CRC Report No. E-133

FUEL EFFECTS OF PARTICULATE MATTER INDEX, VAPOR PRESSURE, AND ETHANOL CONTENT ON VEHICLE EMISSIONS

Final Report

March 2023

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

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Final Report

Fuel Effects of Particulate Matter Index, Vapor Pressure, and Ethanol Content on Vehicle Emissions

Project E-133

Submitted to:

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

March 2023

POWERTRAIN ENGINEERING DIVISION

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Southwest Research Institute® Draft Final Report
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Prepared by:
Matt Blanks, Program Manager
Travis Kostan, Sr. Research Analyst
Kevin Brunner, Staff Engineer

Approved by:

____
Christopher Chadwell, Director
Automotive Propulsion Systems Department
Powertrain Engineering Division

FOREWORD

This report covers development and testing conducted by Southwest Research Institute (SwRI) for Coordinating Research Council (CRC). The Project, performed under CRC contract E-133, was conducted between April of 2020 and October of 2022. The project was based on SwRI's technical proposal to CRC dated February 24, 2020. The internal SwRI project number was 03.25980. The CRC project oversight was led by Amber Leland. The SwRI project manager was Matt Blanks, assisted in testing and development by Peter Lobato and Michael Kader. 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 for this project. 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 Southwest Research Institute (SwRI) on behalf of the Coordinating Research Council (CRC). The project investigated the use of multiple engine technologies and E15 fuels (gasoline containing 15 % ethanol by volume) to determine the impact of additional ethanol content on NO_x emissions and all criteria pollutants.

For this project, four E15 fuels were added to a test matrix already scheduled under CRC Project E-122-2, "Light Duty PEMS Phase 2: Engine Technology and Fuel Property Investigation". These new E15 fuels were produced by splash blending E10 market fuels with fuel-grade denatured ethanol. The final matrix evaluated exhaust emissions from four light-duty vehicles using fuels procured under E-122-2 and fuels blended for this project, E-133. Both on-road and chassis dynamometer tests were used, and both followed the E-122 test route (or cycle). For chassis dynamometer tests, exhaust emissions were measured simultaneously by certification-grade laboratory equipment and a Portable Emission Measurement System (PEMS). For on-road tests, the PEMS was the sole measurement device.

Particulate Matter Index (PMI) and Reid Vapor Pressure (RVP) were the two primary fuel properties studied in E-122-2 to determine their significance in predicting gaseous and PM emissions. With the additional data from the four E15 fuels, the models used in E-122-2 were updated, and ethanol content was included as a third fuel property factor to consider in the emissions regression models. As detailed in E-122-2, correlations between PMI, RVP, and ethanol content with other fuel properties were expected for both coincidental and intrinsic reasons. In cases where any of these fuel properties is determined to be a statistically significant factor, one must keep in mind the confounding effects of other highly correlated parameters which could serve as potential replacement factors. A targeted fuel property design of experiments would be required to unconfound the effects of PMI, RVP, and ethanol from other properties. For these fuels, PMI was shown to be highly correlated with back-end distillation (T70 and up), net heating value, API gravity, and density. RVP was shown to be highly correlated with other light-end distillation properties such as T5, T10, and T20, along with API Gravity and density. Ethanol was highly correlated with net heat of combustion and carbon content. A full correlation matrix is provided in Section 4.0.

All parameters studied indicated statistical significance for at least one of the three fuel properties studied. In most cases the effect was vehicle dependent, meaning the fuel property was a significant predictor for only a subset of the vehicles. PMI was the fuel property most commonly significant in the models and was significant for all parameters studied except for NO_x. RVP and ethanol content were deemed significant for two parameters each. As for the primary purpose of determining the ethanol content significance on emissions, the ethanol variable was deemed a significant predictor of NO_x for the three Tier 3 PFI vehicles, but not the Tier 2 DI vehicle (Vehicle B). The E15 fuels are predicted to produce higher NO_x by 17% for Vehicles A and C and 119% for Vehicle D. However, Vehicle D was a plug-in hybrid vehicle and experienced much higher variability in NO_x emissions than the other vehicles. Vehicle D operated on only battery power for the first part of each test, so the high variability may have been influenced by small differences in engine crank timing and run duration. NO_x results from Vehicle D should be interpreted cautiously.

Ethanol content was also deemed to be a statistically significant predictor of CO for all vehicles, with the E15 fuels predicted to have 21% lower CO than the E10 fuels. The full list of conclusions, including those pertaining to PMI and RVP, is summarized by parameter below in Table 1. Examples are given to show the magnitude of the predicted emission changes across the range of the PMI, RVP, and ethanol values for the fuels tested. Effects are level dependent in most cases, so baseline values for comparison are chosen based on representative levels seen in the data.

TABLE 1. FUEL PROPERTY SIGNIFICANCE SUMMARY AND PREDICTED CHANGES IN EMISSIONS

Parameter	Fuel PMI a Significant Predictor? (Vehicle)	Fuel RVP a Significant Predictor? (Vehicle)	Fuel Ethanol a Significant Predictor? (Vehicle)	Baseline Emissions for Comparison	Predicted Change with PMI Increase of 1 (% Change from Baseline)	Predicted Change with RVP Increase of 5 psi (% Change from Baseline)	Predicted Change with Ethanol Volume Increase of 5% (% Change from Baseline)
PM (mg/mi)	Yes (Vehicles A, B, C)	No	No	A – 0.100 B – 1.300 C – 0.120	A – 0.210 (+110%) B – 3.070 (+136%) C – 0.175 (+46%)	-	-
NO_x (g/mi)	No	No	Yes (Vehicles A, C, D)	A/C – 0.0100 D – 0.0050	-	-	A/C – 0.0117 (+17%) D – 0.0110 (+120%)
CO_2 (g/mi)	Yes (Vehicles A,B,C,D)	Yes (Vehicle A)	No	A/B/C – 300.0 D - 120.0	A/B/C – 302.0 (+0.67%) D – 120.8 (+0.67%)	A – 295.3 (-1.57%)	-
THC (g/mi)	Yes (Vehicles A, C)	No	No	A – 0.0150 C – 0.0075	A – 0.0101 (-33%) C – 0.0039 (-48%)	-	-
NMHC (g/mi)	Yes (Vehicles A, C)	No	No	A – 0.0150 C – 0.0075	A – 0.0098 (-35%) C – 0.0038 (-49%)	-	-
CO (g/mi)	Yes (Vehicles A, C)	Yes (Vehicles B, C)	Yes (Vehicles A,B,C,D)	A – 0.400 B – 0.300 C – 0.200 D – 0.100	A – 0.160 (-60%) C – 0.141 (-30%)	B – 0.362 (+21%) C – 0.266 (+33%)	A – 0.315 (-21%) B – 0.236 (-21%) C – 0.157 (-21%) D – 0.079 (-21%)

2.0 INTRODUCTION

Current U.S. production light-duty vehicles use gasoline-ethanol blends of 90% gasoline and 10% ethanol. There are many vehicles that now accept E15 blends. However, E15 is still not the prevalent fuel in the market and there is much discussion on how the additional ethanol may affect exhaust emissions.

This program evaluated four E15 fuels in conjunction with other fuels evaluated under E-122-2. All fuels were tested in each of four light-duty vehicles representing different engine technologies. Gaseous and particle emissions were measured to understand the impact on NOx and all criteria pollutants. Vehicle testing began in June of 2021 and was completed in November of 2021.

3.0 PROJECT SETUP

All testing was conducted at SwRI's light-duty vehicle laboratory or on public roads within San Antonio. The following sections describe the test fuels, test vehicles, drive cycle, and other details pertaining to the emission testing effort.

3.1 Test Fuels

A total of four E10 market fuels were located and procured under E-122-2. These fuels were comprised of summer and winter grades, each having a low and high Particulate Matter Index (PMI). All market fuels were 87 AKI E10 RUL (regular unleaded) except for the winter-grade, high PMI fuel. This fuel was a 93 AKI E10 PUL (premium unleaded) because a RUL, winter-grade fuel, meeting the RVP and PMI requirements, could not be located. A certification fuel was also procured under E-122-2 (Fuel A).

Each of the E10 market fuels was splash blended with fuel-grade denatured ethanol to produce the four new fuels with 15% ethanol by volume. Table 2 gives analysis results for key fuel properties from each fuel. Appendix A describes the splash blending process and Appendix B gives the results from all fuel analysis conducted with each fuel.

TABLE 2. ANALYSIS RESULTS OF KEY FUEL PROPERTIES

Fuel ID	SwRI Code	Name	Ethanol vol%	PMI	RVP psi	FBP °F	Total Aromatics wt %
A	EM-10967	Certification E10	9.7	1.7779	9.2	387.7	27.575
B	GA-10940	Summer Low PMI E10	9.71	1.1115	8.98	367.3	24.433
C	GA-10920	Summer High PMI E10	9.50	1.9085	7.73	407.9	33.236
D	GA-11027	Winter Low PMI E10	9.55	0.6772	15.25	344.2	25.805
E	CGB-11093	Winter High PMI E10	10.19	1.7708	13.64	392.2	32.700
F	CGB-11037	Summer Low PMI E15	15.02	1.0769	8.74	373.0	23.756
G	CGB-11039	Summer High PMI E15	15.02	1.8040	7.58	395.0	31.878
H	CGB-11156	Winter Low PMI E15	15.23	0.6408	14.21	344.0	17.292
I	CGB-11149	Winter High PMI E15	15.29	1.6348	13.30	396	30.187

3.2 Test Vehicles

Four vehicles were used in this project. CRC supplied one vehicle and SwRI purchased the other vehicles from local dealerships under E-122-2. Table 3 gives a description of each vehicle listing key properties that were targeted for each selection. These technologies include Port Fuel Injection (PFI), Direct Injection (DI), turbo charging, plug-in hybrid, and engine start/stop functionality.

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

- Tasks performed with each vehicle after purchase
- Initial checkout tests and results

TABLE 3. TEST VEHICLES

Test ID	A	B	C	D
Year	2019	2013	2019	2019
Engine Type	PFI NA	DI Turbo	PFI NA	PFI NA
Transmission	6-Speed AT	6-Speed AT	9-Speed AT	e-CVT
Fuel Type	Premium Gasoline (recommended)	Regular Gasoline	Regular Gasoline	Regular Gasoline
Flex Fuel	No	No	No	No
Ethanol Limit listed in Owner's Manual	15%	10%	15%	15%
Start/Stop	No	No	Yes	Plug-In Hybrid
EPA Cert	T3B125 LDV	T2B5 LDV	T3B30 LDT	T3B30 LDV
CA Cert	ULEV125 PC	ULEV II PC	SULEV30 LDT	SULEV30 PC
Weight with Empty Tank, lbs	4,096	3,677	4,320	3,324

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

- Each vehicle was added to SwRI's test vehicle insurance policy
- New vehicles were driven to a 4,000-mile odometer reading on a chassis dynamometer using the US EPA Standard Road Cycle (SRC) and E10 RUL gasoline
- The oil was changed and 500 miles of the SRC was accumulated for oil degreening using RUL E10 gasoline
- Reports were run to check for powertrain recalls, Technical Service Bulletins (TSBs), Diagnostic Trouble Codes (DTCs), and required vehicle software updates
- The coolant freeze-point and fill level were checked
- Tires were inspected

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 were measured, and results were provided to the CRC technical contact for final approval of the vehicle. All vehicles produced emissions well below their certification level. Table 4 gives the results from each checkout test.

TABLE 4. CHECKOUT EMISSION RESULTS

			CO, g/mi	NMOG+NOx, g/mi	PM, mg/mi
Vehicle A	EPA Tier 3 Bin 125 Certification Standard		2.1	0.125	3
	FTP-75 Checkout Results		0.26	0.029	0.7
Vehicle C	EPA Tier 3 Bin 30 Certification Standard		1	0.03	3
	FTP-75 Checkout Results		0.334	0.005	0.6
Vehicle D	EPA Tier 3 Bin 30 Certification Standard		1	0.03	3
	FTP-75 Checkout Results		0.12	0.017	0.6
		NMOG, g/mi	CO, g/mi	NO_X, g/mi	PM, mg/mi
Vehicle B	EPA Tier 2 Bin 5 Certification Standard	0.09	4.2	0.07	10
	FTP-75 Checkout Results	0.027	0.195	0.024	4.9

3.3 Test Route and Cycle

The E-122 test route was originally developed and recorded in San Antonio, TX, and was used for all tests in this project. The color-coded route, shown in Figure 1, starts on SwRI's campus and makes a 26.7-mile circuit within San Antonio. Purple indicates speeds under 35 mph, blue indicates speeds between 35 and 55 mph, and red indicates speeds over 55 mph. The speed and road grade profile of the route were recorded and used to create a chassis dynamometer drive cycle. For chassis dynamometer testing, the recorded transient road grade was simulated by increasing or decreasing the road load applied to the vehicle by the chassis dynamometer.

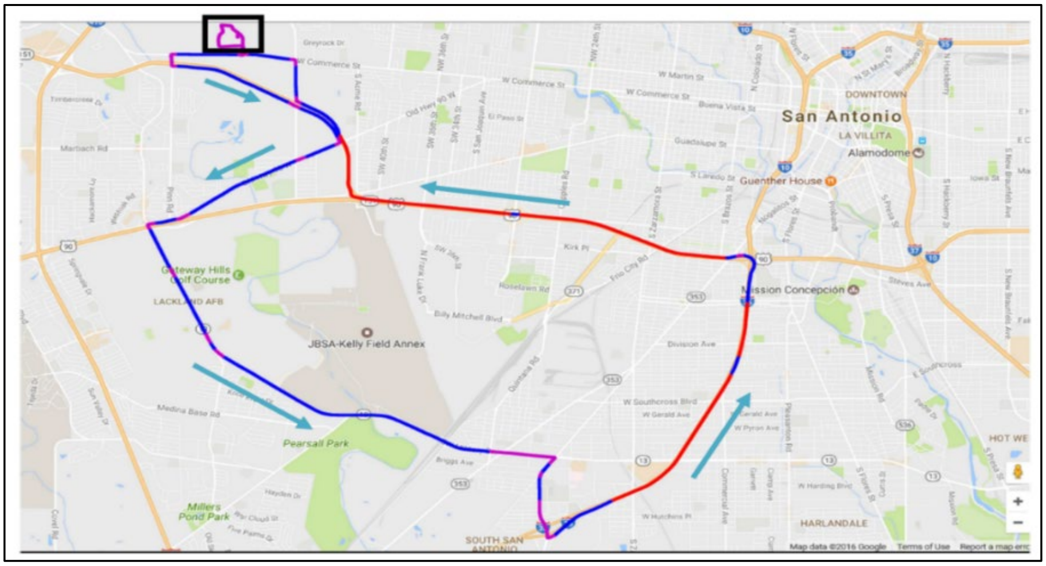


FIGURE 1. E-122 TEST ROUTE

During previous projects, high variability in THC and CO emissions were measured in the cold-start portion of on-road E-122 tests. The driving portion of an on-road test originally began ten seconds after cranking the engine. To reduce the high variability of emissions, an additional ten seconds of idle time was added after cranking the engine. The new idle time is very similar to the idle time required by the FTP-75 cycle. The shift from park to drive was made eighteen seconds after the test began. Figure 2 shows the modified E-122-2 cycle that includes the additional idle time. The modified cycle was used for all tests in this project.

