutants.

TABLE 5: CHECKOUT EMISSION RESULTS

Pollutant	CO, g/mi	NMOG, g/mi	NO_x, g/mi	NMOG+NO_x, g/mi	PM, mg/mi
EPA Tier 3 Bin 70 Certification Standard	1.7	na	na	0.07	3
Vehicle A Checkout Test Results	0.103	0.020	0.015	0.035	2.43
Vehicle B Checkout Test Results	0.490	0.017	0.017	0.034	0.50

3.2.2 Vehicle Problems

Vehicle B's hybrid system did not function correctly during the first week of testing. The hood latch sensor was identified as the inhibiting factor as the vehicles were tested with the hood open using a road-speed radiator cooling fan. To satisfy the sensor, the hood latch bar was removed from the hood and used to close the latch and sensor. All voided tests were rerun the following week. Figure 3 shows the hood latch with bar inserted.

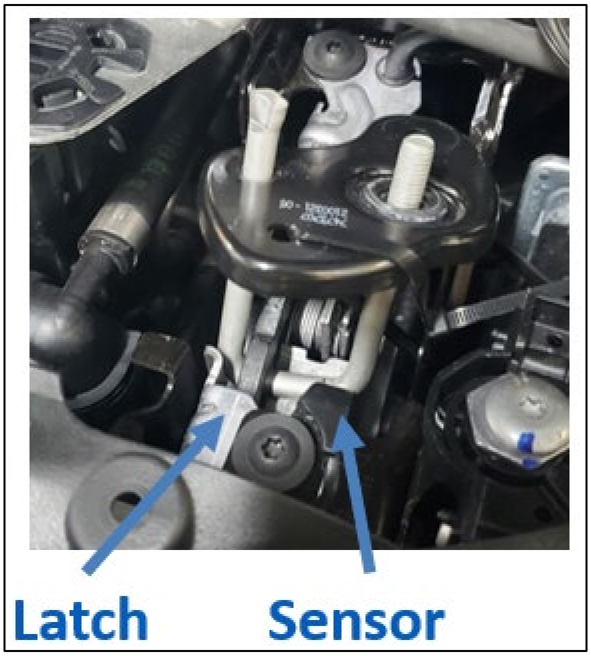

FIGURE 3: VEHICLE B HOOD LATCH

3.2.3 GDI Injection Pressure

Fuel injection pressure was recorded from both vehicle's On-board Diagnostic (OBD) port to investigate how fuel pressure was controlled over the LA92 cycle. Specifically, Parameter ID (PID) SAE 0x23, fuel rail pressure, was recorded. Figure 4 shows fuel pressure from both vehicles over the entire LA92 cycle and Figure 5 gives the first five (5) minutes of the same tests to highlight the cold-start operation. Both vehicles were fueled with certification fuel for these tests.

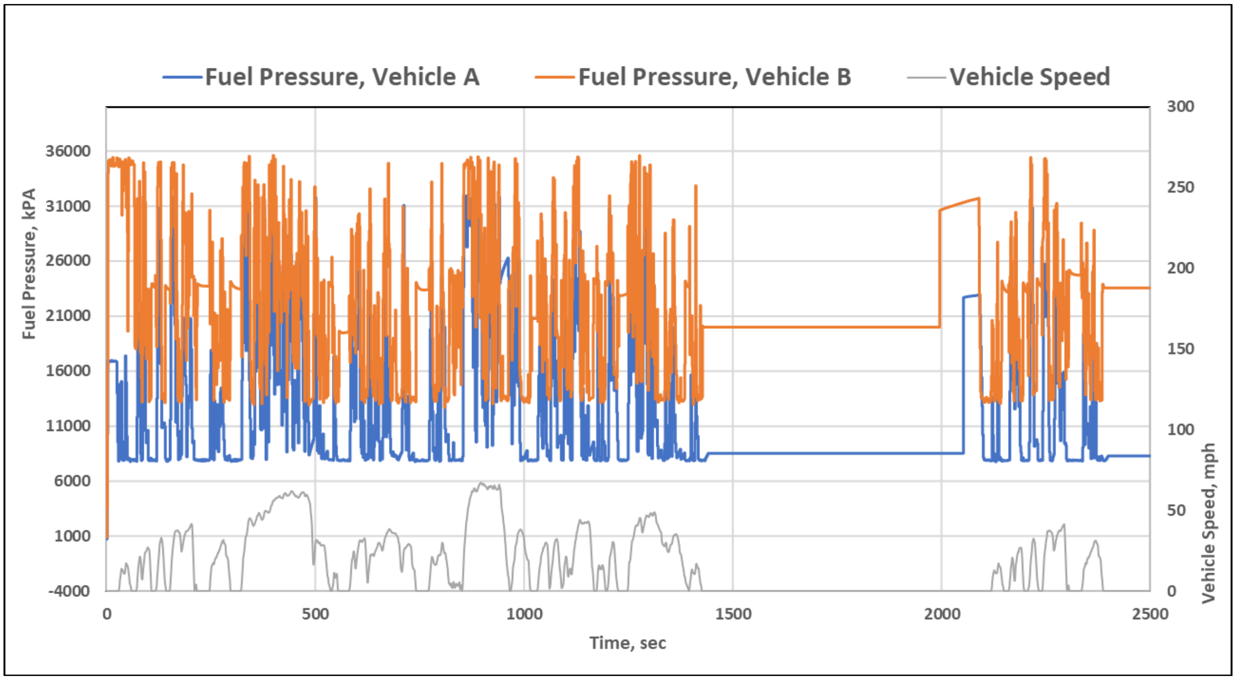

FIGURE 4: CONTINUOUS FUEL PRESSURE OVER LA92 CYCLE

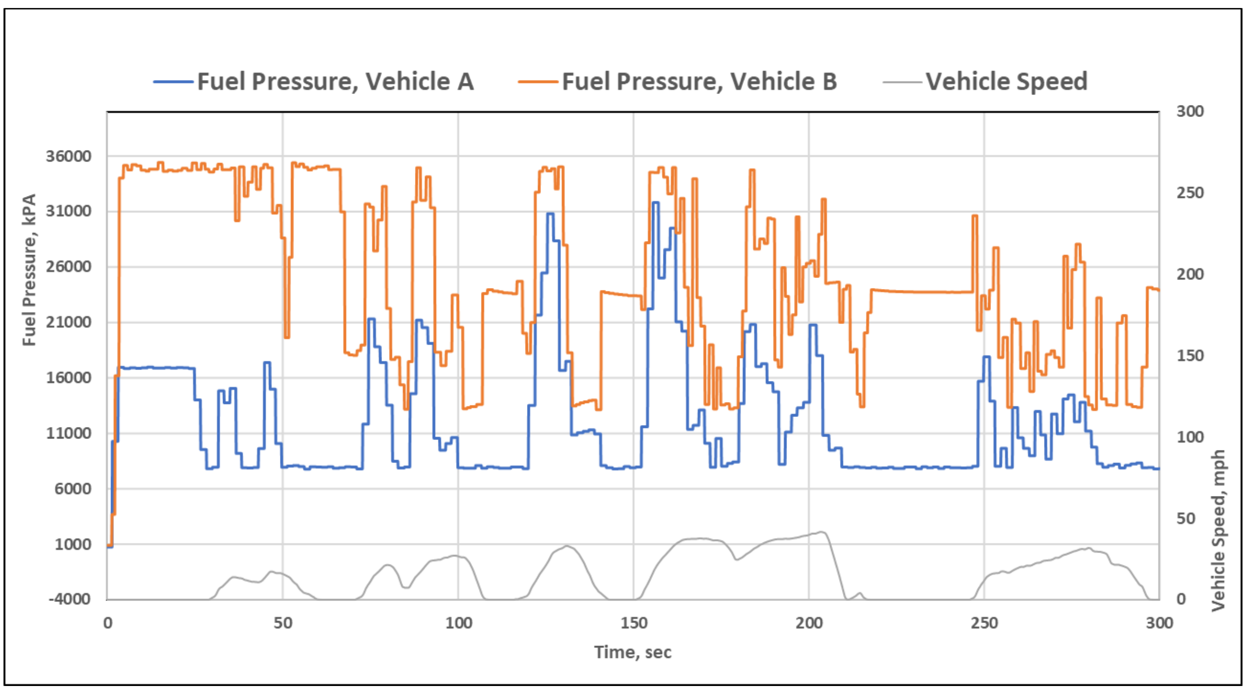

FIGURE 5: CONTINUOUS FUEL PRESSURE OVER COLD-START PORTION OF LA92 CYCLE

Vehicle B produced a fuel injection pressure of 350 bar just after the engine was cranked, compared to 170 bar from Vehicle A. Vehicle B also maintained a higher minimum fuel pressure of 130 bar, compared to the minimum pressure of 80 bar from Vehicle A. Figure 6 is a scatter plot from these same tests comparing fuel pressure to calculated engine load. This view also shows that the maximum and minimum fuel pressures are lower for Vehicle A compared to Vehicle B. Figure 7 is a histogram of the same data showing that Vehicle A operates with less than 100 bar for most of the test while Vehicle B operates between 200 and 250 bar for over fifty percent of the test.

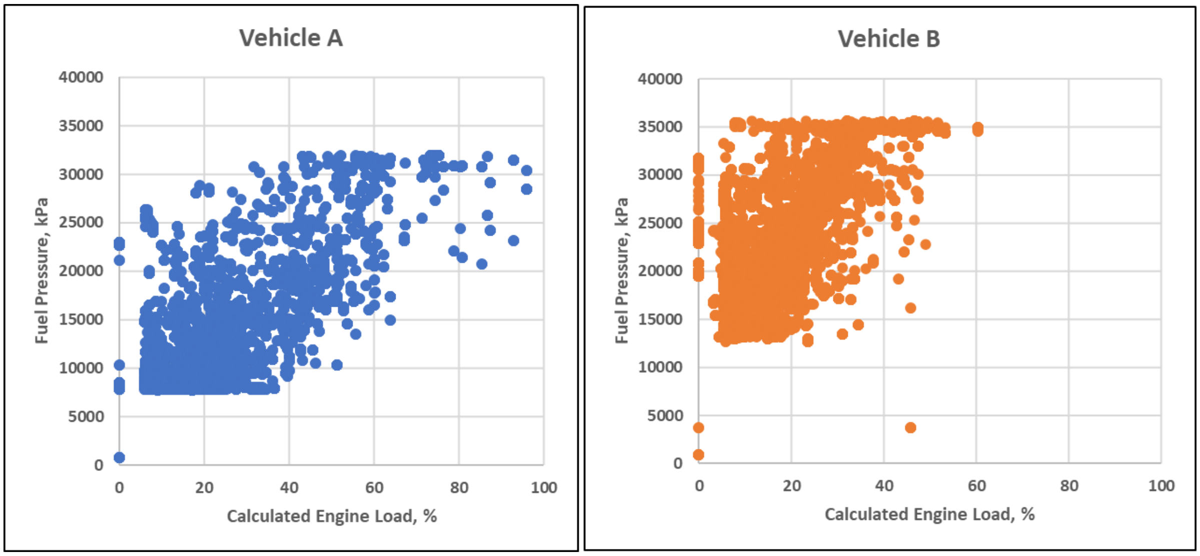

FIGURE 6: SCATTER PLOT OF FUEL PRESSURE OVER LA92 CYCLE

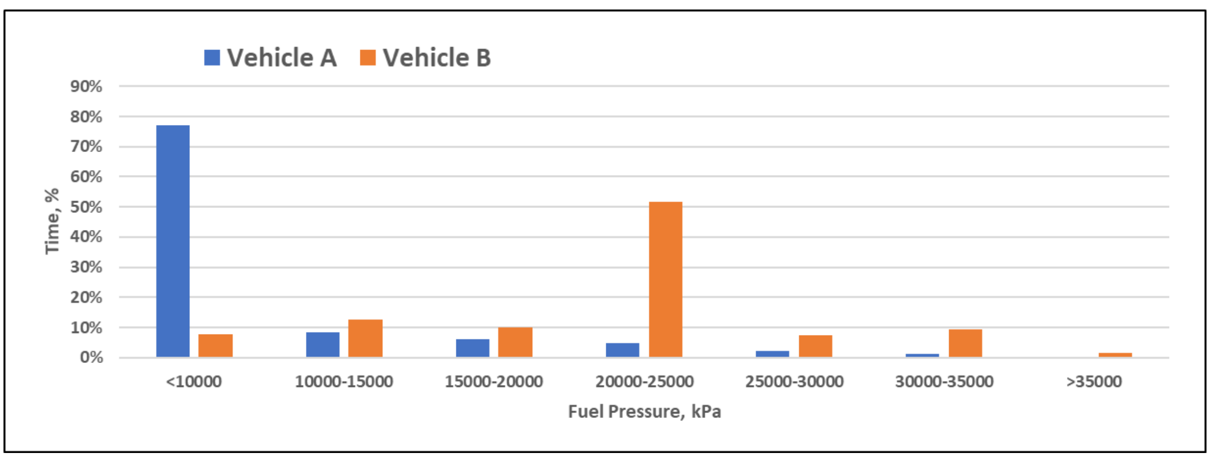

FIGURE 7: HISTOGRAM OF FUEL PRESSURE OVER LA92 CYCLE

3.2.4 Particulate Emission Signature

Low particulate emissions were measured from Vehicle B's FTP-75 checkout test and this trend continued for LA92 tests. Particulate mass, particulate number, and exhaust soot all produced the same trend of significantly low cold-start particle emissions. Figure 8 shows the accumulated exhaust soot from both vehicles over four repeat LA92 tests, using certification fuel. Particulate emissions from Vehicle B were significantly low until approximately 1,000 seconds into the cycle. After 1,000 seconds, Vehicle B began to generate particulate emissions, and even passed the accumulated level from Vehicle A for some tests.

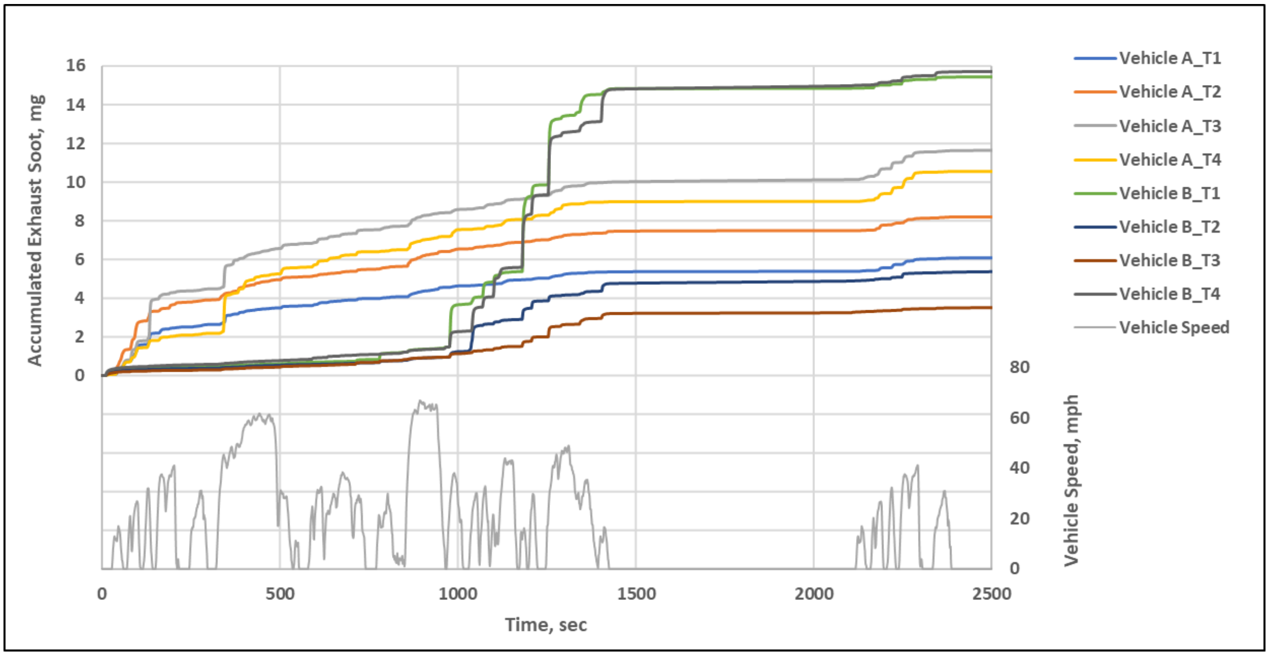

FIGURE 8: ACCUMULATED EXHAUST SOOT OVER THE LA92 CYCLE

Operational OBD data from Vehicle B was examined to determine if there was a correlation between the particulate emission signature and engine parameters recorded by the OBD system. Fuel rate, injection timing, injection pressure, spark timing, fuel-air ratio, EGR rate, and other parameters were investigated, but no correlation was identified that was consistent for the entire LA92 cycle. However, spikes in soot concentration were found to align with engine restarts after the engine was at operating temperature. Figure 9 shows the soot concentration and engine speed over the LA92 cycle.

FIGURE 9: SOOT SPIKES FROM VEHICLE B

While a complete understanding of Vehicle B's control strategy was outside the scope of this project, one (1) additional effort was made to investigate the particulate phenomenon. Fuel injector signals were instrumented and recorded with an oscilloscope over a single LA92 test. Figure 10 shows the fuel injection duration and soot concentration for a small segment of the test. Although no definitive cause for the soot spikes were identified from the fuel injector data, it appears that an initial single injection event followed by a split injection event does have an impact on soot production. Two (2) such sequences are identified by red circles in the figure.

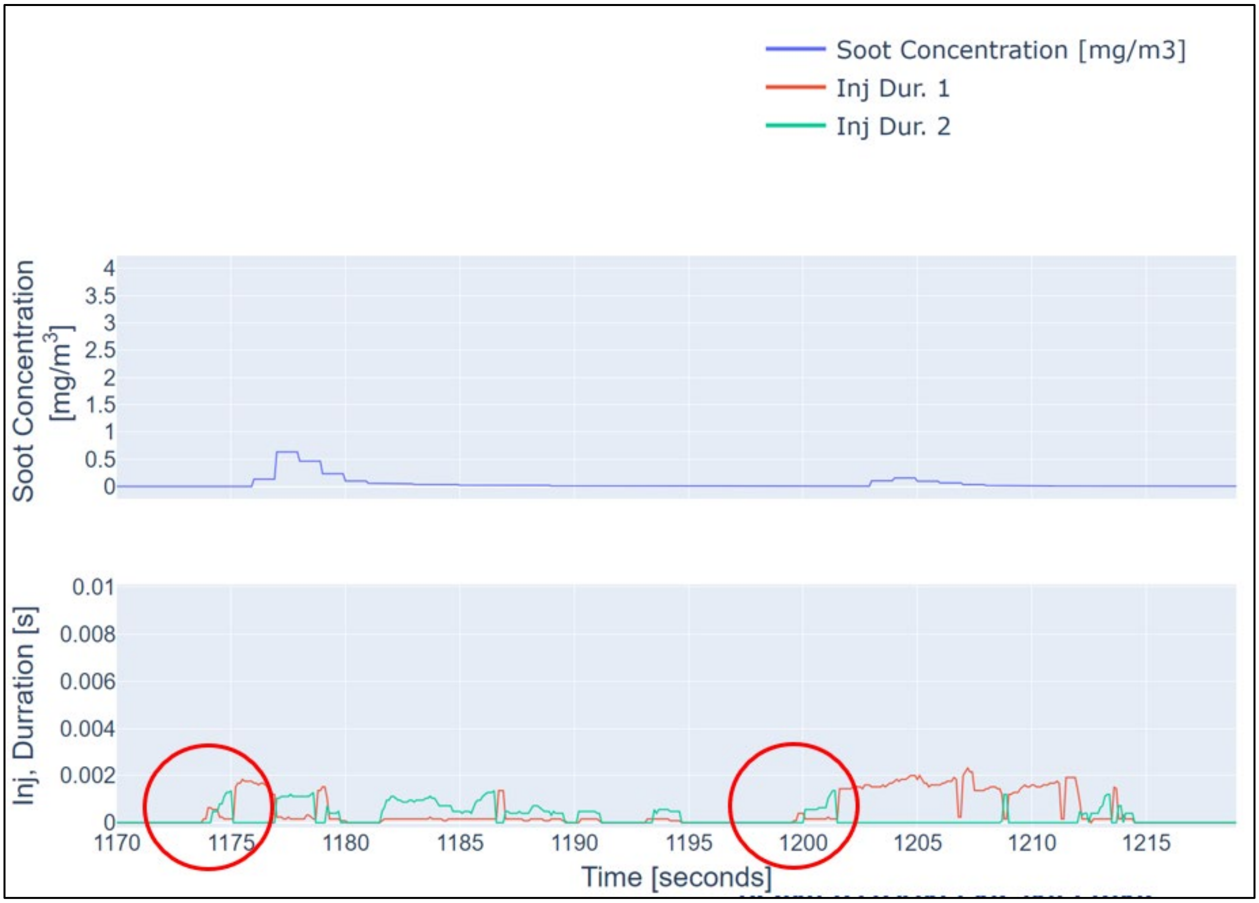

FIGURE 10: FUEL INJECTION DURATION FROM VEHICLE B

3.3 Test Cycle

A 3-phase cold-start LA92 drive schedule was used for all tests in this project. Figure 11 **s**hows the first two (2) phases of this schedule. The LA92 is run in the following manner: Phase 1 and Phase 2 are run consecutively, followed by a ten (10)-minute hot soak, then Phase 3 is run, which is a duplicate of Phase 1. Emissions data were measured for all phases.

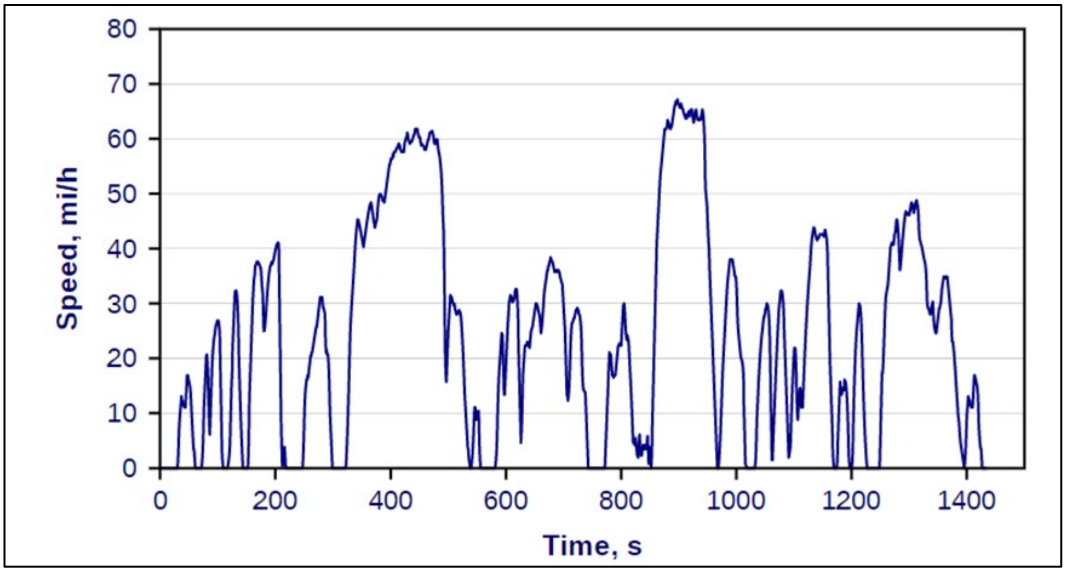

FIGURE 11: PHASE 1 AND 2 OF THE LA92 DRIVE CYCLE

3.4 Chassis Dynamometer

Emissions testing was conducted on a Horiba 48-inch single-roll chassis dynamometer. The dynamometer can electrically simulate inertia weights up to 15,000 lbs over the FTP-75, and provide programmable road-load simulation of up to 200 hp continuous at 65 mph. SwRI derived set road load coefficients using inertia settings and target road-load coefficients from the EPA database for each test vehicle. Table 6 gives the target and derived set road-load coefficients for each vehicle. The same chassis dynamometer and driver were used for all testing in this project. During the soak periods, all vehicles were fitted with a trickle charger to maintain battery condition.

TABLE 6: CHASSIS DYNAMOMETER LOAD SETTINGS

Vehicle ID	A	B
Target Values		
Equivalent Test Weight (lbs)	3625	4250
A (lbf)	30.603	50.0
B (lbf/mph)	0.14139	0.1490
C (lbf/mph**2)	0.018961	0.0187
Set Values		
Equivalent Test Weight (lbs)	3625	4250
A (lbf)	13.47	24.51
B (lbf/mph)	0.1261	0.2651
C (lbf/mph**2)	0.01740	0.01297

3.5 Laboratory Emissions Sampling Systems

For determination of exhaust emissions and fuel economy by the carbon balance method, 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 determined in a manner consistent with light-duty vehicle testing protocols given in 40 CFR Part 1066. A Horiba Constant Volume Sampler (CVS) was used to collect dilute exhaust in sample bags. For the determination of PM emissions, a proportional sample of dilute exhaust was drawn through a 47mm Whatman Teflon membrane filter. Soot, particulate number, and particulate size distribution were also measured from dilute exhaust using analysis methods given below:

Constituent	Analysis Method
Total Hydrocarbon	Flame Ionization Detector
Methane	Gas Chromatograph
Carbon Monoxide	Non-Dispersive Infrared Detector
Carbon Dioxide	Non-Dispersive Infrared Detector
Oxides of Nitrogen	Chemiluminescent Detector
Ammonia	Fourier-transform Infrared Spectroscopy
Nitrous Oxide	Fourier-transform Infrared Spectroscopy
Particulate Mass	Gravimetric Measurement
Particulate Number	EU PMP compliant solid particle number measurement
Soot	Photo-acoustic based AVL Micro Soot Sensor (MSS)
Particulate Size Distribution	Engine exhaust particle sizer with SwRI catalytic stripper

Figure 12 shows the test cell layout for this project.

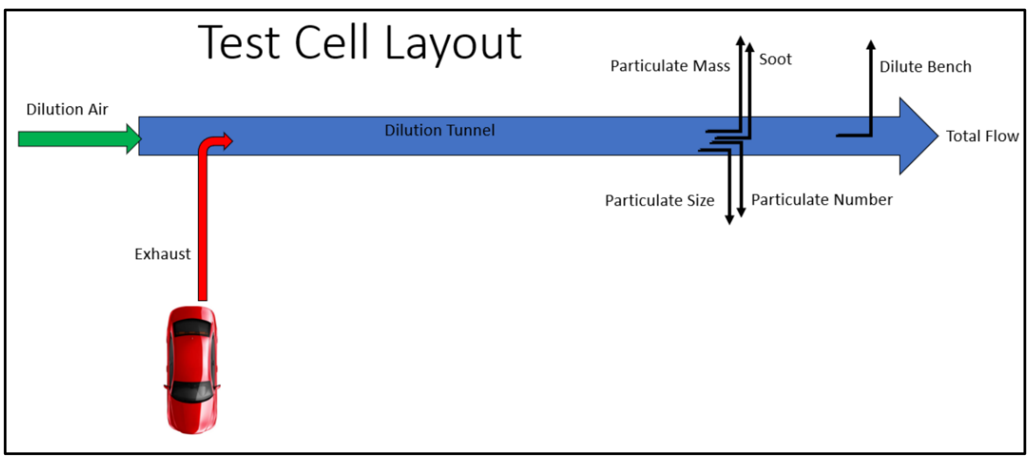

FIGURE 12: TEST CELL LAYOUT

3.6 On-Board Diagnostic and Exhaust Flow Measurement

On-board Diagnostic data were recorded continuously throughout each test. Below is the list of targeted OBD channels. Not all channels were available for each vehicle.

- Absolute Throttle Position
- Relative Throttle Position
- Absolute Throttle Position B
- Commanded Throttle Actuator Control
- Intake Manifold Absolute Pressure
- Mass Air Flow Rate
- Ignition Timing Advance Cylinder #1
- Bank 1 - Sensor 1 Lambda (Wide Range O_2)
- Absolute Load Value
- Engine RPM
- Vehicle Speed
- Calculated Load Value
- Engine Coolant Temperature
- Commanded Evaporative Purge
- Banks 1 - Sensor 1 O_2 Voltage
- Intake Air Temperature
- Commanded Equivalence Ratio

3.7 Experimental Design

Each of the seven (7) test fuels was tested in a single test set comprised of three (3) to four (4) LA92 tests. The order of the test fuels was randomized, but care was taken to avoid vehicles running the same test fuel in each week to avoid potential confounding of any of the fuel properties with unknown systemic differences that may arise in each test week. When the first test set of Vehicle B was voided, the matrix order was reassigned with this consideration in mind, and the final test matrix is shown below in Table 7.

TABLE 7: TEST MATRIX

Vehicle ID	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Vehicle A	Fuel C	Fuel A	Fuel D	Fuel E	Fuel G	Fuel B	Fuel F	na
Vehicle B	Fuel D[1]	Fuel D	Fuel E	Fuel B	Fuel C	Fuel G	Fuel A	Fuel F
[1] Void due to inoperative vehicle hybrid system								

Because each fuel was only tested in a single test set of three (3) or four (4) tests, it is assumed for this project that no drift occurred. Additionally, it is assumed that there was no long-term variance component in any of the emissions results. This assumption means that if repeated testing were to take place on identical test fuels and vehicles, at two (2) different points in time, that these two (2) test sets would converge on the same estimate of the mean.

3.8 Test Procedure

Each vehicle-fuel combination was tested over three repeats of the cold-start LA92 drive cycle. A fourth LA92 cycle was conducted if the first three (3) tests did not meet the listed criteria below. Although a repeatability metric for soot was not established, soot results were monitored, and a fourth test was conducted if one (1) of the first three (3) test results appeared to be an outlier.

Repeatability Criteria

THC Flag
- THC CoV (Std. Dev. / Mean) > 25% for composite results
- Mean THC > 0.02 g/mi for composite results

CO Flag
- Standard deviation of CubeRoot (CO) > 0.05 for composite results
- Mean CO > 0.15 g/mi for composite results

NOx Flag
- NOx CoV (Std. Dev. / Mean) > 25% for composite results
- Mean NOx > 0.01 g/mi for composite results

The following steps were conducted with each vehicle-fuel combination. Details for fuel change, sulfur purge, and vehicle conditioning sequences are given in Appendix B. Steps 1-17 represent a single block in the matrix. Testing began on February 7, 2022, and was completed April 29, 2022.

Test Steps

1. Conduct a fuel drain/fill using test fuel
2. Conduct a sulfur purge
3. Conduct vehicle coast downs
4. Conduct a 2nd and 3rd drain/fill using test fuel
5. Soak vehicle for 24 hours
6. Conduct prep cycles (UDDS + 2X HwFET + US06)
7. Soak vehicle for 24 hours
8. Conduct cold-start LA92 prep
9. Soak vehicle for 24 hours
10. Conduct 1st cold-start LA92
11. Soak vehicle for 24 hours
12. Conduct 2nd cold-start LA92
13. Soak vehicle for 24 hours
14. Conduct 3rd cold-start LA92
15. Review data against predetermine repeatability criterion
16. If required, Soak vehicle for 24 hours
17. If required, Conduct a 4th cold-start LA92

4.0 STATISTICAL ANALYSIS OF RESULTS

This section provides details of the statistical analysis conducted to assess the impact of changes in fuel PMI, RVP, and ethanol content on LA92 weighted emissions results of two (2) high fuel injection pressure vehicles. The full list of parameters studied for weighted LA92 results included

- PM, mg/mi
- Soot, mg/mi
- SPN10, #/mi
- SPN23, #/mi
- THC, g/mi
- CH_4, g/mi
- CO, g/mi
- CO_2, g/mi
- NO_x, g/mi
- NH_3, g/mi
- N_2O, g/mi

Additional analysis is also conducted looking at Phase 1 alone for particulate mass, particulate number, and soot. Initial review of the data showed that the SPN10 and SPN23 measurements were highly correlated (R-squared value of 98.6%). With this level of correlation, only a single model is needed to determine the fuel property impact on solid particle number. Therefore, only SPN10 results are shown. A plot of SPN23 vs. SPN10 is shown below in Figure 13.

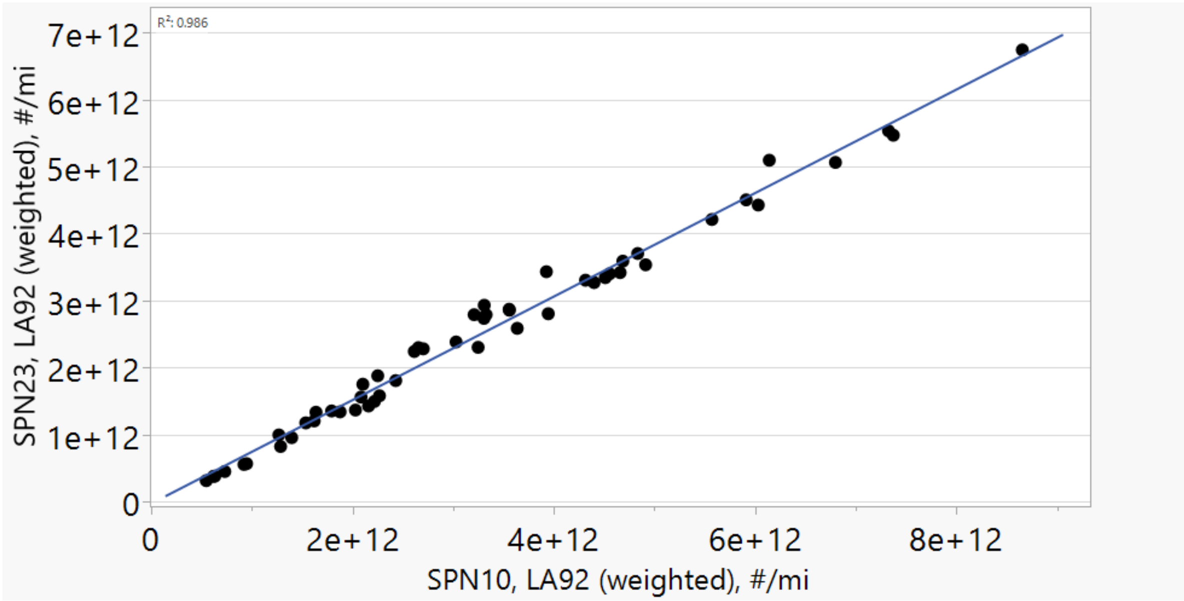

FIGURE 13: SPN23 (#/MI) VS. SPN10 (#/MI)

The sections that follow provide details of the analysis. Section 4.1 includes a fuel property correlation study to determine other fuel properties highly correlated with fuel PMI, RVP, and ethanol content of these test fuels. Section 4.2 provides details of the data transformation process, outlier analysis, and equal variance testing between vehicles. Section 4.3 discusses the modeling methodology and results included. Individual emissions modeling results are provided in Sections 4.3.1 to 4.3.10, and Section 4.4 provides a conclusion and summary table.

4.1 Fuel Property Correlation Study

Significant collinearities existed among the fuel properties. When this occurs, one cannot attribute changes in emissions to changes in PMI, RVP, or ethanol content independent of other highly correlated properties. Though the regression models use PMI, RVP, and ethanol content as predictors, true causation of significant changes in the models may be due to the variables in the model, some other highly correlated fuel properties, or a combination of both. Pearson's correlation coefficients were determined between each of the key fuel properties and a selection of other fuel properties measured in this work. The results are provided in Table 8. The range of the values is between -1 and 1. The closer to the ends of this range, the stronger the correlation, with a value of 1 indicating a positive sloping exact linear relationship between the two (2) variables, -1 indicating a negative sloping exact linear relationship, and a value of 0 indicating no relationship at all between the variables. In the table below, the stronger the correlation, the darker green the cell is colored.

TABLE 8: FUEL PROPERTY CORRELATION MATRIX

	PMI	RVP	Ethanol
PMI	1.000		
RVP (EPA Equation)	-0.460	1.000	
Ethanol (vol%)	-0.046	-0.421	1.000
IBP	0.357	-0.970	0.366
T_5	0.417	-0.996	0.473
T_10	0.368	-0.988	0.466
T_20	0.290	-0.960	0.496
T_30	0.311	-0.899	0.527
T_40	0.342	-0.709	0.413
T_50	0.449	-0.460	-0.561
T_60	0.807	-0.315	-0.279
T_70	0.952	-0.413	-0.003
T_80	0.939	-0.398	0.040
T_90	0.954	-0.404	0.064
T_95	0.899	-0.339	0.062
FBP	0.951	-0.617	0.178
Total Aromatics	0.812	-0.116	-0.039
Recovered	0.117	-0.655	0.853
Residue	0.128	-0.025	-0.639
Loss	-0.145	0.716	-0.834
Net Heat of Combustion (BTU/lb)	-0.313	0.705	-0.912
RON	0.220	0.104	0.461
MON	0.337	0.320	0.071
API Gravity	-0.746	0.901	-0.442
Density @ 15C	0.743	-0.902	0.447
Total Oxygen	-0.077	-0.390	0.998
Carbon Content	0.232	0.264	-0.961
Hydrogen Content	-0.639	0.758	-0.578
H/C Ratio	-0.809	0.639	-0.040
Sulfur by UV	-0.653	0.308	0.019

PMI was found to be highly correlated with total aromatics, H/C ratio, and back-end distillation behavior, including T70, T80, T90, T95, and FBP. An example of PMI vs. T90 is shown in Figure 14. PMI was also somewhat correlated with density and API gravity. It should be noted that any strong correlations observed (highly positive or negative correlation coefficient) are not necessarily an indication that these fuel properties are intrinsically or typically related, but only that they share a relationship within the seven fuels tested in this study. Other bulk compositional properties such as total olefins, total naphthenes, total poly-nuclear aromatics, as well as specific hydrocarbon components or component groups (e.g., C9 and higher aromatics) were not determined in this work, and thus are not included in the correlation analysis.

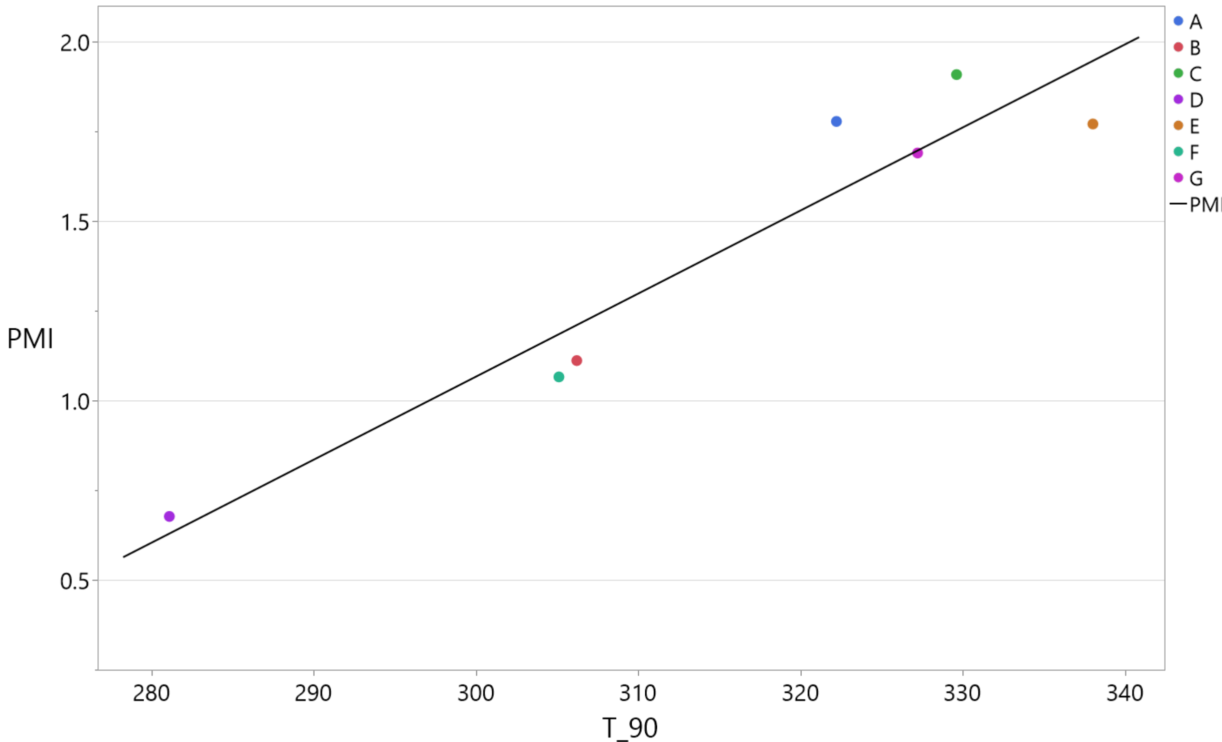

FIGURE 14: FUEL PMI VS. T90

RVP was found to be highly correlated with front-end distillation behavior, including IBP, T10, T20, and T30. RVP was also highly correlated with density and API gravity. apor pressure, distillation, and density may affect the fuel spray formation and breakup, which may affect processes such as fuel-air mixing, in-cylinder fuel distribution, and wall wetting.

Ethanol content was strongly correlated with the net heat of combustion, total oxygen, and carbon content. Lower heat of combustion may increase the mass of fuel injected, which could increase plume length and increase wall wetting. Higher oxygen content and ethanol content may increase the heat of vaporization, inhibiting fuel vaporization and mixing.

Due to the multiple strong correlations between fuel properties (only some of which have been assessed in this work), fuel property effects on emissions cannot be independently attributed to any one fuel property. Therefore, conclusions regarding the significance of PMI, RVP, and ethanol content in the statistical analyses conducted in this work must also additionally consider these other strong correlations when attributing causation.

4.2 Data Transformations, Outliers, and Equal Variance Testing

For each emission parameter, a least squares (LS) linear regression model was run to determine the statistical significance of PMI, RVP, and ethanol content as predictors. A required assumption of these regression models is that model residuals (prediction errors) follow a normal distribution with a constant variance. Therefore, to satisfy the assumptions of the statistical model, a transformation of the emissions parameter is often necessary.

To determine the appropriate transformation, a linear regression model was run with each emissions parameter as a function of "vehicle-fuel," a term which concatenates the vehicle name and the fuel name to create 14 unique levels. Modeling the data this way considers only the within-set repeatability to determine how variability may change with level. This removes the influence of variable selection on the selected transformation. With each emissions model, a Box-Cox transformation analysis was performed to select the appropriate transformation. The Box-Cox method allows the choice of a power transformation or a natural log transformation. Figure 15 shows sample output of a Box-Cox analysis.

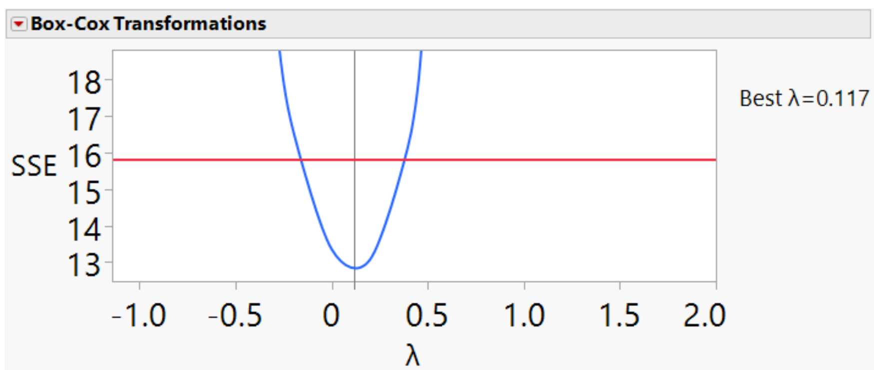

FIGURE 15: EXAMPLE OF BOX-COX ANALYSIS OUTPUT

The transformation is selected based on choosing the value of lambda which minimizes the sum of squared errors (SSE), and the transformed data becomes

$$\text{Transformation} = \begin{cases} Y^{\lambda}, & if\ \lambda \neq 0 \\ \ln(Y), & if\ \lambda = 0 \end{cases}$$

A value of lambda within the 95% confidence interval is represented everywhere along the blue curved line below the straight red line depicted in Figure 15. Therefore, a convenient choice of lambda is often chosen to make the transformation a more traditional value rather than the absolute minimum. In this example, a natural log transformation would be appropriate ($\lambda = 0$).

A factor that may influence the selection of the transformation would be the presence of outliers. Therefore, prior to selecting a transformation, studentized residuals were obtained for the untransformed model. A residual is another term for model prediction error. With this particular model form, the residual is simply the difference between the individual result and the average of all results for that vehicle-fuel combination. A studentized residual is a residual that is divided by an estimate of the standard deviation, and therefore the statistic in this case can be thought of as the number of standard deviations away from the average result of that vehicle-fuel combination. Common cut-offs range from +/- 2 to +/- 3 depending on the application. In this case, the values outside of +/- 2.5 were considered to be outliers.

Outliers and transformations can impact one another. A point may be considered an outlier when a model lacks a proper transformation. Therefore, an iterative process was used to select an appropriate transformation and identify outliers. The algorithm went as follows for each individual emissions parameter separately:

1. Model the untransformed parameter as a function of vehicle-fuel.
2. Determine outliers based on studentized residuals beyond +/- 2.5.
3. Re-run model without outliers and determine the appropriate transformation using the Box-Cox approach.
4. Return outliers to the data set and run a model with the transformed parameter as a function of vehicle-fuel.
5. Determine final outliers based on studentized residuals beyond +/- 2.5.

Next, equal variance testing was conducted to determine whether the variability in each emissions parameter was statistically different between vehicles. Homogeneity of variance across factor levels is a requirement of both the ANOVA model and the t-test used in determining significance of the coefficients in the linear regression model. Therefore, if the variances are statistically different between vehicles, the vehicles would need to be modeled separately. Using the residuals from the final transformed model, after removing outliers, an F-test was conducted to test to check for equal variance between vehicles. Failure to reject the null hypothesis of equal variance meant that both vehicles would be modeled together, while a rejection of the null hypothesis, based on a F-test p-value < 0.05, meant that the vehicles would be modeled separately to determine the fuel property impacts.

The final transformation selected for each emissions parameter, along with the F-test results, are given below in Table 9. It should be noted that in cases where the F-test indicated that the vehicles needed to be modeled separately, the transformation was re-evaluated to determine that it was still appropriate for each vehicle individually, and in all cases this was true.

TABLE 9: SELECTED TRANSFORMATIONS AND VEHICLE VARIANCE EQUALITY TESTING

Parameter	Transformation	F-test Results for Equal Variance Between Vehicles	Model Vehicles Separately or Together?
THC	Ln(THC)	Accept Equal Variance	Together
CH_4	None	Reject Equal Variance	Separately
CO	Ln(CO)	Reject Equal Variance	Separately
CO_2	$Ln(CO_2)$	Accept Equal Variance	Together
NO_x	$Ln(NO_x)$	Accept Equal Variance	Together
NH_3	None	Reject Equal Variance	Separately
N_2O	$SquareRoot(N_2O)$	Accept Equal Variance	Together
PM	CubeRoot(PM)	Reject Equal Variance	Separately
MSS Soot	Ln(MSS Soot)	Reject Equal Variance	Separately
SPN10	Ln(SPN10)	Reject Equal Variance	Separately

4.3 Raw Data and Statistical Analysis

This section provides the results of the statistical analysis. The analysis includes raw data plots, a linear regression model with estimated coefficients, and plots of the emissions parameters vs. PMI, RVP, and ethanol. All analysis was conducted using JMP® Pro 16.2.

In the data plots, untransformed phase-weighted results are shown. The three (3) LA92 phases are weighted using the FTP composite phase-weighting factors to determine an LA92 composite result. That is, each composite emissions result was calculated as:

$$LA92\ (weighted) = 0.43 * \left(\frac{Y_1+Y_2}{D_1+D_2}\right) + 0.57 * \left(\frac{Y_2+Y_3}{D_2+D_3}\right)$$, where:

Y_i = Phase “i” Emissions, either grams, milligrams, or count, as specified
D_i = Phase “i” Distance, miles

A linear regression model was used to determine whether any of the three (3) fuel properties of interest were statistically significant in the emission models for one or both vehicles. Section 4.2 discusses which emission parameter models included data from both vehicles and which were modeled separately by vehicle. The form of the initial regression model was

$$Y_i = \beta_0 + \beta_1 * VehicleA + \beta_2 * PMI + \beta_3 * RVP + \beta_4 * Ethanol + \beta_5 * VehicleA * PMI + \beta_6 * VehicleA * RVP + \beta_7 * VehicleA * Ethanol + \varepsilon_i,$$

where

$Y_i =$ LA92 weighted emissions result, transformed as specified,
$\beta_0 =$model intercept,
$\beta_1 - \beta_7 =$ model variable coefficents ,
$VehicleA = 1$ if i-th result is from Vehicle A, and 0 otherwise,
$PMI =$ PMI of the fuel, continuous,
$RVP =$ RVP of the fuel in psi,
$Ethanol =$ Ethanol of the fuel, volume percent, and
$\varepsilon_i =$ Residual error ~ Normal $(0, \sigma^2)$.

For the emission parameters which were modeled separately by vehicle, the vehicle term and interaction terms were removed from the initial model.

A backwards variable selection process was used to determine which variables were statistically significant. The algorithm for the backwards variable selection is:

1. Begin with the full model including all variables and interactions.
2. If any of the fuel variables have coefficients with p-values > 0.05, identify the least significant variable as the one with the highest p-value.
3. Remove the least significant variable from the model, unless the identified variable is a main effect with interaction effects including this main effect still present in the model. In such cases retain the main effect and move on the next least significant predictor.
4. Re-run the model without the removed variable and repeat steps #2 and #3.
5. Continue this process until only significant variables remain. Insignificant main effects may still remain if the interaction terms involving them cannot be removed.

To help quantify the prediction strength of the variables deemed statistically significant, partial R-squared values are provided. This is determined using the Type III sum of squares for a factor. For models with only a single variable this value is the same as the model R-squared. For models with more than one variable, the value represents the additional prediction capability when adding this term to a model with all other variables. Therefore, for model with multiple variables, partial r-squared values may not add up to the total model r-squared value. For statistically significant effects (enough evidence to say the coefficient of the predictor is non-zero), the strength of prediction was binned into groups based on the partial R-squared values to help separate stronger predictors from weaker predictors. Though the divisions here are subjective, a predictor was considered weak if less than 40%, moderate between 40%-70%, and strong if >70%. The summary tables are color-coded based on these groups, with yellow for weaker predictors, light green for moderate predictors, and dark green for strong predictors. Additionally for fuel property variables determined to be statistically significant, the model coefficients are used to provide an estimate of the impact of that variable on the weighted emissions parameter for the LA92 cycle. Since most parameters utilized models with data transformations, the estimated impact of the fuel properties will be non-linear in original measured units. For PMI, an impact on predictions with a change of 2.0 to 1.5 and 2.0 to 1.0 was assessed, while for RVP and ethanol, changes from 9 psi to 14 psi and 10 percent to 15 percent were assessed, respectively. As mentioned previously, the estimated effect of each of these individual fuel properties is not separable from other highly collinear fuel properties, as shown by the correlation study presented in Section 4.1.

In each section x-y plots are provided for each weighted emissions parameter vs PMI, RVP, and ethanol level by vehicle. These data are shown in untransformed units so that the y-axis values would have more meaning to readers. However, modeling was conducted in most cases using transformed data. The model prediction line for the mean is provided along with 95% confidence intervals for statistically significant effects, and these lines will be non-linear in cases where the model used a data transformation. In cases where more than one fuel property was statistically significant, the model line is not included on the x-y plots, since the model is dependent on more than just a single factor. In these cases, a prediction profiler plot is included following the x-y plots which shows the prediction line for a fuel property, while holding other properties at a constant level. It is important to note that the points in the x-y plots are not adjusting for other properties, and in cases where multiple statistically significant factors are present, it may not be easy to see the relationship in the x-y plot alone. The prediction profiler is helpful in these cases. The sections that follow provide the individual results discussed in this section for each of the emissions parameters.

4.3.1 Statistical Analysis Results for Particulate Matter (PM), mg/mi

A plot of the time-ordered particulate matter data is shown below in Figure 16, separated by vehicle and colored by fuel. The differences in variability between vehicles is clear in the plot, with Vehicle B exhibiting much higher variability than Vehicle A. Therefore, outlier analysis and regression modeling were conducted on an individual vehicle basis. There was only one statistical outlier indicated by the asterisk seen in Set 3 for Vehicle B. This data point was excluded from the regression modeling. Raw data plots of the PM data vs. PMI, RVP, and ethanol are shown in Figure 17, Figure 18, and Figure 19, respectively.

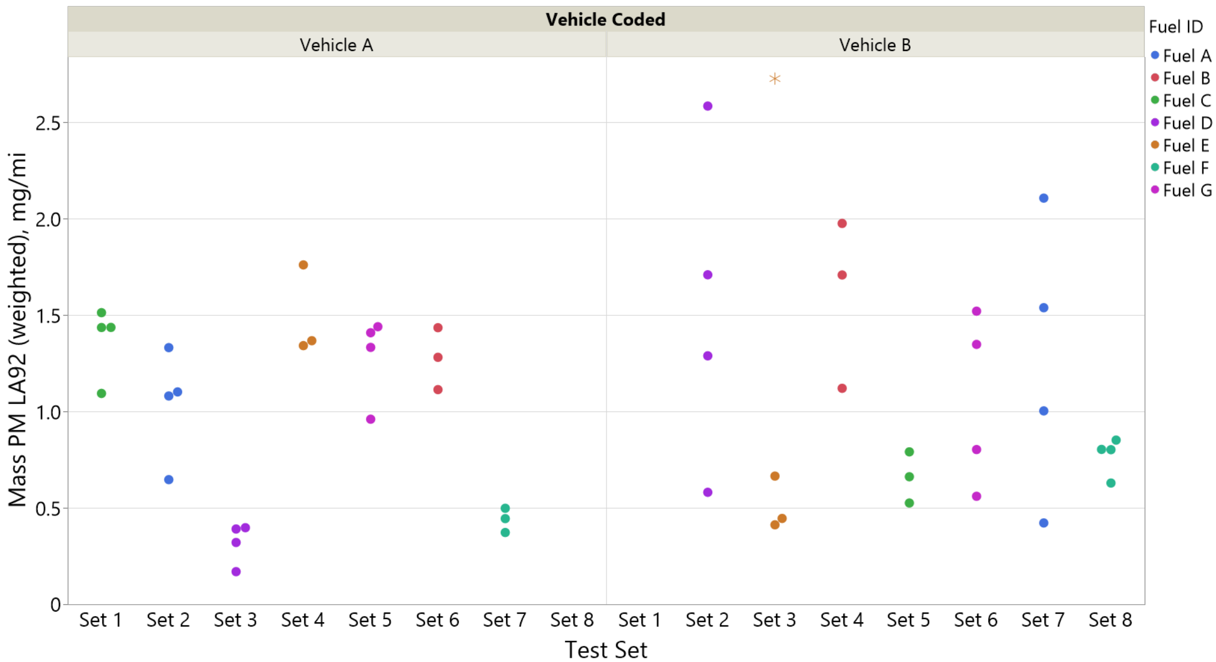

FIGURE 16: LA92 WEIGHTED PM (MG/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

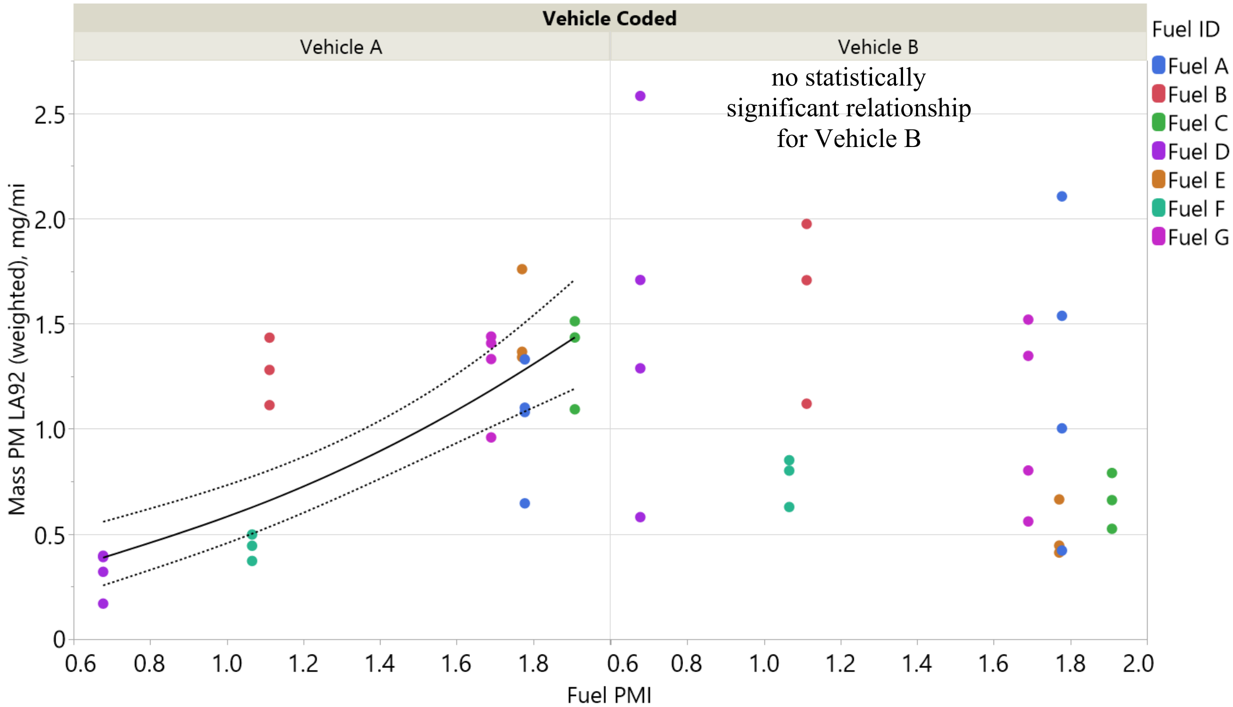

FIGURE 17: MODEL FITS PREDICTING MEAN PM EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 WEIGHTED <u>COMPOSITE</u> DATA

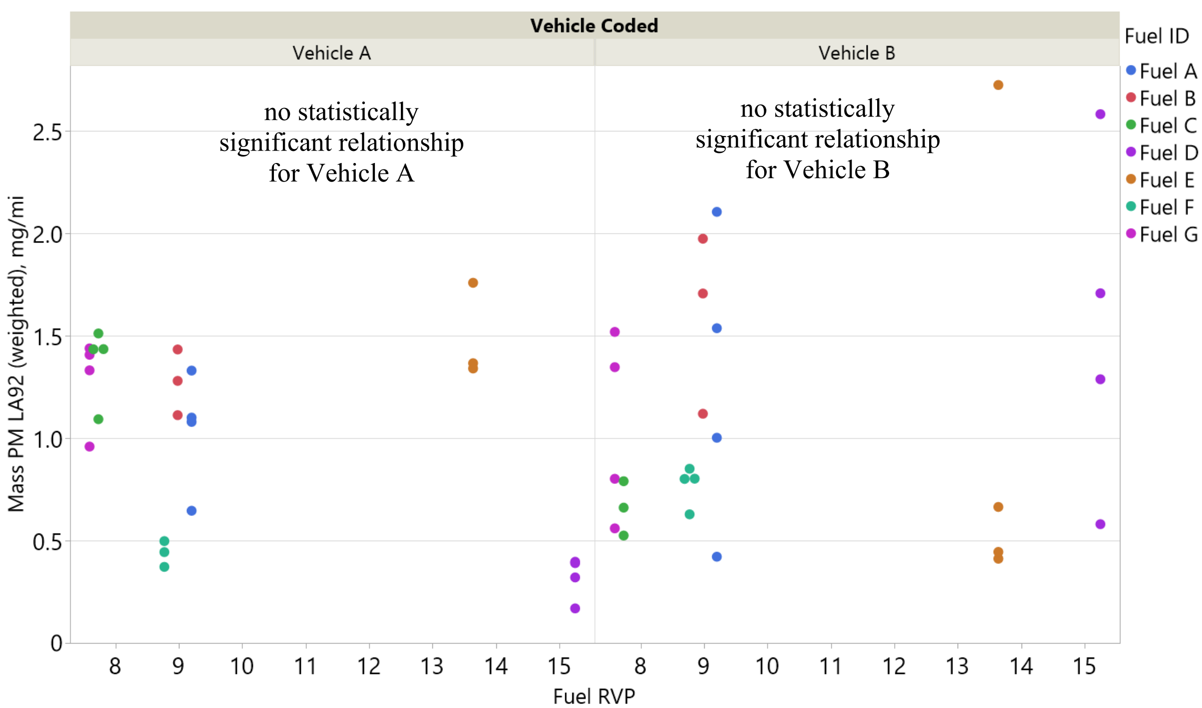

FIGURE 18: LA92 WEIGHTED PM (MG/MI) VS. FUEL RVP BY VEHICLE, COLORED BY FUEL

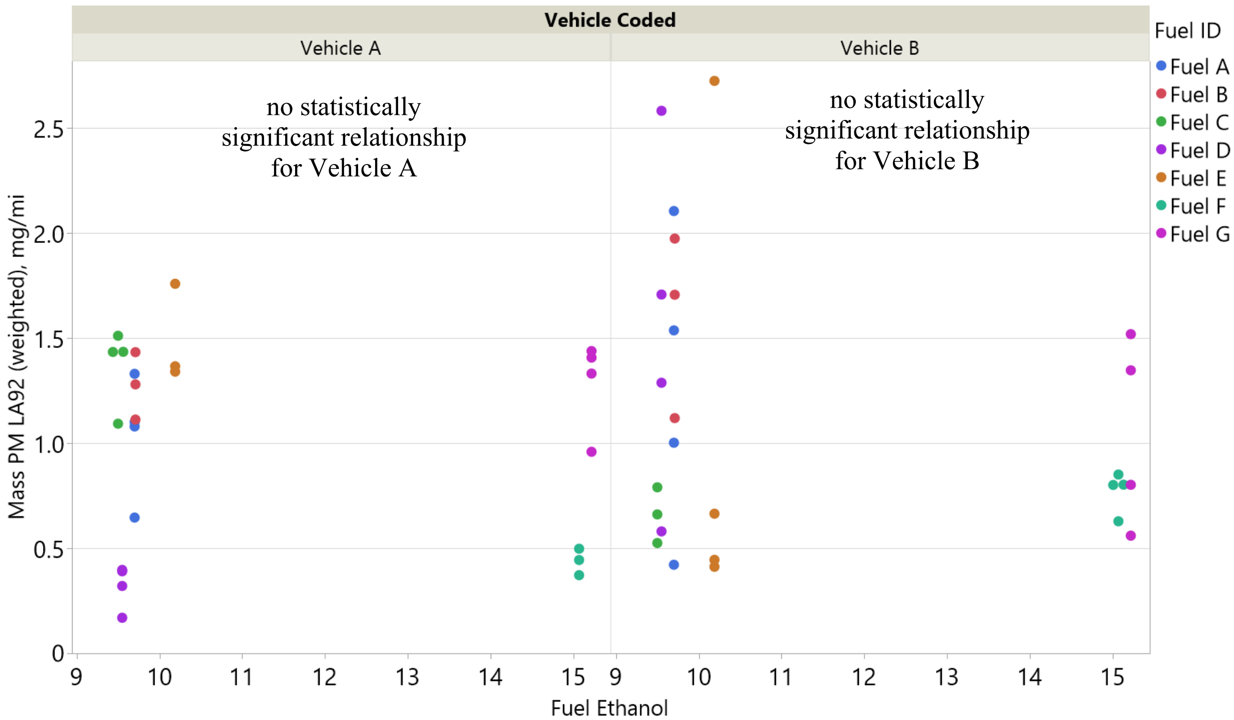

FIGURE 19: LA92 WEIGHTED PM (MG/MI) VS. FUEL ETHANOL BY VEHICLE, COLORED BY FUEL

Using the backwards elimination variable selection process described previously in Section 4.3, only Fuel PMI was statistically significant, and only in the Vehicle A model, shown in Table 10. The final regression model for Vehicle A was:

$$\widehat{\sqrt[3]{PM}} = 0.5107 + 0.3237 * FuelPMI$$

TABLE 10: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING CUBEROOT PM (MG/MI), VEHICLE A ONLY

Parameter Estimates				
Term	**Estimate**	**Prob>|t|**	**Lower 95%**	**Upper 95%**
Intercept	0.5107	<.0001*	0.3503	0.6712
Fuel PMI	0.3237	<.0001*	0.2174	0.4299

The partial R-squared (same here as model R-squared) value for PMI was 63.3 percent, meaning 63.3 percent of the total variability in the Vehicle A can be explained by the fuel PMI. Because PM was modeled using a cube root transformation, the predicted change in PM with changes in fuel PMI is non-linear in untransformed mg/mi units. Table 11 below shows the regression model's predicted change in average PM with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0 for Vehicle A.

TABLE 11: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE PARTICULATE MATTER EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Model Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	PM (mg/mi)	63.3%	1.55→0.99 (-36%)	1.55→0.58 (-63%)	-	-	-	-
B	PM (mg/mi)	-	-	-	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.1.1 LA- 92 Phase 1 Statistical Analysis Results for Particulate Matter (PM), mg/mi

Phase 1 only analysis was also conducted for PM. Looking at phase 1 only reveals different behavior for Vehicle B. As noted in Section 3.2.4, this vehicle had more consistent and lower particle emissions for the first phase of the test. Final results were largely determined by behavior in the second two (2) phases of the test, often catching up or exceeding Vehicle A PM levels. Raw data plots of Phase 1 PM vs. Test Set and fuel PMI are shown in Figure 20 and Figure 21.

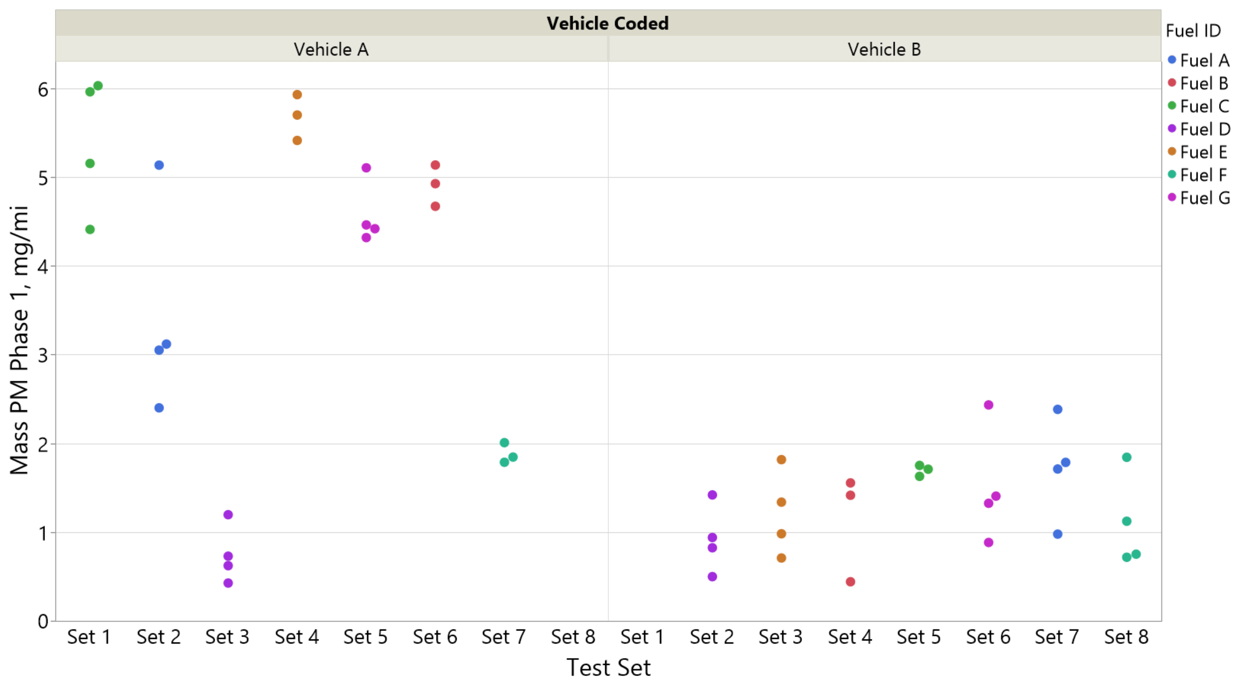

FIGURE 20: LA92 PHASE 1 PM (MG/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

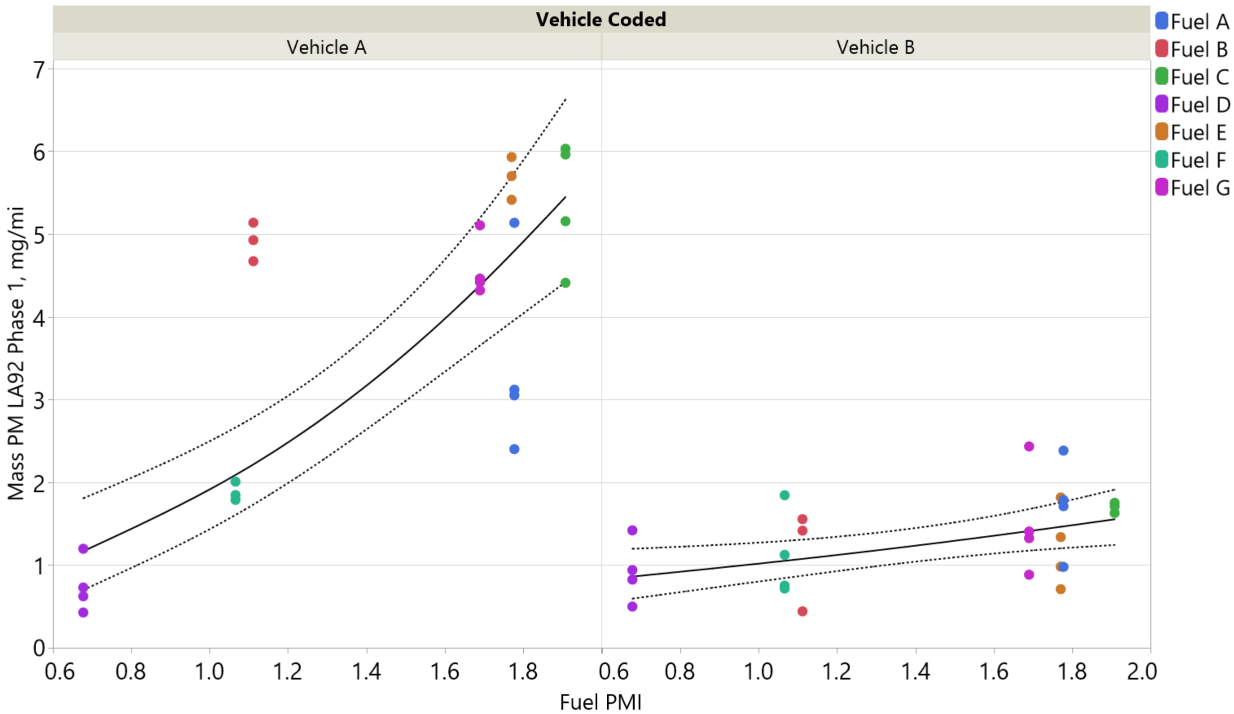

FIGURE 21: MODEL FITS PREDICTING MEAN PM EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 <u>PHASE 1</u> DATA

In the Phase 1 only regression models, the PMI variable is statistically significant now for both vehicles. The model results are shown in Table 12 and Table 13 below.