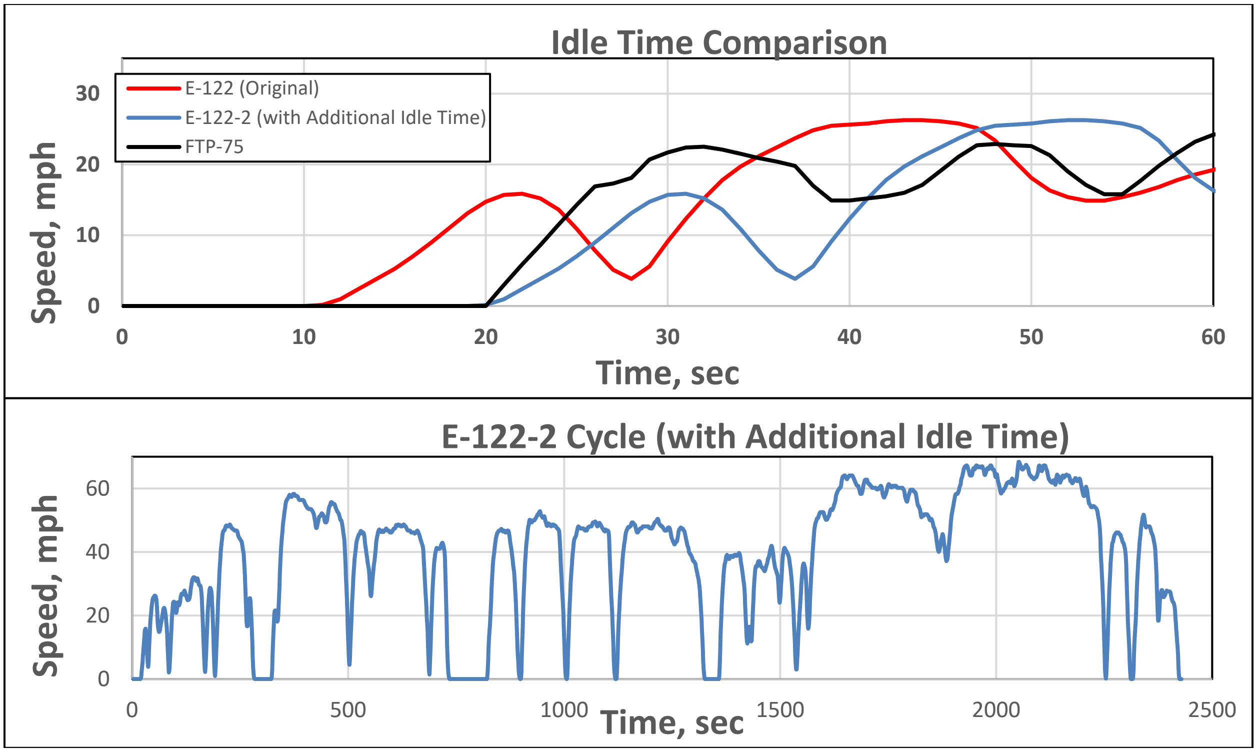


FIGURE 2. MODIFIED E-122 CYCLE TO INCLUDE TEN ADDITIONAL SECONDS OF IDLE

3.3.1 Route Changes and Road Closures

Two route problems were identified before road testing began. The first problem involved a large sewer line replacement on SwRI's campus. This construction closed a small road originally included in the E-122 route. An alternate route was identified that minimized the overall impact on test results.

Also, SwRI's southern gate was closed due to COVID. Plans were made with SwRI's security team to open and close the gate and allow test vehicles to follow the original E-122 route. However, a construction project began at that location to install automated barrier arms. The exact timing of the installation and the resulting traffic interruptions were not well defined. To maintain consistency for all on-road tests, an alternate gate was selected. This did not add any additional distance to the route. Figure 3 shows both route changes.

FIGURE 3. ROUTE CHANGES DUE TO CONSTRUCTION AND COVID

3.4 PEMS

CRC purchased a new Sensors LDV PEMS for this program. The system was specified to meet 40 CFR 1065 requirements and was shipped directly to SwRI from the manufacturer in August of 2019. A Sensors representative traveled to SwRI and helped to assemble the system and provided onsite training during October of 2019. The pictures in Figure 4 were taken during the inspection and assembly process. Major components of the PEMS include a SEMTECH® LDV, FID, EFM, and PM2 module. The system was configured to measure and record the following parameters:

- Exhaust Flow
- Total Hydrocarbon
- Carbon Monoxide
- Carbon Dioxide
- Nitrogen Dioxide
- Nitrogen Monoxide
- Particulate Mass
- OBD and GPS

FIGURE 4. PEMS INITIAL INSPECTION AND ASSEMBLY

3.4.1 PEMS Calibration and Linearization Checks

After assembly, the gaseous analyzers were calibrated against NIST-traceable reference gasses. Each analyzer passed criteria specified in 40 CFR part 1065. Results from these initial calibrations are given in Appendix C. A calibration procedure is not specified by the CFR for measurement of particulate mass, so the PM system did not receive a formal calibration. However, a cigarette lighter was used to confirm that the PEMS was able to detect particles by waving the flame near the sample probe.

Triplicate verifications of the Sensors Exhaust Flow Meter (EFM) were conducted at SwRI using two different reference measurement devices. A Laminar Flow Element (LFE) calibration stand was used to measure flow rates from 50 kg/hr to 500 kg/hr, and a Micromotion CMF025 mass flow meter was used to measure flow rates from 0 kg/hr to 80 kg/hr. Using both reference devices, the anticipated exhaust flow rates at both idle and heavy acceleration were verified. Figure 5 shows pictures taken during the LFE portion of the verification.

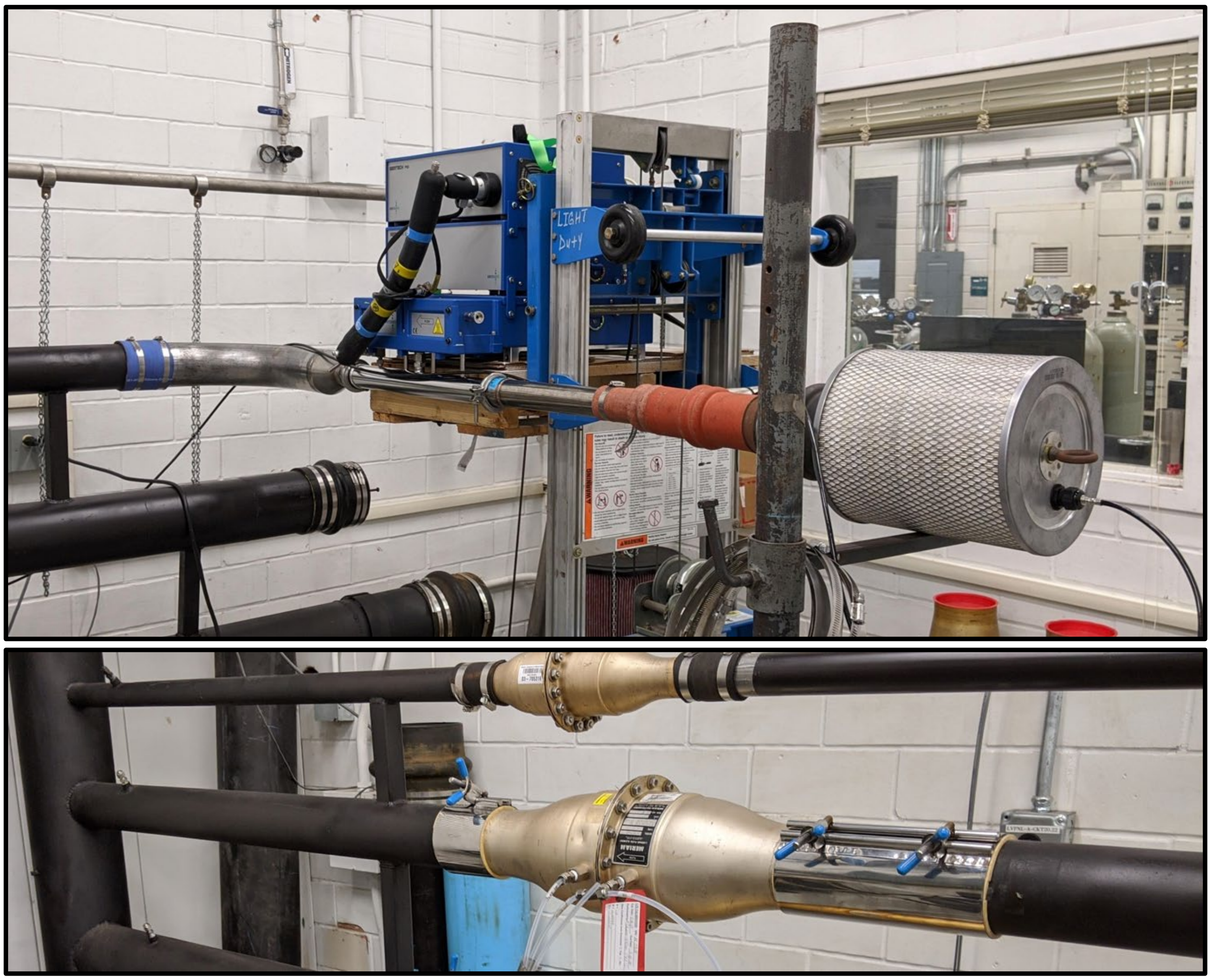


FIGURE 5. EFM CALIBRATION

Initial measurements indicated that the EFM read approximately two percent low compared to the reference devices across most of the flow range. These results did not meet the 40 CFR 1065 specifications for linear regression slope. SwRI sent the results to CRC for review and then forwarded the results to Sensors after receiving CRC approval. Sensors recommended adjusting the EFM calibration and a WebEx was held to give Sensors remote access to the PEMs software. Before changes were made to the EFM calibration, Sensors realized that the linear discharge coefficient in the software did not match the coefficient derived during the original EFM calibration conducted at the Sensors calibration laboratory on June 8, 2020. The correct coefficient was entered into the PEMs software and a second verification was conducted to confirm the change. Figure 6 and Table 5 give the new results showing compliance with 1065 criteria.

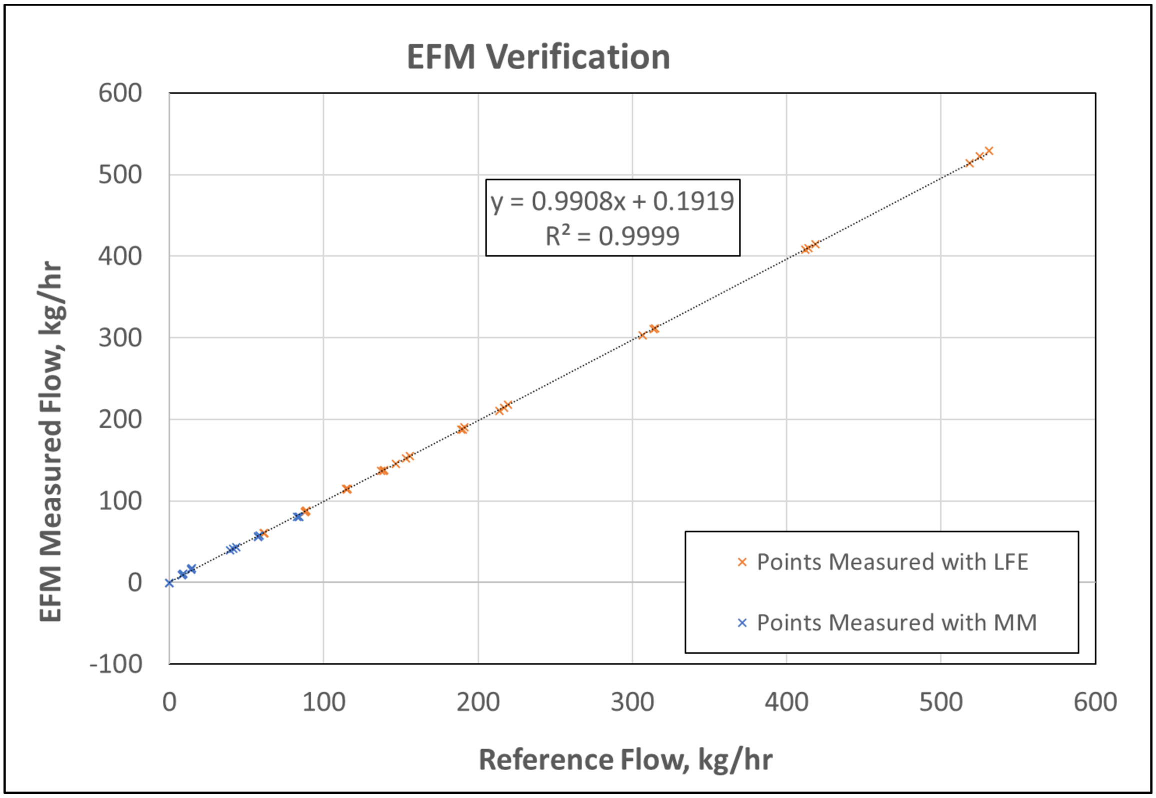


FIGURE 6. REFERENCE VS. MEASURED FROM SECOND EFM VERIFICATION

TABLE 5. 1065 CRITERIA RESULTS FROM SECOND EFM VERIFICATION

Statistic	Result	1065 Criteria	Pass/Fail
Slope (M)	0.99	0.98-1.02	Pass
Intercept (%)	0.036%	≤ 1 % Max	Pass
SEE (%)	0.232%	≤ 2 % Max	Pass
R2	1.000	≥ 0.990	Pass
NPoints	48	≥ 10	Pass

3.4.2 PEMS Mounting Configuration

PEMS components were mounted to a receiver rack and exhaust plumbing was fabricated for each vehicle to allow the PEMS to be moved between vehicles quickly. A flexible section of tubing was welded between the vehicle's tail pipe and the PEMS exhaust flow meter to protect both systems from vibration and damage caused by movement of the PEMS rack relative to the vehicle. Figure 7 shows the final assembly along with a hydraulic jack that was modified to mount and dismount the assembly from each vehicle. The PEMS, battery power supply, FID fuel, and mounting rack weighed 344 lbs in test configuration.