<u>Vehicle A Fitted Equation:</u> $\widehat{\sqrt[3]{PM}} = 0.6663 + 0.5735 * FuelPMI$

TABLE 12: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING CUBEROOT PM (MG/MI), PHASE 1, VEHICLE A ONLY

Parameter Estimates				
Term	**Estimate**	**Prob>|t|**	**Lower 95%**	**Upper 95%**
Intercept	0.6663	<.0001*	0.3859	0.9467
Fuel PMI	0.5735	<.0001*	0.3878	0.7593

Vehicle B Fitted Equation: $\widehat{\sqrt[3]{PM}} = 0.8380 + 0.1679 * FuelPMI$

TABLE 13: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING CUBEROOT PM (MG/MI), PHASE 1, VEHICLE B ONLY

Parameter Estimates				
Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	0.8380	<.0001*	0.6476	1.0284
Fuel PMI	0.1679	0.0122*	0.0400	0.2958

The partial R-squared (same here as model R-squared) value for PMI was 64.0 percent for Vehicle A and much weaker at 23.4 percent for Vehicle B. Table 14 below shows the regression model's predicted change in average PM with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0.

TABLE 14: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 PHASE 1 PARTICULATE MATTER EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	PM (mg/mi)	64.0%	5.96→3.56 (-40%)	5.96→1.91 (-68%)	-	-	-	-
B	PM (mg/mi)	23.4%	1.62→1.29 (-20%)	1.62→1.02 (-37%)	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.2 Statistical Analysis Results for MSS Soot, mg/mi

A plot of the time-ordered micro soot sensor data is shown below in Figure 22 separated by vehicle and colored by fuel. Like PM, differences in variability between vehicles is again evident in the plot, with Vehicle B exhibiting much higher variability than Vehicle A. Therefore, outlier analysis and regression modeling were conducted on an individual vehicle basis. There was one statistical outlier, indicated by the asterisk seen in Set 3 for Vehicle B. These data points were excluded from the regression modeling. Raw data plots of the MSS soot data vs. PMI, RVP, and ethanol content are shown in Figure 23, Figure 24, and Figure 25, respectively.

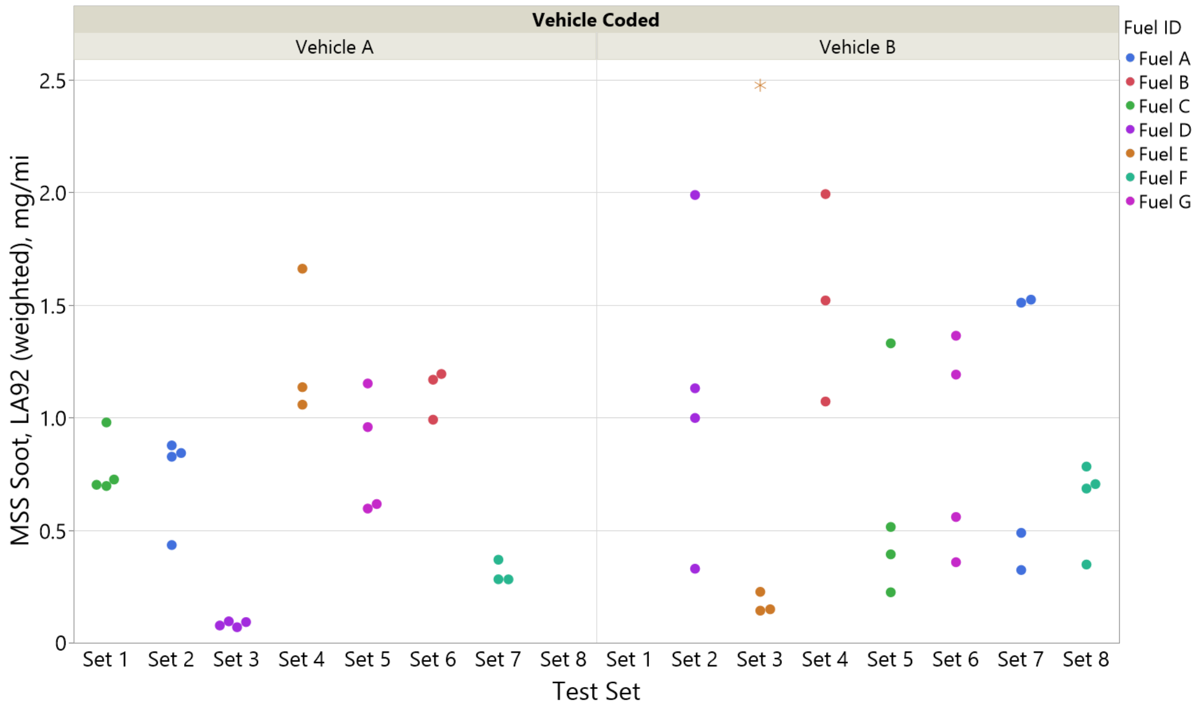

FIGURE 22: LA92 WEIGHTED MSS SOOT (MG/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

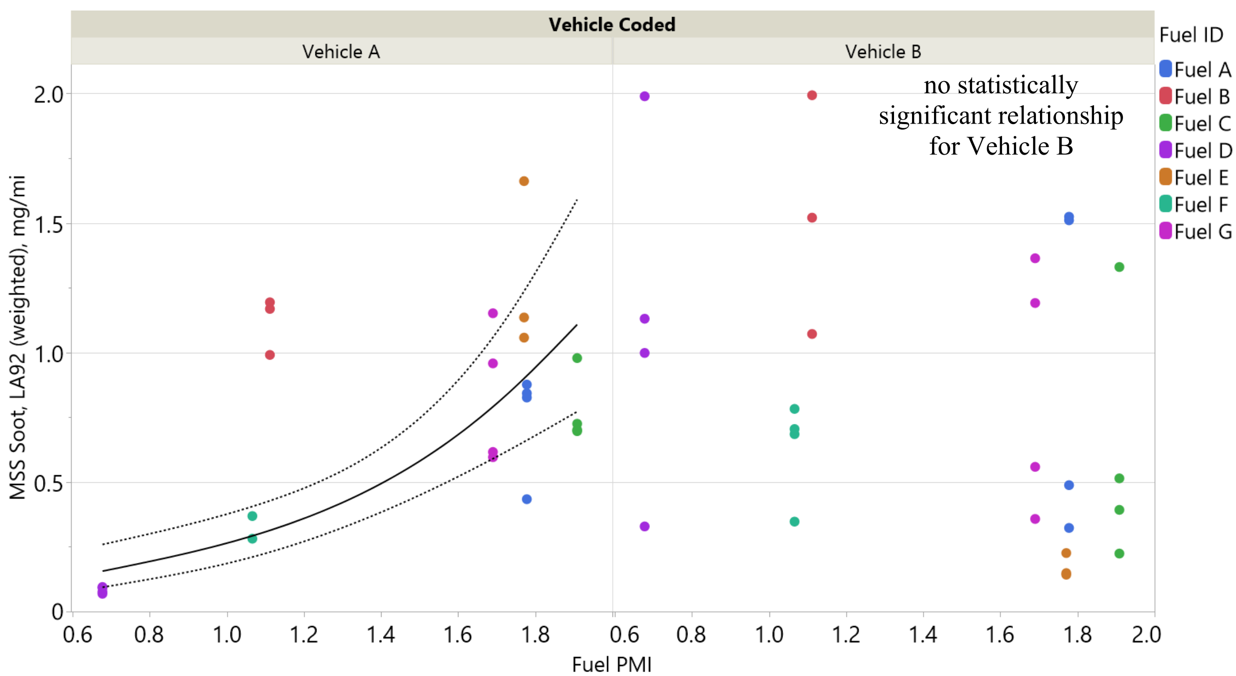

FIGURE 23: MODEL FITS PREDICTING MEAN MSS SOOT EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 WEIGHTED <u>COMPOSITE</u> DATA

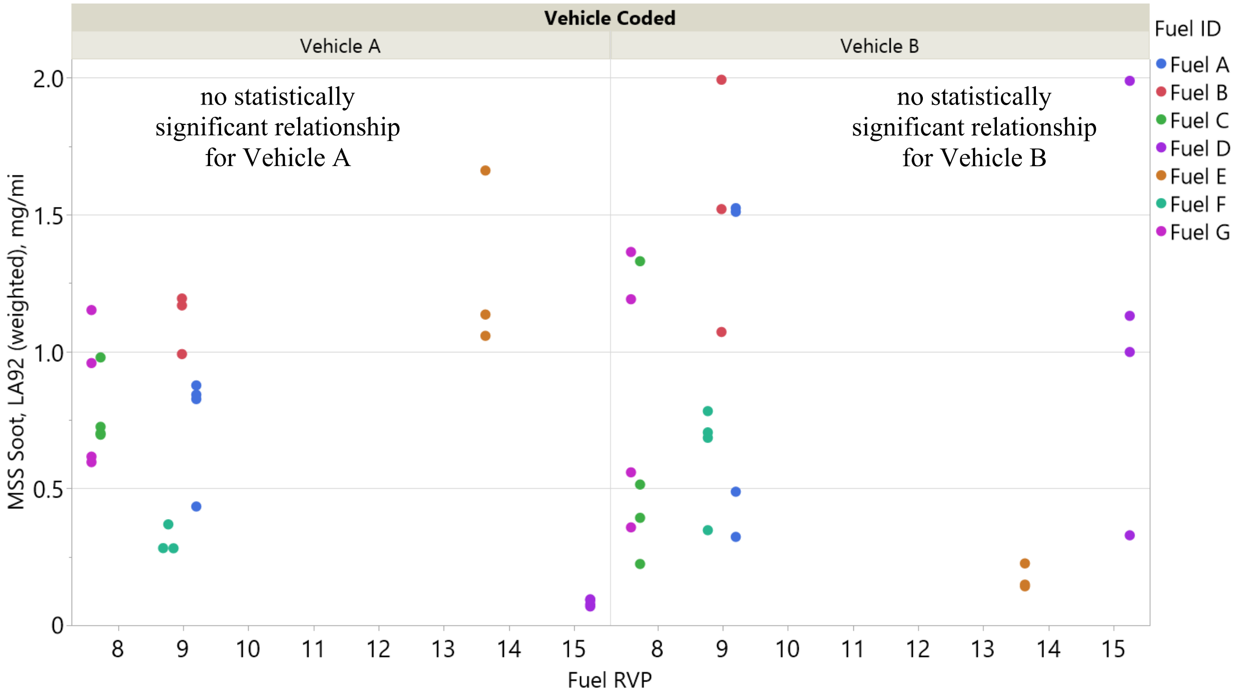

FIGURE 24: LA92 WEIGHTED MSS SOOT (MG/MI) VS. FUEL RVP BY VEHICLE, COLORED BY FUEL

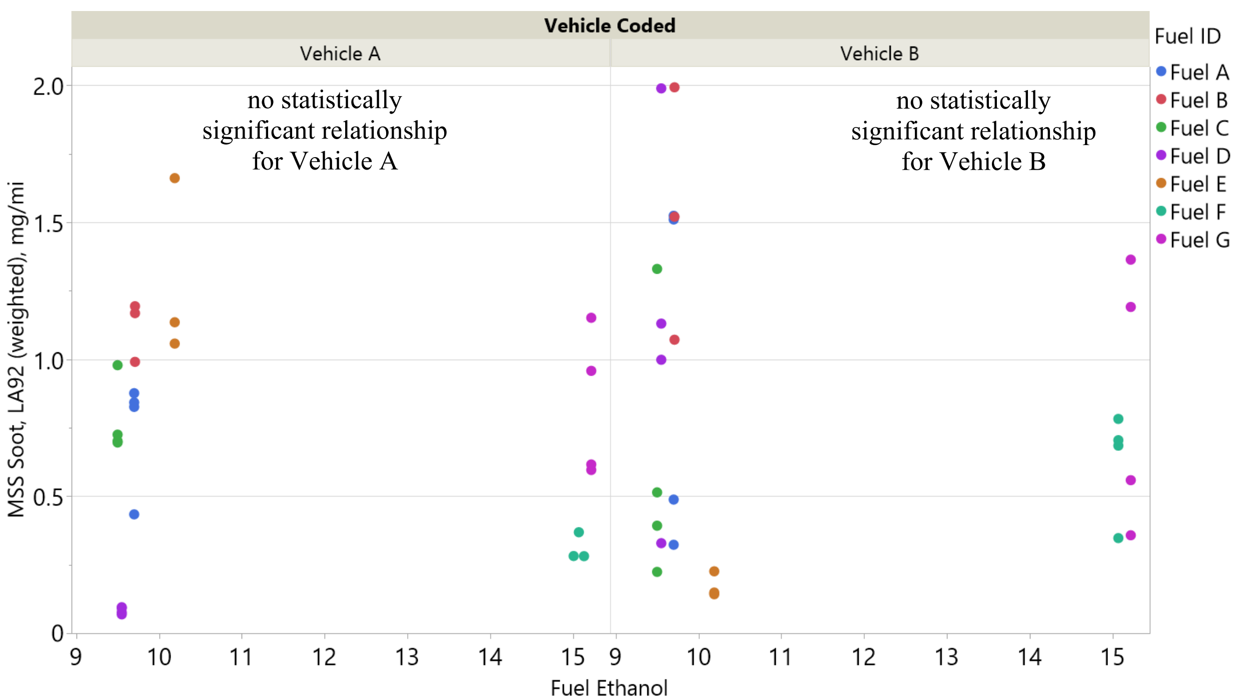

FIGURE 25: LA92 WEIGHTED MSS SOOT (MG/MI) VS. FUEL ETHANOL BY VEHICLE, COLORED BY FUEL

Like PM, only Fuel PMI was statistically significant, and only in the Vehicle A model, shown below in Table 15. The final regression model for Vehicle A was:

$$\widehat{Ln(Soot)} = -2.9244 + 1.5897 * FuelPMI$$

TABLE 15: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN MSS SOOT (MG/MI), VEHICLE A ONLY

Parameter Estimates				
Term	**Estimate**	**Prob>|t|**	**Lower 95%**	**Upper 95%**
Intercept	-2.9244	<.0001*	-3.7804	-2.0684
Fuel PMI	1.5897	<.0001*	1.0228	2.1567

The partial R-squared (same here as model R-squared) value for PMI was 59.4 percent for Vehicle A. Since soot was modeled using a natural log transformation, the estimated impact of fuel PMI is non-linear in untransformed mg/mi units. Table 16 below shows the regression model's predicted change in average MSS Soot with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0 for Vehicle A.

TABLE 16: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE MSS SOOT EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	**Model Parameter**	**Partial R^2**	**PMI 2.0 → 1.5**	**PMI 2.0 → 1.0**	**Partial R^2**	**RVP 9 → 14**	**Partial R^2**	**E10 → E15**
A	**MSS (mg/mi)**	59.4%	1.29→0.58 (-55%)	1.29→0.26 (-80%)	-	-	-	-
B	**MSS (mg/mi)**	-	-	-	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.2.1 LA- 92 Phase 1 Statistical Analysis Results for MSS Soot, mg/mi

The Phase 1 time-ordered data is plotted for Vehicles A and B below in Figure 26 and Figure 27, respectively. Not surprisingly, the MSS data for Vehicle B when looking at Phase 1 alone is very similar to what was seen with the PM data. Vehicle B produced more consistent and lower levels of soot in Phase 1 compared with the full cycle results. The plot of Phase 1 soot vs. fuel PMI is shown in Figure 28.

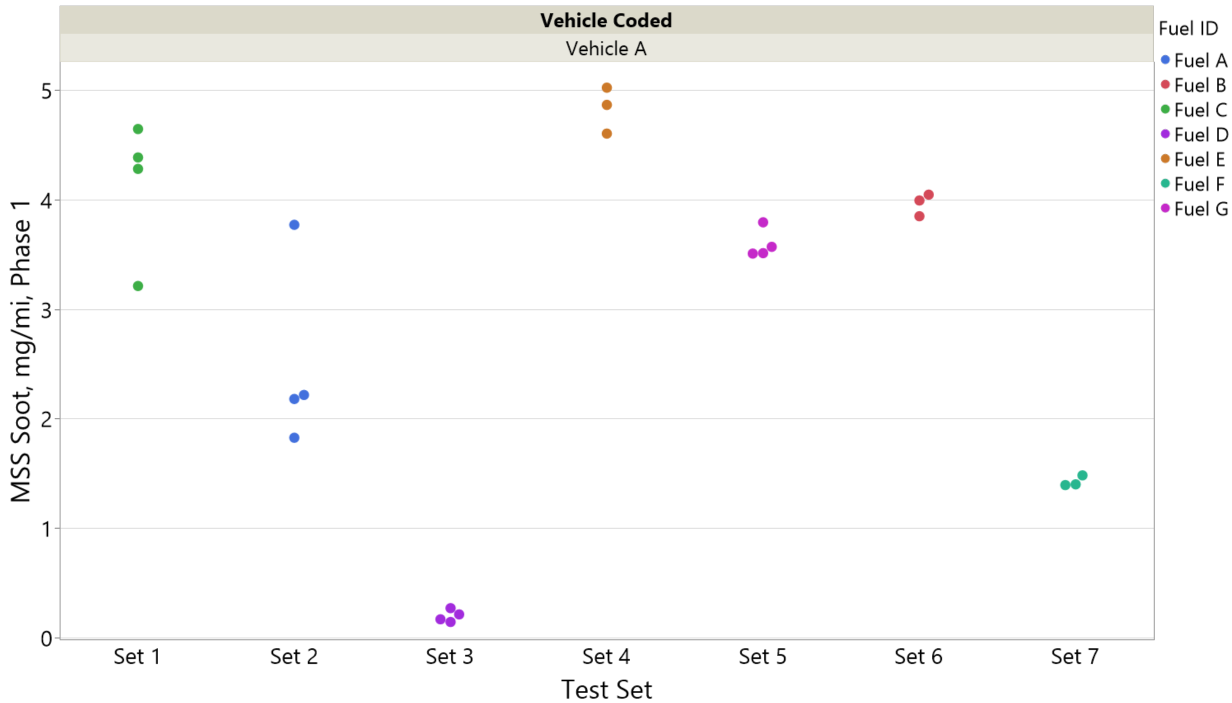

FIGURE 26: LA92 PHASE 1 MSS SOOT (MG/MI) FOR VEHICLE A BY TEST SET, COLORED BY FUEL

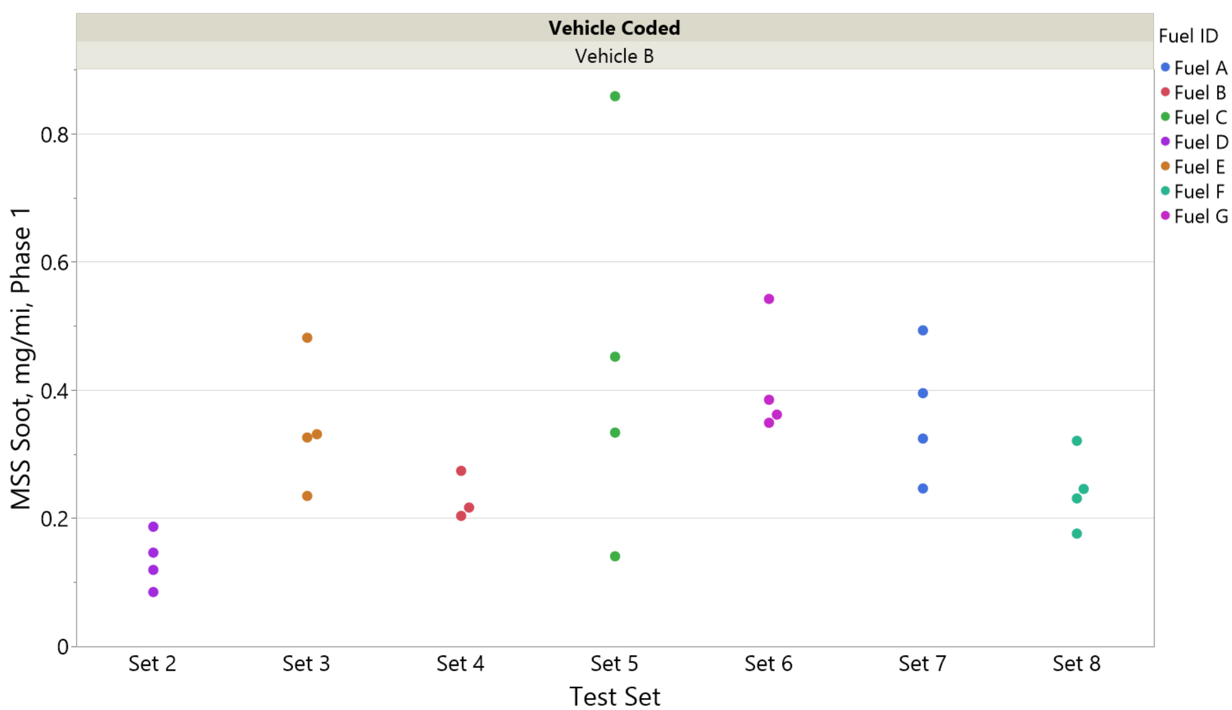

FIGURE 27: LA92 PHASE 1 MSS SOOT (MG/MI) FOR VEHICLE B BY TEST SET, COLORED BY FUEL

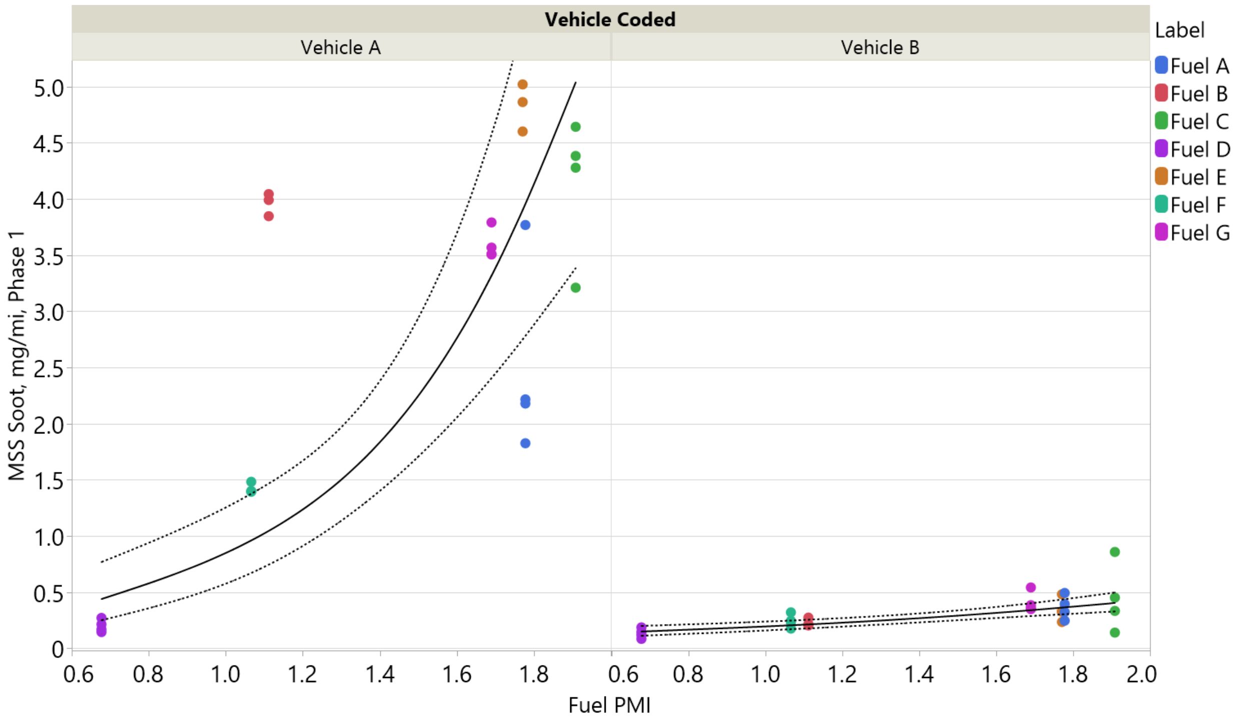

FIGURE 28: MODEL FITS PREDICTING MEAN MSS SOOT EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 PHASE 1 DATA

In the Phase 1 only regression models, the PMI variable is statistically significant now for both vehicles. The model results are shown in Table 17 and Table 18 below.

Vehicle A Fitted Equation: $\widehat{Ln(Soot)} = -2.1507 + 1.9795 * FuelPMI$

TABLE 17: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN MSS SOOT (MG/MI), PHASE 1, VEHICLE A ONLY

Parameter Estimates

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	-2.1507	<.0001*	-3.0931	-1.2083
Fuel PMI	1.9795	<.0001*	1.3554	2.6037

Vehicle B Fitted Equation: $\widehat{Ln(Soot)} = -2.4419 + 0.8062 * FuelPMI$

TABLE 18: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN MSS SOOT (MG/MI), PHASE 1, VEHICLE B ONLY

Parameter Estimates				
Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	-2.4419	<.0001*	-2.9337	-1.9500
Fuel PMI	0.8062	<.0001*	0.4797	1.1327

The partial R-squared (same here as model R-squared) value for PMI was 65.2 percent for Vehicle A and 50.9 percent for Vehicle B. Table 19 below shows the regression model's predicted change in average MSS Soot with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0.

TABLE 19: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 PHASE 1 MSS SOOT EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	MSS (mg/mi)	65.2%	6.10→2.27 (-63%)	6.10→0.84 (-86%)	-	-	-	-
B	MSS (mg/mi)	50.9%	0.44→0.29 (-33%)	0.44→0.19 (-55%)	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.3 Statistical Analysis Results for SPN10, #/mi

A plot of the time-ordered and log-transformed SPN10 data is shown below in Figure 29, separated by vehicle and colored by fuel. There were again statistically significant differences in variability between vehicles, with Vehicle B exhibiting higher variability than Vehicle A for this parameter. Therefore, outlier analysis and regression modeling were conducted on an individual vehicle basis. There was one statistical outlier, indicated by the asterisk seen in Set 3 for Vehicle B. This data point was excluded from the regression modeling. Raw data plots of the SPN10 data vs. PMI, RVP, and ethanol content are shown in Figure 30, Figure 31, and Figure 32, respectively.

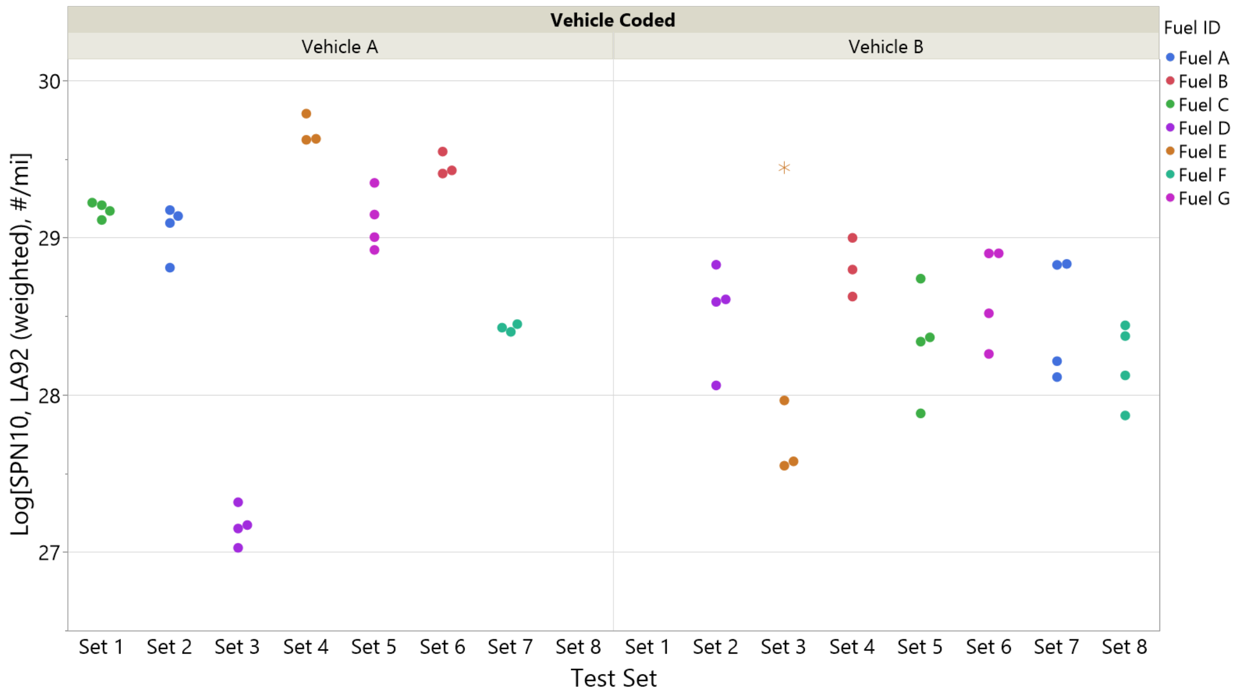

FIGURE 29: LA92 WEIGHTED SPN10 (#/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

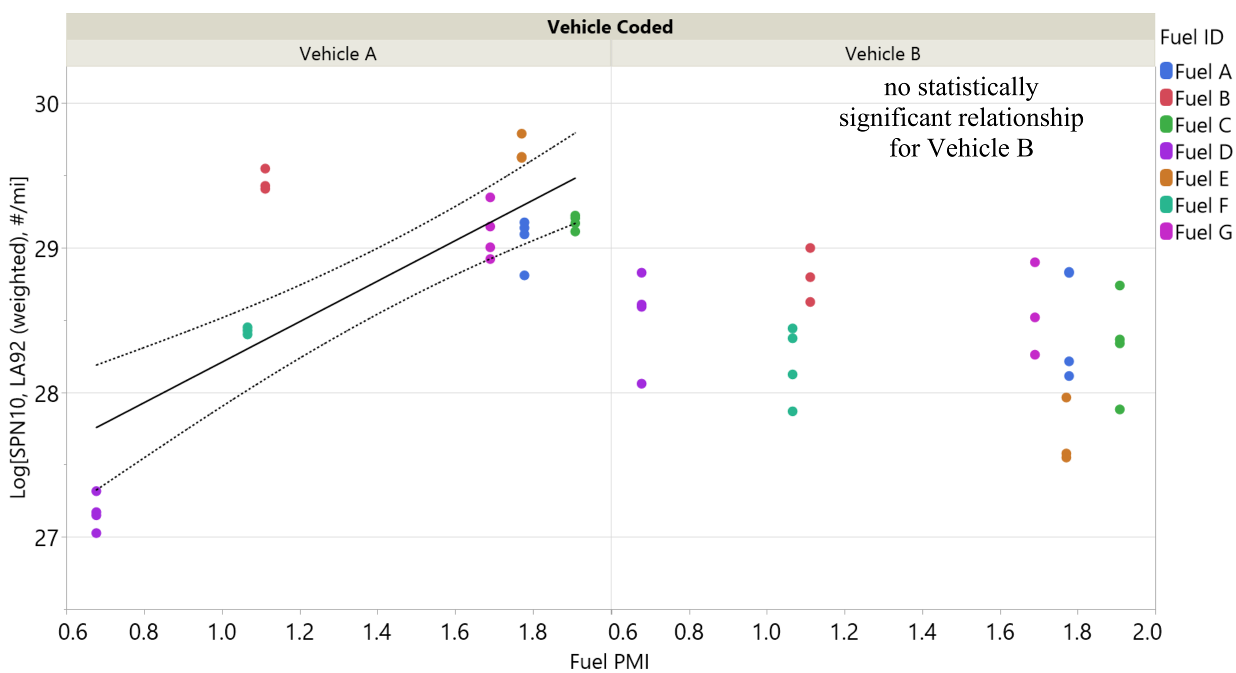

FIGURE 30: MODEL FITS PREDICTING MEAN SPN10 (#/MI) EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 WEIGHTED COMPOSITE DATA

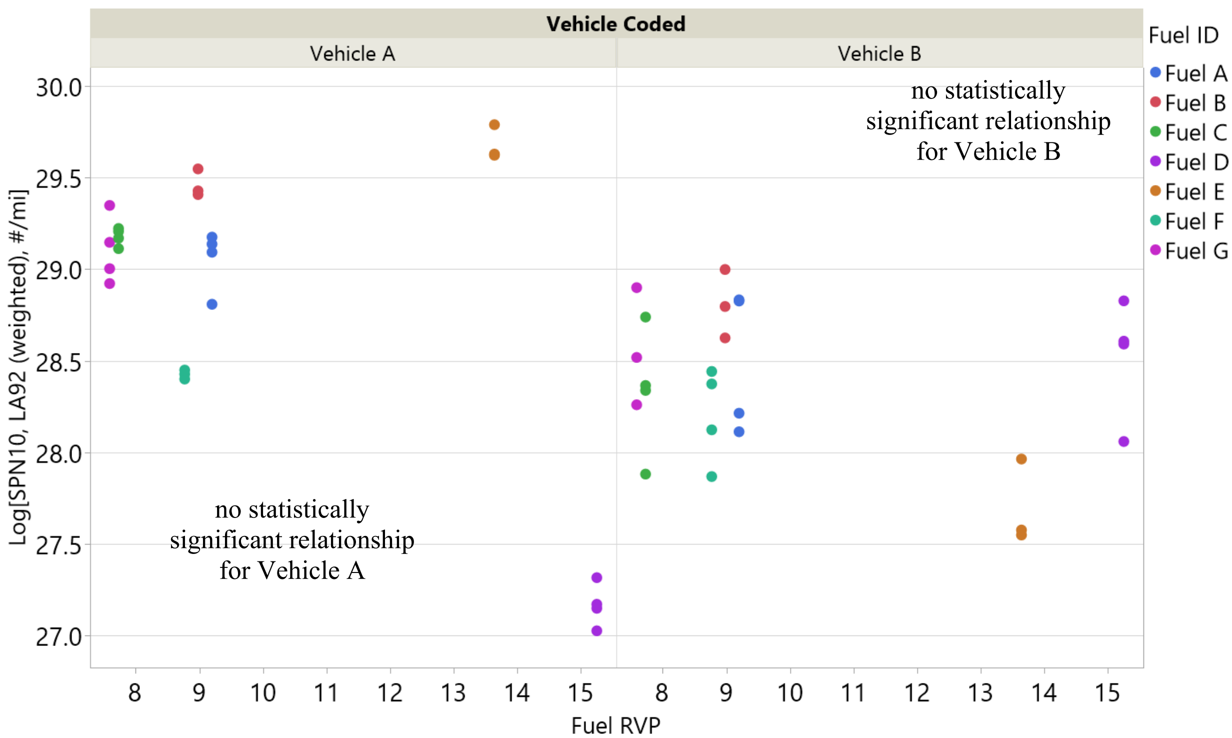

FIGURE 31: LA92 WEIGHTED SPN10 (#/MI) VS. FUEL RVP BY VEHICLE, COLORED BY FUEL

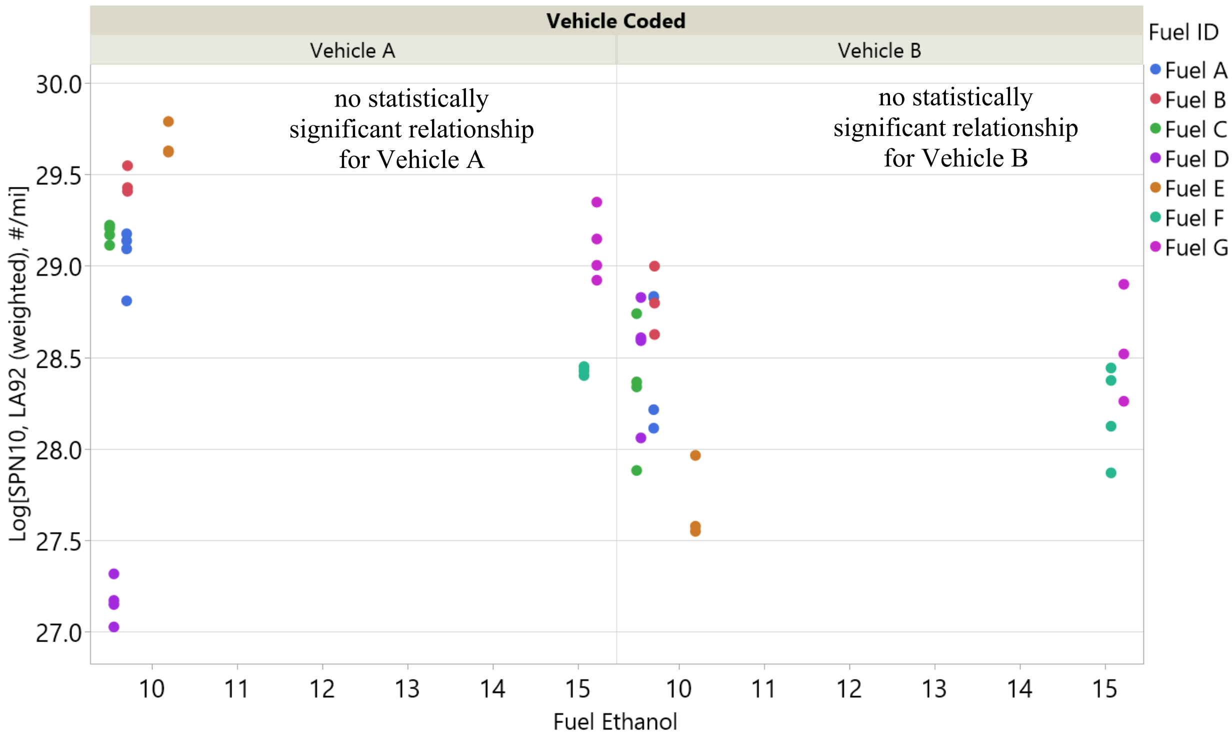

FIGURE 32: LA92 WEIGHTED SPN10 (#/MI) VS. FUEL ETHANOL BY VEHICLE, COLORED BY FUEL

Only Fuel PMI was statistically significant, and only in the Vehicle A model, shown below in Table 20. The final regression model for Vehicle A was:

$$Ln(\widehat{SPN}10) = 26.8077 + 1.4010 * FuelPMI$$

TABLE 20: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN SPN10 (#/MI), VEHICLE A ONLY

Parameter Estimates				
Term	**Estimate**	**Prob>|t|**	**Lower 95%**	**Upper 95%**
Intercept	26.8077	<.0001*	26.0695	27.5460
Fuel PMI	1.4010	<.0001*	0.9121	1.8900

The partial R-squared value for PMI was 60.4 percent for Vehicle A. Table 21 below shows the regression model's predicted change in average SPN10 with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0 for Vehicle A.

TABLE 21: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE SPN10 (#/MI) EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	**Parameter**	**Partial R^2**	**PMI 2.0 → 1.5**	**PMI 2.0 → 1.0**	**Partial R^2**	**RVP 9 → 14**	**Partial R^2**	**E10 → E15**
A	**SPN10 (#/mi)**	60.4%	7.234E+12→ 3.590E+12 (-50%)	7.234E+12→ 1.782E+12 (-75%)	-	-	-	-
B	**SPN10 (#/mi)**	-	-	-	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.3.1 LA- 92 Phase 1 Statistical Analysis Results for SPN10, #/mi

Phase 1 analysis of solid particle number follows the same trend observed with PM and soot. The log of the particle counts by test set is shown in Figure 33. There was one outlier for Vehicle B in Set 3 which was excluded from the regression model. The raw data plot of Phase 1 SPN10 vs. fuel PMI is shown in Figure 34.

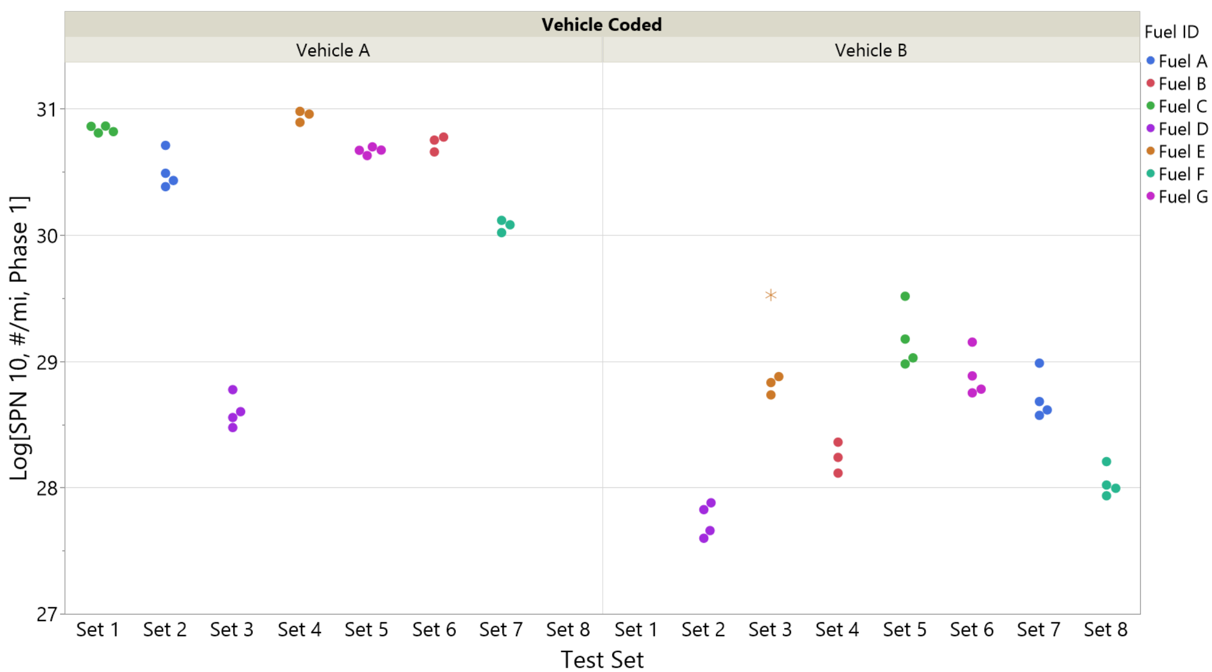

FIGURE 33: LA92 PHASE 1 SPN10 (#/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

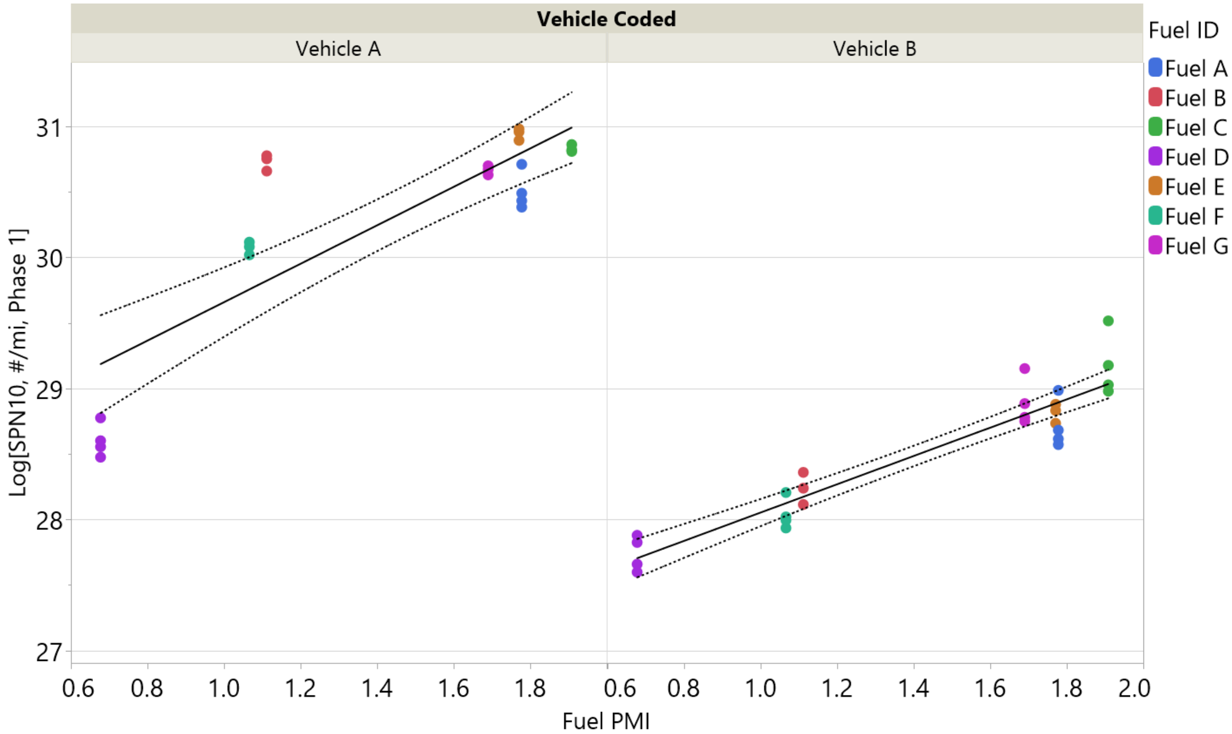

FIGURE 34: MODEL FITS PREDICTING MEAN SPN10 (#/MI) EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 PHASE 1 DATA

In the Phase 1 only regression models, the PMI variable is statistically significant now for both vehicles. The model results are shown in Table 22 and Table 23 below.

Vehicle A Fitted Equation: $Ln(\widehat{SPN}10) = 28.1934 + 1.4659 * FuelPMI$

TABLE 22: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN SPN10 (#/MI), PHASE 1, VEHICLE A ONLY

Parameter Estimates				
Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	28.1934	<.0001*	27.5557	28.8311
Fuel PMI	1.4659	<.0001*	1.0436	1.8882

Vehicle B Fitted Equation: $Ln(\widehat{SPN}10) = 26.9740 + 1.0795 * FuelPMI$

TABLE 23: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN SPN10 (#/MI), PHASE 1, VEHICLE B ONLY

Parameter Estimates				
Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	26.9740	<.0001*	26.7217	27.2263
Fuel PMI	1.0795	<.0001*	0.9108	1.2483

The partial R-squared value for PMI was 69.2 percent for Vehicle A and very strong at 87.9 percent for Vehicle B. Table 24 below shows the regression model's predicted change in average SPN10 with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0.

TABLE 24: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 PHASE 1 SPN10 (#/MI) EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	SPN10 (#/mi)	69.2%	3.292E+13→ 1.582E+13 (-52%)	3.292E+13→ 7.601E+12 (-77%)	-	-	-	-
B	SPN10 (#/mi)	87.9%	4.491E+12→ 2.618E+12 (-42%)	4.491E+12→ 1.526E+12 (-66%)	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.4 Statistical Analysis Results for Total Hydrocarbons (THC), g/mi

A plot of the time-ordered THC data is shown below in Figure 35, separated by vehicle and colored by fuel. There was not a statistically significant difference in variability between vehicles for this parameter. Therefore, outlier analysis and regression modeling were conducted with both vehicles combined. There were two (2) statistical outliers, indicated by the asterisk seen in Set 5 and Set 7 for Vehicle B. These data points were excluded from the regression modeling. Raw data plots of the THC data vs. PMI, RVP, and ethanol content are shown in Figure 36, Figure 37, and Figure 38, respectively.

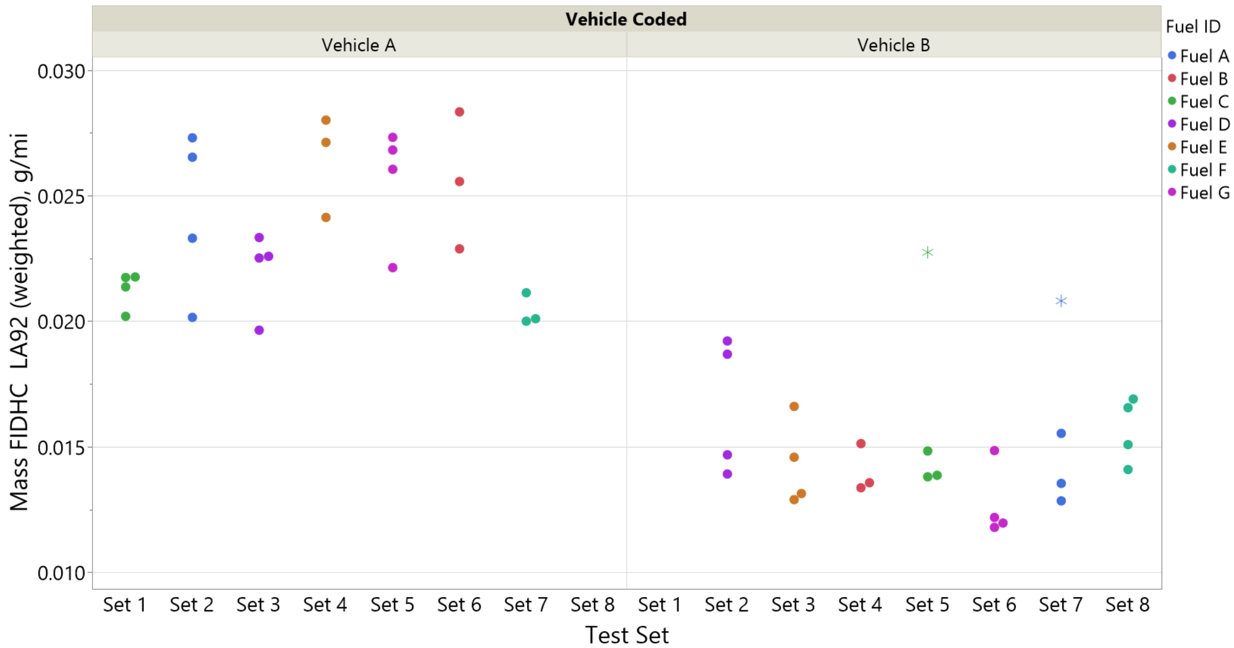

FIGURE 35: LA92 WEIGHTED THC (G/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

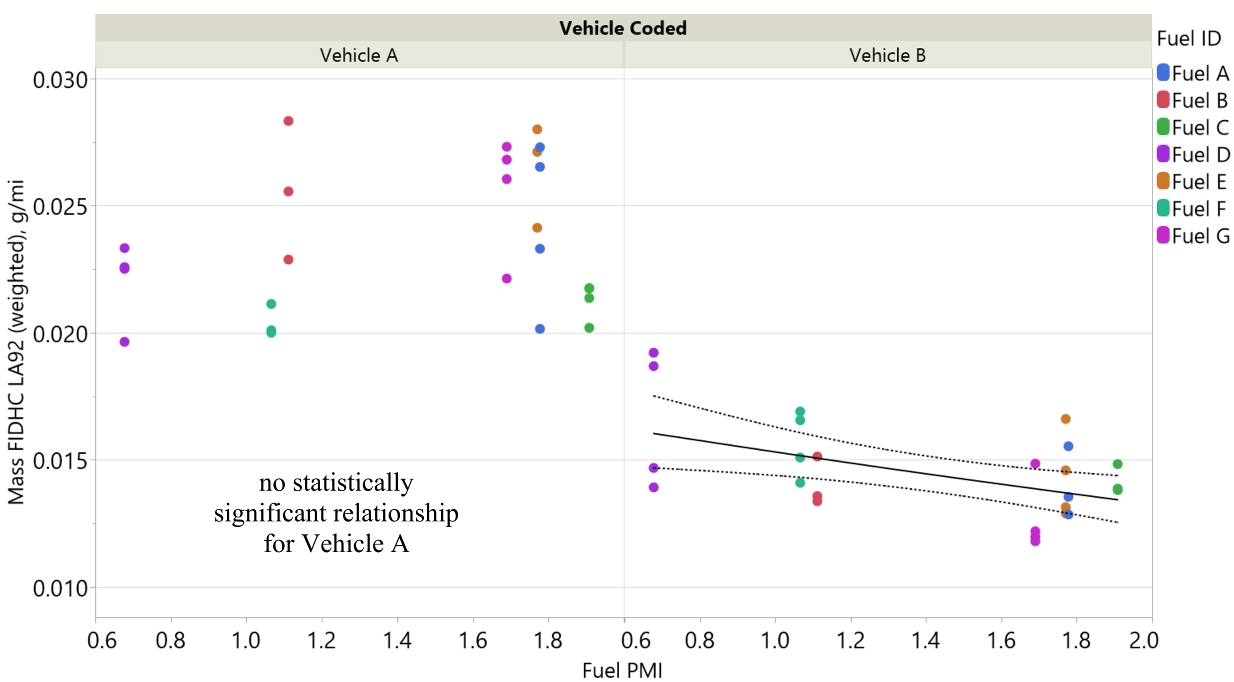

FIGURE 36: MODEL FITS PREDICTING MEAN THC (G/MI) EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 WEIGHTED COMPOSITE DATA

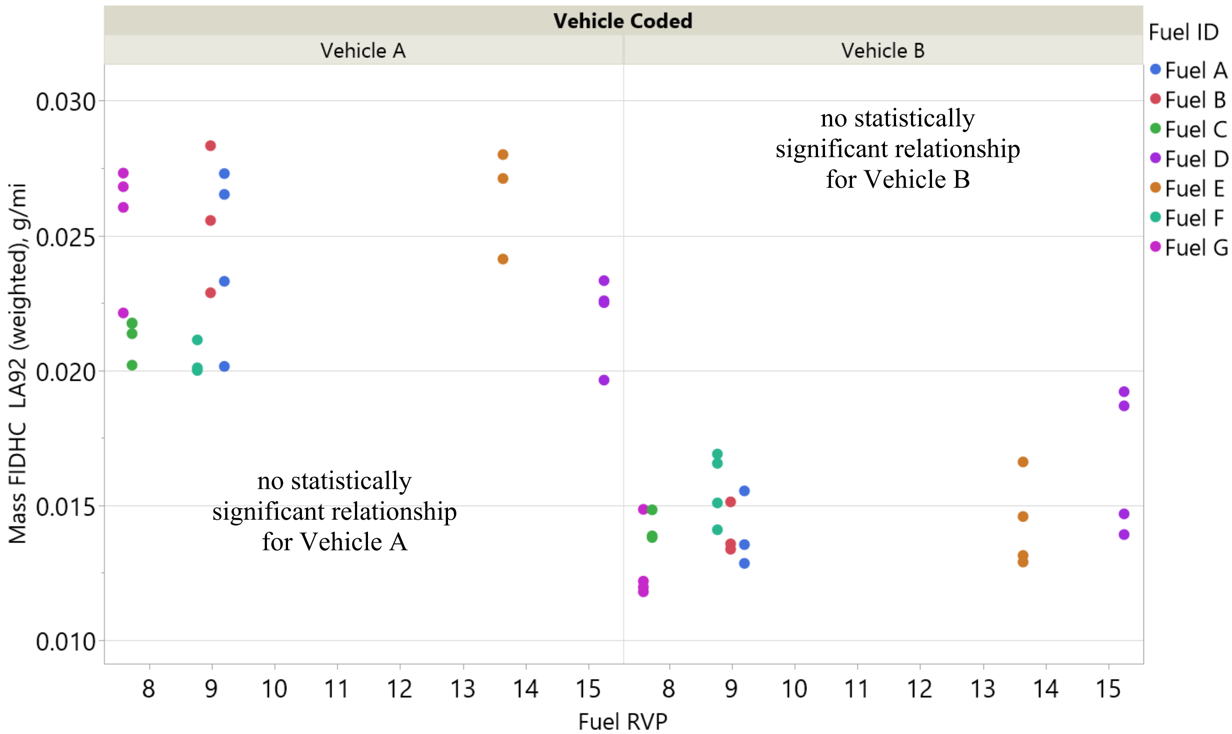

FIGURE 37: LA92 WEIGHTED THC (G/MI) VS. FUEL RVP BY VEHICLE, COLORED BY FUEL

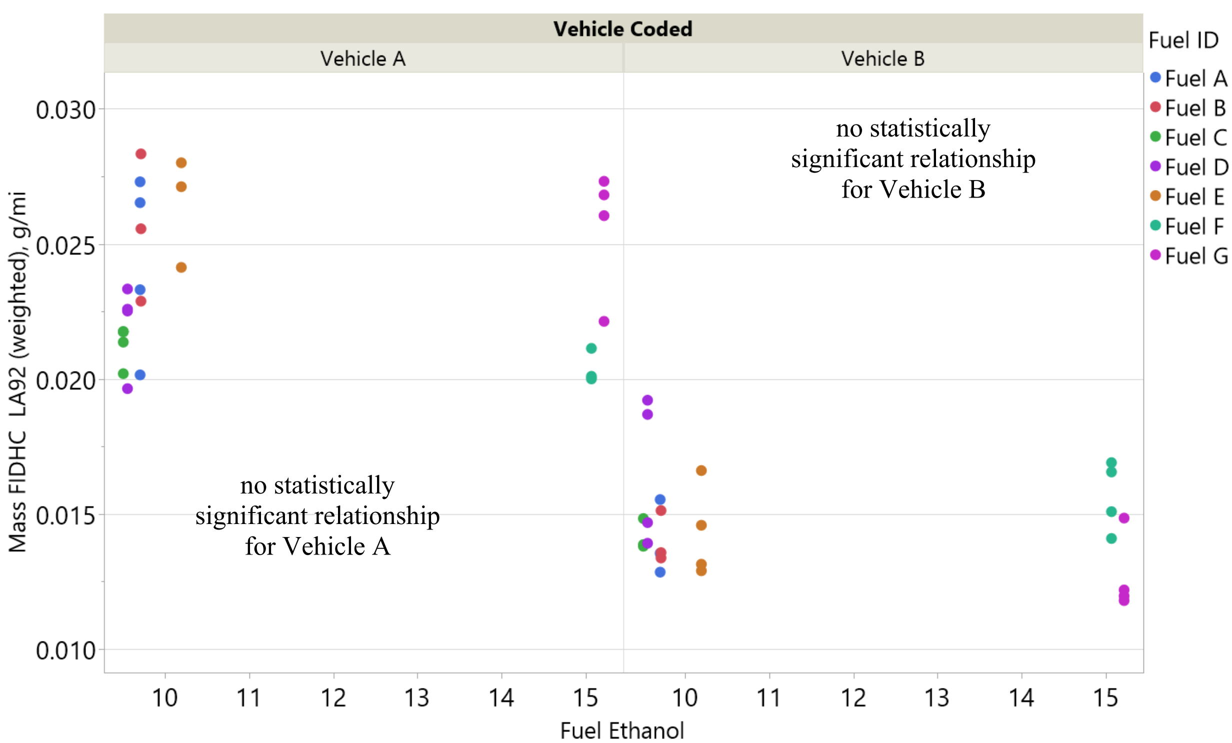

FIGURE 38: LA92 WEIGHTED THC (G/MI) VS. FUEL ETHANOL BY VEHICLE, COLORED BY FUEL

The regression model with both vehicles indicated a statistically significant interaction effect between vehicles and Fuel PMI. Table 25 below shows the regression coefficients, expanded to show all terms (each two-level factor is one-half the total effect). Looking at the estimated impact of Fuel PMI on each vehicle and the confidence intervals of the coefficients, Fuel PMI is only statistically significant for Vehicle B (the 95% confidence interval for Vehicle A overlaps zero). The Fuel RVP, ethanol content, and other interaction terms were not statistically significant. The regression model was re-run using Vehicle B data only, and this regression model is shown in Table 26. The final regression model for Vehicle B was:

$$Ln(\widehat{THC}) = -4.0353 - 0.1441 * FuelPMI$$

TABLE 25: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN THC (G/MI), BOTH VEHICLES

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	-3.9419	<.0001*	-4.0522	-3.8316
Vehicle Coded[Vehicle A]	0.2431	<.0001*	0.2102	0.2759
Vehicle Coded[Vehicle B]	-0.2431	<.0001*	-0.2759	-0.2102
Fuel PMI	-0.0392	0.2914	-0.1131	0.0347
(Fuel PMI-1.42538)*Vehicle Coded[Vehicle A]	0.1050	0.0064*	0.0311	0.1789
(Fuel PMI-1.42538)*Vehicle Coded[Vehicle B]	-0.1050	0.0064*	-0.1789	-0.0311

TABLE 26: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN THC (G/MI), VEHICLE B ONLY

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-4.035333	0.073928	-54.58	<.0001*
Fuel PMI	-0.144145	0.050087	-2.88	0.0085*

The partial R-squared value for PMI was 26.5 percent, meaning that, though statistically significant, it was a relatively weak predictor when considering the total variability. Table 27 below shows the regression model's predicted change in average THC with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0 for Vehicle B.

TABLE 27: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE THC (G/MI) EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	THC (g/mi)	-	-	-	-	-	-	-
B	THC (g/mi)	26.5%	0.0133→ 0.0143 (+8%)	0.0133→ 0.0154 (+14%)	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.5 Statistical Analysis Results for Methane (CH_4), g/mi

A plot of the time-ordered CH_4 data is shown below in Figure 39, separated by vehicle and colored by fuel. There were statistically significant differences in variability between vehicles, with Vehicle B exhibiting higher variability than Vehicle A for this parameter. Therefore, outlier analysis and regression modeling were conducted on an individual vehicle basis. There were two (2) borderline statistical outliers, which are the high and low value on Set 2 for Vehicle B. Since the removal of these points can lead to overly optimistic variance estimates and subsequently false positives in the determination of significance of model variables, these points were retained. The mean of the test set is practically unchanged regardless of whether these points are retained or rejected. Raw data plots of the CH_4 data vs. PMI, RVP, and ethanol content are shown in Figure 40, Figure 41, and Figure 42, respectively.

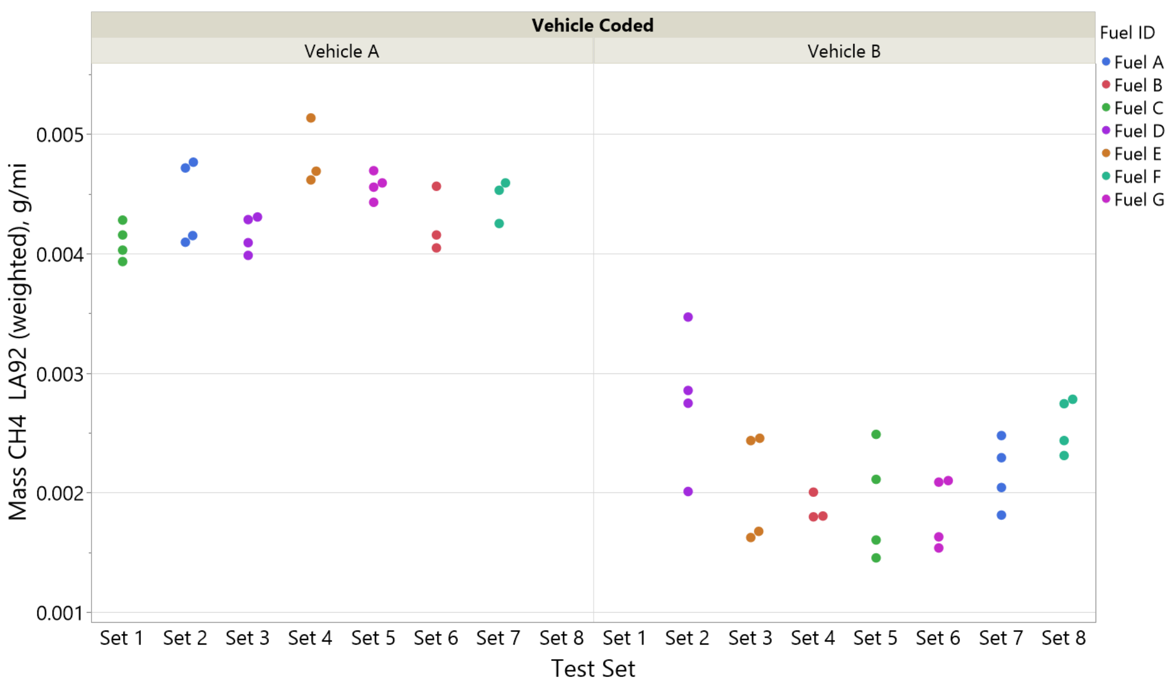

FIGURE 39: LA92 WEIGHTED CH_4 (G/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

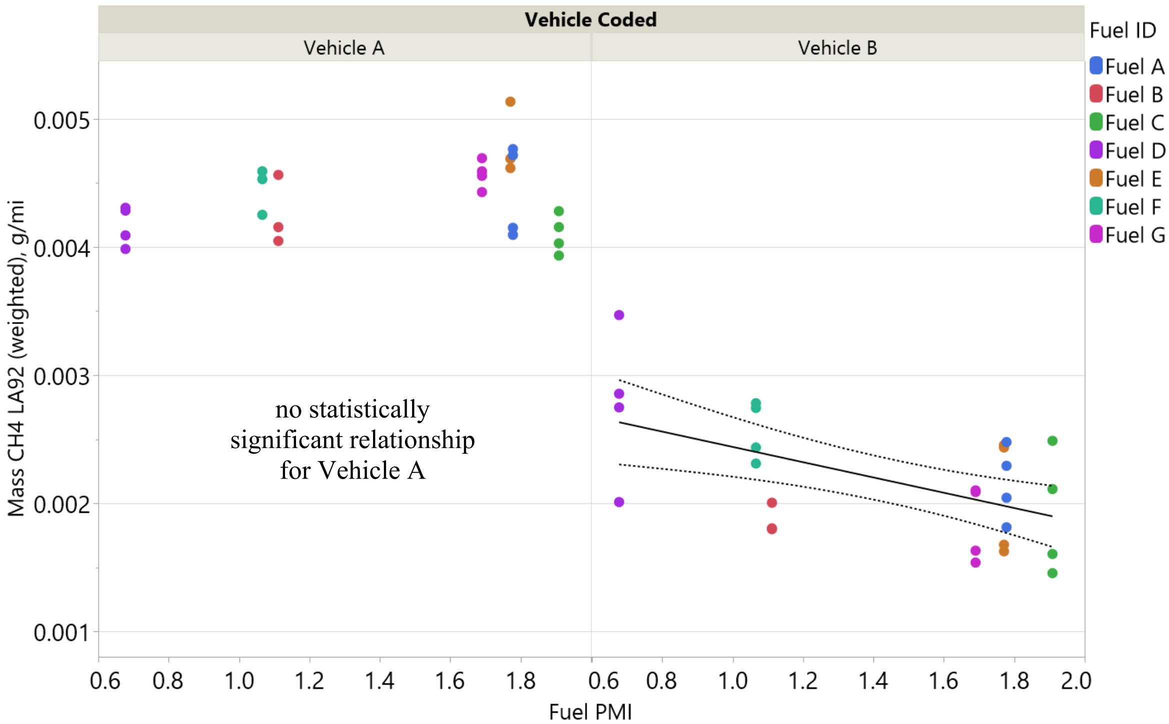

FIGURE 40: MODEL FITS PREDICTING MEAN CH_4 (G/MI) EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 WEIGHTED COMPOSITE DATA

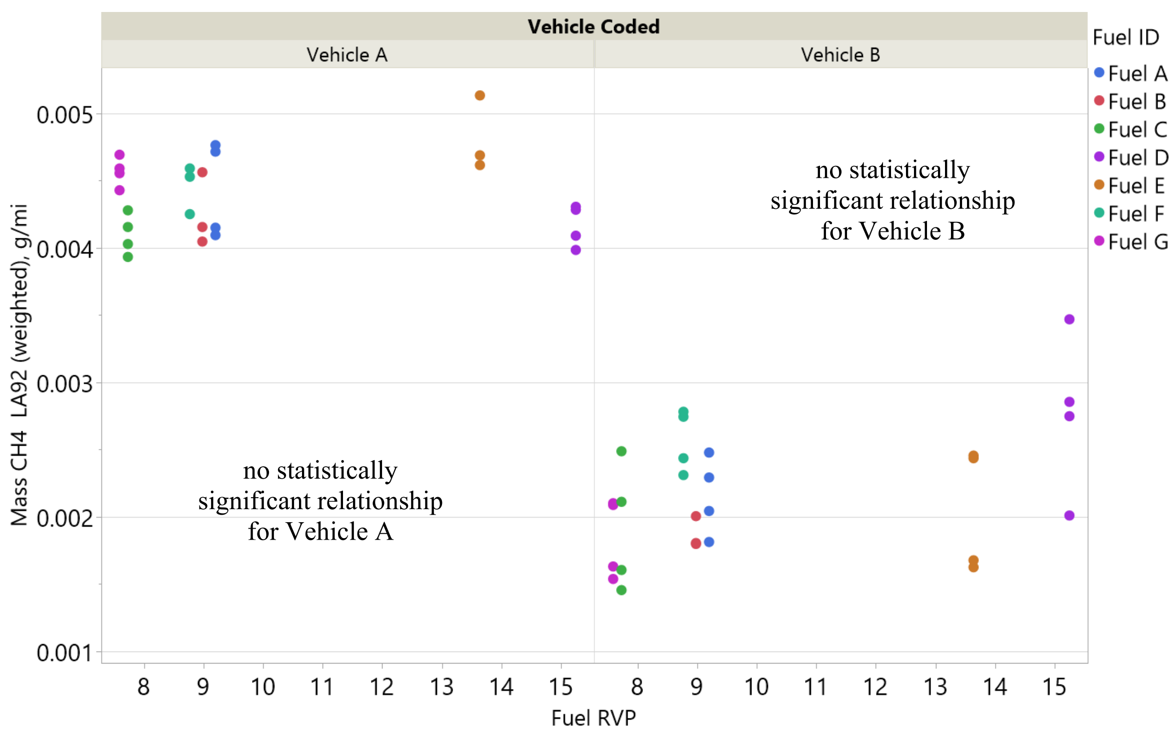

FIGURE 41: LA92 WEIGHTED CH_4 (G/MI) VS. FUEL RVP BY VEHICLE, COLORED BY FUEL

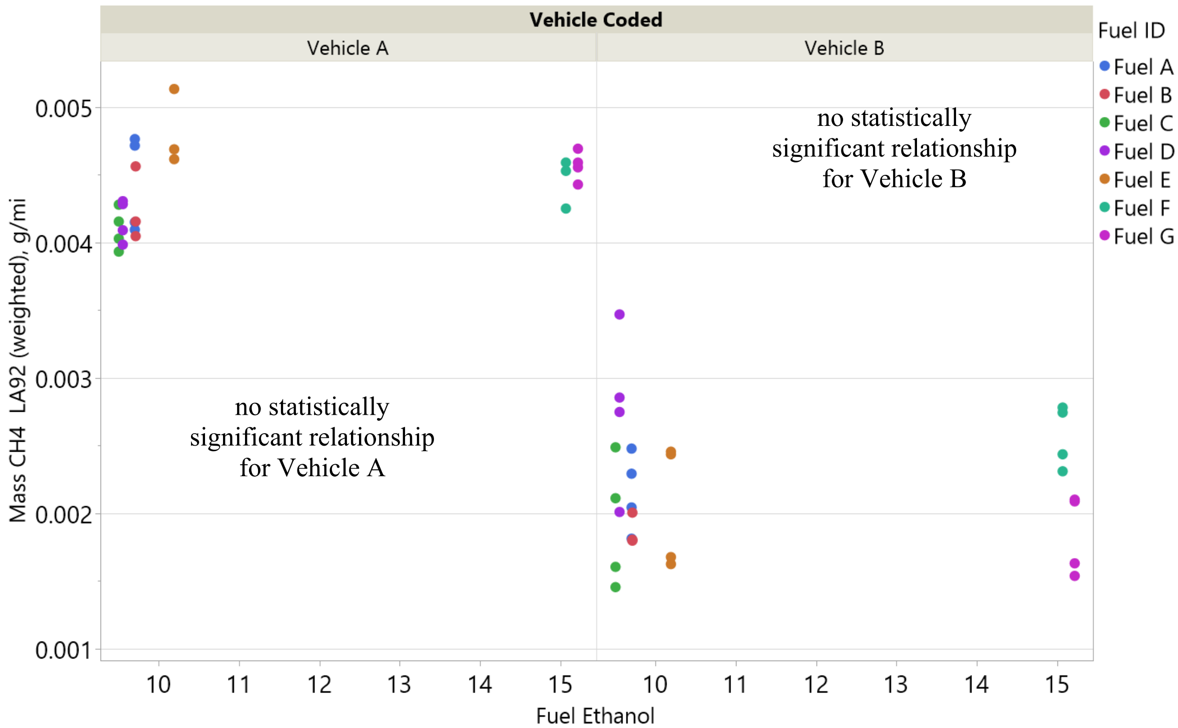

FIGURE 42: LA92 WEIGHTED CH_4 (G/MI) VS. FUEL ETHANOL BY VEHICLE, COLORED BY FUEL

The regression model results were similar to what was observed with THC, with only Fuel PMI being statistically significant, and only for Vehicle B. As seen in Table 28, this parameter was also estimated to decrease with increased PMI levels. The final regression model for Vehicle B was:

$$\widehat{CH_4} = 0.00304 - 0.0006 * FuelPMI$$

TABLE 28: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING CH_4 (G/MI), VEHICLE B ONLY

Parameter Estimates				
Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	0.00304	<.0001*	0.00247	0.00360
Fuel PMI	-0.00060	0.0031*	-0.00097	-0.00022

The partial R-squared value for PMI was 30.0 percent, meaning that, though statistically significant, it was a relatively weak predictor when considering the total variability. Table 29 below shows the regression model's predicted change in average CH_4 with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0 for Vehicle B.