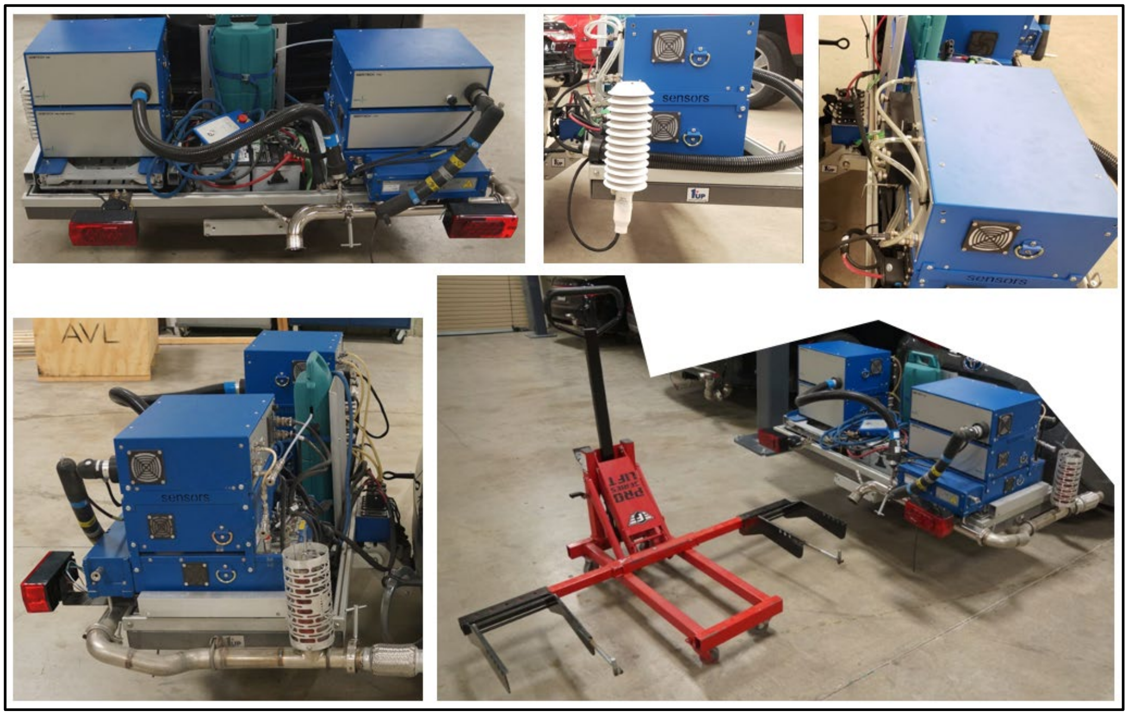


FIGURE 7. PEMS COMPONENT MOUNTING

3.5 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 lb 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 was used for all testing in this project. During the soak periods, all conventional vehicles were fitted with a trickle charger to maintain battery conditions. Vehicle D (plug-in hybrid) was connected to a level two charger during soak periods.

TABLE 6. CHASSIS DYNAMOMETER LOAD SETTINGS

Vehicle ID	A	B	C	D
Target				
ETW (lbs)	4750	4000	4750	3625
A (lbf)	26.79	26.347	38.24	18.816
B (lbf/mph)	0.6021	0.40519	0.2803	0.38689
C (lbf/mph**2)	0.0166	0.021578	0.02328	0.012501
Set				
ETW (lbs)	4750	4000	4750	3625
A (lbf)	11.62	9.67	19.81	9.79
B (lbf/mph)	0.0765	0.079	0.1647	-0.0465
C (lbf/mph**2)	0.01998	0.02195	0.02167	0.01684

3.6 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 Kynar bags. For the determination of PM emissions, a proportional sample of dilute exhaust was drawn through a 47mm Whatman Teflon membrane filter. Soot was also measured from dilute exhaust using an AVL Micro Soot Sensor (MSS).

Continuous, second-by-second emissions were also determined by extracting and analyzing a sample of raw exhaust drawn from the tailpipe directly after the PEMS flow meter and sample zone. The raw exhaust concentration was used along with the CVS exhaust flow measurement to calculate the continuous mass rate for each exhaust component. The laboratory diluted and raw exhaust emissions were analyzed as follows:

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
Particulate Mass	Gravimetric Measurement
Soot	AVL Micro Soot Sensor

The CVS tunnel flowrate for each vehicle was selected to give acceptable emission concentrations for dilute measurement while also minimizing tailpipe vacuum. The PEMS sample extraction pressure was checked and confirmed to be acceptable by Sensors before testing began. Figure 8 shows the test cell layout for this project.

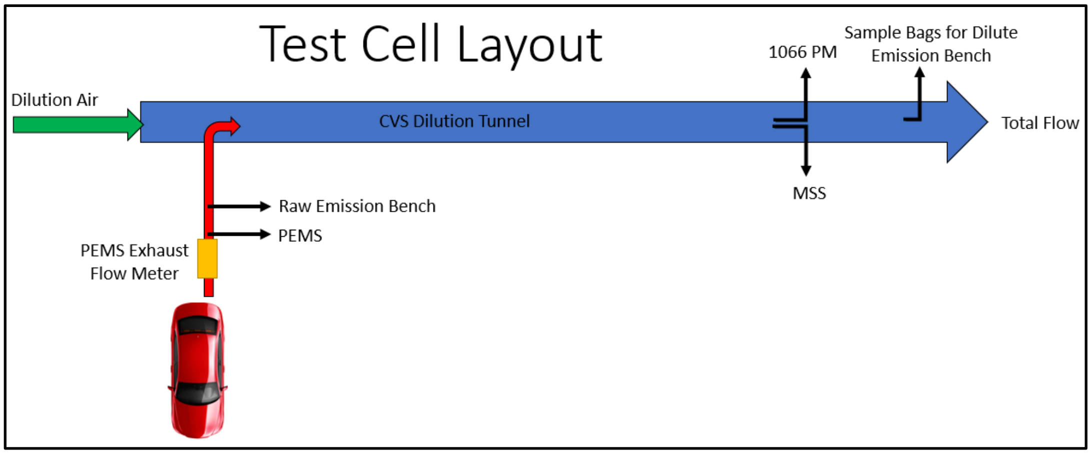


FIGURE 8. TEST CELL LAYOUT

3.7 On-Board Diagnostic (OBD) and Exhaust Flow Measurement

On-board Diagnostic (OBD) data was recorded by the PEMS continuously throughout each test. The PEMS was chosen as the OBD data acquisition system to maintain consistency between dynamometer and on-road tests. Below is a list of recorded OBD channels. Not all channels were available for each vehicle.

- Engine coolant temperature
- Fuel flow rate
- Engine speed
- Intake air temperature
- Mass air flow rate
- Fuel rail pressure
- Barometric pressure
- Ambient air temperature
- Engine oil temperature
- Engine fuel rate
- Lambda
- Engine load
- Torque
- Accelerator pedal position
- Fuel rail pressure

3.8 Test Procedure

Below is the testing sequence used for this project. Details for fuel change, sulfur purge, and vehicle conditioning sequences are given in Appendix D. Each fuel-vehicle combination was tested twice following steps 1-16 below. Table 7 gives the final test matrix that was followed for this project. Steps 1-16 below represent a single block in the matrix. The summer matrix began in June 2021 and was followed by the winter matrix which began in November of 2021. The last test was conducted on November 19, 2021.

Fuel Change and Preconditioning Sequence (Flushing to a New Test Fuel)

1. Conduct a fuel drain/fill using test fuel
2. Conduct a sulfur purge
3. Conduct vehicle coast downs
4. Conduct a 2^{nd} and 3^{rd} drain/fill using test fuel
5. Soak vehicle for 12 hours
6. Conduct prep cycles (UDDS + HwFET + US06)
7. Soak vehicle for 12 hours
8. Conduct a cold-start LA92
9. Soak vehicle for 12 hours

Emissions Test Procedure

10. Conduct a fuel drain/fill using test fuel
11. Conduct a Hot 505
12. Soak for a minimum of 8 hours while loading the evaporative canister
13. Conduct an E-122 test on the chassis dynamometer and collect:
    a. Dilute gaseous and particulate mass emissions
    b. Raw gaseous emissions (using CVS exhaust flow measurement)
    c. PEMS gaseous and particulate mass emissions
    d. OBD data
14. Soak for a minimum of 8 hours (no canister loading)
15. Conduct an E-122 test on public roads and collect:
    a. PEMS gaseous and particulate mass emissions
    b. OBD data
16. Repeat steps 10-15 (total of 2 dynamometer and 2 on-road tests)

TABLE 7. E-133 TEST MATRIX

Summer Test Matrix		Winter Fuels Test Matrix	
Set 1	Set 2	Set 3	Set 4
Vehicle A	Vehicle C	Vehicle D	Vehicle B
Vehicle B	Vehicle D	Vehicle A	Vehicle C
Vehicle C	Vehicle A	Vehicle B	Vehicle D
Vehicle D	Vehicle B	Vehicle C	Vehicle A

E15 Fuels	
	Fuel F
	Fuel G
	Fuel H
	Fuel I

To facilitate on-road testing, a staging area was established for conducting calibrations and moving the PEMS from vehicle to vehicle. Calibration gases, shore power, and other accessories were placed on carts so that the same items could be used for both on-road and dynamometer tests to reduce variability. The staging area was a covered garage with an overhead door to protect from inclement weather but allow the PEMS to soak at the outdoor temperature. Vehicle B and C were used to conduct trial runs and establish standardized testing procedures. Appendix E gives examples of step-by-step check lists developed for this project.

4.0 STATISTICAL ANALYSIS OF RESULTS

Statistical analysis was conducted to explore the significance of ethanol content as a factor in predicting NO_x and other exhaust emissions. Additionally, since this data set is an add-on to CRC project E-122-2, fuel PMI and RVP effects were re-examined with the additional data. The four market fuels obtained in E-122-2 were chosen to have both high and low PMI fuels at both high and low RVP values. The splash blending of these four market fuels to E15 additionally allowed for testing of ethanol content as a factor in predicting emissions. This resulted in a total of nine test fuels with the inclusion of the E10 certification fuel. A regression model was run for each emission parameter separately to determine if any of these three fuel properties were statistically significant factors. Correlations between PMI, RVP, and Ethanol with other fuel properties was expected for both coincidental and intrinsic reasons. In cases where any of these fuel properties is determined to be a statistically significant predictor, one must keep in mind the confounding effects of other highly correlated parameters which could serve as potential replacement predictors. 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. For these specific nine test fuels included in the analysis, PMI was shown to be highly correlated with back-end distillation (T70 and up), net heating value, API gravity, and density. RVP was shown to be highly correlated with light-end distillation properties such as T5, T10, and T20, along with API Gravity and density. Ethanol was highly correlated with net heat of combustion and carbon content. A full correlation matrix is provided below in Table 8. Cells are formatted to show a darker green color as the correlation strength increases, regardless of direction. Figure 9 provides an example of some of the correlations seen, showing ethanol content with net heat of combustion and ethanol content with carbon content.

TABLE 8. PMI, RVP, AND ETHANOL CORRELATIONS WITH OTHER FUEL PROPERTIES

	PMI	RVP	Ethanol
PMI	1.000	-0.517	-0.167
RVP (EPA Equation)	-0.517	1.000	0.036
Ethanol (vol%)	-0.167	0.036	1.000
IBP	0.434	-0.969	-0.155
T_5	0.504	-0.995	-0.086
T_10	0.457	-0.992	-0.055
T_20	0.384	-0.970	0.009
T_30	0.437	-0.914	0.124
T_40	0.539	-0.667	0.178
T_50	0.463	-0.565	-0.657
T_60	0.702	-0.560	-0.601
T_70	0.947	-0.446	-0.223
T_80	0.954	-0.430	-0.146
T_90	0.962	-0.420	-0.125
T_95	0.922	-0.379	-0.099
FBP	0.971	-0.556	-0.068
Total Aromatics	0.872	-0.307	-0.306
Recovered	0.537	-0.703	0.132
Residue	-0.091	0.161	0.430
Loss	-0.540	0.700	-0.206
Net Heat of Combustion	-0.396	0.163	0.966
RON	0.205	0.375	0.563
MON	0.362	0.346	0.333
API Gravity	-0.805	0.858	-0.152
Density @ 15C	0.804	-0.862	0.150
Total Oxygen	-0.212	0.084	0.997
Carbon Content	0.346	-0.184	-0.962
Hydrogen Content	-0.854	0.657	-0.022
Hydrogen/Carbon	-0.816	0.579	0.545
Sulfur by UV	-0.736	0.259	0.055

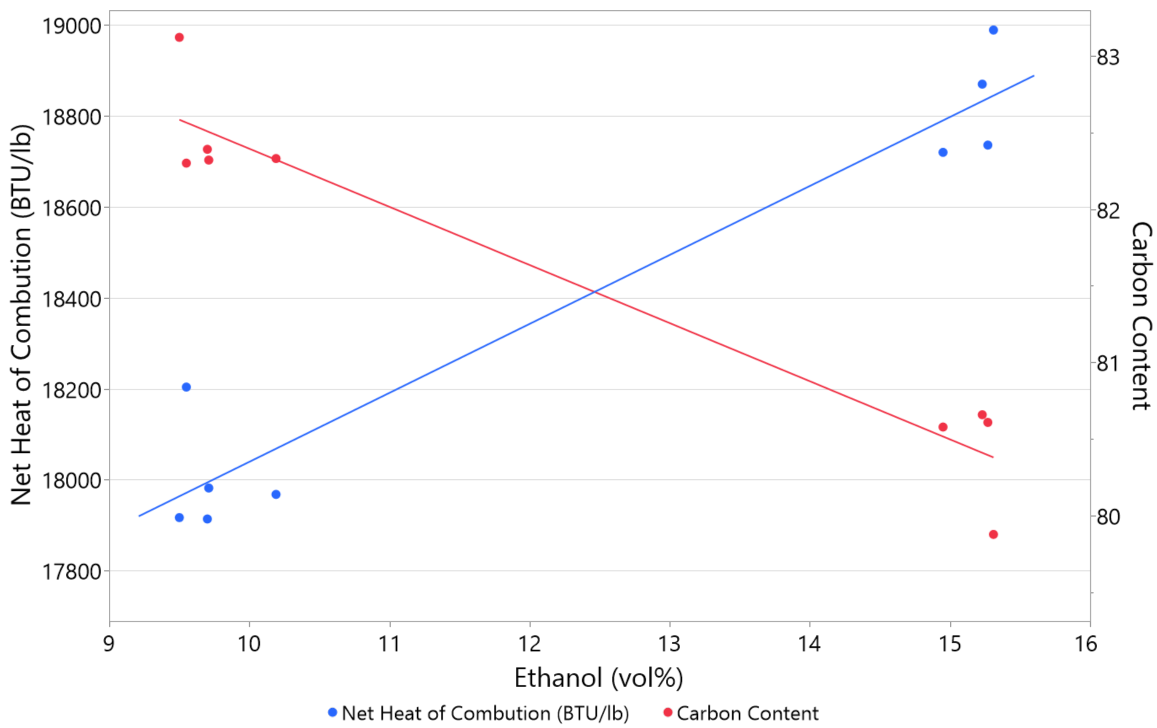


FIGURE 9. NET HEAT OF COMBUSTION AND CARBON CONTENT VS. ETHANOL CONTENT

The sections that follow provide details of the regression models. Section 4.1 describes the data transformations used and outlier removal process. Section 4.2 provides individual results by emissions parameter, and finally, a summary of results is provided in Section 4.3.

4.1 Data Transformations and Outlier Removal

When assessing the statistical significance of the variables used in a regression model, it is required that the model residuals be normally distributed with a constant variance. Whenever the emissions variability is level-dependent, a transformation is required to satisfy this model assumption. To determine if a transformation was necessary, a Box-Cox analysis was used. The model used across all parameters for the Box-Cox analysis was

$$Y \sim \text{Vehicle-Fuel-Set}.$$

Since it was not of interest to determine predictor variable significance in this transformation exercise, this single predictor variable represents a concatenation of all factor differences tested. At each unique factor level, there were only two data points, allowing us to understand the best transformation to apply using repeated values across all emissions levels regardless of fuel property variable significance. The Box-Cox analysis method returns a function of sum of squared error (SSE) vs. various choices of lambda. The function is minimized at the optimal choice of lambda, and the transformation becomes the following:

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

An example of the PM model is shown below in Figure 10. Values below the red line in the plot are within a 95% confidence interval for the value of lambda. Therefore, it is common practice to choose well known choices of powers within the confidence limits as opposed to the exact optimal value. In the example shown, the cube root transformation was chosen ($\lambda = 0.33$) instead of the true function minimum at $\lambda = 0.292$. A summary of all transformations used is given in Table 9. In all cases, these transformations were the same as those used in CRC project E-122-2.