TABLE 29: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE CH_4 (G/MI) EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	CH_4 (g/mi)	-	-	-	-	-	-	-
B	CH_4 (g/mi)	30.0%	0.0018→ 0.0021 (+17%)	0.0018→ 0.0024 (+33%)	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.6 Statistical Analysis Results for Carbon Monoxide (CO), g/mi

A plot of the time-ordered CO data is shown below in Figure 43 for Vehicle A, and Figure 44 for Vehicle B. The data required separate plots due to the magnitude differences between Vehicles. Vehicle B had a much larger spread in CO results, which were statistically significantly higher than Vehicle A, even using transformed data. Therefore, outlier analysis and regression modeling were conducted on an individual vehicle basis. There was one statistical outlier, which is indicated by the asterisk on Set 5 for Vehicle A. This data point was excluded from the regression modeling. Raw data plots of the CO data vs. PMI, RVP, and ethanol content are shown in Figure 45 through Figure 50 for both vehicles.

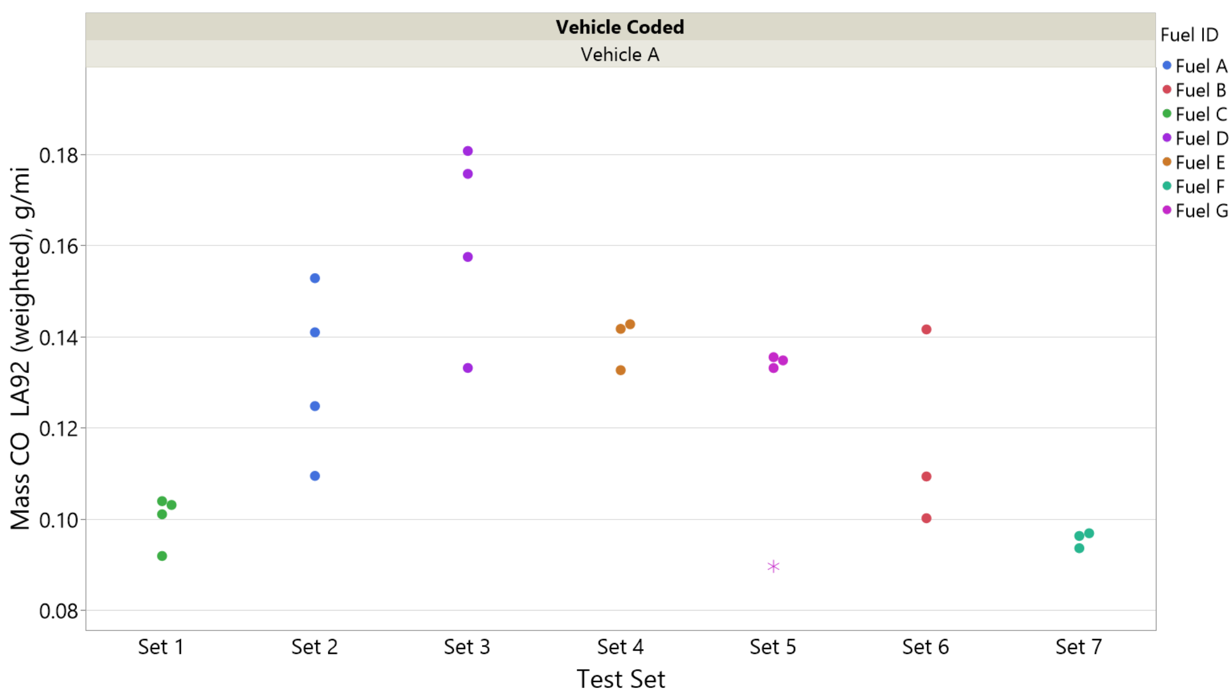

FIGURE 43: VEHICLE A LA92 WEIGHTED CO (G/MI) BY TEST SET, COLORED BY FUEL

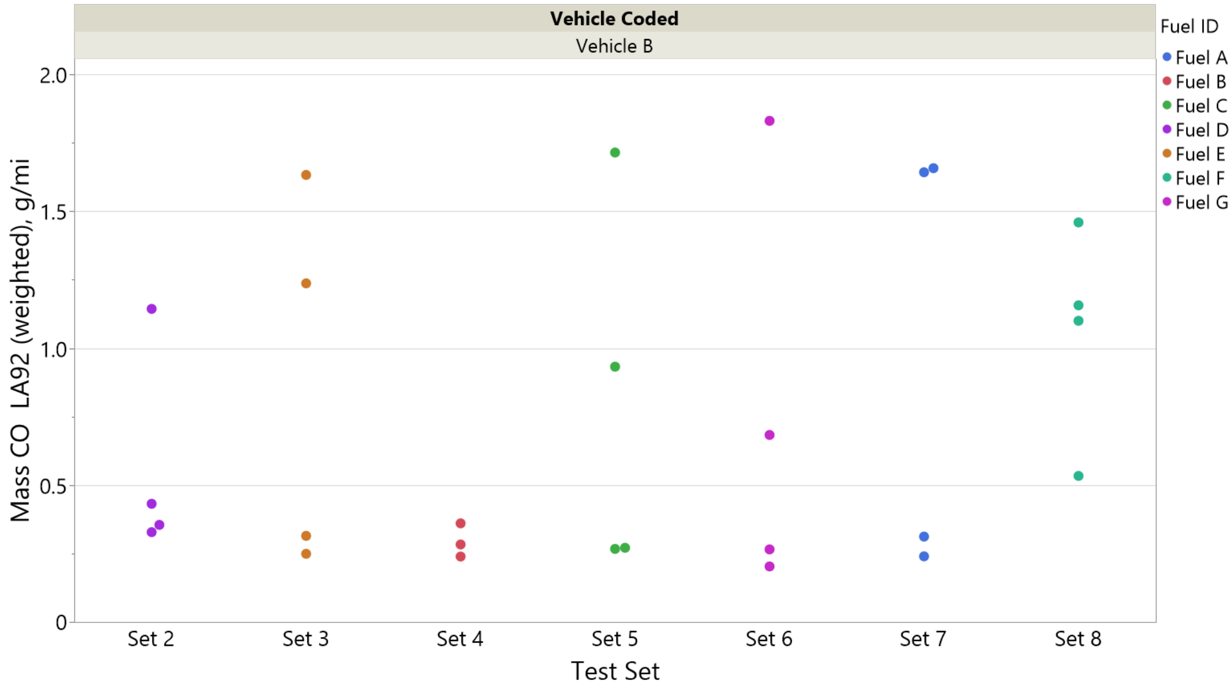

FIGURE 44: VEHICLE B LA92 WEIGHTED CO (G/MI) BY TEST SET, COLORED BY FUEL

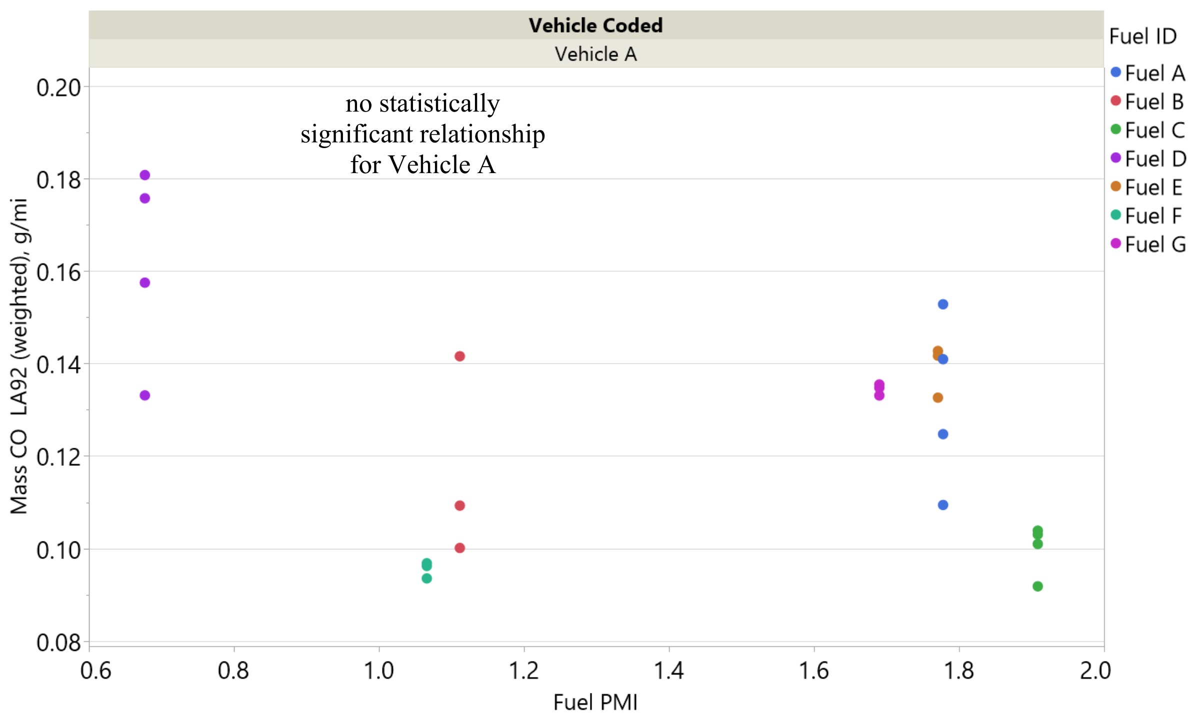

FIGURE 45: VEHICLE A LA92 WEIGHTED CO (G/MI) VS. FUEL PMI, COLORED BY FUEL

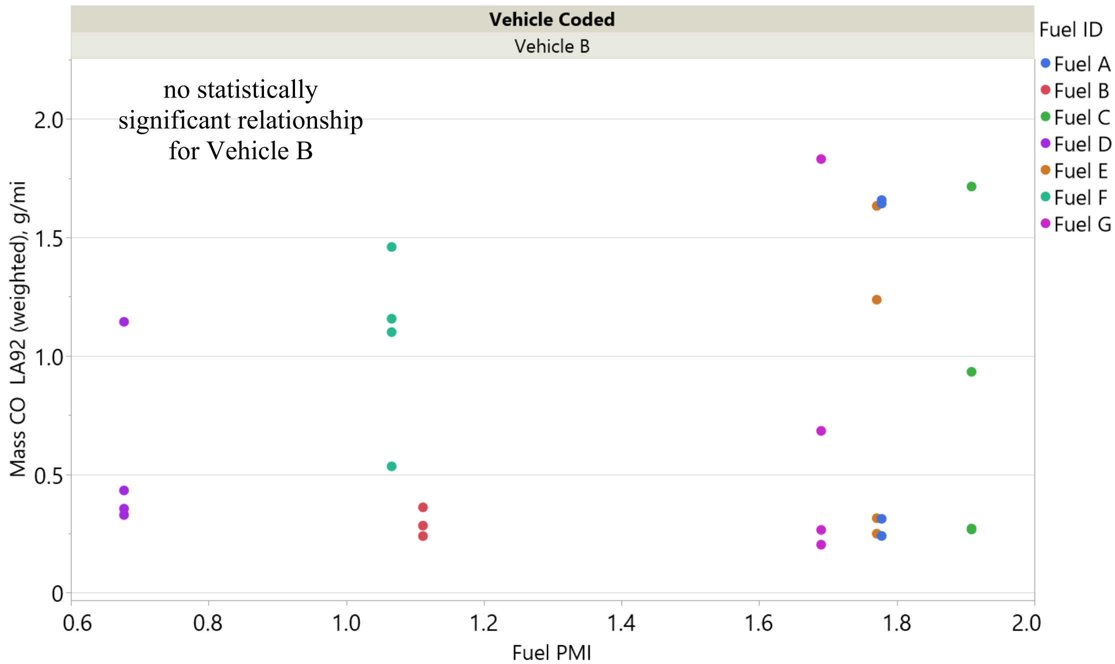

FIGURE 46: VEHICLE B LA92 WEIGHTED CO (G/MI) VS. FUEL PMI, COLORED BY FUEL

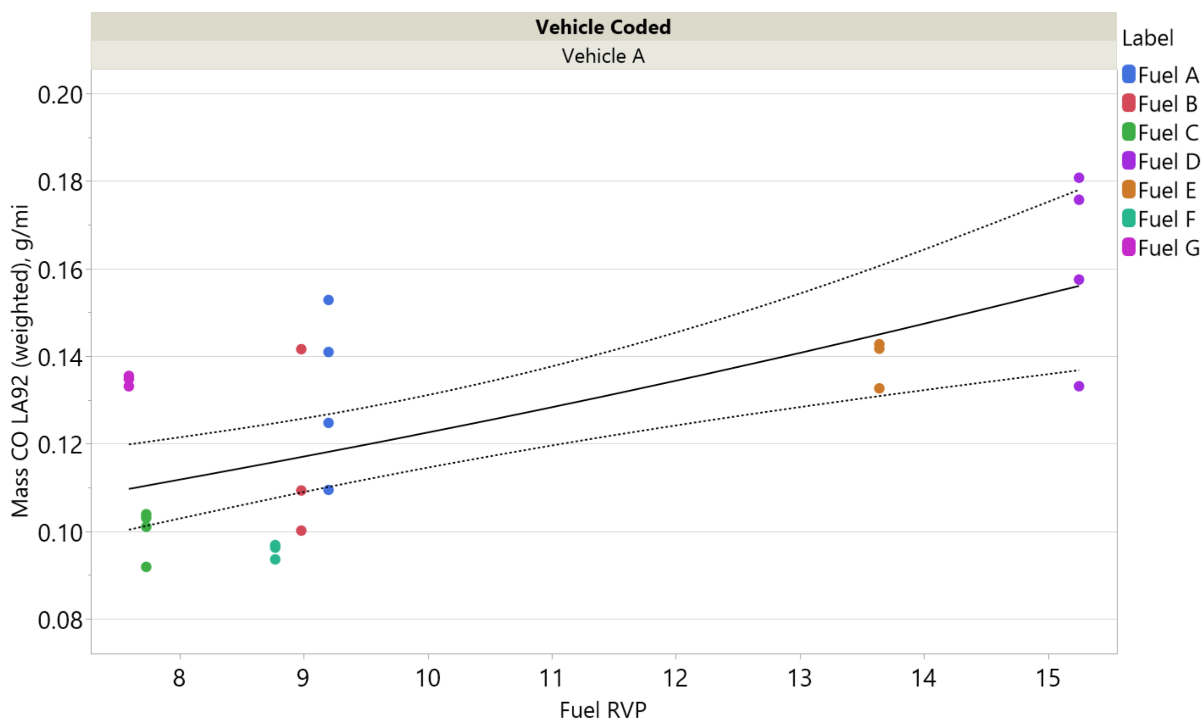

FIGURE 47: VEHICLE A MODEL FIT PREDICTING MEAN CH_4 (G/MI) EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 WEIGHTED COMPOSITE DATA

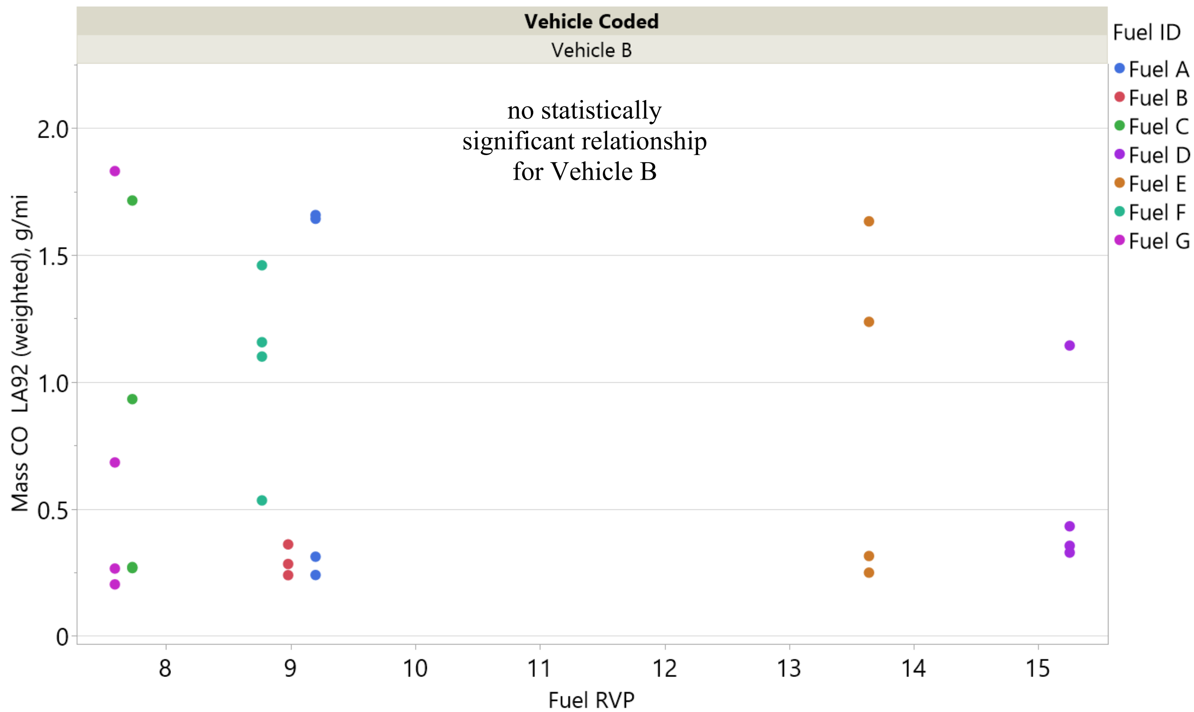

FIGURE 48: VEHICLE B LA92 WEIGHTED CO (G/MI) VS. FUEL RVP, COLORED BY FUEL

FIGURE 49: VEHICLE A LA92 WEIGHTED CO (G/MI) VS. FUEL ETHANOL, COLORED BY FUEL

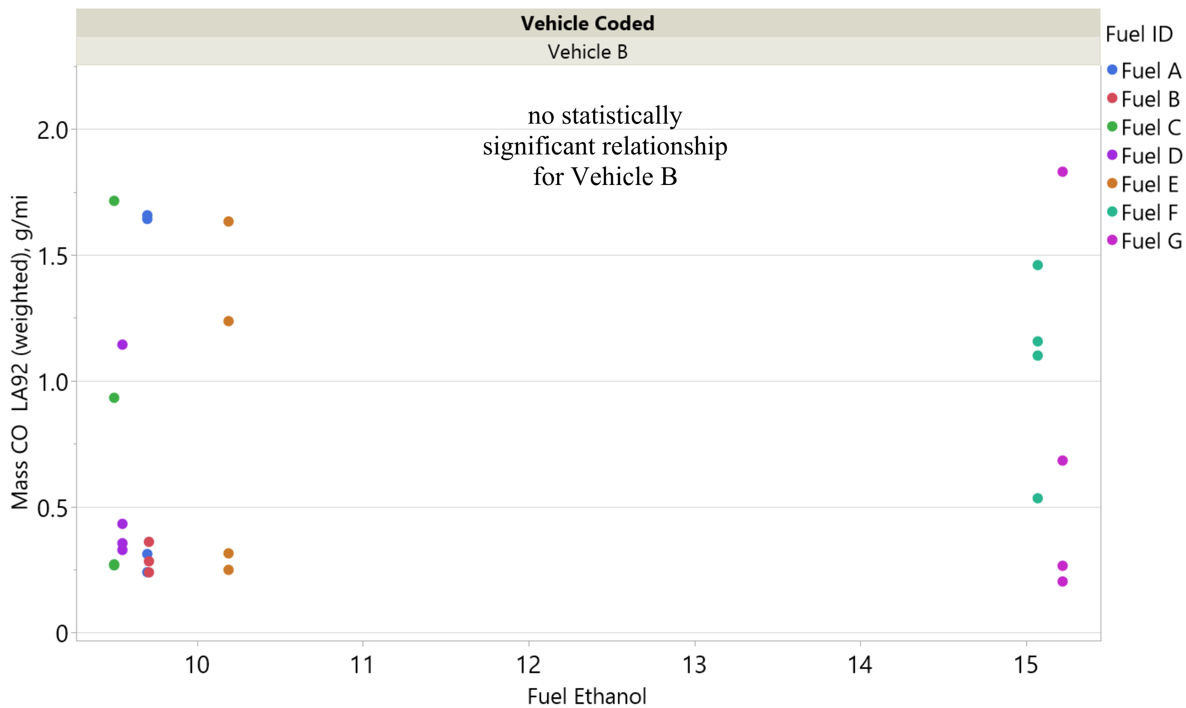

FIGURE 50: VEHICLE B LA92 WEIGHTED CO (G/MI) VS. FUEL ETHANOL, COLORED BY FUEL

Only fuel RVP was statistically significant, and only in the Vehicle A model, shown below in Table 30. The final regression model for Vehicle A was:

$$\widehat{Ln(CO)} = -2.5596 + 0.046 * FuelRVP$$

TABLE 30: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN CO (G/MI), VEHICLE A ONLY

Parameter Estimates

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	-2.5596	<.0001*	-2.8028	-2.3164
Fuel RVP	0.0460	0.0004*	0.0232	0.0689

The partial R-squared value for RVP was 44.2 percent. Table 31 below shows the regression model's predicted change in average CO (g/mi) with a change in fuel RVP from 9 psi to 14 psi for Vehicle A.

TABLE 31: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE CO (G/MI) EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	CO (g/mi)	-	-	-	44.2%	0.117 → 0.147 (+26%)	-	-
B	CO (g/mi)	-	-	-	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.7 Statistical Analysis Results for Carbon Dioxide (CO_2), g/mi

A plot of the time-ordered CO_2 data is shown below in Figure 51, separated by vehicle and colored by fuel. There was not a statistically significant difference in variability between vehicles for this parameter. Therefore, outlier analysis and regression modeling were conducted with both vehicles combined. There was one statistical outlier, indicated by the asterisk seen in Set 2 for Vehicle B. This data point was excluded from the regression modeling. Raw data plots of the CO_2 data vs. PMI, RVP, and ethanol content are shown in Figure 52, Figure 53, and Figure 54, respectively.

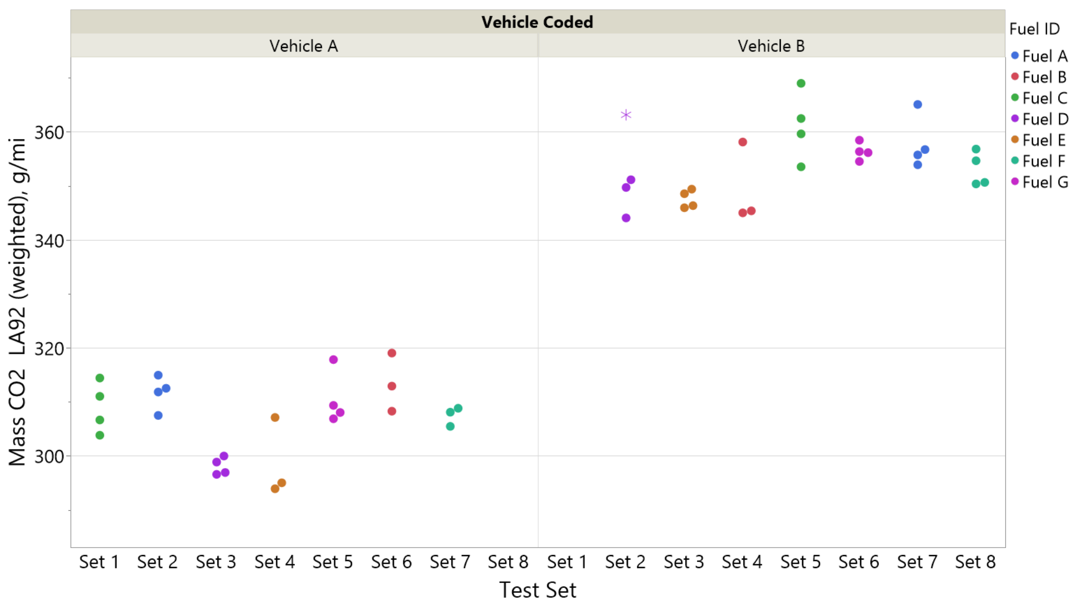

FIGURE 51: LA92 WEIGHTED CO_2 (G/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

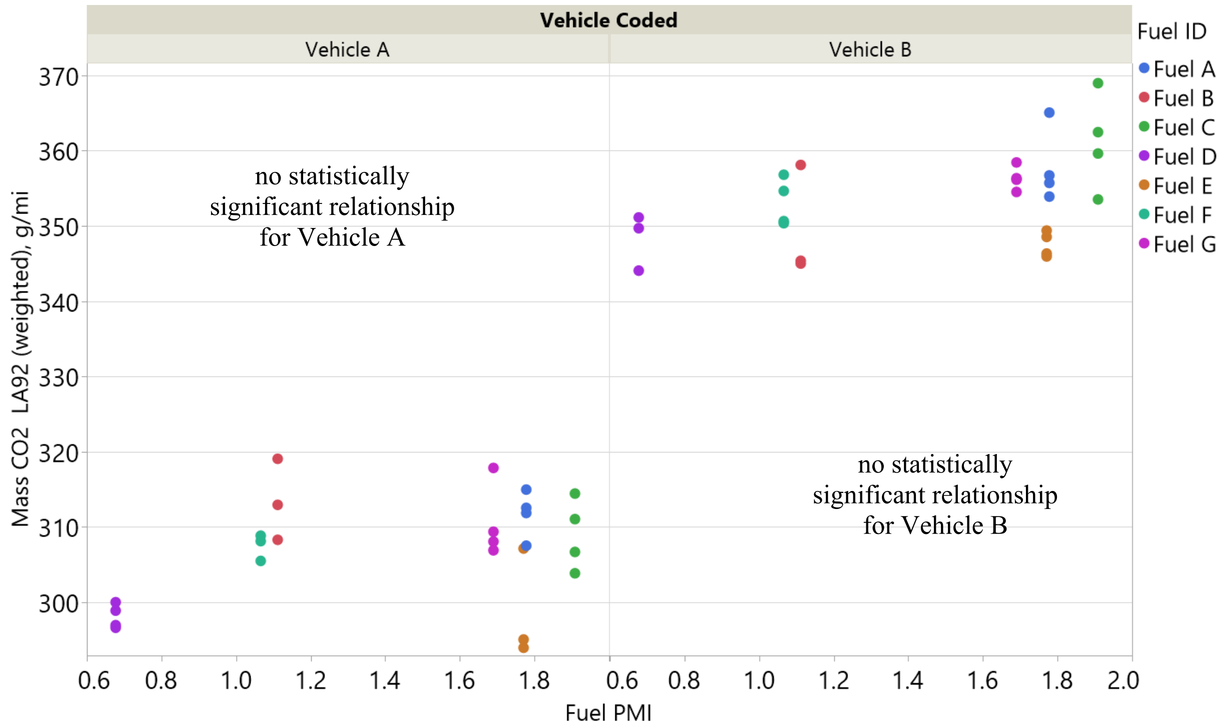

FIGURE 52: LA92 WEIGHTED CO_2 (G/MI) VS. FUEL PMI BY VEHICLE, COLORED BY FUEL

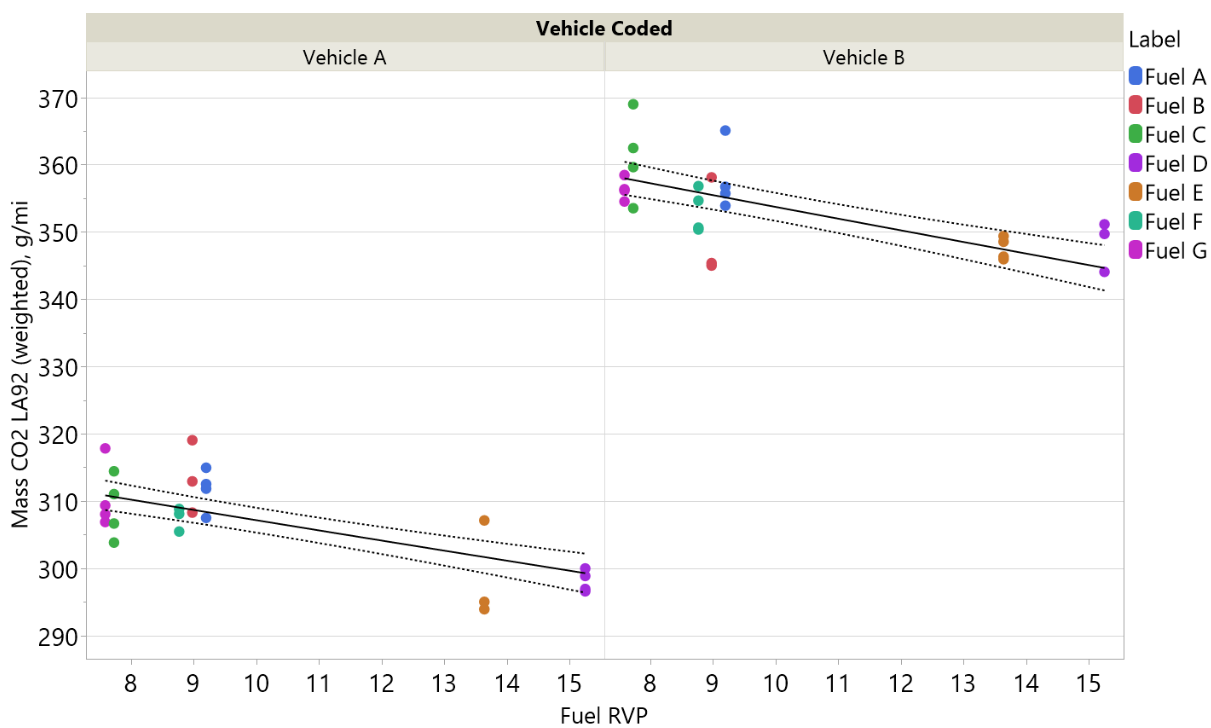

FIGURE 53: MODEL FIT PREDICTING MEAN CO_2 (G/MI) EMISSIONS BY FUEL PMI WITH 95% CONFIDENCE LIMITS, LA92 WEIGHTED COMPOSITE DATA

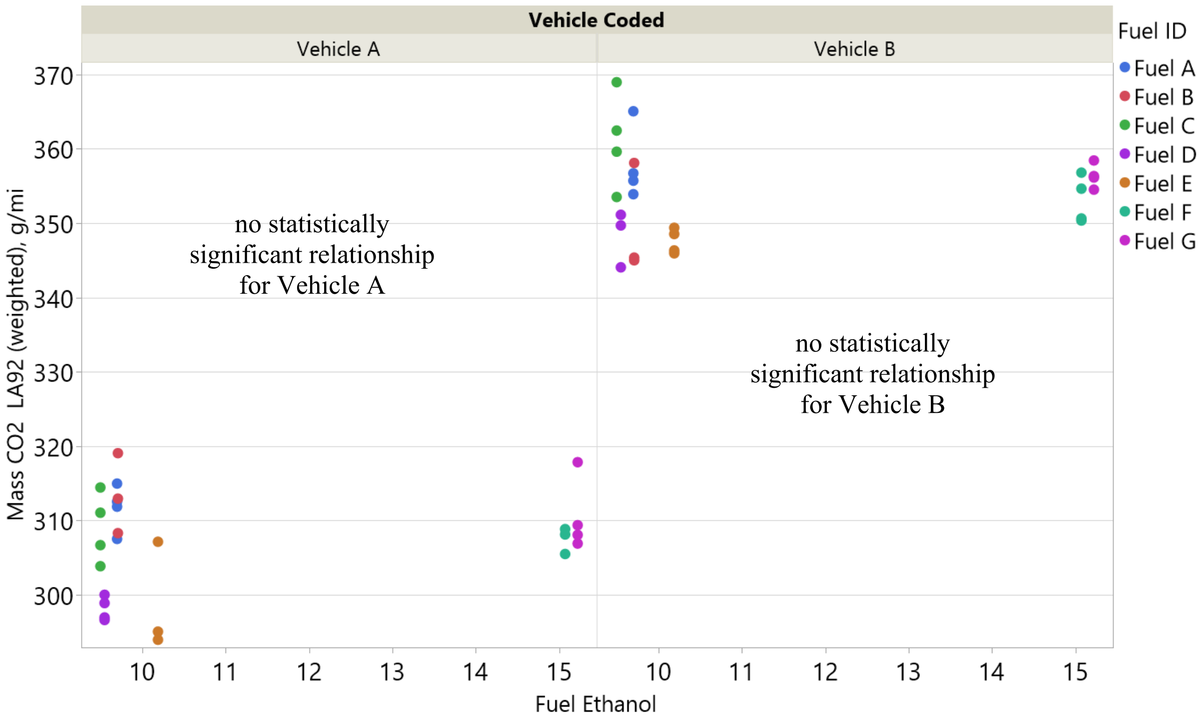

FIGURE 54: LA92 WEIGHTED CO_2 (G/MI) VS. FUEL ETHANOL BY VEHICLE, COLORED BY FUEL

For this model, fuel RVP was statistically significant, with no statistically significant interaction between vehicle and fuel RVP. PMI, ethanol content, and their interaction terms with Vehicle, were all not statistically significant for this parameter. The final regression model using both vehicles is given in Table 32 as:

$$\widehat{Ln(CO_2)} = 5.918 - 0.1412 * VehicleA - 0.005 * FuelRVP$$

TABLE 32: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN CO_2 (G/MI), BOTH VEHICLES

Indicator Function Parameterization				
Term	**Estimate**	**Prob>|t|**	**Lower 95%**	**Upper 95%**
Intercept	5.9180	<.0001*	5.9019	5.9341
Vehicle Coded[Vehicle A]	-0.1412	<.0001*	-0.1495	-0.1328
Fuel RVP	-0.0050	<.0001*	-0.0064	-0.0035

The partial R-squared value for RVP in this model was 43.3 percent. Table 33 below shows the regression model's predicted change in average CO_2 (g/mi) with a change in fuel RVP from 9 psi to 14 psi.

TABLE 33: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE CO_2 (G/MI) EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	CO_2 (g/mi)	-	-	-	43.3%	308.5 → 300.9 (-2.5%)	-	-
B	CO_2 (g/mi)	-	-	-	43.3%	355.3 → 346.5 (-2.5%)	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.8 Statistical Analysis Results for Nitrogen Oxides (NO_x), g/mi

A plot of the time-ordered NO_x data is shown below in Figure 55, separated by vehicle and colored by fuel. There was not a statistically significant difference in variability between vehicles for this parameter. Therefore, outlier analysis and regression modeling were conducted with both vehicles combined. There were two (2) statistical outliers, indicated by the asterisk seen in Set 5 for Vehicle A and Set 2 for Vehicle B. These data points were excluded from the regression modeling. Raw data plots of the NO_x data vs. PMI, RVP, and ethanol content are shown in Figure 56, Figure 57, and Figure 58, respectively.

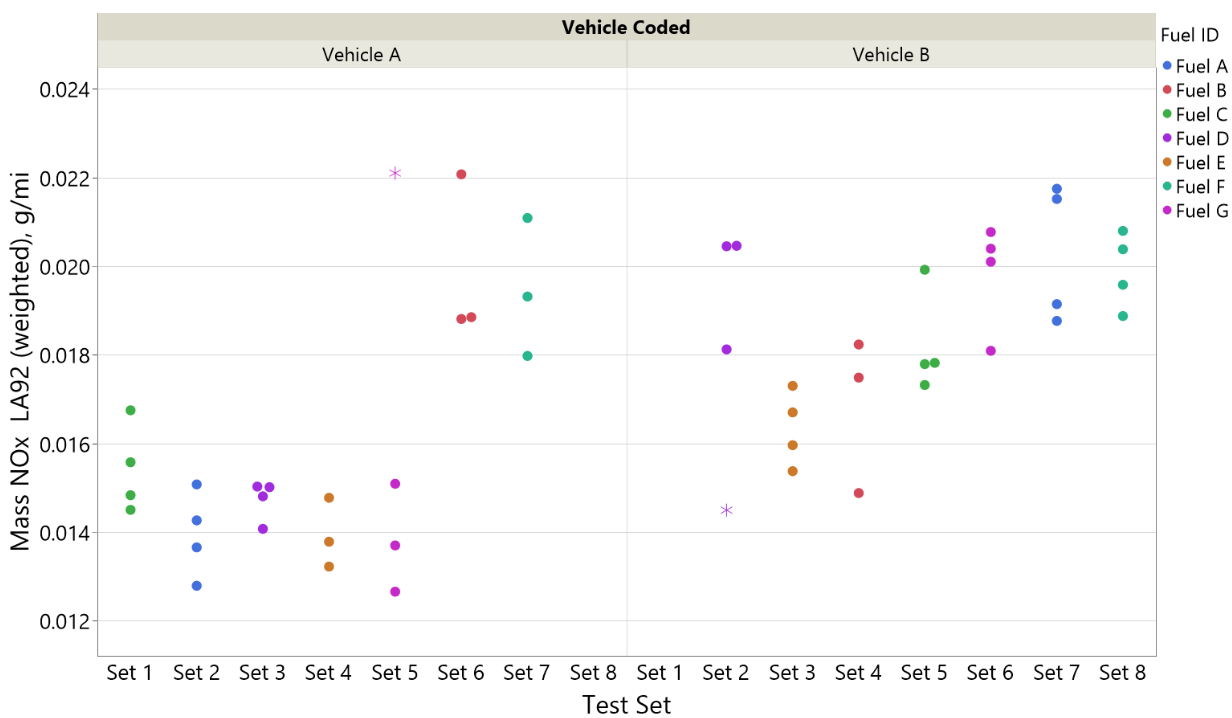

FIGURE 55: LA92 WEIGHTED NO_X (G/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

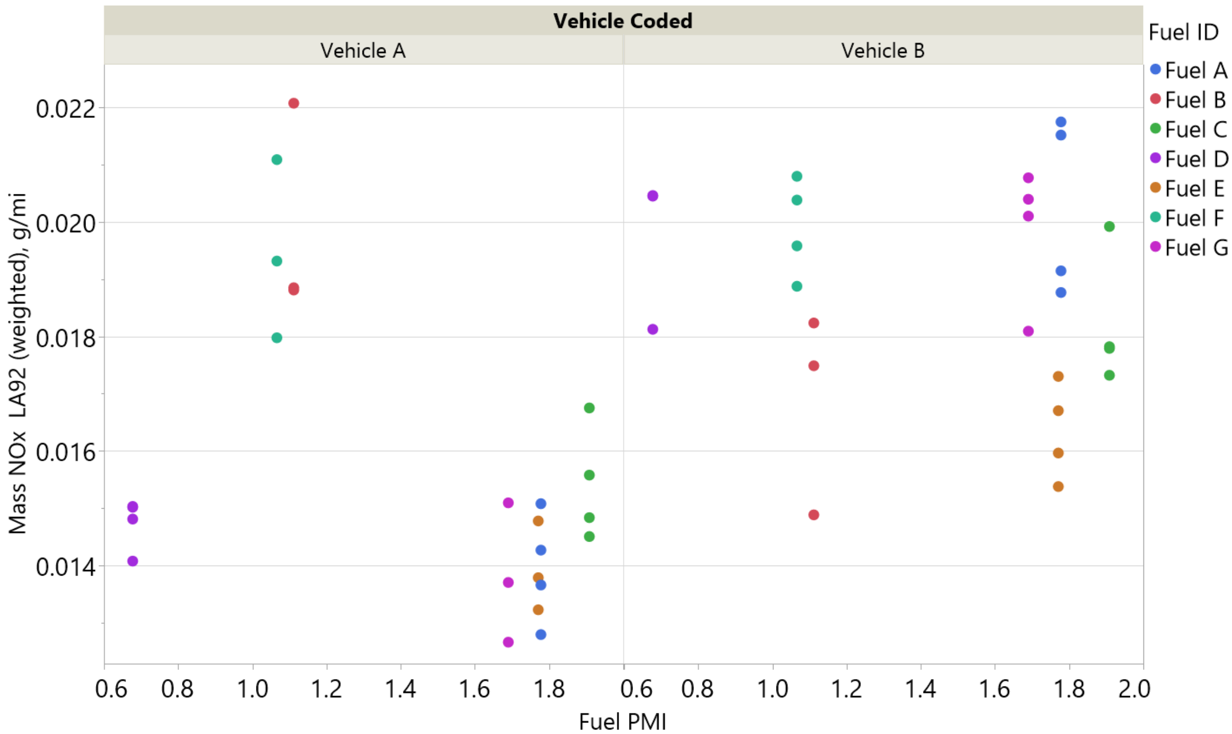

FIGURE 56: LA92 WEIGHTED NO_X (G/MI) VS. FUEL PMI BY VEHICLE, COLORED BY FUEL

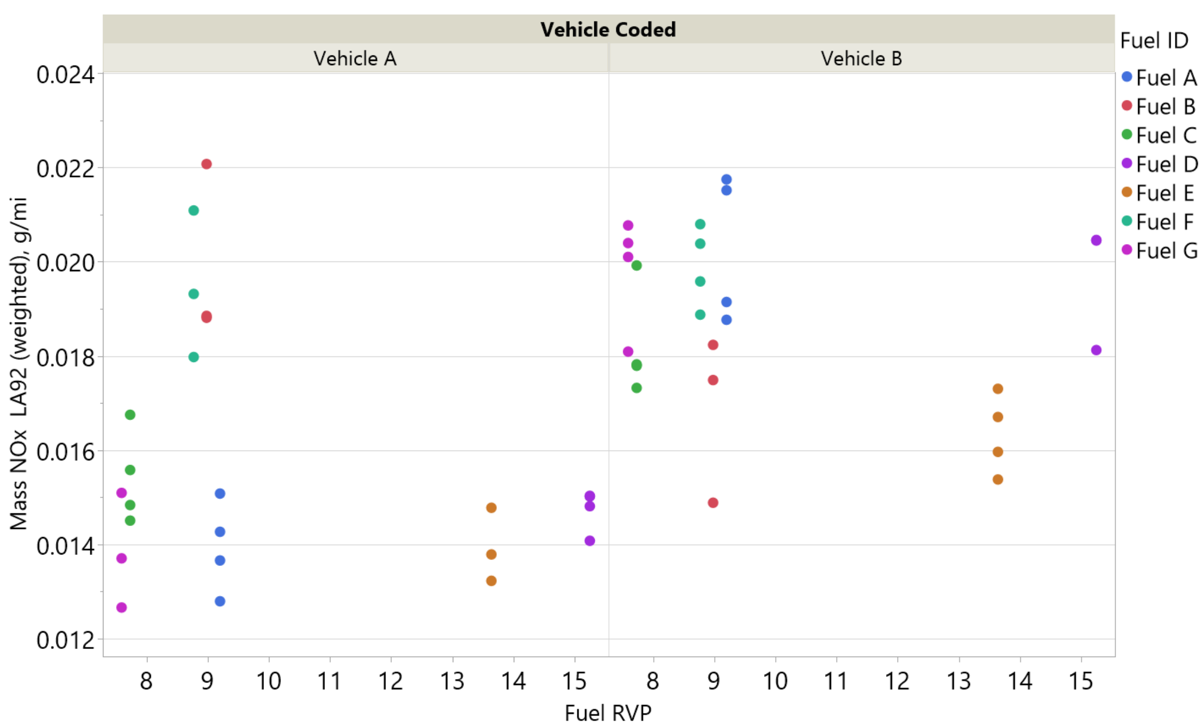

FIGURE 57: LA92 WEIGHTED NO_X (G/MI) VS. FUEL RVP BY VEHICLE, COLORED BY FUEL

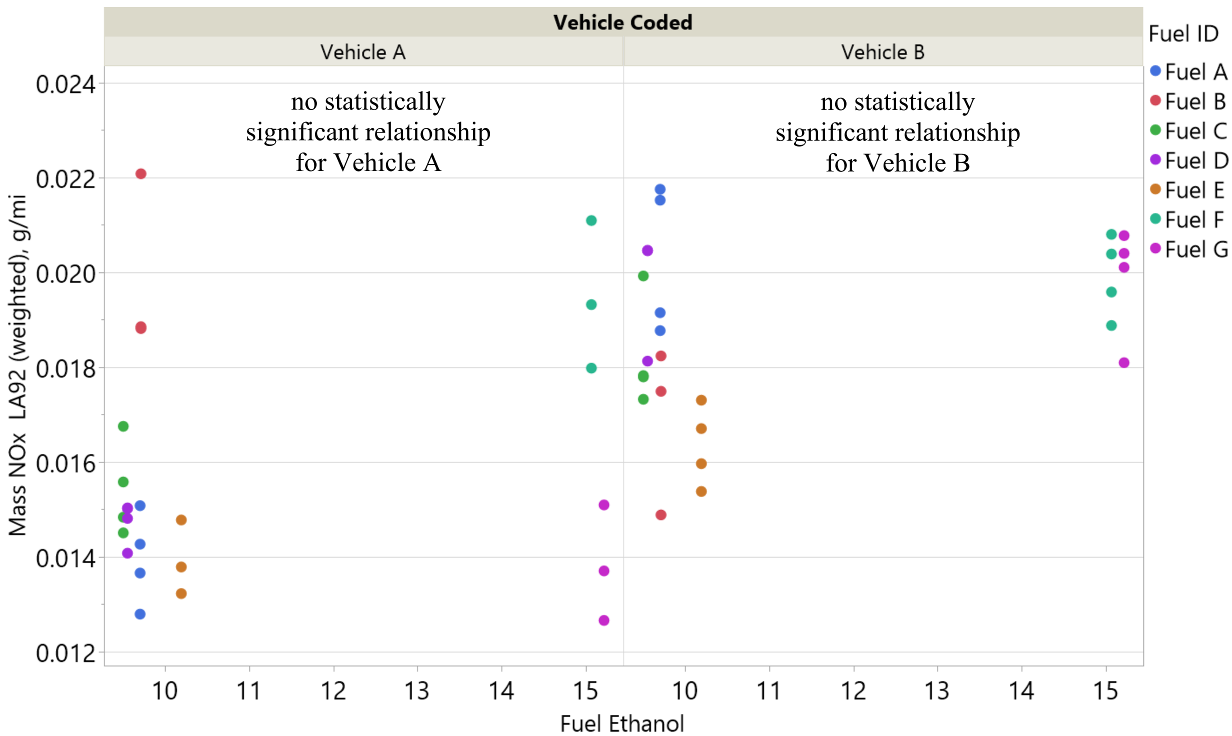

FIGURE 58: LA92 WEIGHTED NO_X (G/MI) VS. FUEL ETHANOL BY VEHICLE, COLORED BY FUEL

For this model, both Fuel PMI and Fuel RVP were statistically significant, with no statistically significant interaction between these effects and vehicle. Ethanol content was not statistically significant for this parameter. The final regression model using both vehicles and the indicator function parameterization is shown in Table 34 as:

$$\widehat{Ln(NO_x)} = -3.5088 - 0.1841 * VehicleA - 0.1616 * FuelPMI - 0.0234 * FuelRVP$$

TABLE 34: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING LN NO_X (G/MI), BOTH VEHICLES

Indicator Function Parameterization				
Term	**Estimate**	**Prob>|t|**	**Lower 95%**	**Upper 95%**
Intercept	-3.5088	<.0001*	-3.7294	-3.2881
Vehicle Coded[Vehicle A]	-0.1841	<.0001*	-0.2476	-0.1206
Fuel PMI	-0.1616	0.0003*	-0.2443	-0.0790
Fuel RVP	-0.0234	0.0007*	-0.0363	-0.0104

Since this model has multiple significant fuel properties, a prediction profiler plot is shown below in Figure 59 in order to view the estimated impact of a given fuel property after accounting for the modeled impact of the other fuel property.

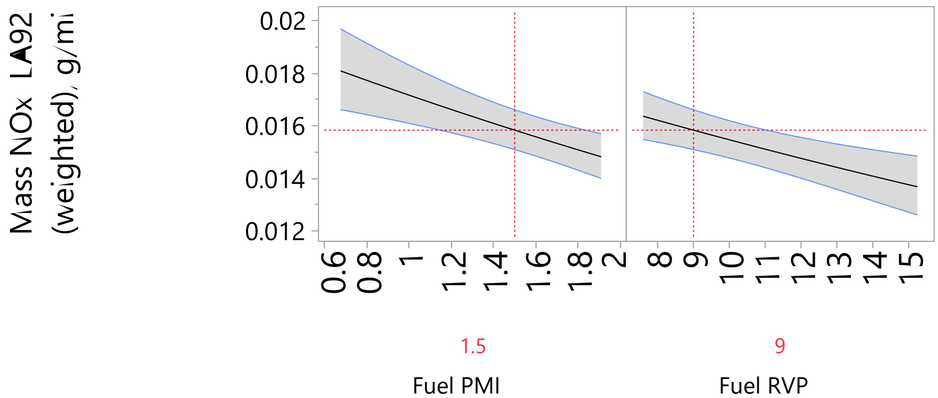

FIGURE 59: PREDICTION PROFILER FOR MEAN NO_X BASED ON PMI AND RVP WITH 95% CONFIDENCE LIMITS

The partial R-squared value for PMI in this model was 23.8 percent, and for RVP was 20.2, meaning that both factors are relatively weak predictors when compared to the total variability. Table 35 below shows the regression model's predicted change in average NO_x (g/mi) with a change in fuel PMI from 2.0 to 1.5 and from 2.0 to 1.0, holding RVP constant at 9 psi. Additionally, changes of RVP from 9 psi to 14 psi are assessed, holding PMI constant at 1.5.

TABLE 35: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE NO_X (G/MI) EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	NO_x (g/mi)	23.8%	0.0146→ 0.0158 (+8.4%)	0.0146→ 0.0172 (+17.5%)	20.2%	0.0158 → 0.0141 (-11.0%)	-	-
B	NO_x (g/mi)	23.8%	0.0176→ 0.0190 (+8.4%)	0.0176→ 0.0206 (+17.5%)	20.2%	0.0190 → 0.0169 (-11.0%)	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.9 Statistical Analysis Results for Ammonia (NH_3), g/mi

A plot of the time-ordered NH_3 data is shown below in Figure 60, separated by vehicle and colored by fuel. There were statistically significant differences in variability between vehicles. Therefore, outlier analysis and regression modeling were conducted separately by vehicle. There was one statistical outlier, indicated by the asterisk seen in Set 4 for Vehicle A. This data point was excluded from the regression modeling. Raw data plots of the NH_3 data vs. PMI, RVP, and ethanol content are shown in Figure 61, Figure 62, and Figure 63, respectively.

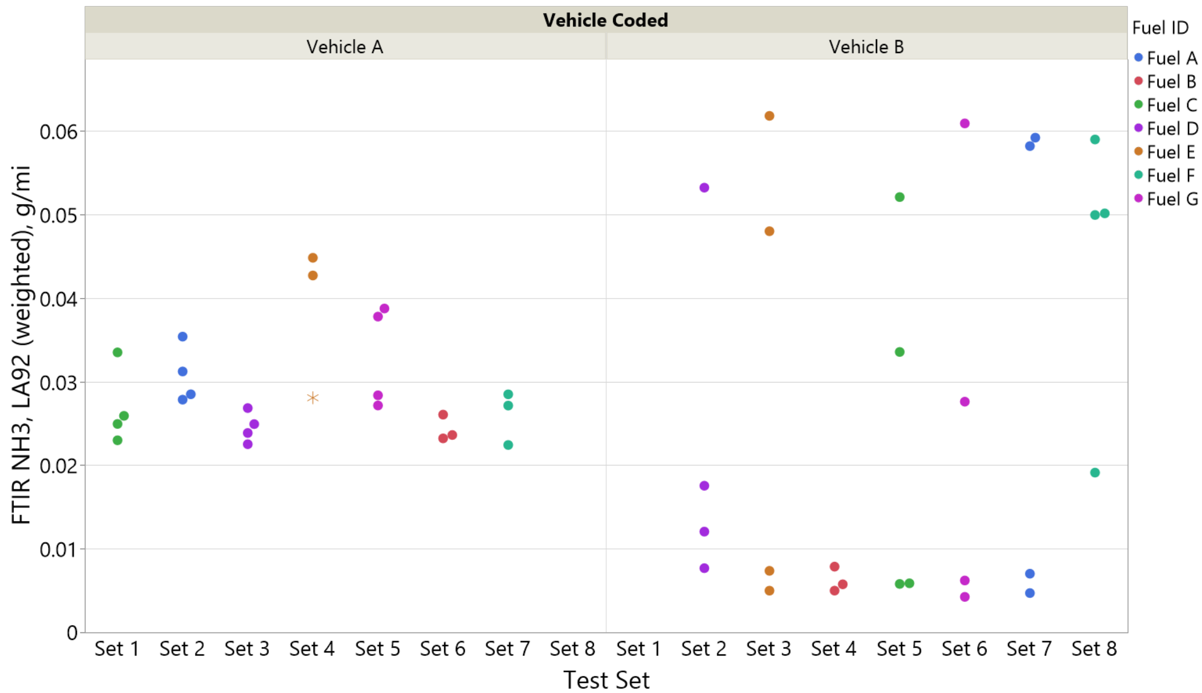

FIGURE 60: LA92 WEIGHTED NH_3 (G/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

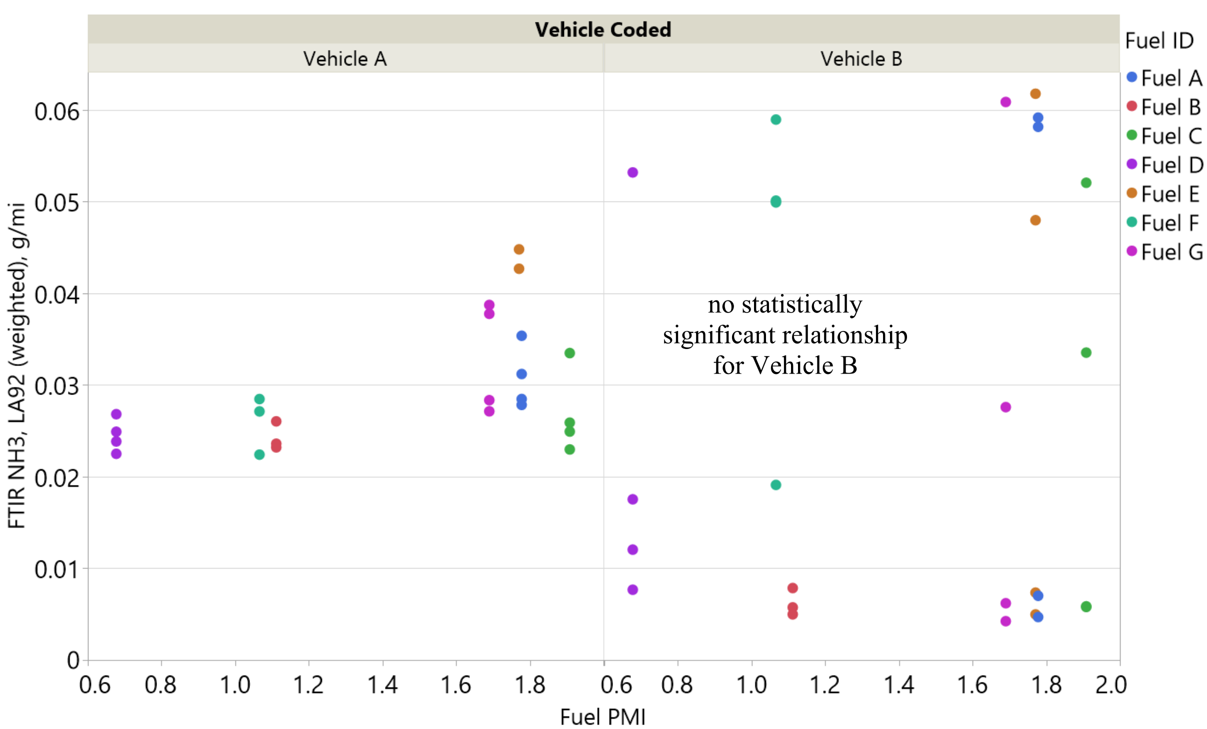

FIGURE 61: LA92 WEIGHTED NH_3 (G/MI) VS. FUEL PMI BY VEHICLE, COLORED BY FUEL

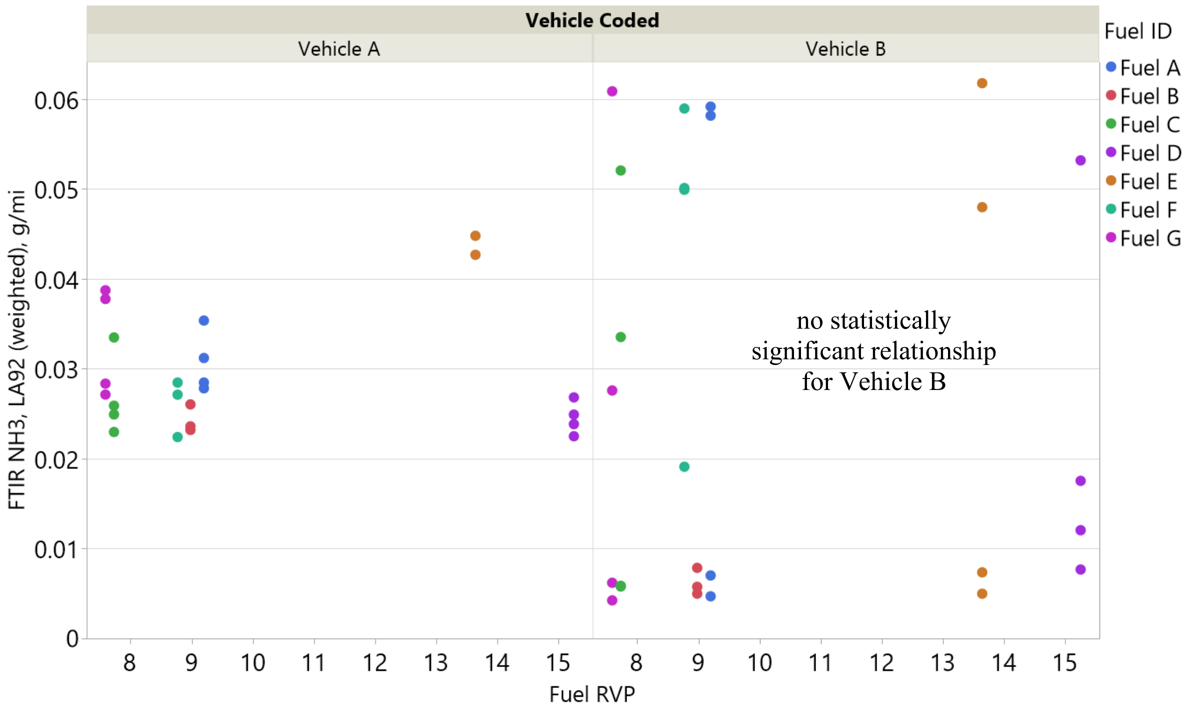

FIGURE 62: LA92 WEIGHTED NH_3 (G/MI) VS. FUEL RVP BY VEHICLE, COLORED BY FUEL

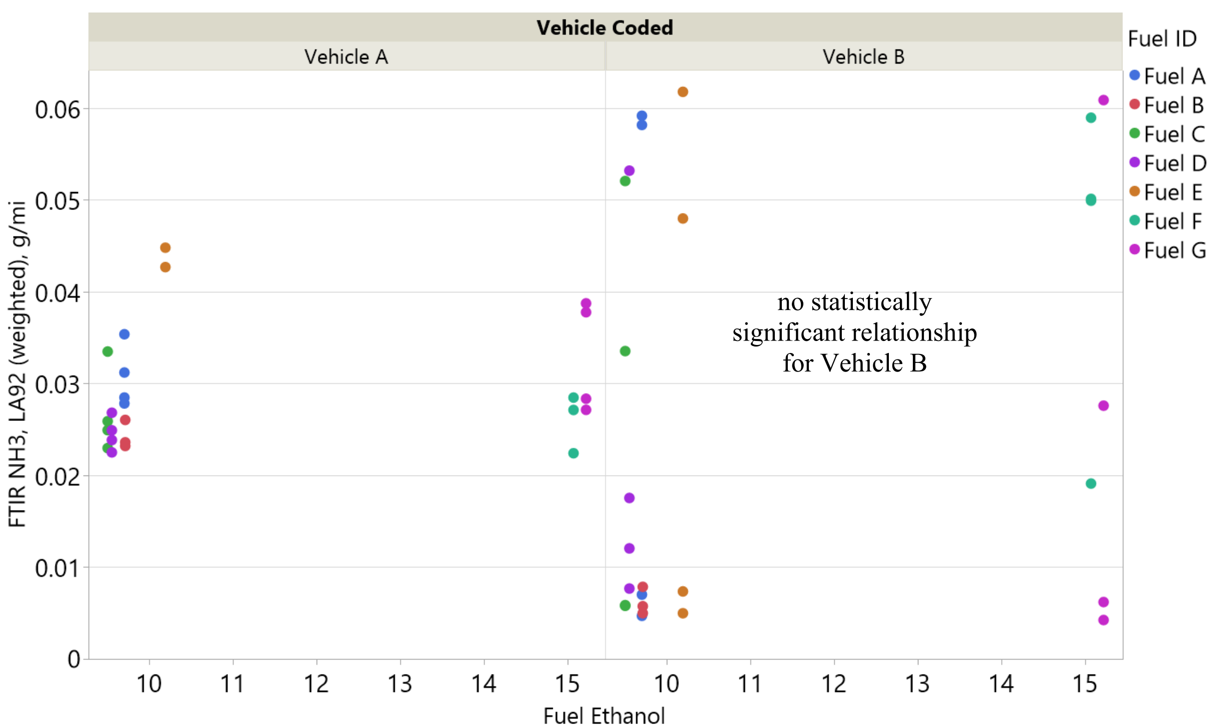

FIGURE 63: LA92 WEIGHTED NH_3 (G/MI) VS. FUEL ETHANOL BY VEHICLE, COLORED BY FUEL

For this model, all three fuel property variables were statistically significant, but only in the Vehicle A model. The final regression model for Vehicle A is shown in Table 36 as:

$$\widehat{NH_3} = -0.02607 + 0.01462 * FuelPMI + 0.002 * FuelRVP + 0.00127 * FuelEthanol$$

TABLE 36: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING NH_3 (G/MI), VEHICLE A ONLY

Parameter Estimates

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	-0.02607	0.0240*	-0.04833	-0.00380
Fuel PMI	0.01462	<.0001*	0.00916	0.02008
Fuel RVP	0.00200	0.0003*	0.00104	0.00296
Fuel Ethanol	0.00127	0.0053*	0.00042	0.00212

Since this model has multiple significant fuel properties, a prediction profiler plot is shown below in Figure 64 in order to view the estimated impact of a given fuel property after accounting for the modeled impact of the other fuel properties.

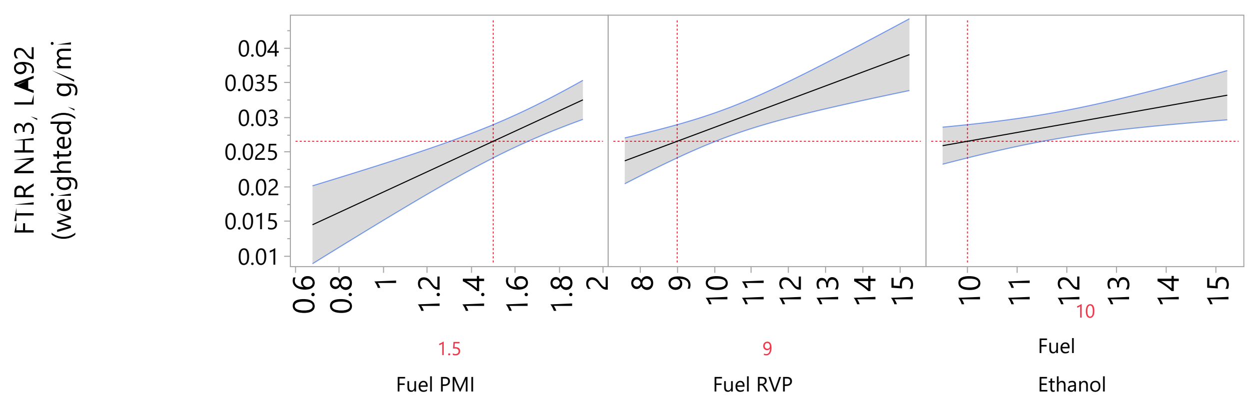

FIGURE 64: VEHICLE A PREDICTION PROFILER FOR MEAN NH_3 BASED ON PMI, RVP, AND ETHANOL WITH 95% CONFIDENCE LIMITS

The partial R-squared value was 58.9 percent for PMI, 35.8 percent for RVP, and 18.9 percent for ethanol. Therefore, only fuel PMI is seen to have moderate prediction capability. Table 37 below shows the regression model's predicted change in average NH_3 (g/mi) with a change in fuel PMI from 2.0 to 1.5 and from 2.0 to 1.0, holding RVP constant at 9 psi and ethanol at 10% volume. Additionally, changes of RVP from 9 psi to 14 psi are assessed, holding PMI constant at 1.5 and ethanol at 10% volume. Finally, a change in ethanol from 10% to 15% is assessed, holding PMI constant at 1.5 and RVP constant at 9 psi.

TABLE 37: MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE NH_3 (G/MI) EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	NH_3 (g/mi)	58.9%	0.0339 → 0.0266 (-22%)	0.0339 → 0.0193 (-43%)	35.8%	0.0266 → 0.0366 (+38%)	18.9%	0.0266 → 0.0329 (+24%)
B	NH_3 (g/mi)	-	-	-	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

4.3.10 Statistical Analysis Results for Nitrous Oxide (N_2O), g/mi

A plot of the time-ordered N_2O data is shown below in Figure 65, separated by vehicle and colored by fuel. There was not a statistically significant difference in variability between vehicles for this parameter. Therefore, outlier analysis and regression modeling were conducted with both vehicles combined. There were three (3) statistical outliers, indicated by the asterisks seen in Sets 1 and 2 for Vehicle A and Set 7 for Vehicle B. These data points were excluded from the regression modeling. Raw data plots of the N_2O data vs. PMI, RVP, and ethanol content are shown in Figure 66, Figure 67, and Figure 68, respectively.