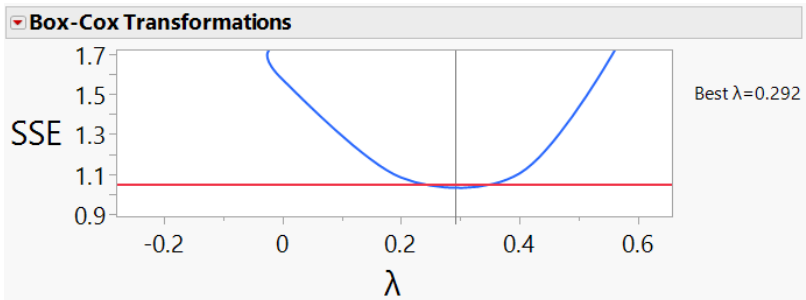


FIGURE 10. BOX-COX ANALYSIS FOR PARTICULATE MATTER

TABLE 9. TRANSFORMATION SUMMARY

Parameter	Transformation
PM	CubeRoot(PM)
NOx	Ln (NOx), Vehicle D separate
CO2	Ln (CO2)
THC	Ln (THC)
NMHC	Ln (NMHC)
CH4	Ln (CH4)

For NO_x , the variability was dependent not only on level, but also on vehicle, with Vehicle D exhibiting much higher variability than the other vehicles, even at similar NO_x levels. Therefore, Vehicle D was modeled separately from the other 3 vehicles. For all other parameters, homogeneity across factor levels was verified by visual inspection of model residuals, and these models considered all vehicles together.

The data was inspected for outliers using studentized residuals from the model used in the transformation analysis and the response variable using the selected transformation. Residuals represent the difference between the actual value and the model predicted value, and studentized residuals are divided by an estimate of the standard deviation. Therefore, a studentized residual may be thought of as the estimated number of standard deviations away from where the data point was predicted to be. Typical cut-offs range from ± 2 to ± 3 depending on the model and the project goals. In this case, ± 2.5 was chosen as the cut-off and values with residuals having an absolute value greater than the cutoff were deemed outliers. The starred values in Figure 11 are examples of two data points which were excluded from the analysis of CO. All parameters had only one or two data points removed as outliers, except for NO_x which had four, all from Vehicle D. Vehicle A had one outlier (for CO), Vehicle B had one outlier (for PM), Vehicle C had three outliers (for THC, NMHC, and CO), and Vehicle D had five outliers (one for PM and four for NO_x). The raw data plots showing all outliers removed can be found in Appendix F.

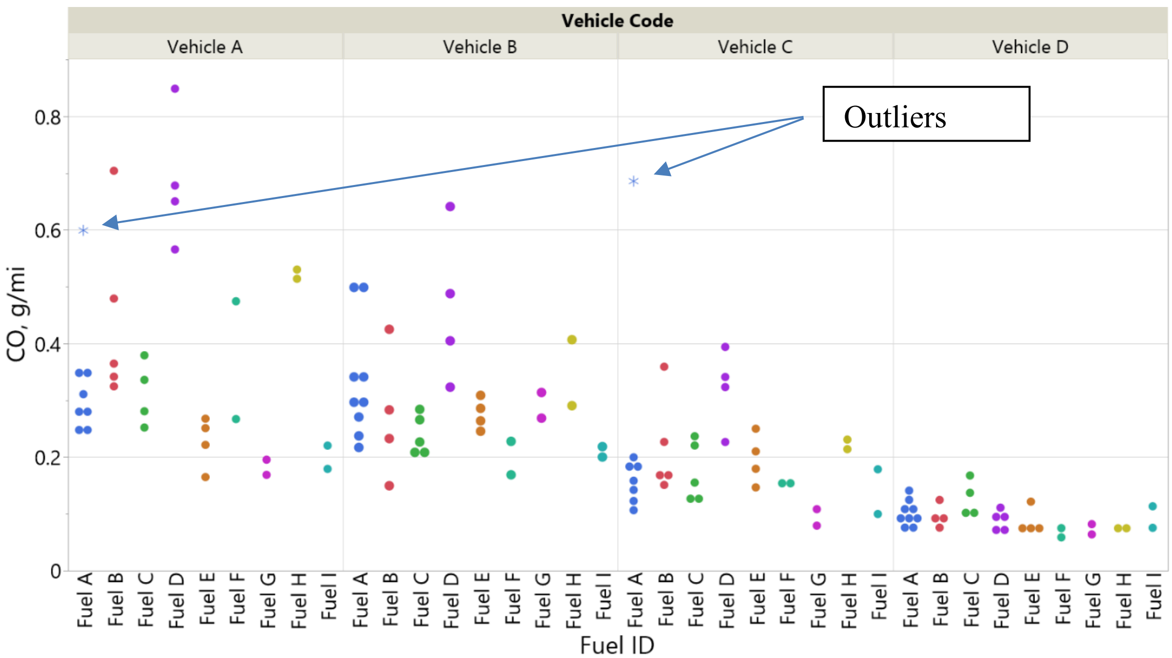


FIGURE 11. OUTLIER DATA POINTS FOR CO, G/MI

4.2 Regression Model Results by Parameter

Following data transformations and outlier removal, a regression model was built for each of the emissions results. The model included the categorical variable for vehicle, the continuous variables PMI, RVP, and ethanol content, along with all two-way interactions between these variables. The response variable was transformed using the selected transformation discussed previously in Section 4.1. A backwards variable selection technique was used which begins with all predictor variables in the model and removes the least significant predictor for each iteration. The model is re-run without the predictor, and the process repeats until only significant variables remain in the model. Variable significance is determined by looking at the p-value of the F-test for each effect in the Analysis of Variance (ANOVA) table. The outcomes of the models are given in the following sections.

4.2.1 PMI, RVP, and Ethanol as Predictors of PM

The output from the final PM model is shown in Table 10. The ANOVA results indicated that the fuel PMI variable is statistically significant but is vehicle dependent. The regression model coefficients and confidence intervals indicate the PMI variable is significant for Vehicles A, B, and C, but not for Vehicle D. Using the model coefficients, Table 11 below provides model predictions of changes in PM with a PMI increase of one. A representative baseline value is chosen for the examples based on observed PM levels on the lower PMI fuels in this data. A plot of the transformed PM vs. fuel PMI is shown in Figure 12.

TABLE 10. CUBE ROOT (PM) ~ VEHICLE + FUEL PMI + (VEHICLE * FUEL PMI)

Term	Estimate	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	0.505	19.96	0.00	0.46	0.56
Vehicle Code[Vehicle A]	-0.176	-13.09	0.00	-0.20	-0.15
Vehicle Code[Vehicle B]	0.640	47.06	0.00	0.61	0.67
Vehicle Code[Vehicle C]	-0.178	-13.35	0.00	-0.20	-0.15
Vehicle Code[Vehicle D]	-0.286	-21.24	0.00	-0.31	-0.26
Fuel PMI	0.151	9.08	0.00	0.12	0.18
(Fuel PMI-1.44487)*Vehicle Code[Vehicle A]	-0.021	-0.72	0.47	-0.08	0.04
(Fuel PMI-1.44487)*Vehicle Code[Vehicle B]	0.211	7.23	0.00	0.15	0.27
(Fuel PMI-1.44487)*Vehicle Code[Vehicle C]	-0.085	-2.96	0.00	-0.14	-0.03
(Fuel PMI-1.44487)*Vehicle Code[Vehicle D]	-0.104	-3.68	0.00	-0.16	-0.05

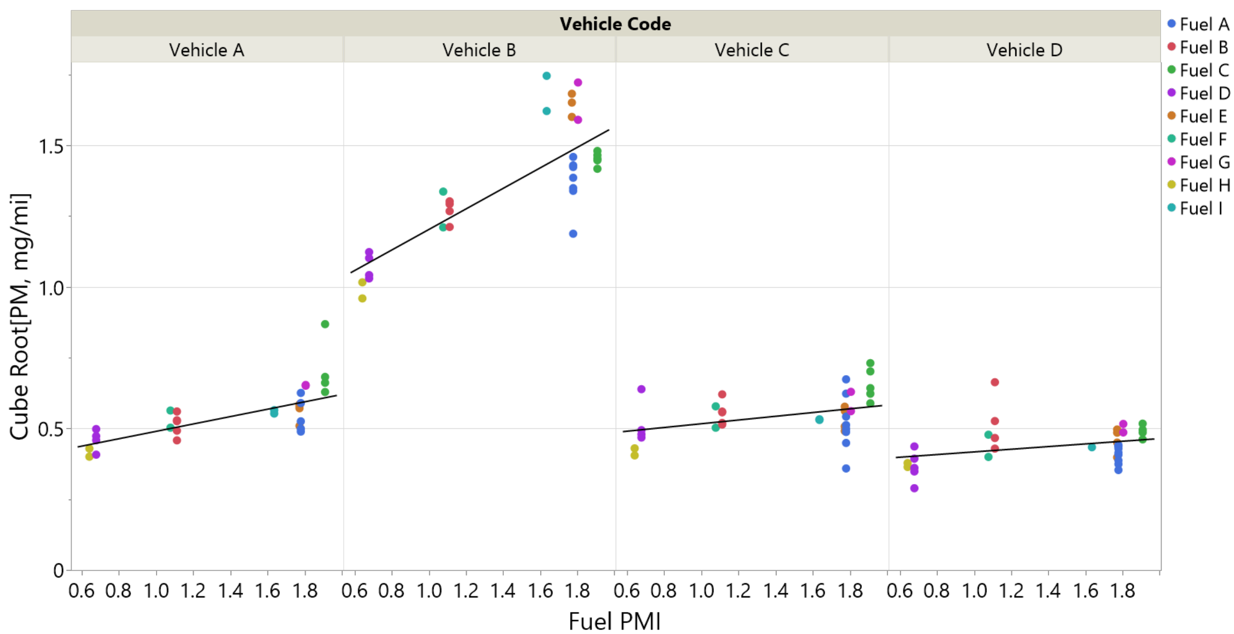


FIGURE 12. PLOT OF CUBE ROOT (PM, MG/MI) VS. FUEL PMI BY VEHICLE

TABLE 11. SIGNIFICANT FUEL VARIABLES AND PREDICTED CHANGES FOR PM

Parameter	Fuel PMI a Significant Predictor? (Vehicle)	Fuel RVP a Significant Predictor? (Vehicle)	Fuel Ethanol a Significant Predictor? (Vehicle)	Baseline Emissions for Comparison	Predicted Change with PMI Increase of 1 (% Change from Baseline)
PM (mg/mi)	Yes (Vehicles A, B, C)	No	No	A – 0.100 B – 1.300 C – 0.120	A – 0.210 (+110%) B – 3.070 (+136%) C – 0.175 (+46%)

4.2.2 PMI, RVP, and Ethanol as Predictors of NO_x

The variability in NO_x was much higher for Vehicle D than for the other three vehicles, both before and after the natural log transformation, and therefore Vehicle D data was modeled separately from the other vehicles. The output from the model for Vehicles A, B, and C indicated ethanol was a significant predictor for Vehicles A and C. The data indicated a very similar effect for these two vehicles, so the model was re-run without Vehicle B, and the interaction term vehicle*ethanol was no longer significant. The ethanol variable was also significant in the model for Vehicle D. However, for this vehicle, the plot of the data suggests that the significance of the ethanol term in the model is primarily driven by low NO_x on two of the E10 fuels, Fuel A and Fuel B. The effect is not consistent across all fuels, indicating that there are likely other key factors at play not considered here. The significance and magnitude of the ethanol variable coefficient for this vehicle should be considered cautiously. Table 12 and Table 13 give the model results. Using the model coefficients for the ethanol variables, Table 14 provides model predictions of changes in NO_x with a change in ethanol content from 10% to 15%. A representative baseline value is chosen for the examples based on observed NO_x levels in the data on the E10 fuels. A plot of transformed NO_x vs. ethanol content is shown in Figure 13.

TABLE 12. LN (NO_X) ~ VEHICLE + FUEL ETHANOL FOR VEHICLES A AND C

Term	Estimate	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-5.01	-36.5	0.00	-5.28	-4.74
Vehicle Code[Vehicle A]	-0.10	-3.54	0.00	-0.16	-0.04
Vehicle Code[Vehicle C]	0.101	3.54	0.00	0.04	0.16
Fuel Ethanol	0.032	2.65	0.01	0.01	0.06

TABLE 13. LN (NO_X) ~ FUEL ETHANOL FOR VEHICLE D

Parameter Estimates					
Term	**Estimate**	**t Ratio**	**Prob>|t|**	**Lower 95%**	**Upper 95%**
Intercept	-6.96	-11.3	0.00	-8.23	-5.70
Fuel Ethanol	0.157	2.91	0.01	0.05	0.27

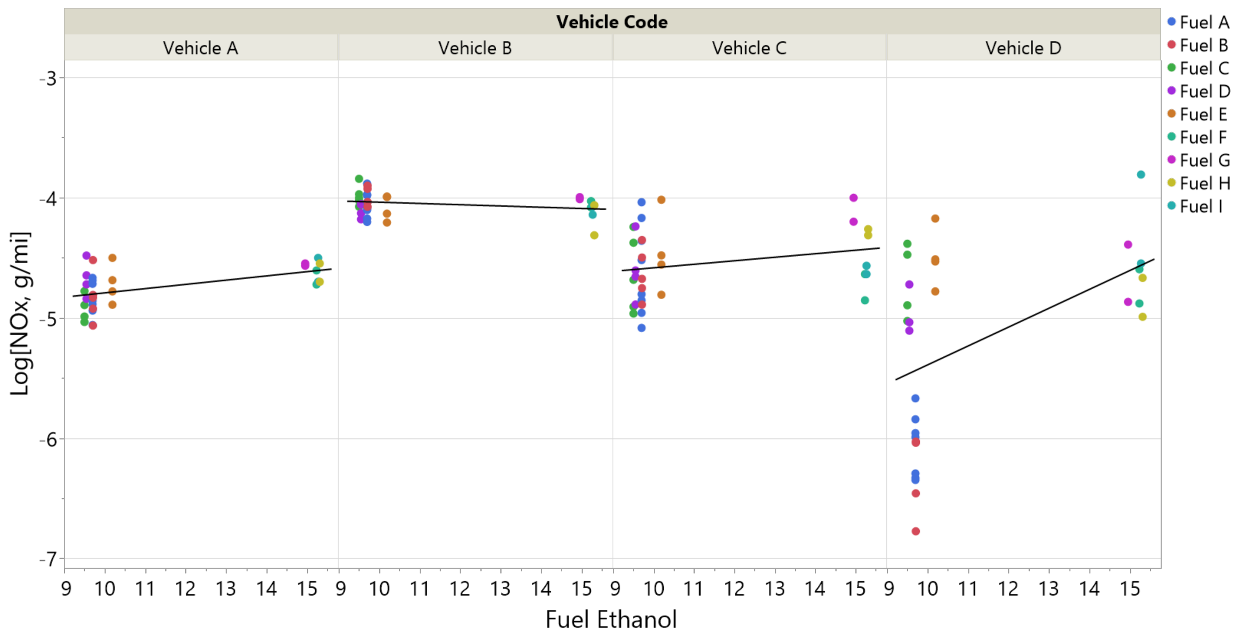


FIGURE 13. PLOT OF LN (NO_X) VS. FUEL ETHANOL BY VEHICLE

TABLE 14. SIGNIFICANT FUEL VARIABLES AND PREDICTED CHANGES FOR NO_X

Parameter	Fuel PMI a Significant Predictor? (Vehicle)	Fuel RVP a Significant Predictor? (Vehicle)	Fuel Ethanol a Significant Predictor? (Vehicle)	Baseline Emissions for Comparison	Predicted Change with Ethanol Volume Increase of 5% (% Change from Baseline)
NO_x (g/mi)	No	No	Yes (Vehicles A, C, D)	A/C – 0.0100 D – 0.0050	A/C – 0.0117 (+17%) D – 0.0110 (+120%)

4.2.3 PMI, RVP, and Ethanol as Predictors of CO_2

The output from the final CO_2 model is shown in Table 15. The PMI variable was determined to be statistically significant without any significant vehicle dependency. RVP was additionally significant, but only for Vehicle A. Based on the model coefficients, Table 16 provides model predictions of changes in CO_2 with a PMI increase of one for all vehicles and the predicted change in CO_2 with an RVP increase of 5 psi for Vehicle A. A representative baseline value is chosen for the examples based on observed performance level on the lower PMI fuels. Plots of Ln(CO_2) vs. fuel PMI and Ln(CO_2) vs. fuel RVP are shown in Figure 14 and Figure 15, respectively for Vehicles A, B, and C. Vehicle D vs. these same parameters is shown separately in Figure 16 due to the difference in CO_2 levels for this plug-in hybrid vehicle.

TABLE 15. LN (CO_2) ~ VEHICLE + FUEL PMI + FUEL RVP + (VEHICLE * FUEL RVP)

Term	Estimate	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	5.477	604.0	0.00	5.46	5.49
Vehicle Code[Vehicle A]	0.256	121.6	0.00	0.25	0.26
Vehicle Code[Vehicle B]	0.180	86.53	0.00	0.18	0.18
Vehicle Code[Vehicle C]	0.231	111.1	0.00	0.23	0.24
Vehicle Code[Vehicle D]	-0.67	-317	0.00	-0.67	-0.66
Fuel PMI	0.007	2.09	0.04	0.00	0.01
Fuel RVP	-0.00	-2.20	0.03	-0.00	-0.00
(Fuel RVP-10.6452)*Vehicle Code[Vehicle A]	-0.00	-2.62	0.01	-0.00	-0.00
(Fuel RVP-10.6452)*Vehicle Code[Vehicle B]	0.001	1.04	0.30	-0.00	0.00
(Fuel RVP-10.6452)*Vehicle Code[Vehicle C]	0.001	0.84	0.40	-0.00	0.00
(Fuel RVP-10.6452)*Vehicle Code[Vehicle D]	0.001	0.75	0.46	-0.00	0.00

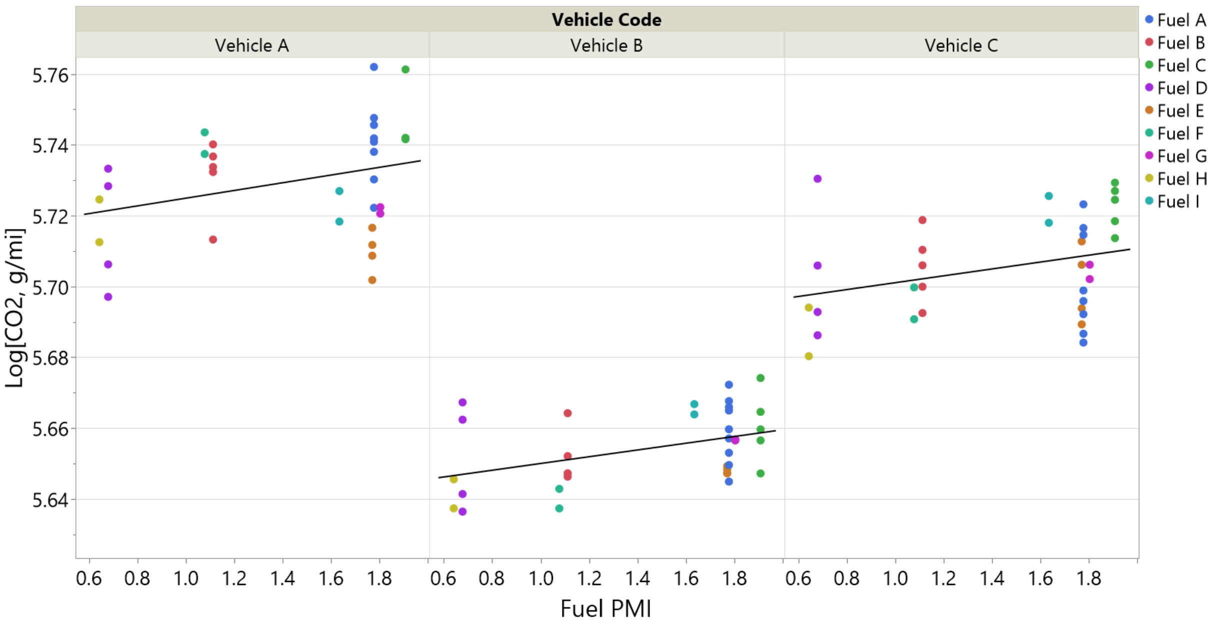


FIGURE 14. PLOT OF LN (CO_2) VS. FUEL PMI FOR VEHICLES A, B, C

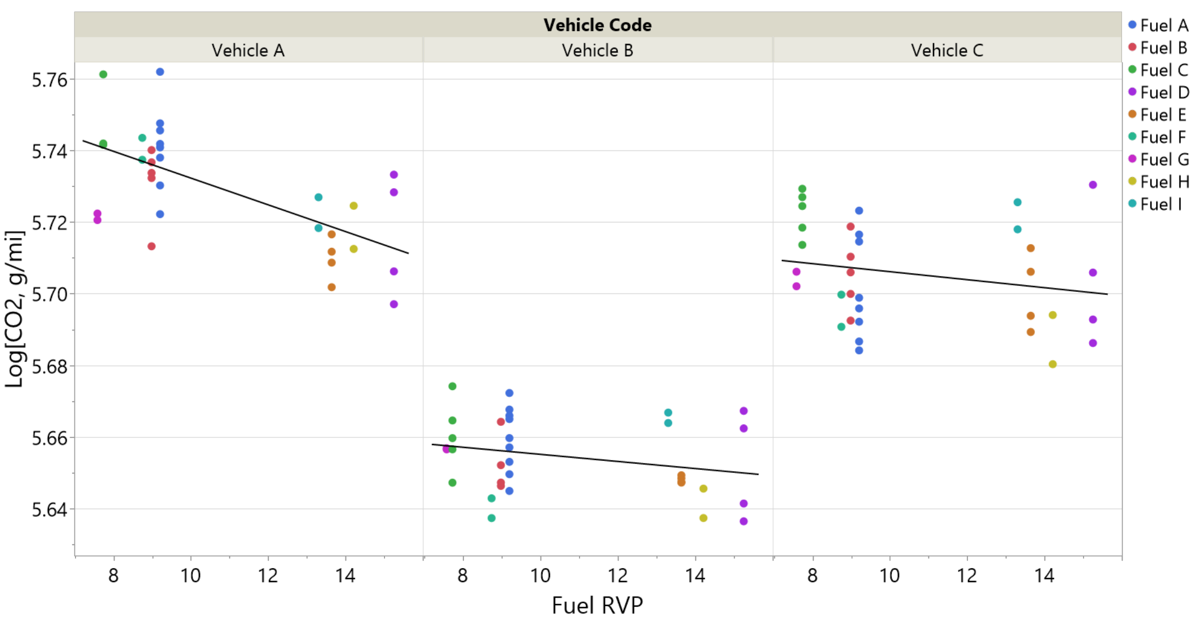


FIGURE 15. PLOT OF LN (CO_2) VS. FUEL RVP FOR VEHICLES A, B, C

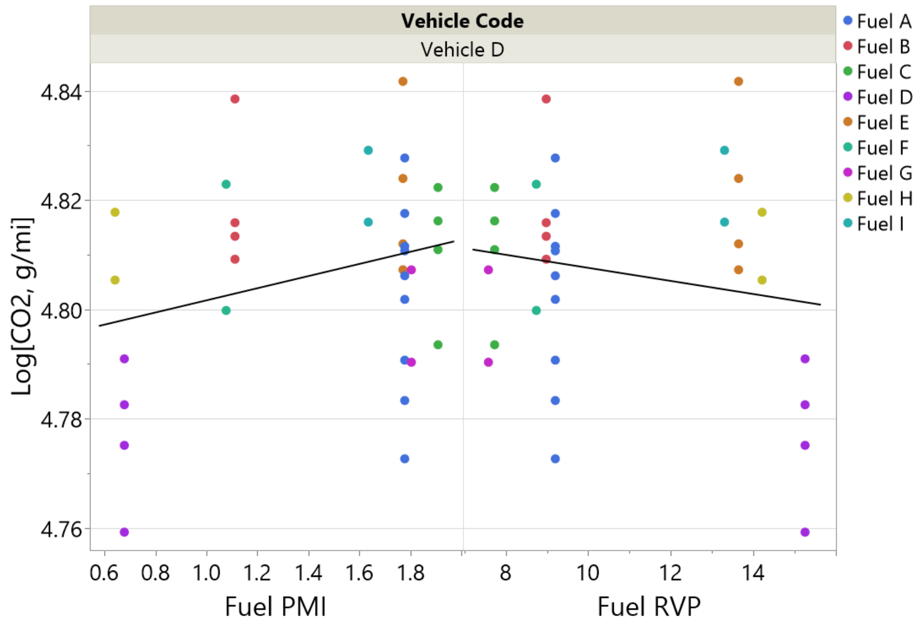


FIGURE 16. PLOT OF LN (CO_2) VS. FUEL PMI AND FUEL RVP FOR VEHICLE D

TABLE 16. SIGNIFICANT FUEL VARIABLES AND PREDICTED CHANGES FOR CO_2

Parameter	Fuel PMI a Significant Predictor? (Vehicle)	Fuel RVP a Significant Predictor? (Vehicle)	Fuel Ethanol a Significant Predictor? (Vehicle)	Baseline Emissions for Comparison	Predicted Change with PMI Increase of 1 (% Change from Baseline)	Predicted Change with RVP Increase of 5 psi (% Change from Baseline)
CO_2 (g/mi)	Yes, (Vehicles A,B,C,D)	Yes (Vehicle A)	No	A/B/C – 300.0 D - 120.0	A/B/C – 302.0(+0.67%) D – 120.8 (+0.67%)	A – 295.3 (-1.57%)

4.2.4 PMI, RVP, and Ethanol as Predictors of THC and NMHC

The output from the THC regression model is shown below in Table 17. To avoid redundancy, the NMHC data is excluded here due to the high correlation between the two parameters ($R^2 = 0.97$). However, the NMHC data can be found in Appendix F. The PMI variable was determined to be statistically significant, but the ANOVA model indicated that the interaction term was statistically significant. Based on the regression coefficients and confidence intervals, the PMI variable is statistically significant for Vehicles A and C. Using the model coefficients, Table 18 below provides model predictions of changes in THC and NMHC with a PMI increase of one for these two vehicles. A representative baseline value is chosen for the examples based on observed performance level on the lower PMI fuels. A plot of THC vs. fuel PMI is shown in Figure 17.

TABLE 17. LN (THC) ~ VEHICLE + FUEL PMI + (VEHICLE * FUEL PMI)

Term	Estimate	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-4.28	-63.7	0.00	-4.41	-4.14
Vehicle Code[Vehicle A]	0.388	9.99	0.00	0.31	0.46
Vehicle Code[Vehicle B]	0.320	8.26	0.00	0.24	0.40
Vehicle Code[Vehicle C]	-0.50	-13.8	0.00	-0.58	-0.43
Vehicle Code[Vehicle D]	-0.20	-5.42	0.00	-0.28	-0.13
Fuel PMI	-0.32	-6.95	0.00	-0.41	-0.23
(Fuel PMI-1.39913)*Vehicle Code[Vehicle A]	-0.08	-1.00	0.32	-0.24	0.08
(Fuel PMI-1.39913)*Vehicle Code[Vehicle B]	0.201	2.52	0.01	0.04	0.36
(Fuel PMI-1.39913)*Vehicle Code[Vehicle C]	-0.35	-4.47	0.00	-0.50	-0.19
(Fuel PMI-1.39913)*Vehicle Code[Vehicle D]	0.225	2.93	0.00	0.07	0.38

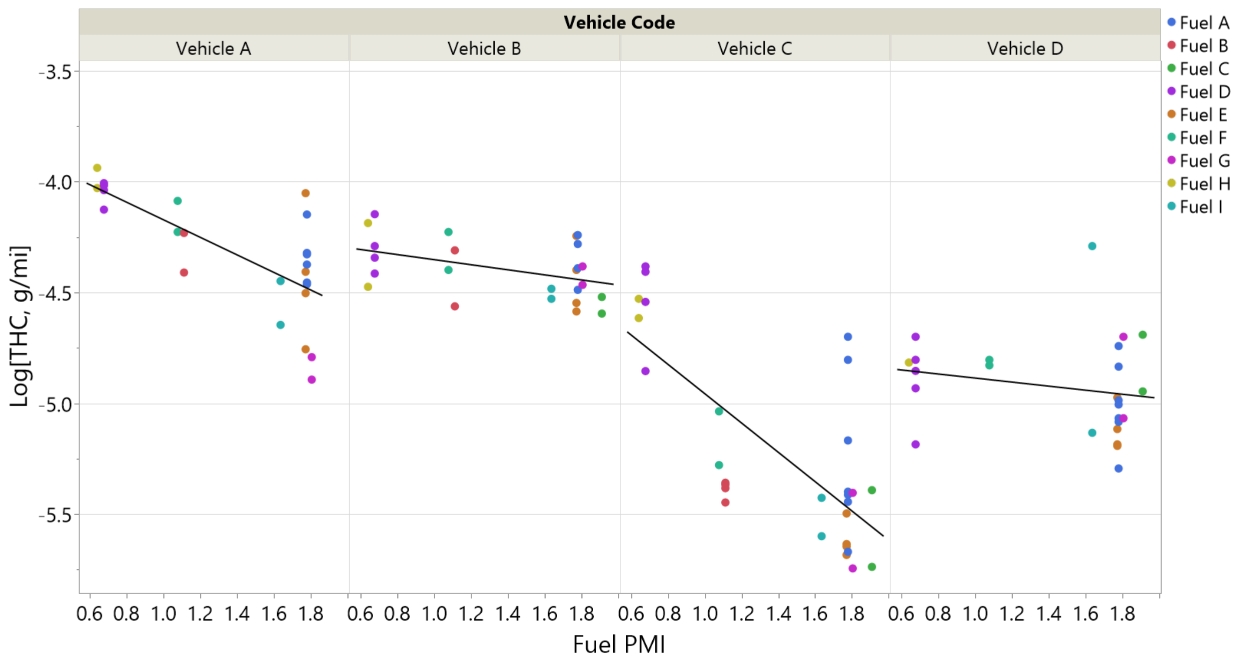


FIGURE 17. PLOT OF LN (THC) VS. FUEL PMI BY VEHICLE

TABLE 18. SIGNIFICANT FUEL VARIABLES AND PREDICTED CHANGES FOR THC AND NMHC

Parameter	Fuel PMI a Significant Predictor? (Vehicle)	Fuel RVP a Significant Predictor? (Vehicle)	Fuel Ethanol a Significant Predictor? (Vehicle)	Baseline Emissions for Comparison	Predicted Change with PMI Increase of 1 (% Change from Baseline)
THC (g/mi)	Yes (Vehicles A, C)	No	No	A – 0.0150 C – 0.0075	A – 0.0101 (-33%) C – 0.0039 (-48%)
NMHC (g/mi)	Yes (Vehicles A, C)	No	No	A – 0.0150 C – 0.0075	A – 0.0098 (-35%) C – 0.0038 (-49%)

4.2.5 PMI, RVP, and Ethanol as Predictors of CO

The output from the final CO model is shown in Table 19. The ANOVA results indicated that PMI, RVP, and Ethanol variables were all statistically significant. For PMI and RVP, however, the significance was vehicle dependent. The regression model coefficients and confidence intervals indicate the PMI variable is only significant for Vehicles A and C, while the RVP effect is only significant for Vehicles B and C. Using the model coefficients, Table 20 provides model predictions of changes in CO with changes in these three fuel properties. A representative baseline value is chosen for the examples based on observed CO levels on the lower PMI fuels in this data. A plot of the transformed CO vs. PMI, RVP, and ethanol content is shown in Figure 18, Figure 19, and Figure 20, respectively.