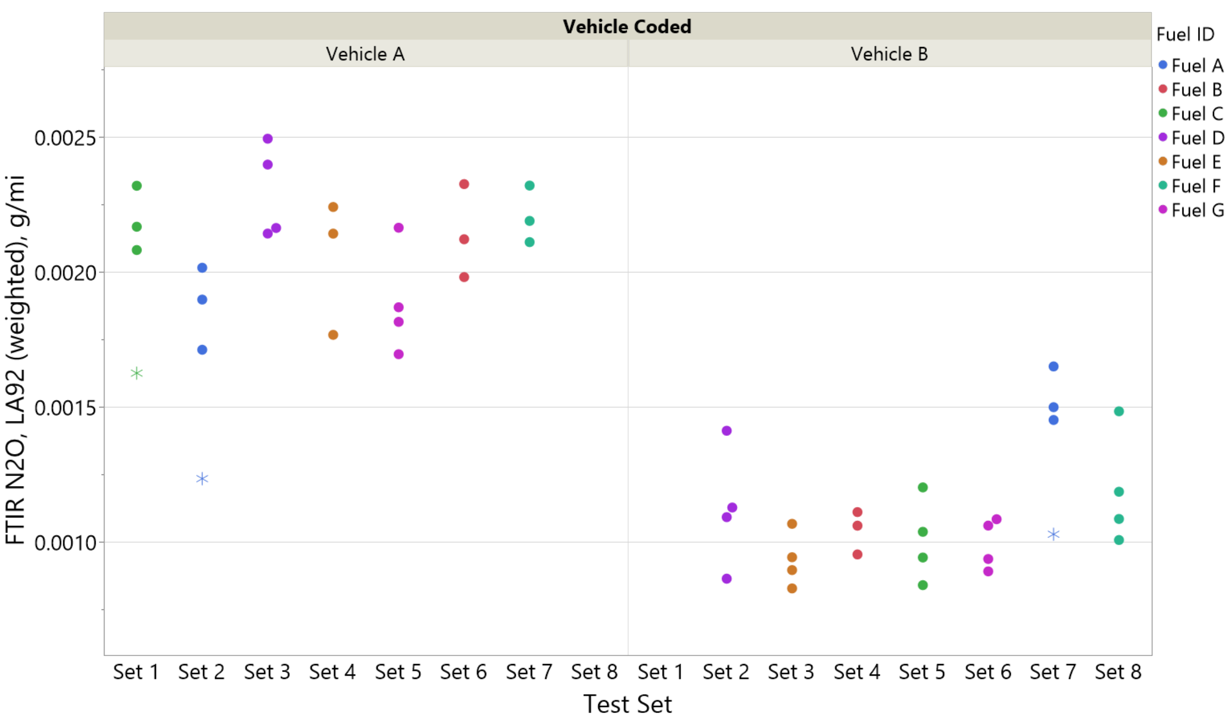

FIGURE 65: LA92 WEIGHTED N_2O (G/MI) BY VEHICLE AND TEST SET, COLORED BY FUEL

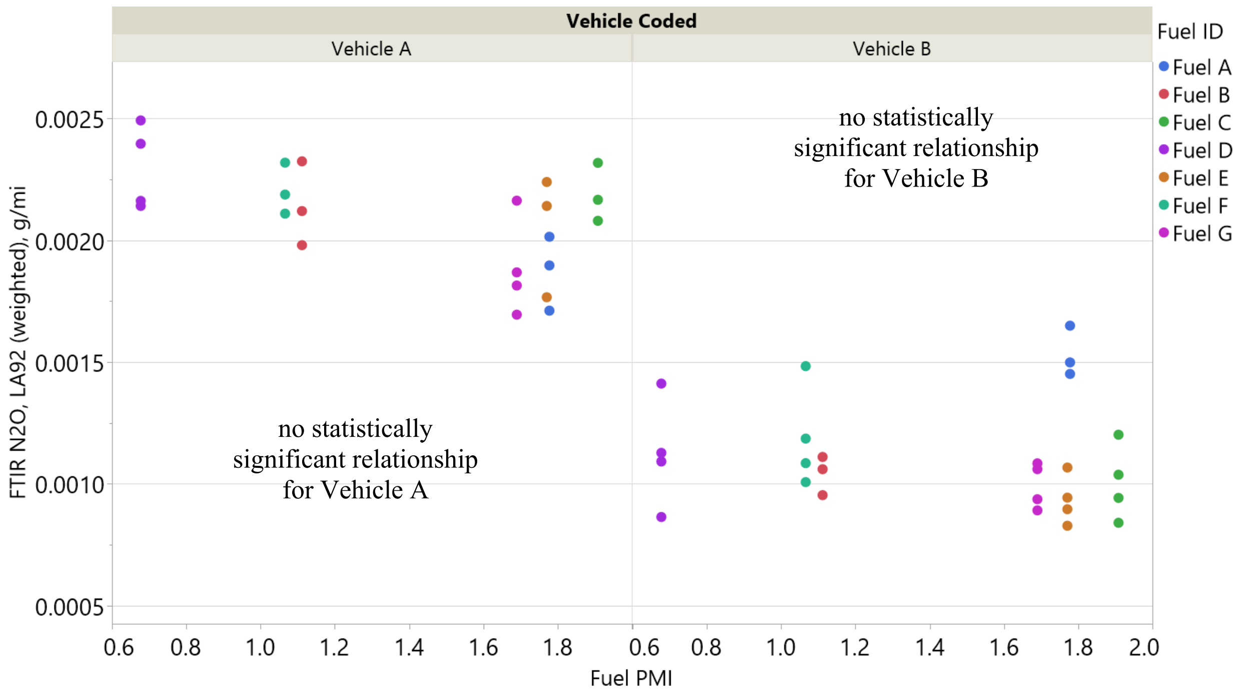

FIGURE 66: LA92 WEIGHTED N_2O (G/MI) VS. FUEL PMI BY VEHICLE, COLORED BY FUEL

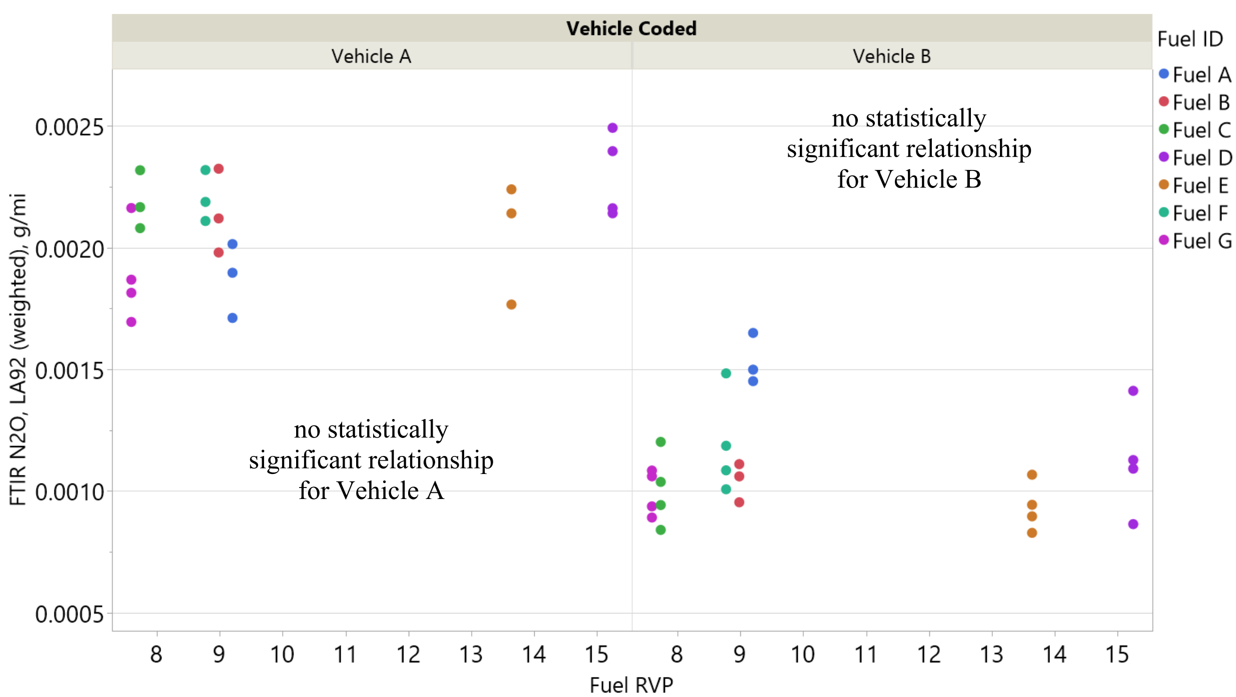

FIGURE 67: LA92 WEIGHTED N_2O (G/MI) VS. FUEL RVP BY VEHICLE, COLORED BY FUEL

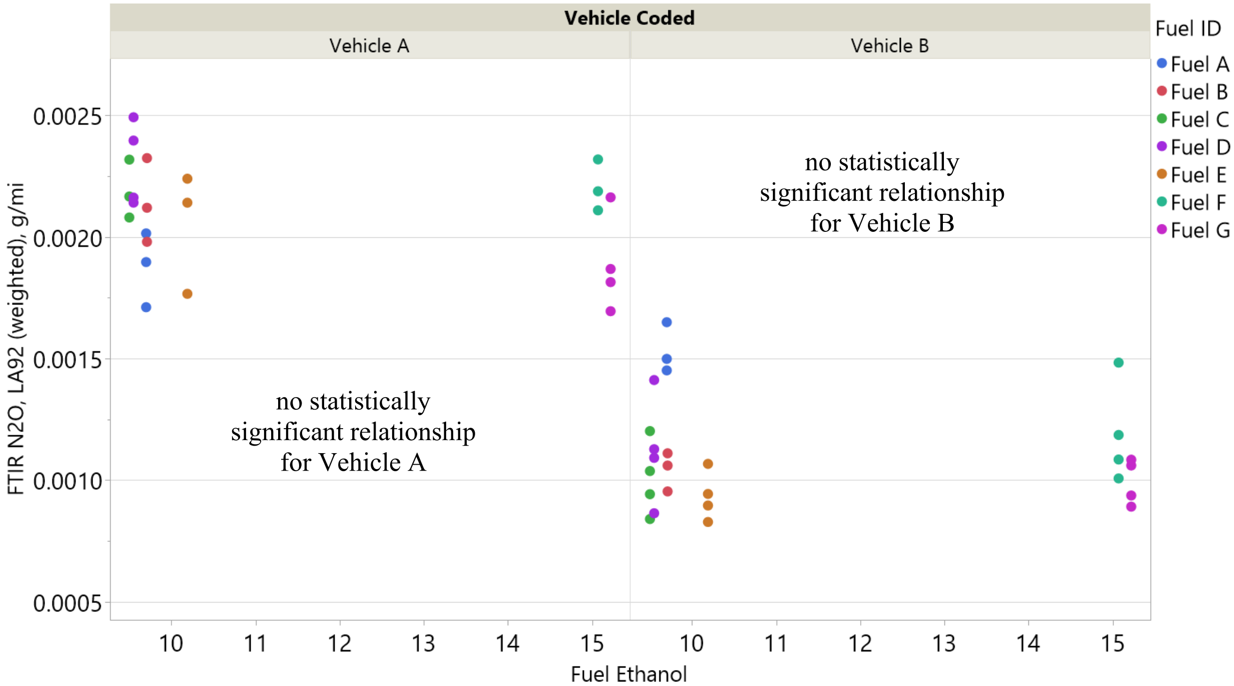

FIGURE 68: LA92 WEIGHTED N_2O (G/MI) VS. FUEL ETHANOL BY VEHICLE, COLORED BY FUEL

For this model, none of the fuel property variables were statistically significant predictors. The final variable to be removed which was closest to the p-value 0.05 threshold was Fuel PMI, shown below in Table 38 as having a p-value of 0.07 and indicating a negative correlation with N_2O.

TABLE 38: REGRESSION MODEL COEFFICIENT ESTIMATES PREDICTING SQRT N_2O (G/MI), BOTH VEHICLES

Indicator Function Parameterization

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	0.0355	<.0001*	0.0326	0.0383
Vehicle Coded[Vehicle A]	0.0126	<.0001*	0.0109	0.0142
Fuel PMI	-0.0017	0.0723	-0.0035	0.0002

5.0 CONCLUSIONS

This scoping project evaluated fuel property impacts on exhaust emissions from two (2) light-duty vehicles using seven (7) test fuels. Statistical analysis was conducted to determine whether any of the emissions generated by these high fuel injection pressure vehicles were significantly impacted by the differences in fuel PMI, Reid Vapor Pressure (RVP), or ethanol content. The emissions data used for the analysis were generated over the LA92 cycle and phase-weighted using the FTP composite weight factors (see Section 4.3). Regression models were run to determine the statistical significance (based on a 5% level of significance) of PMI, RVP, and ethanol content as predictors in the emissions models. Due to the limited number of fuels and the large number of fuel properties, some strong correlations existed between the fuel properties being studied and other fuel properties, including, for example, back-end distillation (T70 and higher) and density with PMI, front-end distillation (T30 and lower) with RVP, lower heating value, atomic composition, and distillation recovery with ethanol. It should be noted that the correlations observed are not necessarily an indication that these fuel properties are intrinsically or typically related, but only that they share a relationship within the seven fuels tested in this study. With these correlations present, one cannot attribute changes in emissions to changes in PMI, RVP, or ethanol content independent of these other highly correlated properties. A targeted fuel property design of experiments would be needed to unconfound the effects of PMI, RVP, and ethanol from these other properties and quantify their effects independently. A summary of fuel property correlations identified in this work was presented in Section 4.1.

For the analysis, a regression model was run separately for each of the 10 types of criteria pollutant emissions measured. A backwards variable selection technique was used to reduce the model terms down to only statistically significant factors, based on a 5% level of significance. To help quantify the prediction strength of the variables deemed statistically significant, partial R-squared values are provided. These values represent the additional percentage of the variance explained by a variable relative to a reduced model with all variables except that one. For models with only a single variable this value is the same as the model R-squared. For statistically significant effects (enough evidence to say the coefficient of the predictor is non-zero), the strength of prediction was binned into groups based on the partial R-squared values to help separate stronger predictors from weaker predictors. Though the divisions here are subjective, a predictor was considered weak if less than 40%, moderate between 40%-70%, and strong if >70%. The summary tables are color-coded based on these groups, with yellow for weaker predictors, light green for moderate predictors, and dark green for strong predictors. Additionally, the regression equation was used to assess the estimated average change in emissions across the range tested for that fuel property. It is worth noting that since most emissions were modeled with data transformations, the predicted change will be non-linear in original measured units. It is also worth stating that these models are predicting an average emissions level based on each fuel property level, and therefore may not accurately capture the performance of each individual fuel.

As the primary interest in the study was to quantify the impact of fuel properties on soot and particulate matter (PM) emissions, these are summarized first in Table 39 for the LA92 weighted composite data, along with SPN10. For these emissions, cold-start Phase 1 data was also analyzed on its own in addition to the weighted LA92 composite data, and these results are summarized in Table 40. In both the composite and Phase 1 only models of the current study, there was no statistical significance of RVP or ethanol for either vehicle. For Vehicle A, fuel PMI was statistically significant in both PM, Soot, and SPN10 models for Phase 1 alone and in the weighted composite data. PMI was a moderate predictor, explaining approximately 60%-65% of the variability observed in this vehicle. Vehicle B, however, showed no impact of fuel PMI on the full weighted cycle results, but was statistically significant for PM, Soot, and SPN10 when looking at Phase 1 alone. For this vehicle, the prediction strength of PMI was weak for PM, moderate for MSS Soot, and strong for SPN10. For these statistically significant factors, the summary tables below show the vehicle-specific regression model's predicted change in average PM, soot, and SPN10 for each vehicle with a change in fuel PMI from 2.0 to 1.5 and additionally from 2.0 to 1.0.

For the fuel property variables with coefficients determined to not be statistically different from zero, dashed lines (-) are shown for all table entries corresponding to that factor.

TABLE 39: SUMMARY OF MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 WEIGHTED COMPOSITE SOOT AND PARTICLE EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Model Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	PM (mg/mi)	63.3%	1.55→0.99 (-36%)	1.55→0.58 (-63%)	-	-	-	-
	MSS (mg/mi)	59.4%	1.29→0.58 (-55%)	1.29→0.26 (-80%)	-	-	-	-
	SPN10 (#/mi)	60.4%	7.234E+12→ 3.590E+12 (-50%)	7.234E+12→ 1.782E+12 (-75%)	-	-	-	-
B	PM (mg/mi)	-	-	-	-	-	-	-
	MSS (mg/mi)	-	-	-	-	-	-	-
	SPN10 (#/mi)	-	-	-	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

TABLE 40: SUMMARY OF MODEL PREDICTIONS OF FUEL PROPERTY IMPACTS ON LA92 PHASE 1 SOOT AND PARTICLE EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Model Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	PM (mg/mi)	64.0%	5.96→3.56 (-40%)	5.96→1.91 (-68%)	-	-	-	-
	MSS (mg/mi)	65.2%	6.10→2.27 (-63%)	6.10→0.84 (-86%)	-	-	-	-
	SPN10 (#/mi)	69.2%	3.292E+13→ 1.582E+13 (-52%)	3.292E+13→ 7.601E+12 (-77%)	-	-	-	-
B	PM (mg/mi)	23.4%	1.62→1.29 (-20%)	1.62→1.02 (-37%)	-	-	-	-
	MSS (mg/mi)	50.9%	0.44→0.29 (-33%)	0.44→0.19 (-55%)	-	-	-	-
	SPN10 (#/mi)	87.9%	4.491E+12→ 2.618E+12 (-42%)	4.491E+12→ 1.526E+12 (-66%)	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

Fuel property impacts were also evaluated for gaseous emissions and are summarized in Table 41. There was a moderate relationship seen between fuel PMI and NH_3 for Vehicle A. There was also a moderate relationship seen with RVP and CO_2 on both vehicles, and with RVP and CO for Vehicle A. Though there are other instances in the table where fuel properties were statistically significant, the relationships observed were fairly weak compared to the variability in the data. It is worth noting that Vehicle B exhibited much higher variability than Vehicle A on several parameters, and this high variability may have masked potential fuel impacts.

TABLE 41: REGRESSION MODEL SUMMARY OF FUEL PROPERTY IMPACTS ON LA92 GASEOUS EMISSIONS

		PMI			RVP, psi		Ethanol, vol%	
Vehicle	Model Parameter	Partial R^2	PMI 2.0 → 1.5	PMI 2.0 → 1.0	Partial R^2	RVP 9 → 14	Partial R^2	E10 → E15
A	THC (g/mi)	-	-	-	-	-	-	-
	CH_4 (g/mi)	-	-	-	-	-	-	-
	CO (g/mi)	-	-	-	44.2%	0.117 → 0.147 (+26%)	-	-
	CO_2 (g/mi)	-	-	-	43.3%	308.5 → 300.9 (-2.5%)	-	-
	NO_x (g/mi)	23.8%	0.0146→ 0.0158 (+8.4%)	0.0146→ 0.0172 (+17.5%)	20.2%	0.0158 → 0.0141 (-11.0%)	-	-
	NH_3 (g/mi)	58.9%	0.0339 → 0.0266 (-22%)	0.0339 → 0.0193 (-43%)	35.8%	0.0266 → 0.0366 (+38%)	18.9%	0.0266 → 0.0329 (+24%)
	N_2O (g/mi)	-	-	-	-	-	-	-
B	THC (g/mi)	26.5%	0.0133→ 0.0143 (+8%)	0.0133→ 0.0154 (+14%)	-	-	-	-
	CH_4 (g/mi)	30.0%	0.0018→ 0.0021 (+17%)	0.0018→ 0.0024 (+33%)	-	-	-	-
	CO (g/mi)	-	-	-	-	-	-	-
	CO_2 (g/mi)	-	-	-	43.3%	355.3 → 346.5 (-2.5%)	-	-
	NO_x (g/mi)	23.8%	0.0176→ 0.0190 (+8.4%)	0.0176→ 0.0206 (+17.5%)	20.2%	0.0190 → 0.0169 (-11.0%)	-	-
	NH_3 (g/mi)	-	-	-	-	-	-	-
	N_2O (g/mi)	-	-	-	-	-	-	-

A dashed line (-) on the table means that the fuel property was not statistically significant.

Vehicle B exhibited an interesting particle emissions signature. Results for this vehicle were consistently low for Phase 1, while Phases 2 and 3 were highly variable and had an increased rate of emissions. Additionally, although both vehicles were marketed to have the same maximum fuel injection pressure, the injection control strategies were very different. Vehicle B produced a fuel injection pressure of 350 bar just after the engine was cranked, compared to 170 bar from Vehicle A. Vehicle B also maintained a higher minimum fuel pressure of 130 bar, compared to the minimum pressure of 80 bar from Vehicle A. The higher injection pressure for Phase 1, discussed in Section 3.2, may play a role in why Vehicle B generally produced lower PM through the range of low and high PMI fuels. Vehicle technology is further discussed in Section 3.2.4. These vehicles were selected to understand how PMI, ethanol, and RVP could impact emissions for vehicles operating at 350 bar fuel injection pressure. However, these results were inconclusive, due to the injection control strategies which reduced injection pressures to a level lower than the pressure of interest. Nonetheless, this Phase 1 data shows when comparing Vehicle A to Vehicle B that there was a decreased relationship between PM emissions and Fuel PMI due to differences in vehicle technology that include increased fuel injection pressure, combustion chamber geometry, injector location, engine operational differences (e.g., stop/ start), etc. Further work should be performed to evaluate injection pressure sensitivity of tailpipe PM to PMI.

6.0 NEXT STEPS / RECOMMENDATIONS

This scoping project investigates the exhaust emissions response of two (2) Tier 3 compliant vehicles using a matrix of test fuels. For all fuels, Vehicle A produced a higher rate of PM in the cold-start phase of the cycle, and a lower rate after achieving operational temperature. Vehicle B, however, gave the opposite signature with lower PM produced during the cold-start phase and a higher rate of PM after the vehicle was warm during Phase 2 of the LA-92 cycle. Based on this, it is recommended to always perform specific evaluations of the cold start phase of the emissions test.

The large discrepancy between PM signatures suggests that engine control strategy should be carefully considered when trying to understand the effect of fuel properties on PM emissions. It also suggests that the interaction between fuel properties and PM emissions can be very vehicle specific. As previously discussed, fuel PMI was found to be a significant predictor of PM emissions for only vehicle A, when considering the entire LA-92 cycle.

To further investigate, future testing should include high-speed engine instrumentation to allow engine control strategy effects to be separated from fuel property effects on PM emissions. With low PM levels measured, it remains critical to include modal soot (ex: AVL MSS) and possibly particle size (ex: SPN23, SPN10) instrumentation to determine if additional repeat tests are required and to evaluate where in the test mode PM and PN is being generated.

Considering Vehicle A generated lower weighted PM with the lowest PMI fuel and lower injection pressure compared to Vehicle B on the same fuel, there are likely other strategies or technologies to achieve low PM. Additional vehicles with 350+ bar peak injection pressures and/or certified to meet PM of 1 mg/mi or less should also be included to sample a wider segment of the Tier 3 vehicle market. Prescreening checkout tests should be performed on each vehicle for any future testing to ensure targets (fuel pressure, emissions level, etc.) and repeatability can be achieved. Additionally, more work is needed to separate fuel PMI, RVP, and ethanol effects from other collinear properties of the fuels tested in this study. For example, a fuel with higher backend distillation and low PMI could be tested.

APPENDIX A

TEST FUEL ACQUISITION AND ANALYSES

Appendix A. Test Fuel Acquisition and Analyses

Four commercial test fuels were obtained by SwRI during CRC Project E-122-2 and also used for this program. The fuels were differentiated by a winter batch and a summer batch. Both high and low PMI fuels were obtained for each batch. SwRI acquire these fuels with the help of CRC members who identified locations based on internal analyses. CRC initially targeted 1,700 of each fuel but then increased this volume to 2,200 gallons.

Winter Fuels:

- 2,164 gallons of low PMI RUL E10 from the Marathon terminal in Salt Lake City
- 2,182 gallons of high PMI PUL E10 from the Chevron Richmond Technology Center

Summer Fuels:

- 2,152 gallons of low PMI RUL E10 from the same Marathon terminal in Salt Lake City
- 1,686 gallons of high PMI RUL E10 from the Motiva terminal in San Antonio

The procedure to acquire the fuels included the following steps:

1. Steam-clean and dry a tanker truck compartment
2. Drive tanker to terminal and rinse lines and compartment with 50 gallons of desired gasoline
3. Immediately fill the rinsed compartment with the desired gasoline
4. Deliver fuel to SwRI for analysis and off-loading
5. Repeat for additional batches of fuel

Each fuel was analyzed according to the following list of analyses.

- D5191 Reid Vapor Pressure
- D4815 / D5599 Oxygenates
- D5453 Sulfur
- D86 Distillation
- D381 Existent Gum
- D240 Net Heat of Combustion
- D5291 Carbon / Hydrogen
- D4052 Specific Gravity
- D2699 Research Octane Number
- D2700 Motor Octane Number
- D6729 Detailed Hydrocarbon Analyses

			CRC Summer 2020 Fuels		CRC Winter 2021 Fuels		
		Fuel Description	Low PMI E10 RUL	High PMI E10 RUL	E10 Low PMI RUL	E10 High PMI PUL	
		CRC Fuel ID	Fuel B	Fuel C	Fuel D	Fuel E	
		Fuel Source	Marathon Terminal (Salt Lake City)	Motiva Terminal (San Antonio)	Marathon Terminal (Salt Lake City)	Chevon Richmond Technology Center	
		SwRI Fuel Code	GA-10940	GA-10920	GA-11027	CGA-11053	CGB-11093
		Sample Code	FLRD-3606	FLRD-3560	FLRD-3914	FLRD-3979	FLRD-3788
		Sample Source	Drum Sample after Tanker Offloading	Tanker Manifold Sample	Tanker Manifold Sample	Drum Sample after Tanker Offloading	Sample after TOP TIER Additive Treatment
		Date of Sample	7/20/2020	5/29/2020	1/15/2021	3/26/2021	6/18/2021
		Current Volume	2,152 gallons	1,686 gallons	2,164 gallons	2,182 gallons	2,182 gallons
ASTM Method	**Test Request**	**Test Units**	**Results**	**Results**	**Results**	**Results**	**Results**
D6729	Detailed Hydrocarbon Analysis	--	completed	completed	completed	completed	completed
PMI	PM Index	*calculated*	1.1115	1.9085	0.6772	1.7708	n/a
D86	Distillation						
	IBP	Deg. F	96	103	81	78	n/a
	5%	Deg. F	121	125	93	100	n/a
	10%	Deg. F	130	131	103	109	n/a
	15%	Deg. F	136	135	112	117	n/a
	20%	Deg. F	141	139	120	125	n/a
	30%	Deg. F	150	146	134	141	n/a
	40%	Deg. F	158	153	146	155	n/a
	50%	Deg. F	203	198	154	173	n/a
	60%	Deg. F	227	235	194	242	n/a
	70%	Deg. F	246	264	224	268	n/a
	80%	Deg. F	273	297	248	302	n/a
	90%	Deg. F	306	330	281	338	n/a
	95%	Deg. F	333	351	303	367	n/a
	FBP	Deg. F	367	408	344	392	n/a
	Recovered	mL	98	98.4	97	97	n/a
	Residue	mL	0.9	0.7	0.7	0.7	n/a
	Loss	mL	1.6	0.9	2.2	2.0	n/a
D86	Driveability Index	--	1109.8	1119.5	896.7	971.2	n/a
D5191	Vapor Pressure (Mini Method)						
	RVP (EPA Equation)	psi	8.98	7.73	15.25	13.64	n/a
	DVPE (ASTM Equation)	psi	8.87	7.61	15.2	13.57	n/a
D240	Heat of Combustion						
	GROSS	BTU/lb	19244	19147	19494	19225	n/a
	GROSS	MJ/kg	44.760	44.536	45.344	44.717	n/a
	GROSS	cal/g	10690.8	10637.2	10830.3	10680.6	n/a
D240	Heat of Combustion						
	NET	BTU/lb	17982	17917	18204	17968	n/a
	NET	MJ/kg	41.827	41.675	42.341	41.794	n/a
	NET	cal/g	9990.3	9953.9	10113.1	9982.2	n/a
D2699	Research Octane Number (RON)	--	92.5	91.2	91	97.2	n/a
D2700	Motor Octane Number (MON)	--	83.7	82.7	82.9	87.9	n/a
D381	Existent Gums Content						
	Unwashed Wt	mg/100 mL	9.5	16.0	9.5	1.5	20.0
	Washed Wt	mg/100 mL	<0.5	<0.5	<0.5	0.5	0.5
D4052	API Gravity	--	60.1	57.5	66.1	60.7	n/a
	Specific Gravity	--	0.7386	0.7486	0.7161	0.7362	n/a
	Density @ 15°C	g/mL	0.7384	0.7484	0.7160	0.7360	n/a
D4815	Oxygenates and Oxygen Content						
	Methanol (MeOH)	vol%	<0.3	<0.2	<0.2	<0.2	n/a
	Ethanol (EtOH)	vol%	9.71	9.50	9.55	10.19	n/a
	Isopropanol (iPA)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	tert-Butanol (tBA)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	n-Propanol (nPA)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	Methyl tert-butylether (MTBE)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	sec-Butanol (sBA)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	Diisopropylether (DIPE)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	Isobutanol (iBA)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	Ethyl tert-butylether (ETBE)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	tert-Pentanol (tPA)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	n-Butanol (nBA)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	tert-amyl methylether (TAME)	vol%	<0.2	<0.2	<0.2	<0.2	n/a
	Ethanol (EtOH)	wt%	10.43	10.07	<0.2	10.99	n/a
	Total Oxygen	wt%	3.62	3.49	3.67	3.81	n/a
D5291	Carbon Content	wt%	82.32	83.12	82.30	82.33	n/a
	Hydrogen Content	wt%	13.83	13.48	14.15	13.78	n/a
D5453	Sulfur by UV	ppm	7.1	6.2	11.4	5.1	n/a

CRC E-135 Project Blended Fuels				
		Fuel Description	Summer E15 Low PMI	Summer E15 High PMI
		Fuel Name	Fuel F (splash blend of Fuel B)	Fuel G (splash blend of Fuel C)
		SwRI Fuel Code	CGB-11285	CGB-11286
		Fuel Blend Number	2022-009	2022-010
		Sample Location	Tote 08-029s	Tote 08-038s
		Sample Code	FLRD-4456 / FLRD-4458	FLRD-4457 / FLRD-4459
		Sample Dates	3/4/2022 / 3/10/2022	3/4/2022 / 3/10/2022
ASTM Method	**Test Request**	**Test Units**	**Results**	**Results**
D5191	Vapor Pressure (Mini Method)			
	RVP (EPA Equation)	psi	8.77	7.59
	DVPE (ASTM Equation)	psi	8.66	7.46
D4052	API Gravity	--	59.1	56.7
	Specific Gravity	--	0.7423	0.7519
	Density @ 15°C	g/mL	0.742	0.7516
	Density @ 15°C	g/L	742.0	751.6
D5599	Oxygenates and Oxygen Content			
	Diisopropylether (DIPE)	vol%	<0.1	<0.1
	Ethyl tert-butylether (ETBE)	vol%	<0.1	<0.1
	Ethanol (EtOH)	vol%	15.08	15.12
	Ethanol (EtOH)	WT%	16.13	15.97
	Isobutanol (iBA)	vol%	<0.1	<0.1
	Isopropanol (iPA)	vol%	<0.1	<0.1
	Methanol (MeOH)	vol%	<0.1	<0.1
	Methyl tert-butylether (MTBE)	vol%	<0.1	<0.1
	n-Butanol (nBA)	vol%	<0.1	<0.1
	n-Propanol (nPA)	vol%	<0.1	<0.1
	sec-Butanol (sBA)	vol%	<0.1	<0.1
	tert-amyl methylether (TAME)	vol%	<0.1	<0.1
	tert-Butanol (tBA)	vol%	<0.1	<0.1
	tert-Pentanol (tPA)	vol%	<0.1	<0.1
	Total Oxygen	WT%	5.60	5.54
D5599	Oxygenates and Oxygen Content			
duplicate	Diisopropylether (DIPE)	vol%	<0.1	<0.1
	Ethyl tert-butylether (ETBE)	vol%	<0.1	<0.1
	Ethanol (EtOH)	vol%	15.07	15.22
	Ethanol (EtOH)	WT%	16.12	16.07
	Isobutanol (iBA)	vol%	<0.1	<0.1
	Isopropanol (iPA)	vol%	<0.1	<0.1
	Methanol (MeOH)	vol%	<0.1	<0.1
	Methyl tert-butylether (MTBE)	vol%	<0.1	<0.1
	n-Butanol (nBA)	vol%	<0.1	<0.1
	n-Propanol (nPA)	vol%	<0.1	<0.1
	sec-Butanol (sBA)	vol%	<0.1	<0.1
	tert-amyl methylether (TAME)	vol%	<0.1	<0.1
	tert-Butanol (tBA)	vol%	<0.1	<0.1
	tert-Pentanol (tPA)	vol%	<0.1	<0.1
	Total Oxygen	WT%	5.59	5.58
D240	Heat of Combustion			
	GROSS	BTU/lb	18849	18708
	GROSS	MJ/kg	43.843	43.515
	GROSS	cal/g	10472	10393
D240	Heat of Combustion			
	NET	BTU/lb	17599	17496
	NET	MJ/kg	40.935	40.697
	NET	cal/g	9777	9720
D2622	Sulfur by X-ray	wt%	8.2	8.0
D2699	Research Octane Number (RON)	--	95.3	94.0
D2700	Motor Octane Number (MON)	--	84.5	84.1
D5291	Carbon Content	wt%	80.60	80.68
	Hydrogen Content	wt%	13.70	13.28
D6729	DHA Analysis	--	Complete	Complete
PMI	Particulate Matter Index	--	1.066	1.690
D86	Distillation			
	IBP	Deg. F	97	102
	5%	Deg. F	124	127
	10%	Deg. F	133	133
	15%	Deg. F	139	137
	20%	Deg. F	144	141
	30%	Deg. F	152	149
	40%	Deg. F	157	156
	50%	Deg. F	162	161
	60%	Deg. F	216	215
	70%	Deg. F	243	258
	80%	Deg. F	269	291
	90%	Deg. F	305	327
	95%	Deg. F	329	350
	FBP	Deg. F	375	399
	Recovered	mL	99.2	99.0
	Residue	mL	0.5	0.7
	Loss	mL	0.3	0.3

EM-10967-F

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Certificate of Analysis

Telephone: (800) 969-2542

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PRODUCT:	EPA Tier 3 EEE Emission Certification Fuel, General Testing - Regular	Batch No.:	HH2921LT10-10
		Tank No.:	TK107
Specification No.:	HF2021	Date:	10/10/2019

TEST	METHOD	UNITS	SPECIFICATIONS MIN	TARGET	MAX	RESULTS
Distillation - IBP	ASTM D86[2]	°F				96.5
5%		°F				120.2
10%		°F	120		140	129.0
20%		°F				138.5
30%		°F				147.3
40%		°F				154.3
50%		°F	190		210	195.1
60%		°F				233.2
70%		°F				256.0
80%		°F				282.0
90%		°F	315		335	322.2
95%		°F				341.5
Distillation - EP		°F	380		420	387.7
Recovery		%		Report		97.1
Residue		ml			2.0	0.8
Loss		%		Report		2.1
Gravity @ 60° F	ASTM D4052[2]	°API		Report		58.90
Density @ 15.56° C	ASTM D4052[2]	kg/l		Report		0.7425
Reid Vapor Pressure EPA Equation	ASTM D5191[2]	psi	8.7		9.2	9.2
Carbon	ASTM D5291[2]	wt fraction		Report		0.8239
Hydrogen	ASTM D5291[2]	wt fraction		Report		0.1387
Hydrogen/Carbon ratio	ASTM D5291[2]	mole/mole		Report		2.006
Oxygen	ASTM D4815[2]	wt %		Report		3.74
Ethanol content	ASTM D5599-00[2]	vol %	9.6		10.0	9.7
Total oxygentates other than ethanol	ASTM D4815[2]	vol %			0.1	None Detected
Sulfur	ASTM D5453[2]	mg/kg	8.0		11.0	9.2
Phosphorus	ASTM D3231[2]	g/l			0.0013	None Detected
Lead	ASTM D3237[2]	g/l			0.0026	None Detected
Composition, aromatics	ASTM D5769[1]	vol %	21.0		25.0	22.2
C6 aromatics (benzene)	ASTM D5769[1]	vol %	0.5		0.7	0.6
C7 aromatics (toluene)	ASTM D5769[1]	vol %	5.2		6.4	5.6
C8 aromatics	ASTM D5769[1]	vol %	5.2		6.4	5.5
C9 aromatics	ASTM D5769[1]	vol %	5.2		6.4	5.5
C10+ aromatics	ASTM D5769[1]	vol %	4.4		5.6	5.0
Composition, olefins	ASTM D6550[2]	wt %	4.0		10.0	7.0
Oxidation Stability	ASTM D525[2]	minutes	1000			1000+
Copper Corrosion	ASTM D130[2]				1	1a
Existent gum, washed	ASTM D381[2]	mg/100mls			3.0	1.0
Existent gum, unwashed	ASTM D381[2]	mg/100mls		Report		2.0
Research Octane Number	ASTM D2699[2]			Report		92.3
Motor Octane Number	ASTM D2700[2]			Report		84.5
R+M/2	D2699/2700[2]		87.0		88.4	88.4
Sensitivity	D2699/2700[2]		7.5			7.8
Net Heat of Combustion	ASTM D240[2]	BTU/lb		Report		17914

Quality Assurance Technician

ANAB ACCREDITED TESTING LABORATORY

[1] Haltermann Solutions is accredited to ISO/IEC 17025 by ANAB for the tests referred to with this footnote.

[2] Tested by ISO/IEC 17025 accredited subcontractor.

Main Lab, 15600 West Hardy Rd., Houston, TX 77060 USA

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APPENDIX B

DETAILED TEST PROCEDURES

FUEL CHANGE PROCEDURE

1. Drain vehicle fuel completely via fuel rail whenever possible.
2. Turn vehicle ignition to RUN position for 30 seconds allowing fuel level reading to stabilize. Confirm the return of fuel gauge reading to zero.
3. Turn ignition off. Fill fuel tank to 40% with 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 B. Apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system. Engine oil temperature in the sump will be measured and recorded during the sulfur removal cycle.
5. Perform four (4) vehicle coast downs from 70 to 30 mph, with the last two (2) measured. The vehicle will be checked for any obvious and gross source of change in the vehicle's mechanical friction if the individual run fails to meet the following repeatability criteria: 1) maximum difference of 0.5 seconds between back-to-back coastdown runs from 70 to 30 mph; and 2) maximum ±7 percent difference in average 70 to 30 mph coastdown time from the running average for a given vehicle.
6. Drain fuel and refill to 40% with test fuel. Fill-up fuel should be at approximately 50°F.
7. Drain fuel again and refill to 40% with test fuel. Fill-up fuel should be at approximately 50°F.
8. Soak vehicle for at least 12 hours to allow fuel temperature to stabilize to the test temperature.

CATALYST SULFUR PURGE CYCLE

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

1. Drive the vehicle from idle to 55 mph and hold speed for five (5) minutes (to bring catalyst to full working temperature).
2. Reduce vehicle speed to 30 mph and hold speed for one (1) minute.
3. Accelerate at WOT (wide-open throttle) for a minimum of five (5) seconds, to achieve a speed greater than 70 mph. Continue WOT above 70 mph, if necessary to achieve five (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 three (3) and four (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.
8. The protocol is complete if the necessary parameters have been achieved.

VEHICLE CONDITIONING

1. Move vehicle to test area without starting engine. Start vehicle and perform UDDS followed by two (2) HWYFET followed by a US06 test. During the prep cycle, apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system. Following the first two (2) prep cycles, allow vehicle to idle in park for two (2) minutes, then shut-down the engine for two (2)-five (5) minutes. Following the last prep cycle, allow the vehicle to idle for two (2) minutes, then shut down the engine in preparation for the soak.
2. Move vehicle to test area without starting engine.
3. Park vehicle in soak area at proper temperature (75 °F) for 12-36 hours. During the soak period, maintain the nominal charge of the vehicle's battery using an appropriate charging device.
4. Move vehicle to test area without starting engine.
5. Conduct LA-92 prep cycle and then soak vehicle for 12-36 hours.