TABLE 19. LN (CO) ~ VEHICLE + FUEL PMI + FUEL RVP + FUEL ETHANOL + (VEHICLE * FUEL PMI) + (VEHICLE * FUEL RVP)

Term	Estimate	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-0.88	-3.86	0.00	-1.33	-0.43
Vehicle Code[Vehicle A]	0.507	11.96	0.00	0.42	0.59
Vehicle Code[Vehicle B]	0.394	9.46	0.00	0.31	0.48
Vehicle Code[Vehicle C]	-0.09	-2.38	0.02	-0.17	-0.02
Vehicle Code[Vehicle D]	-0.81	-19.8	0.00	-0.89	-0.73
Fuel PMI	-0.33	-5.45	0.00	-0.45	-0.21
Fuel RVP	0.021	2.12	0.04	0.00	0.04
Fuel Ethanol	-0.05	-5.01	0.00	-0.07	-0.03
(Fuel PMI-1.39541)*Vehicle Code[Vehicle A]	-0.59	-5.76	0.00	-0.79	-0.39
(Fuel PMI-1.39541)*Vehicle Code[Vehicle B]	0.189	1.85	0.07	-0.01	0.39
(Fuel PMI-1.39541)*Vehicle Code[Vehicle C]	-0.02	-0.22	0.82	-0.22	0.17
(Fuel PMI-1.39541)*Vehicle Code[Vehicle D]	0.422	3.99	0.00	0.21	0.63
(Fuel RVP-11.3525)*Vehicle Code[Vehicle A]	-0.03	-1.90	0.06	-0.07	0.00
(Fuel RVP-11.3525)*Vehicle Code[Vehicle B]	0.016	0.94	0.35	-0.02	0.05
(Fuel RVP-11.3525)*Vehicle Code[Vehicle C]	0.036	2.17	0.03	0.00	0.07
(Fuel RVP-11.3525)*Vehicle Code[Vehicle D]	-0.02	-1.03	0.31	-0.05	0.02

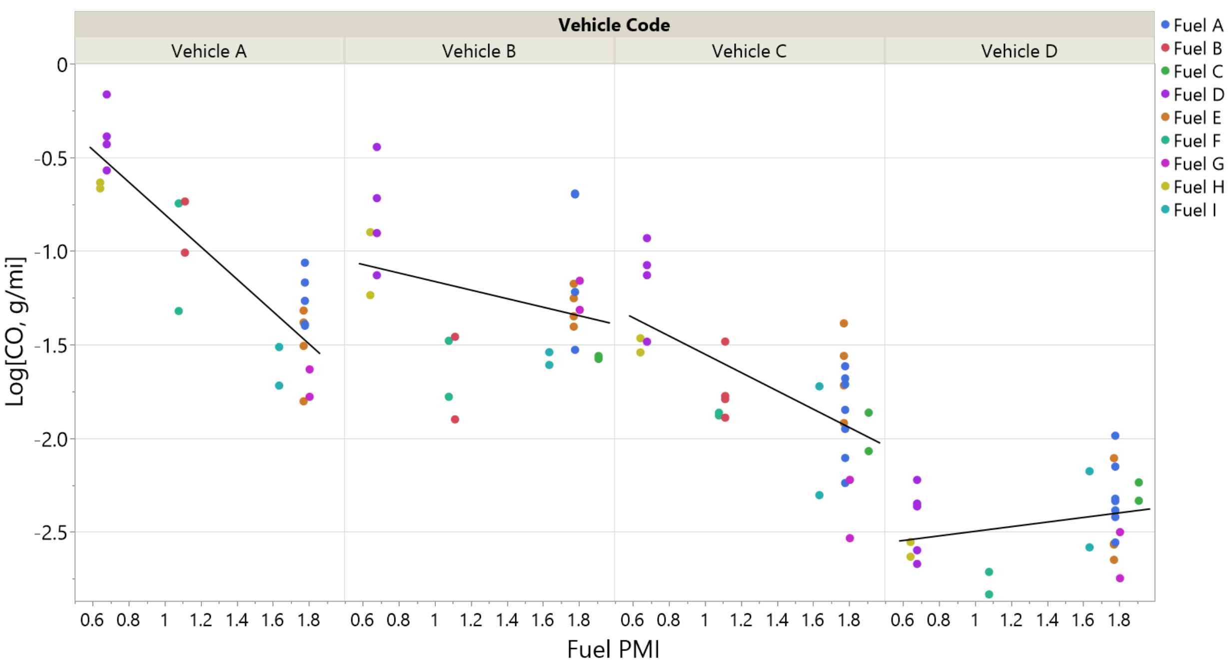


FIGURE 18. PLOT OF LN (CO) VS. FUEL PMI BY VEHICLE

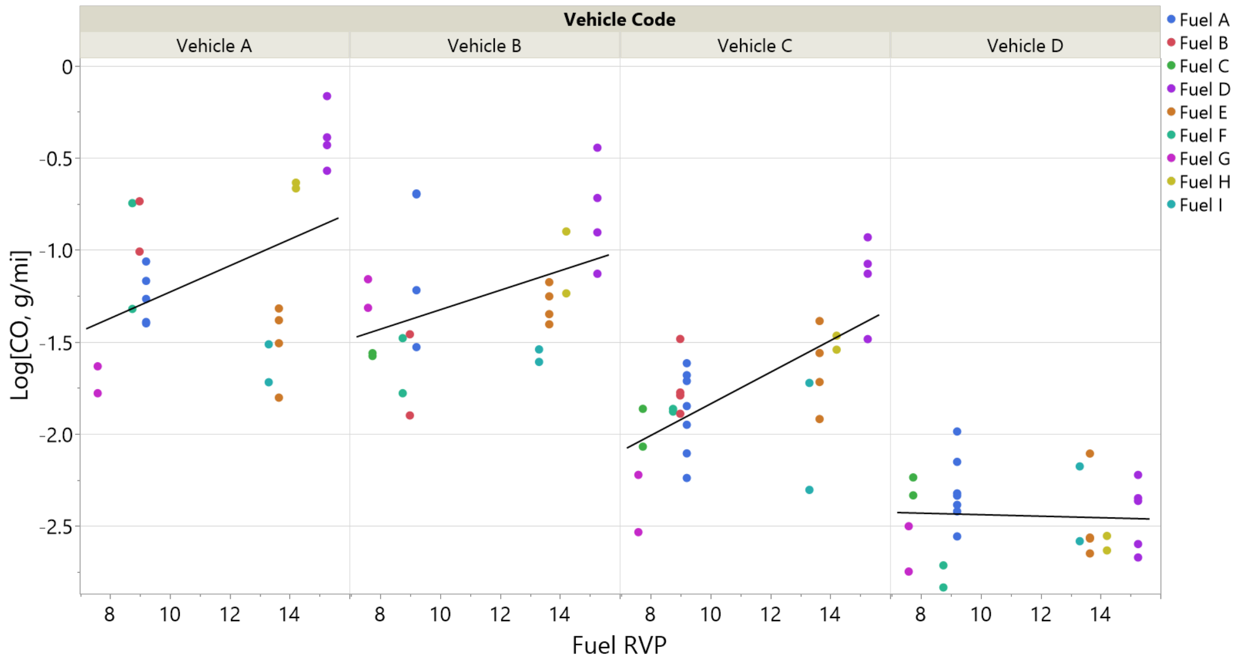


FIGURE 19. PLOT OF LN (CO) VS. FUEL RVP BY VEHICLE

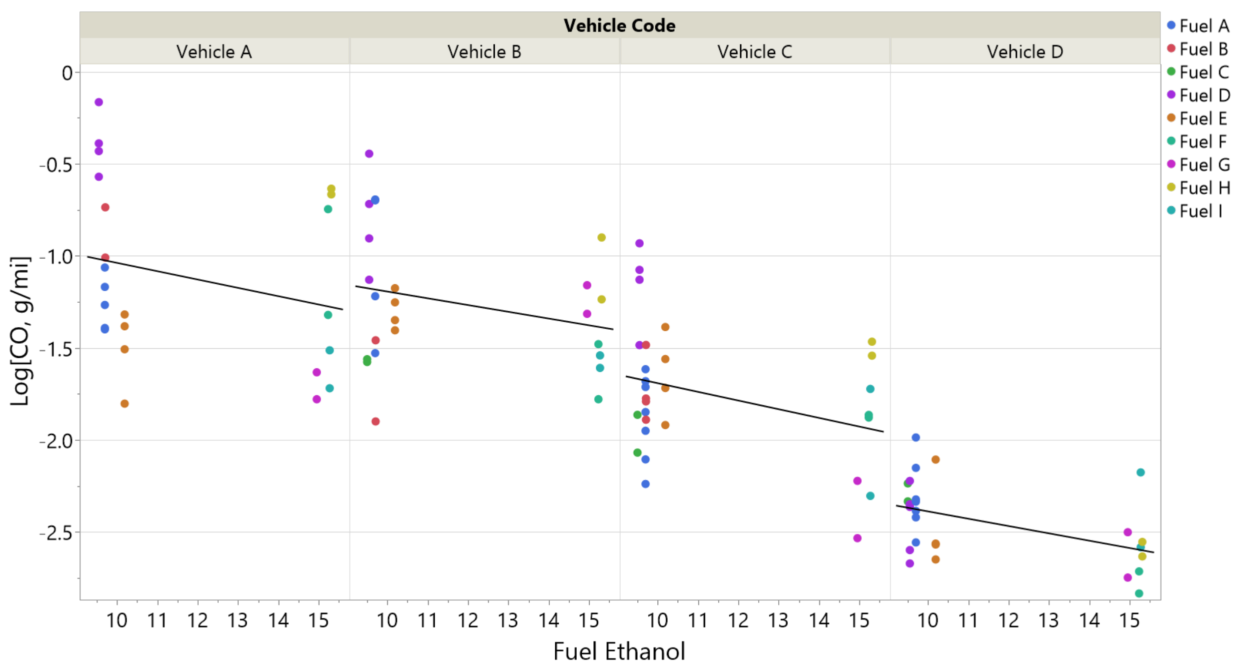


FIGURE 20. PLOT OF LN (CO) VS. FUEL ETHANOL BY VEHICLE

TABLE 20. SIGNIFICANT FUEL VARIABLES AND PREDICTED CHANGES FOR CO

Parameter	Fuel PMI a Significant Predictor? (Vehicle)	Fuel RVP a Significant Predictor? (Vehicle)	Fuel Ethanol a Significant Predictor? (Vehicle)	Baseline Emissions for Comparison	Predicted Change with PMI Increase of 1 (% Change from Baseline)	Predicted Change with RVP Increase of 5 psi (% Change from Baseline)	Predicted Change with Ethanol Volume Increase of 5% (% Change from Baseline)
CO (g/mi)	Yes (Vehicles A, C)	Yes (Vehicles B, C)	Yes (Vehicles A,B,C,D)	A – 0.400 B – 0.300 C – 0.200 D – 0.100	A – 0.160 (-60%) C – 0.141 (-30%)	B – 0.362 (+21%) C – 0.266 (+33%)	A – 0.315 (-21%) B – 0.236 (-21%) C – 0.157 (-21%) D – 0.079 (-21%)

4.3 Regression Models Summary

All parameters studied (PMI, RVP and Ethanol) indicated statistical significance for at least one of the three fuel properties studied. In most cases the effect was vehicle dependent, meaning the fuel property was a significant predictor for only a subset of the vehicles. PMI was the fuel property most commonly significant in the models, significant for all parameters studied except for NO_x, while RVP and ethanol content were deemed significant for two parameters each. As for the primary purpose of determining the ethanol content significance on emissions, the ethanol variable was deemed a significant predictor of NO_x for the three Tier 3 PFI vehicles, but not the Tier 2 DI vehicle (Vehicle B). The E15 fuels predicted to have higher NO_x by 17% for Vehicles A and C and 120% for Vehicle D. However, the latter was a plug-in hybrid vehicle which experienced much higher variability in NO_x emissions compared to the other vehicles, and only had lower NO_x on two out of five E10 fuels, driving the significance of the model coefficient. Results for Vehicle D NO_x should be interpreted cautiously and may have been influenced by small variations in crank timing and duration of engine operation. Higher ethanol content was also deemed to be a statistically significant predictor of CO for all vehicles, with the E15 fuels predicted to have 21% lower CO than the E10 fuels. The full list of conclusions, including those pertaining to PMI and RVP, is summarized by parameter below in Table 21. In the table, examples are given to show the magnitude of the predicted emission changes across the range of the PMI, RVP, and ethanol values for the fuels tested. Effects are level dependent in most cases, so baseline values for comparison are chosen based on representative levels seen in data.