APPENDIX C

INDIVIDUAL TEST RESULTS

Vehicle ID	Test Date	Fuel ID	THC, g/mi	THC, g/mi	THC, g/mi	THC, g/mi	CO, g/mi	CO, g/mi	CO, g/mi	CO, g/mi	NOx, g/mi	NOx, g/mi	NOx, g/mi	NOx, g/mi	CO2, g/mi	CO2, g/mi	CO2, g/mi	CO2, g/mi
			Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92
A	2/8/2022	GA-10920	0.307	0.005	0.011	0.021	0.632	0.064	0.037	0.092	0.047	0.013	0.012	0.015	473.7	297.4	412.2	314.4
A	2/9/2022	GA-10920	0.323	0.005	0.010	0.022	0.600	0.076	0.046	0.101	0.043	0.014	0.008	0.015	447.6	290.2	410.7	306.7
A	2/10/2022	GA-10920	0.315	0.005	0.009	0.022	0.707	0.074	0.035	0.104	0.042	0.014	0.012	0.016	452.9	287.0	407.5	303.8
A	2/11/2022	GA-10920	0.284	0.005	0.011	0.020	0.557	0.082	0.030	0.103	0.049	0.015	0.010	0.017	450.7	293.5	429.1	311.0
A	2/15/2022	EM-10967	0.294	0.005	0.011	0.020	0.854	0.068	0.072	0.109	0.034	0.015	0.007	0.015	475.1	297.0	422.8	315.0
A	2/21/2022	EM-10967	0.364	0.004	0.010	0.023	1.008	0.077	0.069	0.125	0.040	0.013	0.007	0.014	478.9	293.8	416.1	311.8
A	2/22/2022	EM-10967	0.403	0.005	0.013	0.027	1.093	0.086	0.117	0.141	0.047	0.013	0.005	0.014	471.8	291.0	392.6	307.5
A	2/24/2022	EM-10967	0.416	0.006	0.011	0.027	1.290	0.091	0.086	0.153	0.042	0.011	0.007	0.013	456.4	296.1	414.0	312.5
A	3/1/2022	GA-11027	0.293	0.004	0.011	0.020	1.422	0.062	0.057	0.133	0.037	0.013	0.011	0.014	433.9	284.5	395.6	300.0
A	3/2/2022	GA-11027	0.353	0.004	0.012	0.023	2.282	0.064	0.073	0.181	0.029	0.014	0.016	0.015	428.8	280.8	396.0	296.6
A	3/3/2022	GA-11027	0.357	0.004	0.011	0.023	2.557	0.044	0.042	0.176	0.037	0.014	0.011	0.015	430.6	283.6	392.8	298.9
A	3/7/2022	GA-11027	0.374	0.004	0.011	0.023	1.860	0.066	0.040	0.157	0.060	0.013	0.012	0.015	435.5	281.1	393.6	296.9
A	3/10/2022	GB-11093	0.407	0.006	0.011	0.027	1.103	0.088	0.097	0.142	0.043	0.013	0.011	0.015	432.4	279.5	388.4	295.0
A	3/11/2022	GB-11093	0.366	0.005	0.011	0.024	1.026	0.085	0.071	0.133	0.046	0.011	0.011	0.013	432.5	278.5	385.1	293.9
A	3/14/2022	GB-11093	0.438	0.005	0.012	0.028	1.219	0.084	0.078	0.143	0.040	0.012	0.011	0.014	451.3	290.8	405.9	307.1
A	3/18/2022	CGB-11286	0.403	0.006	0.010	0.027	1.149	0.083	0.031	0.135	0.040	0.011	0.009	0.013	453.2	292.8	412.0	309.4
A	3/21/2022	CGB-11286	0.332	0.005	0.012	0.022	0.763	0.054	0.039	0.090	0.050	0.021	0.014	0.022	472.6	289.4	404.0	306.9
A	3/22/2022	CGB-11286	0.416	0.006	0.011	0.027	1.104	0.079	0.085	0.133	0.051	0.014	0.007	0.015	478.1	300.8	413.7	317.8
A	3/23/2022	CGB-11286	0.396	0.005	0.011	0.026	1.048	0.084	0.106	0.135	0.054	0.012	0.006	0.014	462.5	291.2	405.8	308.0
A	4/6/2022	GA-10940	0.424	0.006	0.009	0.028	1.313	0.081	0.034	0.142	0.057	0.021	0.011	0.022	452.1	304.2	407.9	319.0
A	4/7/2022	GA-10940	0.381	0.005	0.012	0.026	0.849	0.061	0.025	0.100	0.046	0.018	0.014	0.019	450.4	292.5	401.2	308.3
A	4/8/2022	GA-10940	0.327	0.006	0.011	0.023	0.875	0.069	0.041	0.109	0.054	0.017	0.013	0.019	456.0	297.0	408.1	312.9
A	4/15/2022	CGB-11285	0.302	0.004	0.011	0.020	0.958	0.046	0.041	0.094	0.060	0.017	0.019	0.019	449.9	292.8	405.0	308.8
A	4/18/2022	CGB-11285	0.317	0.004	0.011	0.021	0.977	0.050	0.025	0.097	0.051	0.017	0.011	0.018	447.9	289.6	399.7	305.5
A	4/20/2022	CGB-11285	0.301	0.004	0.011	0.020	0.915	0.053	0.035	0.096	0.052	0.020	0.017	0.021	443.9	292.6	403.3	308.1
B	2/15/2022	GA-11027	0.262	0.000	0.002	0.014	2.668	0.215	0.019	0.328	0.093	0.011	0.048	0.018	594.7	321.1	449.9	344.1
B	2/21/2022	GA-11027	0.309	0.003	0.002	0.019	3.229	0.299	0.015	0.432	0.151	0.012	0.033	0.020	720.1	335.4	448.1	363.2
B	2/22/2022	GA-11027	0.312	0.003	0.002	0.019	2.157	0.241	0.448	0.355	0.133	0.013	0.030	0.020	636.5	326.9	446.1	351.1
B	2/24/2022	GA-11027	0.220	0.004	0.002	0.015	2.458	1.154	0.016	1.144	0.074	0.011	0.021	0.014	600.2	328.1	438.8	349.7
B	3/1/2022	GB-11093	0.302	0.001	0.002	0.017	1.057	1.317	0.357	1.237	0.106	0.010	0.024	0.016	590.5	323.7	445.7	345.9
B	3/2/2022	GB-11093	0.246	0.000	0.002	0.013	1.018	0.297	0.015	0.315	0.104	0.011	0.032	0.017	592.6	323.5	453.4	346.3
B	3/3/2022	GB-11093	0.245	0.000	0.002	0.013	1.030	0.221	0.019	0.249	0.116	0.010	0.022	0.017	611.5	325.6	443.6	348.5
B	3/7/2022	GB-11093	0.256	0.001	0.002	0.015	0.797	1.810	0.014	1.633	0.089	0.011	0.018	0.015	596.5	327.1	446.0	349.4
B	3/10/2022	GA-10940	0.252	0.000	0.002	0.013	1.548	0.229	0.028	0.283	0.093	0.009	0.033	0.015	599.2	323.8	425.2	345.0
B	3/11/2022	GA-10940	0.286	0.000	0.001	0.015	1.438	0.186	0.029	0.239	0.108	0.012	0.025	0.017	589.9	323.5	441.8	345.4
B	3/14/2022	GA-10940	0.249	0.001	0.001	0.014	1.617	0.314	0.014	0.361	0.113	0.012	0.032	0.018	620.2	336.0	444.6	358.1
B	3/22/2022	GA-10920	0.255	0.001	0.001	0.014	0.975	0.250	0.019	0.271	0.137	0.011	0.021	0.018	628.8	336.2	456.0	359.6
B	3/23/2022	GA-10920	0.256	0.002	0.002	0.015	1.003	1.887	0.043	1.715	0.134	0.010	0.028	0.018	613.8	340.5	454.9	362.5
B	4/4/2022	GA-10920	0.406	0.002	0.002	0.023	1.840	0.951	0.020	0.933	0.142	0.012	0.036	0.020	700.3	343.0	452.3	369.0
B	4/6/2022	CGB-11286	0.228	0.000	0.002	0.012	0.836	0.249	0.044	0.265	0.129	0.014	0.026	0.020	623.2	331.6	445.4	354.5
B	4/7/2022	CGB-11286	0.224	0.000	0.002	0.012	0.785	0.183	0.024	0.203	0.130	0.014	0.028	0.021	615.9	334.2	443.3	356.2
B	4/8/2022	CGB-11286	0.206	0.001	0.001	0.012	0.737	2.036	0.024	1.831	0.131	0.011	0.023	0.018	601.7	337.1	449.3	358.4
B	4/11/2022	CGB-11286	0.270	0.001	0.002	0.015	0.823	0.725	0.043	0.683	0.137	0.011	0.047	0.020	604.1	334.5	450.0	356.3
B	4/14/2022	EM-10967	0.379	0.001	0.002	0.021	1.389	1.791	0.151	1.658	0.166	0.010	0.026	0.019	684.9	339.5	451.3	365.1
B	4/15/2022	EM-10967	0.239	0.000	0.002	0.013	0.944	0.298	0.020	0.312	0.189	0.011	0.030	0.022	610.0	333.2	453.8	355.7
B	4/18/2022	EM-10967	0.248	0.001	0.002	0.014	1.072	0.209	0.016	0.240	0.150	0.014	0.030	0.022	602.0	334.6	455.3	356.7
B	4/20/2022	EM-10967	0.277	0.001	0.001	0.016	1.151	1.799	0.019	1.643	0.161	0.010	0.027	0.019	602.3	332.6	439.0	353.9
B	4/26/2022	CGB-11285	0.258	0.001	0.002	0.014	1.160	1.176	0.086	1.101	0.151	0.012	0.032	0.020	618.3	331.1	460.1	354.7
B	4/27/2022	CGB-11285	0.274	0.001	0.002	0.015	1.358	0.525	0.030	0.534	0.117	0.012	0.039	0.020	622.9	333.1	460.8	356.8
B	4/28/2022	CGB-11285	0.293	0.002	0.002	0.017	1.275	1.584	0.020	1.460	0.156	0.012	0.037	0.021	619.6	327.8	441.8	350.6
B	4/29/2022	CGB-11285	0.289	0.002	0.002	0.017	1.217	1.242	0.022	1.157	0.131	0.011	0.037	0.019	606.5	328.4	438.5	350.4

Vehicle ID	Test Date	Fuel ID	CH4, g/mi	CH4, g/mi	CH4, g/mi	CH4, g/mi	NMHC, g/mi	NMHC, g/mi	NMHC, g/mi	NMHC, g/mi	FE, mpg	FE, mpg	FE, mpg	FE, mpg	NH3, g/mi	NH3, g/mi	NH3, g/mi	NH3, g/mi	N2O, g/mi	N2O, g/mi	N2O, g/mi	N2O, g/mi
			Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92
A	2/8/2022	GA-10920	0.044	0.002	0.008	0.004	0.262	0.004	0.003	0.017	18.31	29.33	21.15	27.75	0.128	0.020	0.015	0.025	0.023	0.000	0.004	0.002
A	2/9/2022	GA-10920	0.044	0.002	0.007	0.004	0.278	0.003	0.003	0.018	19.37	30.03	21.20	28.38	0.126	0.020	0.026	0.026	0.036	0.000	0.005	0.002
A	2/10/2022	GA-10920	0.041	0.001	0.007	0.004	0.273	0.004	0.003	0.018	19.15	30.35	21.41	28.66	0.116	0.018	0.012	0.023	0.030	0.000	0.005	0.002
A	2/11/2022	GA-10920	0.040	0.002	0.007	0.004	0.229	0.004	0.003	0.015	19.25	29.63	20.31	28.02	0.111	0.031	0.008	0.033	0.029	0.000	0.005	0.002
A	2/15/2022	EM-10967	0.042	0.002	0.007	0.004	0.238	0.003	0.003	0.015	18.06	29.01	20.37	27.36	0.178	0.019	0.029	0.028	0.016	0.000	0.003	0.001
A	2/21/2022	EM-10967	0.048	0.001	0.007	0.004	0.298	0.003	0.003	0.018	17.89	29.30	20.71	27.62	0.140	0.025	0.025	0.031	0.023	0.000	0.004	0.002
A	2/22/2022	EM-10967	0.048	0.002	0.010	0.005	0.334	0.003	0.003	0.021	18.15	29.60	21.92	28.07	0.161	0.026	0.059	0.035	0.026	0.000	0.004	0.002
A	2/24/2022	EM-10967	0.051	0.002	0.007	0.005	0.345	0.004	0.003	0.021	18.77	29.10	20.81	27.53	0.166	0.021	0.025	0.028	0.028	0.000	0.005	0.002
A	3/1/2022	GA-11027	0.040	0.002	0.008	0.004	0.238	0.002	0.002	0.015	19.20	29.44	21.19	27.97	0.096	0.019	0.037	0.024	0.034	0.000	0.005	0.002
A	3/2/2022	GA-11027	0.047	0.001	0.009	0.004	0.287	0.002	0.003	0.017	19.35	29.86	21.19	28.25	0.135	0.020	0.037	0.027	0.028	0.000	0.005	0.002
A	3/3/2022	GA-11027	0.047	0.001	0.008	0.004	0.292	0.002	0.002	0.017	19.25	29.54	21.35	28.06	0.142	0.016	0.017	0.023	0.030	0.000	0.006	0.002
A	3/7/2022	GA-11027	0.043	0.001	0.008	0.004	0.311	0.002	0.002	0.018	19.12	29.86	21.30	28.25	0.109	0.020	0.026	0.025	0.028	0.000	0.006	0.002
A	3/10/2022	GB-11093	0.054	0.002	0.009	0.005	0.354	0.004	0.003	0.022	19.71	30.61	22.09	29.06	0.158	0.034	0.068	0.043	0.030	0.000	0.006	0.002
A	3/11/2022	GB-11093	0.052	0.002	0.008	0.005	0.315	0.003	0.003	0.019	19.68	30.72	22.26	29.16	0.166	0.039	0.027	0.045	0.029	0.000	0.006	0.002
A	3/14/2022	GB-11093	0.053	0.002	0.008	0.005	0.363	0.003	0.003	0.022	18.88	29.45	21.11	27.92	0.160	0.020	0.037	0.028	0.025	0.000	0.005	0.002
A	3/18/2022	CGB-11286	0.047	0.002	0.007	0.005	0.336	0.004	0.003	0.021	18.86	29.34	20.87	27.83	0.099	0.026	0.011	0.028	0.032	0.000	0.004	0.002
A	3/21/2022	CGB-11286	0.044	0.002	0.009	0.004	0.273	0.003	0.003	0.017	18.10	29.75	21.29	28.01	0.155	0.019	0.032	0.027	0.021	0.000	0.004	0.002
A	3/22/2022	CGB-11286	0.051	0.002	0.008	0.005	0.344	0.004	0.003	0.021	17.88	28.56	20.77	27.04	0.214	0.026	0.057	0.038	0.029	0.000	0.003	0.002
A	3/23/2022	CGB-11286	0.050	0.002	0.008	0.005	0.326	0.004	0.002	0.020	18.47	29.54	21.18	27.92	0.172	0.030	0.049	0.039	0.027	0.000	0.004	0.002
A	4/6/2022	GA-10940	0.047	0.002	0.006	0.005	0.355	0.004	0.002	0.023	18.87	28.25	21.06	26.93	0.129	0.021	0.008	0.026	0.028	0.000	0.005	0.002
A	4/7/2022	GA-10940	0.044	0.002	0.008	0.004	0.318	0.004	0.004	0.020	18.99	29.32	21.42	27.89	0.112	0.019	0.015	0.023	0.025	0.000	0.007	0.002
A	4/8/2022	GA-10940	0.041	0.002	0.007	0.004	0.271	0.004	0.003	0.018	18.75	28.92	21.06	27.45	0.146	0.016	0.024	0.024	0.030	0.000	0.007	0.002
A	4/15/2022	CGB-11285	0.045	0.001	0.008	0.004	0.241	0.002	0.002	0.015	19.07	29.43	21.29	27.56	0.103	0.018	0.022	0.022	0.027	0.000	0.006	0.002
A	4/18/2022	CGB-11285	0.044	0.002	0.009	0.005	0.258	0.002	0.002	0.016	19.15	29.74	21.56	27.92	0.095	0.025	0.019	0.028	0.028	0.000	0.006	0.002
A	4/20/2022	CGB-11285	0.048	0.002	0.009	0.005	0.238	0.002	0.002	0.015	19.33	29.43	21.40	27.65	0.125	0.022	0.020	0.027	0.026	0.001	0.007	0.002
B	2/15/2022	GA-11027	0.029	0.000	0.002	0.002	0.227	0.000	0.000	0.012	13.99	26.12	18.65	24.39	0.006	0.008	0.001	0.008	0.015	0.000	0.001	0.001
B	2/21/2022	GA-11027	0.032	0.001	0.002	0.003	0.270	0.002	0.000	0.016	11.56	25.02	18.73	23.12	0.043	0.017	0.002	0.018	0.019	0.000	0.000	0.001
B	2/22/2022	GA-11027	0.029	0.001	0.002	0.003	0.277	0.002	0.000	0.016	13.09	25.64	18.79	23.91	0.002	0.013	0.008	0.012	0.020	0.000	0.000	0.001
B	2/24/2022	GA-11027	0.029	0.002	0.002	0.003	0.186	0.001	0.000	0.011	13.88	25.45	19.12	23.98	0.004	0.060	0.004	0.053	0.023	0.000	0.000	0.001
B	3/1/2022	GB-11093	0.028	0.001	0.002	0.002	0.267	0.000	0.000	0.014	14.45	26.30	19.20	24.78	0.008	0.053	0.008	0.048	0.017	0.000	0.000	0.001
B	3/2/2022	GB-11093	0.024	0.000	0.002	0.002	0.216	0.000	0.000	0.011	14.40	26.43	18.93	24.78	0.003	0.008	0.001	0.007	0.015	0.000	0.000	0.001
B	3/3/2022	GB-11093	0.025	0.000	0.002	0.002	0.215	0.000	0.000	0.011	13.96	26.28	19.31	24.57	0.004	0.005	0.001	0.005	0.016	0.000	0.000	0.001
B	3/7/2022	GB-11093	0.024	0.001	0.002	0.002	0.226	0.000	0.000	0.012	14.31	26.00	19.23	24.57	0.009	0.069	0.005	0.062	0.017	0.000	0.000	0.001
B	3/10/2022	GA-10940	0.028	0.000	0.002	0.002	0.225	0.000	0.000	0.012	14.27	26.49	20.22	24.91	0.005	0.006	0.001	0.006	0.017	0.000	0.000	0.001
B	3/11/2022	GA-10940	0.026	0.000	0.002	0.002	0.260	0.000	0.000	0.013	14.49	26.50	19.44	24.91	0.003	0.005	0.001	0.005	0.020	0.000	0.000	0.001
B	3/14/2022	GA-10940	0.028	0.001	0.001	0.002	0.216	0.000	0.000	0.011	13.79	25.54	19.31	24.00	0.003	0.009	0.001	0.008	0.018	0.000	0.000	0.001
B	3/22/2022	GA-10920	0.021	0.000	0.001	0.001	0.228	0.000	0.000	0.012	13.80	25.90	19.11	24.21	0.006	0.006	0.001	0.006	0.016	0.000	0.000	0.001
B	3/23/2022	GA-10920	0.021	0.001	0.002	0.002	0.229	0.001	0.000	0.012	14.14	25.41	19.15	24.07	0.005	0.058	0.006	0.052	0.019	0.000	0.000	0.001
B	4/4/2022	GA-10920	0.031	0.001	0.002	0.002	0.366	0.001	0.000	0.020	12.38	25.29	19.28	23.61	0.062	0.034	0.004	0.034	0.016	0.000	0.001	0.001
B	4/6/2022	CGB-11286	0.024	0.000	0.002	0.002	0.199	0.000	0.000	0.010	13.76	25.88	19.33	24.23	0.009	0.006	0.001	0.006	0.015	0.000	0.000	0.001
B	4/7/2022	CGB-11286	0.024	0.000	0.002	0.002	0.195	0.000	0.000	0.010	13.92	25.73	19.41	24.16	0.004	0.005	0.001	0.004	0.019	0.000	0.000	0.001
B	4/8/2022	CGB-11286	0.022	0.001	0.001	0.002	0.179	0.000	0.000	0.009	14.25	25.28	19.16	24.02	0.002	0.069	0.005	0.061	0.016	0.000	0.000	0.001
B	4/11/2022	CGB-11286	0.024	0.001	0.002	0.002	0.240	0.000	0.000	0.012	14.19	25.67	19.11	24.16	0.002	0.031	0.002	0.028	0.017	0.000	0.002	0.001
B	4/14/2022	EM-10967	0.029	0.001	0.002	0.002	0.342	0.000	0.000	0.018	12.52	25.14	19.10	23.61	0.012	0.065	0.006	0.058	0.019	0.000	0.000	0.001
B	4/15/2022	EM-10967	0.026	0.000	0.002	0.002	0.208	0.000	0.000	0.011	14.08	25.85	18.98	24.21	0.002	0.008	0.001	0.007	0.030	0.000	0.000	0.002
B	4/18/2022	EM-10967	0.026	0.001	0.002	0.002	0.216	0.000	0.000	0.011	14.26	25.70	18.94	24.14	0.002	0.005	0.001	0.005	0.026	0.000	0.000	0.001
B	4/20/2022	EM-10967	0.028	0.001	0.001	0.002	0.243	0.000	0.000	0.013	14.25	25.66	19.63	24.34	0.001	0.067	0.004	0.059	0.026	0.000	0.000	0.001
B	4/26/2022	CGB-11285	0.027	0.001	0.002	0.002	0.225	0.000	0.000	0.011	13.90	25.92	18.75	23.99	0.002	0.056	0.006	0.050	0.018	0.000	0.000	0.001
B	4/27/2022	CGB-11285	0.028	0.001	0.002	0.002	0.239	0.000	0.000	0.012	13.78	25.84	18.71	23.86	0.012	0.021	0.002	0.019	0.017	0.000	0.001	0.001
B	4/28/2022	CGB-11285	0.028	0.001	0.002	0.003	0.258	0.001	0.000	0.014	13.85	26.10	19.51	24.27	0.001	0.057	0.004	0.050	0.022	0.000	0.001	0.001
B	4/29/2022	CGB-11285	0.028	0.001	0.003	0.003	0.254	0.000	0.000	0.013	14.17	26.14	19.65	24.33	0.001	0.067	0.004	0.059	0.026	0.000	0.000	0.001

Vehicle ID	Test Date	Fuel ID	PM, mg/mi	PM, mg/mi	PM, mg/mi	PM, mg/mi	SPN 23, #/mi	SPN 23, #/mi	SPN 23, #/mi	SPN 23, #/mi	SPN 10, #/mi	SPN 10, #/mi	SPN 10, #/mi	SPN 10, #/mi	Soot, mg/mi	Soot, mg/mi	Soot, mg/mi	Soot, mg/mi
			Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92	Phase 1	Phase 2	Phase 3	LA92
A	2/8/2022	GA-10920	6.03	1.25	1.43	1.51	2.08E+13	2.67E+12	1.66E+12	3.54E+12	2.54E+13	3.90E+12	2.44E+12	4.91E+12	4.64	0.53	0.30	0.73
A	2/9/2022	GA-10920	5.96	1.16	1.57	1.43	2.03E+13	2.56E+12	1.69E+12	3.42E+12	2.43E+13	3.67E+12	2.55E+12	4.66E+12	4.38	0.51	0.33	0.70
A	2/10/2022	GA-10920	4.41	1.27	1.32	1.44	1.91E+13	2.95E+12	1.71E+12	3.70E+12	2.40E+13	3.88E+12	2.56E+12	4.83E+12	3.21	0.90	0.34	0.98
A	2/11/2022	GA-10920	5.16	0.87	0.81	1.09	2.11E+13	2.35E+12	1.49E+12	3.27E+12	2.53E+13	3.33E+12	2.25E+12	4.40E+12	4.28	0.52	0.26	0.70
A	2/15/2022	EM-10967	3.12	0.46	1.17	0.65	1.27E+13	1.68E+12	2.46E+12	2.30E+12	1.65E+13	2.45E+12	3.36E+12	3.25E+12	2.22	0.32	0.59	0.43
A	2/21/2022	EM-10967	5.14	0.78	1.87	1.08	1.76E+13	2.42E+12	3.74E+12	3.31E+12	2.18E+13	3.24E+12	4.84E+12	4.31E+12	3.77	0.64	1.27	0.84
A	2/22/2022	EM-10967	2.40	0.94	2.22	1.10	1.20E+13	3.05E+12	4.16E+12	3.59E+12	1.57E+13	3.98E+12	5.30E+12	4.69E+12	1.83	0.79	1.32	0.88
A	2/24/2022	EM-10967	3.05	1.20	1.69	1.33	1.36E+13	2.74E+12	3.37E+12	3.34E+12	1.74E+13	3.76E+12	4.39E+12	4.51E+12	2.18	0.73	1.03	0.83
A	3/1/2022	GA-11027	0.62	0.40	0.19	0.40	1.39E+12	3.38E+11	1.41E+11	3.79E+11	2.33E+12	5.45E+11	2.54E+11	6.18E+11	0.15	0.07	0.05	0.08
A	3/2/2022	GA-11027	0.73	0.14	0.14	0.17	2.01E+12	3.09E+11	1.22E+11	3.85E+11	3.14E+12	5.13E+11	2.29E+11	6.31E+11	0.27	0.09	0.07	0.10
A	3/3/2022	GA-11027	0.43	0.23	1.33	0.32	1.65E+12	4.06E+11	1.35E+11	4.53E+11	2.64E+12	6.53E+11	2.59E+11	7.30E+11	0.17	0.09	0.04	0.09
A	3/7/2022	GA-11027	1.20	0.22	1.95	0.39	1.58E+12	2.58E+11	1.16E+11	3.17E+11	2.52E+12	4.52E+11	2.57E+11	5.46E+11	0.21	0.06	0.04	0.07
A	3/10/2022	GB-11093	5.93	1.55	1.26	1.76	2.37E+13	6.00E+12	3.43E+12	6.74E+12	2.79E+13	7.82E+12	4.84E+12	8.65E+12	5.02	1.53	0.75	1.66
A	3/11/2022	GB-11093	5.41	1.08	1.63	1.34	2.18E+13	4.66E+12	3.42E+12	5.47E+12	2.61E+13	6.47E+12	4.77E+12	7.37E+12	4.60	0.88	0.68	1.06
A	3/14/2022	GB-11093	5.70	1.15	0.92	1.37	2.42E+13	4.63E+12	3.09E+12	5.53E+12	2.85E+13	6.30E+12	4.53E+12	7.33E+12	4.86	0.96	0.57	1.14
A	3/18/2022	CGB-11286	4.32	0.80	0.48	0.96	1.64E+13	2.10E+12	1.55E+12	2.81E+12	2.01E+13	3.11E+12	2.36E+12	3.94E+12	3.51	0.47	0.26	0.62
A	3/21/2022	CGB-11286	4.42	1.25	1.19	1.41	1.69E+13	1.77E+12	2.23E+12	2.59E+12	2.09E+13	2.65E+12	3.20E+12	3.64E+12	3.51	0.43	0.51	0.60
A	3/22/2022	CGB-11286	5.11	1.10	1.43	1.33	1.74E+13	2.61E+12	2.88E+12	3.40E+12	2.15E+13	3.59E+12	4.02E+12	4.55E+12	3.79	0.82	0.63	0.96
A	3/23/2022	CGB-11286	4.46	1.28	1.16	1.44	1.71E+13	3.50E+12	3.59E+12	4.21E+12	2.10E+13	4.72E+12	4.80E+12	5.57E+12	3.57	1.02	0.98	1.15
A	4/6/2022	GA-10940	4.93	1.19	1.84	1.43	1.72E+13	4.47E+12	3.41E+12	5.06E+12	2.07E+13	6.15E+12	4.62E+12	6.80E+12	4.04	1.03	1.11	1.19
A	4/7/2022	GA-10940	5.14	1.04	1.47	1.28	1.84E+13	3.77E+12	3.34E+12	4.50E+12	2.27E+13	5.02E+12	4.58E+12	5.91E+12	3.99	1.02	0.93	1.17
A	4/8/2022	GA-10940	4.67	0.91	1.06	1.11	1.88E+13	3.67E+12	3.25E+12	4.43E+12	2.32E+13	5.13E+12	4.52E+12	6.03E+12	3.85	0.83	0.84	0.99
A	4/15/2022	CGB-11285	2.01	0.26	0.51	0.37	8.22E+12	1.05E+12	1.17E+12	1.43E+12	1.09E+13	1.66E+12	1.91E+12	2.16E+12	1.48	0.22	0.22	0.28
A	4/18/2022	CGB-11285	1.79	0.40	0.81	0.50	8.80E+12	1.19E+12	1.09E+12	1.58E+12	1.16E+13	1.76E+12	1.75E+12	2.27E+12	1.40	0.32	0.18	0.37
A	4/20/2022	CGB-11285	1.85	0.35	0.59	0.44	9.04E+12	1.05E+12	1.53E+12	1.50E+12	1.20E+13	1.62E+12	2.40E+12	2.22E+12	1.39	0.22	0.28	0.28
B	2/15/2022	GA-11027	0.50	0.49	1.74	0.58	5.79E+11	1.17E+12	1.74E+12	1.18E+12	1.03E+12	1.49E+12	2.45E+12	1.54E+12	0.12	0.33	0.43	0.33
B	2/21/2022	GA-11027	0.82	1.34	0.97	1.29	6.18E+11	2.38E+12	1.70E+12	2.24E+12	1.21E+12	2.72E+12	2.34E+12	2.61E+12	0.19	1.09	0.49	1.00
B	2/22/2022	GA-11027	0.94	1.54	4.43	1.71	6.49E+11	2.51E+12	8.23E+11	2.30E+12	1.28E+12	2.84E+12	1.28E+12	2.65E+12	0.15	1.26	0.22	1.13
B	2/24/2022	GA-11027	1.42	2.72	1.67	2.58	5.15E+11	3.13E+12	2.25E+12	2.93E+12	9.68E+11	3.48E+12	2.92E+12	3.31E+12	0.08	2.20	0.71	1.99
B	3/1/2022	GB-11093	1.82	0.59	0.73	0.66	1.96E+12	4.59E+11	7.69E+11	5.58E+11	3.48E+12	7.48E+11	1.20E+12	9.21E+11	0.33	0.13	0.21	0.15
B	3/2/2022	GB-11093	0.71	0.38	1.14	0.45	1.92E+12	4.61E+11	9.59E+11	5.70E+11	3.32E+12	7.51E+11	1.68E+12	9.47E+11	0.33	0.13	0.22	0.14
B	3/3/2022	GB-11093	1.34	0.32	0.89	0.41	1.67E+12	8.82E+11	1.40E+12	9.58E+11	3.01E+12	1.26E+12	1.93E+12	1.40E+12	0.23	0.22	0.34	0.23
B	3/7/2022	GB-11093	0.98	2.44	7.63	2.72	3.79E+12	4.73E+12	1.07E+13	5.09E+12	6.65E+12	5.61E+12	1.26E+13	6.14E+12	0.48	2.32	6.01	2.48
B	3/10/2022	GA-10940	0.44	2.15	0.82	1.97	9.41E+11	3.78E+12	8.36E+11	3.43E+12	1.84E+12	4.25E+12	1.38E+12	3.93E+12	0.20	2.23	0.27	1.99
B	3/11/2022	GA-10940	1.42	1.74	1.54	1.71	8.50E+11	3.05E+12	9.65E+11	2.79E+12	1.62E+12	3.43E+12	1.61E+12	3.21E+12	0.22	1.70	0.21	1.52
B	3/14/2022	GA-10940	1.56	1.11	0.98	1.12	9.90E+11	2.42E+12	1.55E+12	2.28E+12	2.07E+12	2.79E+12	2.03E+12	2.70E+12	0.27	1.14	0.82	1.07
B	3/22/2022	GA-10920	1.75	0.68	1.48	0.79	2.75E+12	1.47E+12	1.81E+12	1.56E+12	4.69E+12	1.90E+12	2.51E+12	2.08E+12	0.45	0.52	0.55	0.51
B	3/23/2022	GA-10920	1.63	0.42	1.01	0.53	2.16E+12	7.70E+11	5.38E+11	8.27E+11	3.85E+12	1.16E+12	9.89E+11	1.28E+12	0.14	0.23	0.17	0.22
B	4/4/2022	GA-10920	1.71	0.59	0.79	0.66	4.16E+12	1.20E+12	1.46E+12	1.37E+12	6.59E+12	1.75E+12	2.11E+12	2.03E+12	0.86	0.36	0.48	0.39
B	4/6/2022	CGB-11286	1.33	0.45	1.35	0.56	1.84E+12	1.26E+12	2.06E+12	1.34E+12	3.15E+12	1.71E+12	2.98E+12	1.88E+12	0.38	0.33	0.73	0.36
B	4/7/2022	CGB-11286	1.41	0.74	1.15	0.80	1.94E+12	1.81E+12	1.66E+12	1.81E+12	3.50E+12	2.37E+12	2.39E+12	2.43E+12	0.36	0.57	0.53	0.56
B	4/8/2022	CGB-11286	0.88	1.37	1.44	1.35	1.76E+12	2.97E+12	2.50E+12	2.87E+12	3.06E+12	3.59E+12	3.44E+12	3.56E+12	0.35	1.27	0.86	1.19
B	4/11/2022	CGB-11286	2.43	1.44	1.88	1.52	2.65E+12	2.85E+12	3.09E+12	2.86E+12	4.58E+12	3.46E+12	4.09E+12	3.56E+12	0.54	1.42	1.23	1.36
B	4/14/2022	EM-10967	2.38	1.52	1.09	1.54	2.20E+12	2.83E+12	1.93E+12	2.74E+12	3.88E+12	3.32E+12	2.63E+12	3.31E+12	0.40	1.67	0.50	1.52
B	4/15/2022	EM-10967	1.79	0.96	0.91	1.00	1.46E+12	1.35E+12	1.33E+12	1.36E+12	2.56E+12	1.74E+12	1.88E+12	1.79E+12	0.32	0.51	0.39	0.49
B	4/18/2022	EM-10967	0.98	0.42	0.00	0.42	1.58E+12	1.20E+12	1.05E+12	1.21E+12	2.68E+12	1.55E+12	1.67E+12	1.62E+12	0.25	0.34	0.22	0.32
B	4/20/2022	EM-10967	1.71	2.14	1.94	2.11	1.71E+12	2.95E+12	1.61E+12	2.79E+12	2.86E+12	3.43E+12	2.37E+12	3.33E+12	0.49	1.64	0.62	1.51
B	4/26/2022	CGB-11285	0.72	0.79	1.01	0.80	7.52E+11	1.91E+12	2.30E+12	1.88E+12	1.36E+12	2.24E+12	3.11E+12	2.25E+12	0.18	0.75	0.53	0.70
B	4/27/2022	CGB-11285	1.12	0.78	0.84	0.80	8.11E+11	1.85E+12	1.19E+12	1.75E+12	1.48E+12	2.17E+12	1.72E+12	2.10E+12	0.23	0.85	0.30	0.78
B	4/28/2022	CGB-11285	0.75	0.58	1.15	0.63	8.53E+11	9.69E+11	1.48E+12	9.99E+11	1.44E+12	1.20E+12	2.04E+12	1.27E+12	0.25	0.36	0.30	0.35
B	4/29/2022	CGB-11285	1.84	0.75	1.38	0.85	1.05E+12	1.33E+12	1.61E+12	1.34E+12	1.78E+12	1.58E+12	2.20E+12	1.64E+12	0.32	0.72	0.53	0.69