TABLE 21. FUEL PROPERTY SIGNIFICANCE SUMMARY AND PREDICTED CHANGES IN EMISSIONS

Parameter	Fuel PMI a Significant Predictor? (Vehicle)	Fuel RVP a Significant Predictor? (Vehicle)	Fuel Ethanol a Significant Predictor? (Vehicle)	Baseline Emissions for Comparison	Predicted Change with PMI Increase of 1 (% Change from Baseline)	Predicted Change with RVP Increase of 5 psi (% Change from Baseline)	Predicted Change with Ethanol Volume Increase of 5% (% Change from Baseline)
PM (mg/mi)	Yes (Vehicles A, B, C)	No	No	A – 0.100 B – 1.300 C – 0.120	A – 0.210 (+110%) B – 3.070 (+136%) C – 0.175 (+46%)	-	-
NO_x (g/mi)	No	No	Yes (Vehicles A, C, D)	A/C – 0.0100 D – 0.0050	-	-	A/C – 0.0117 (+17%) D – 0.0110 (+120%)
CO_2 (g/mi)	Yes (Vehicles A,B,C,D)	Yes (Vehicle A)	No	A/B/C – 300.0 D - 120.0	A/B/C – 302.0 (+0.67%) D – 120.8 (+0.67%)	A – 295.3 (-1.57%)	-
THC (g/mi)	Yes (Vehicles A, C)	No	No	A – 0.0150 C – 0.0075	A – 0.0101 (-33%) C – 0.0039 (-48%)	-	-
NMHC (g/mi)	Yes (Vehicles A, C)	No	No	A – 0.0150 C – 0.0075	A – 0.0098 (-35%) C – 0.0038 (-49%)	-	-
CO (g/mi)	Yes (Vehicles A, C)	Yes (Vehicles B, C)	Yes (Vehicles A,B,C,D)	A – 0.400 B – 0.300 C – 0.200 D – 0.100	A – 0.160 (-60%) C – 0.141 (-30%)	B – 0.362 (+21%) C – 0.266 (+33%)	A – 0.315 (-21%) B – 0.236 (-21%) C – 0.157 (-21%) D – 0.079 (-21%)

5.0 NEXT STEPS

This report covers PEMS testing in mild ambient conditions. As suggested in the final report for CRC Project E-122-2, to fully understand the ability of a PEMS to measure emissions in all real-world conditions, additional testing would be required. Below is a list of possible conditions that could be encountered if tests were conducted in different climates and locations.

- Ambient temperatures above 49°C (Death Valley, CA) and below -7°C (Denver, CO)
- Barometric pressures below 85 kPa (Denver, CO)
- Road grades above 6 % (Raton Pass, NM)

APPENDIX A

E15 Fuel Blending and Ethanol Analysis

Five 55-gallon drums of commercially available, fuel-grade denatured ethanol were purchased with the request that the ethanol in these drums originate from the same bulk tank prior to filling. Once the drums of ethanol were received, a sample from one was obtained for analyses according to ASTM D 4806-20, excluding Silicon (ASTM D7757), and the analyses results are listed in the following table.

Denatured Ethanol Analyses According to ASTM D4806-20 excluding silicon D7757*

			Fuel Code	GA-11024
			Location	Drums
			Date	1/12/2021
			Sample Location	Drum 3 of 5
			Source	Suncoast
	D4806-14 Specifications		**Laboratory Code**	FLRD-3910
Property	**Min**	**Max**	**Test Method**	**Result**
Acidity, mass %		0.007	ASTM D1613	0.0029
Copper by AA, ppm		0.1	ASTM D3237M **	<0.01
Solvent-washed Gum, mg /100 mL				
Unwashed wt			ASTM D381	2.5
Washed wt		5.0		0.5
API Gravity			ASTM D4052	46.98
Specific Gravity			ASTM D4052	0.7942
Density @ 15°C, g/L				792.5
Sulfur Content, mass ppm		10 (CARB)	ASTM D5453	2.96
Ethanol Content, wt%				97.11
EtOH, vol%	92.1			96.96
Methanol Content, wt%			ASTM D5501	0.03
MeOH, vol%		0.5		0.03
Water Content, mass %		1.26	ASTM D6304 ***	0.64042
pHe	6.5	9.0	ASTM D6423	7.79
Total Chloride, mass ppm		6		<1
Total Sulfate, mass ppm		4.0	ASTM D7319	<1
Potential Sulfate, ppm				<1

* SwRI confirmed with the supplier that all drums originated from the same tank and confirmed with the manufacturer that there should not be any silicon introduced during the manufacturing and packaging process

** D3237M was substituted for 1688

*** D6304 was substituted for E1064

Once accepted, the fuel-grade denatured ethanol was splash blended into each of the four E10 fuels to increase the ethanol concentration to 15 percent by volume. The total blend amount for each fuel was 220 gallons. A stainless-steel blending tote was used to mix the base fuel and denatured ethanol on a weight basis. Prior to each blend, the tote was flushed with a small portion of the base fuel.

The ethanol was then added to the base fuel in the tote. Mixing of the two components was conducted in the tote using an air-powered stirrer that ensures thorough mixing of the ethanol and base fuel. A sample from each blend was analyzed in duplicate for oxygenates (ASTM D5599) to verify the blends. Additionally, distillation (ASTM D86) and detailed hydrocarbon analysis (ASTM D6729) were also performed in addition to other analyses listed in APPENDIX B. One tote blend was prepared at a time until the four blends were completed. After analysis and approval, the blended fuels were transferred to new inspected epoxy-phenolic lined drums.

APPENDIX B

Fuel Analysis Results for Fuels F, G, H, and I

CRC E-133 Fuels

ASTM Method	Test Request	Test Units	Results	Results	Results	Results
		Fuel Description	Summer E15 Low PMI	Summer E15 High PMI	Winter E15 Low PMI	Winter E15 High PMI
		Fuel Name	Fuel F (splash blend of Fuel B)	Fuel G (splash blend of Fuel C)	Fuel H (splash blend of Fuel D)	Fuel I (splash blend of Fuel E)
		SwRI Fuel Code	CGB-11037	CGB-11039	CGB-11156	CGB-11149
		Fuel Blend Number	2021-005	2021-006	2021-031	2021-032
		Sample Location	Tote 08-030S	Tote 08-037S	Tote 08-038s	Tote 08-030s
		Sample Code	FLRD-3938/FLRD-3945/FLRD-4250	FLRD-3939/FLRD-3946/FLRD-4251	FLRD-4209 / FLRD-4213	FLRD-4190 / FLRD-4199
		Sample Dates	3/1/2021- 3/5/2021 - 11/02/21	3/3/2021 - 3/5/2021 - 11/02/21	9/27/01& 10/4/2021	9/7/2021 & 9/20/2021
D5191	Vapor Pressure (Mini Method)					
	RVP (EPA Equation)	psi	8.74	7.58	14.21	13.3
	DVPE (ASTM Equation)	psi	8.63	7.45	14.15	13.22
D4052	API Gravity	--	59.2	56.8	63.2	59.8
	Specific Gravity	--	0.7419	0.7514	0.7268	0.7396
	Density @ 15°C	g/mL	0.7417	0.7511	0.7265	0.7393
	Density @ 15°C	g/L	741.7	751.1	726.5	739.3
D5599	Oxygenates and Oxygen Content					
	Diisopropylether (DIPE)	vol%	<0.1	<0.1	<0.1	<0.1
	Ethyl tert-butylether (ETBE)	vol%	<0.1	<0.1	<0.1	<0.1
	Ethanol (EtOH)	vol%	15.23	14.95	15.31	15.27
	Ethanol (EtOH)	WT%	16.30	15.80	16.83	16.39
	Isobutanol (iBA)	vol%	<0.1	<0.1	<0.1	<0.1
	Isopropanol (iPA)	vol%	<0.1	<0.1	<0.1	<0.1
	Methanol (MeOH)	vol%	<0.1	<0.1	<0.1	<0.1
	Methyl tert-butylether (MTBE)	vol%	<0.1	<0.1	<0.1	<0.1
	n-Butanol (nBA)	vol%	<0.1	<0.1	<0.1	<0.1
	n-Propanol (nPA)	vol%	<0.1	<0.1	<0.1	<0.1
	sec-Butanol (sBA)	vol%	<0.1	<0.1	<0.1	<0.1
	tert-amyl methylether (TAME)	vol%	<0.1	<0.1	<0.1	<0.1
	tert-Butanol (tBA)	vol%	<0.1	<0.1	<0.1	<0.1
	tert-Pentanol (tPA)	vol%	<0.1	<0.1	<0.1	<0.1
	Total Oxygen	WT%	5.66	5.48	5.84	5.69
D5599	Oxygenates and Oxygen Content					
duplicate	Diisopropylether (DIPE)	vol%	<0.1	<0.1	<0.1	<0.1
	Ethyl tert-butylether (ETBE)	vol%	<0.1	<0.1	<0.1	<0.1
	Ethanol (EtOH)	vol%	14.81	15.09	15.14	15.31
	Ethanol (EtOH)	WT%	15.85	15.94	16.53	16.39
	Isobutanol (iBA)	vol%	<0.1	<0.1	<0.1	<0.1
	Isopropanol (iPA)	vol%	<0.1	<0.1	<0.1	<0.1
	Methanol (MeOH)	vol%	<0.1	<0.1	<0.1	<0.1
	Methyl tert-butylether (MTBE)	vol%	<0.1	<0.1	<0.1	<0.1
	n-Butanol (nBA)	vol%	<0.1	<0.1	<0.1	<0.1
	n-Propanol (nPA)	vol%	<0.1	<0.1	<0.1	<0.1

	sec-Butanol (sBA)	vol%	<0.1	<0.1	<0.1	<0.1
	tert-amyl methylether (TAME)	vol%	<0.1	<0.1	<0.1	<0.1
	tert-Butanol (tBA)	vol%	<0.1	<0.1	<0.1	<0.1
	tert-Pentanol (tPA)	vol%	<0.1	<0.1	<0.1	<0.1
	Total Oxygen	WT%	5.5	5.53	5.74	5.69
D240	Heat of Combustion					
	GROSS	BTU/lb	18870	18720	18989	18736
	GROSS	MJ/kg	43.89	43.543	44.168	43.579
	GROSS	cal/g	10483	10400	10549.4	10408.6
D240	Heat of Combustion					
	NET	BTU/lb	17596	17492	17705	17484
	NET	MJ/kg	40.929	40.685	41.182	40.667
	NET	cal/g	9775.8	9717.5	9836.1	9713.1
D2622	Sulfur by X-ray	wt%	8.5	8.0	10.9	5.3
D2699	Research Octane Number (RON)	--	94.3	93.8	94.7	99.7
D2700	Motor Octane Number (MON)	--	84.7	84.4	84.0	88.7
	R+M/2	--	89.5	89.1	89.4	94.2
D5291	Carbon Content	wt%	80.66	80.58	79.88	80.61
	Hydrogen Content	wt%	13.95	13.46	14.08	13.72
D6729	DHA Analysis	--	Complete	Complete	Complete	Complete
PMI	Particulate Matter Index	--	1.0769	1.8040	0.6408	1.6348
D86	Distillation					
	IBP	Deg. F	95	101	80	80
	5%	Deg. F	123	126	94	99
	10%	Deg. F	132	133	106	109
	15%	Deg. F	139	137	115	117
	20%	Deg. F	144	141	123	125
	30%	Deg. F	152	149	138	142
	40%	Deg. F	157	156	149	156
	50%	Deg. F	161	161	156	164
	60%	Deg. F	217	213	161	195
	70%	Deg. F	242	256	215	261
	80%	Deg. F	269	290	245	292
	90%	Deg. F	305	325	280	329
	95%	Deg. F	330	348	306	352
	FBP	Deg. F	373	395	344	396
	Recovered	mL	98.4	98.3	96.3	97.8
	Residue	mL	0.7	0.8	0.9	1.0
	Loss	mL	0.9	0.9	2.8	1.2

APPENDIX C

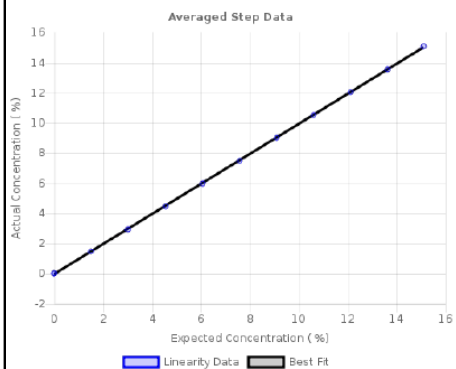
INITIAL PEMS CALIBRATION RESULTS

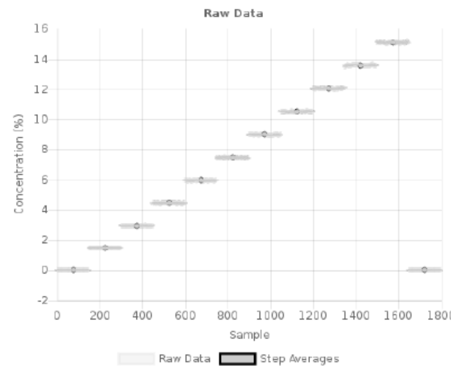
Linearity Certificate

Cert. No.	
Test Date	26 AUG 2020
Expiration Date	30 SEP 2020

Test Information	
Analyzer	CO/CO2 Analyzer
Analyzer Serial	511092
Enclosure Serial	A19512184
Gas Species	CO_2
Regulation	US Regulation 1065
Gas Divider Model	
Gas Divider Serial	
Bottle Conc.	15.139(%)
Bottle Name	SX025970
Bottle Serial	SX025970

	Value	Criteria	Result
Slope	1	$0.99 \le m \le 1.01$	Pass
Intercept	-0.305	$\lvert b \rvert \le 1.000\%$	Pass
SEE	0.271	SEE ≤ 1.000%	Pass
R^2	1	$R^2 \ge 0.998$	Pass
Overall			**Pass**





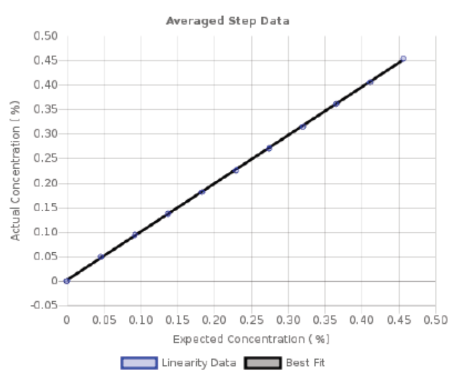
This document certifies that the PEMS listed below meets the linearization requirements listed in Table 1 of CFR40 Part 1065.307. Linearization testing was performed using procedures specified in CFR40 Part 1065.307 with gas standards traceable to the National Institute of Standards (NIST). The PEMS listed below is in compliance with EPA regulations provided that emissions testing is performed within 35 days from the test date listed on this document.

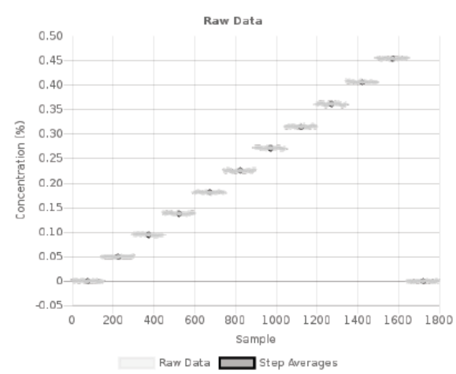
Linearity Certificate

Cert. No.	
Test Date	26 AUG 2020
Expiration Date	30 SEP 2020

Test Information	
Analyzer	CO/CO2 Analyzer
Analyzer Serial	511092
Enclosure Serial	A19512184
Gas Species	CO
Regulation	US Regulation 1065
Gas Divider Model	
Gas Divider Serial	
Bottle Conc.	0.4569(%)
Bottle Name	SX025970
Bottle Serial	SX025970

	Value	Criteria	Result
Slope	0.99	$0.99 \le m \le 1.01$	Pass
Intercept	0.22	$\lvert b \rvert \le 1.000\%$	Pass
SEE	0.441	SEE ≤ 1.000%	Pass
R^2	1	$R^2 \ge 0.998$	Pass
Overall			**Pass**





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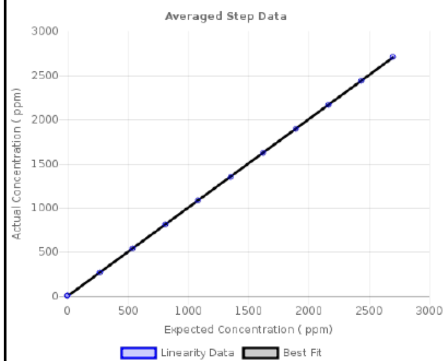
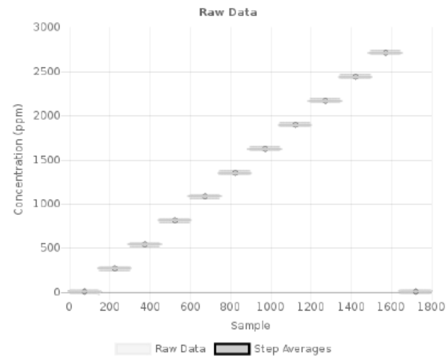
Linearity Certificate

Cert. No.	
Test Date	26 AUG 2020
Expiration Date	30 SEP 2020

Test Information	
Analyzer	NO/NO2 Analyzer
Analyzer Serial	511474
Enclosure Serial	A19512184
Gas Species	NO
Regulation	US Regulation 1065
Gas Divider Model	
Gas Divider Serial	
Bottle Conc.	2705(ppm)
Bottle Name	SX025970
Bottle Serial	SX025970

	Value	Criteria	Result
Slope	1	0.99 ≤ m ≤ 1.01	Pass
Intercept	0.006	|b| ≤ 1.000%	Pass
SEE	0.076	SEE ≤ 1.000%	Pass
R^2	1	$R^2 \geq 0.998$	Pass
Overall			**Pass**





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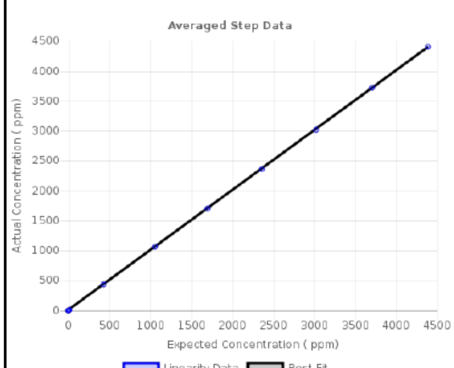
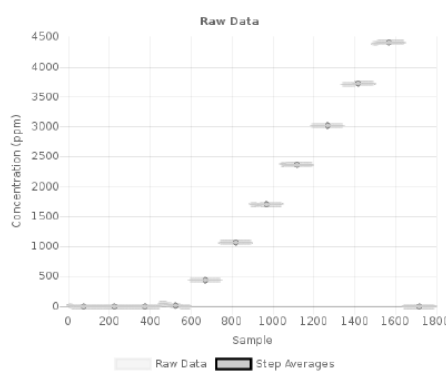
Linearity Certificate

Cert. No.	
Test Date	26 AUG 2020
Expiration Date	30 SEP 2020

Test Information	
Analyzer	FID Analyzer
Analyzer Serial	0
Enclosure Serial	G18509179
Gas Species	THC
Regulation	US Regulation 1065
Gas Divider Model	
Gas Divider Serial	
Bottle Conc.	4398(ppm)
Bottle Name	SX025970
Bottle Serial	SX025970

	Value	Criteria	Result
Slope	1	0.99 ≤ m ≤ 1.01	Pass
Intercept	0.036	|b| ≤ 1.000%	Pass
SEE	0.107	SEE ≤ 1.000%	Pass
R^2	1	$R^2 \geq 0.998$	Pass
Overall			**Pass**





This document certifies that the PEMS listed below meets the linearization requirements listed in Table 1 of CFR40 Part 1065.307. Linearization testing was performed using procedures specified in CFR40 Part 1065.307 with gas standards traceable to the National Institute of Standards (NIST). The PEMS listed below is in compliance with EPA regulations provided that emissions testing is performed within 35 days from the test date listed on this document.

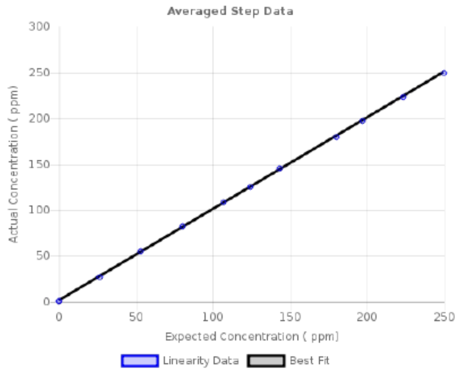
sensors

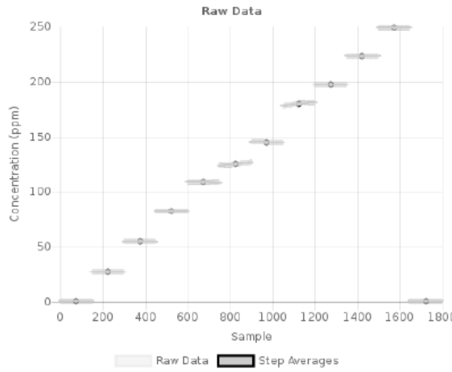
Linearity Certificate

Cert. No.	
Test Date	12 OCT 2020
Expiration Date	16 NOV 2020

Test Information	
Analyzer	NO/NO2 Analyzer
Analyzer Serial	511474
Enclosure Serial	A19512184
Gas Species	NO_2
Regulation	US Regulation 1065
Gas Divider Model	
Gas Divider Serial	
Bottle Conc.	249.8(ppm)
Bottle Name	SX88969
Bottle Serial	SX88969

	Value	Criteria	Result
Slope	1	$0.99 \leq m \leq 1.01$	Pass
Intercept	0.575	$\lvert b \rvert \leq 1.000\%$	Pass
SEE	0.377	SEE ≤ 1.000%	Pass
R^2	1	$R^2 \geq 0.998$	Pass
Overall			**Pass**





This document certifies that the PEMS listed below meets the linearization requirements listed in Table 1 of CFR40 Part 1065.307. Linearization testing was performed using procedures specified in CFR40 Part 1065.307 with gas standards traceable to the National Institute of Standards (NIST). The PEMS listed below is in compliance with EPA regulations provided that emissions testing is performed within 35 days from the test date listed on this document.

APPENDIX D

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 the "Catalyst Sulfur Purge Cycle" section of this appendix. Apply side fan cooling to the fuel tank to alleviate the heating effect of the exhaust system. Engine oil temperature in the sump will be measured and recorded during the sulfur removal cycle.
5. Perform four vehicle coast downs from 70 to 30 mph, with the last two measured. The vehicle will be checked for any obvious and gross source of change in the vehicle's mechanical friction if the individual run fails to meet the following repeatability criteria: 1) maximum difference of 0.5 seconds between back-to-back coastdown runs from 70 to 30 mph; and 2) maximum ±7 percent difference in average 70 to 30 mph coastdown time from the running average for a given vehicle.
6. Drain fuel and refill to 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 5 minutes (to bring catalyst to full working temperature).
2. Reduce vehicle speed to 30 mph and hold speed for one minute.
3. Accelerate at WOT (wide-open throttle) for a minimum of 5 seconds, to achieve a speed greater than 70 mph. Continue WOT above 70 mph, if necessary to achieve 5-second acceleration duration. Hold the peak speed for 15 seconds and then decelerate to 30 mph.
4. Maintain 30 mph for one minute.
5. Repeat steps 3 and 4 to achieve 5 WOT excursions.
6. One sulfur removal cycle has been completed.
7. Repeat steps 1 to 5 for the second sulfur removal cycle.
8. The protocol is complete if the necessary parameters have been achieved.

VEHICLE CONDITIONING

1. Move vehicle to test area without starting engine. Start vehicle and perform UDDS followed by two 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 prep cycles, allow vehicle to idle in park for two minutes, then shut-down the engine for 2-5 minutes. Following the last prep cycle, allow the vehicle to idle for two 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 E

STEP-BY-STEP CHECK LIST

Example of a Fuel Change Procedure

Vehicle ID:	**Vehicle A**
Procedure	**Fuel Drain and Fill**
Project:	**25980.01.005**
□	Record vehicle odometer ____________________.
	First Fuel Change
□	Drain fuel from vehicle using T on the fuel rail
□	Drain until fuel flow drops off. **DO NOT OVERDRAIN.**
□	Press start button twice and wait **30** seconds allowing fuel gauge level to stabilize.
□	Confirm fuel level reads zero. If gage does not read zero, use a scan tool to verify fuel level.
□	Press ignition key off.
□	**Verify SwRI Fuel Code: ADD FUEL CODE**
□	**Verify Fuel Tag on car is same as fuel code above**
□	Verify fuel fill drum matches using "2-person rule"
□	Initials: _________, _________
□	Verify fuel temperature: __________ < 50 degC
□	Fill tank with **7 Gallons** **If you empty a drum and start the last drum of that fuel in the cold box notify David Zamarripa or Michael Kader to get another drum sent over**
□	Record exact value from flow counter: __________
□	Start Vehicle and idle for 30 seconds
□	Technician's Signature: ____
□	Witness' Signature: ____

Example of Laboratory Procedure for Chassis Dynamometer Test

Fuel:	**xFuel**
Project:	**25980.01.005**
CVS Filter #	
	Filter naming format (VEH HDT C)
PEMS Filter #	
	Filter naming format (VEH HDT P)
Set	
Run #	
	E122 Dyno PEMS to be done at same time
	In Test Cell
☐	Install vehicle on chassis dyno with straps (Set Tension at 350 lbs)
☐	Open Hood.
☐	Fan: **Road Speed** in designated position
☐	Exhaust: RMT,HARDPIPE
☐	Connect Fan Temp (Mod5 Ai1)
☐	Record fuel gauge level________________
☐	Record vehicle odometer ____________________.
☐	Key-on and check DTCs.
☐	Record codes here: ____
	CDTCS
☐	Verify ambient temperature reading is between 20.0 and 24.4°C (68 to 72°F).
☐	Record ambient temperature:__________°C.
☐	Verify Absolute Humidity is reading between 8.8 and 10.2 gm H_2O / kg Dry Air.
☐	Record Absolute Humidity:__________ gm H_2O / kg Dry Air.
☐	Select "Run". Select "Test Schedule". Select "EmissionTest" And Run Test
☐	Select 'File'. Select 'Open Answer File'. Select file: Vehicle A_E122
☐	Select "ID/Preferences" and make correct entries.
☐	Select "Test Options".
☐	Select "Measure Emissions".
☐	Select "Bags".
☐	Select "Use COL".
☐	Post Cat : THC 5000, O2 25%, CO2 20%, CO 5%, Nox Auto, CH4 1000 ppm, NO 4000ppm
☐	Select "Clean" Bagline.
☐	Select Test Type: **CRC_E122**
☐	Turn on Dilution Heat.
☐	Select Shift Schedule
☐	Shift 1: **CRC_E122**
☐	Select "Do Cert Z/S/Z" in "Zero Span Options".
☐	Select CVS flow rates:
☐	Bag 1: **320**
☐	Select "Vehicle Data" and make correct entries.
☐	Select "Fuel Table"
☐	**Check Values against Fuel Table Page**
☐	Select 'File'. Select 'Save Answer File'. Select 'OK'. Select 'Overwrite' file: Vehicle A_E122
☐	Record Horiba Run No.__________.
☐	Select "File". Select "Run Test".
	Dyno RTM
☐	Select "Vehicle Database". Select: 'File Name' Box: Vehicle A
☐	Verify Coefficients
☐	Inertia: 4750 lbs.
☐	Set A: 11.62 lbs.
☐	Set B: 0.0765 lbs. /mph
☐	Set C: 0.01998 lbs./mph^2
☐	Select "Road Load Simulation".
☐	Select Grade "Analog Grade". **ON**
☐	Select "Set Up", select "Brake Assist", and select: **OFF**
☐	Enter test number in comment box on "Road Load Simulation" screen.
☐	Enter PL Record No.__________.

☐	Press F1 and Verify green dyno light in test cell is on.
	Confirm pendant start switch is set to "start"
	HDT
☐	From HDT home screen select "Edit Config"
☐	Select "Other Cell" tab press "LOAD" and select: Current OBD Reader
☐	Press "Make Current" and "SAVE".
☐	From HDT home screen select "Edit Config"
☐	Select "Other Project" tab press "LOAD" and select: Vehicle A
☐	Press "Make Current" and "SAVE".
☐	Under "Other Channel" tab press "LOAD" and select: Vehicle A_E122
☐	Press "Make Current" and "SAVE".
☐	In drop down menu, select "Transient" and press Run Test.
☐	Select: E122_HDT Command Cycle for both User Cycle and Command Cycle.
☐	Select AutoStart line goes LOW to HIGH
☐	Complete Test Info section with Test Number (Vehicle A**_xFUEL_E122D_Tx)** and Odometer. Type Playback in comment section for record keeping.
☐	Press Continue.
☐	Select "Use None" in the channel offset window.
☐	Record HDT Run Number: _______________________
☐	Press Start prior to starting prep
	PM Sampling
☐	Verify PM Propane Recovery is current and valid.
☐	Within 10 minutes of SOT, checkout 2 PP47mm filters from the filter room
☐	Record Filter numbers at top of work request
☐	Start Sample pump only (no dilution) on PM Cart and select AUTO button
☐	Sample Pump 2 flow = "1.5" setting on roots meter #2
	To Start Test
☐	Verify Co-Pilot has started recording
☐	Verify all vehicle accessories are off
☐	**Verify traction control is off. If not, perform the following:** **Press Steering wheel settings menu** **Navigate to Traction control** **Press OK**
☐	Start of Test: Push start then continue on pendent; Start vehicle and **press the green function button** on the in cab module.
☐	**Leave car in park until shift schedule indicates; hold brake until first accel**
	End of Test:
☐	Push end test on Dyno pendent and **press the green function button** as soon as test ends
☐	Press "End Test" on HDT
	After Test:
☐	Record codes here: ____
☐	Key-off vehicle
☐	Remove Horiba and PEMS PM filter and take to Filter Room
☐	Press "Stop" on HDT
☐	CDTCS: Run these reports: :"Bag Data", "Zero/Span Data", and"1 HZ Data"
☐	PC Host: Rename Remote files and copy reports to Light duty results in local file "R" drive
☐	Technician's Signature: ____

Example of PEMS Procedure for Chassis Dynamometer Test

Fuel:	**xFuel**
Project:	**25980.01.005**
	PEMS (day prior)
□	Schedule a new test to wake up at least 1 hour prior to desired test time
□	**Bottle Rack**
□	Roll bottle racks into test cell
□	Turn on FID Fuel big bottle and set to 45 PSI
□	Turn on Nitrogen, CAL (Quad), and Nox and set to 30 PSI
	PEMS
□	Install PEMS on receiver hitch
□	Connect exhaust flange to vehicle (lower PEMS prior to connecting)
□	After Car is installed, **connect shore power**
□	Connect both bottles to FID T
	PEMS Setup
□	Boot computer UN/PW on Laptop
□	Connect Wifi to SensorTechA19512188 Pw: 1b26tzhp2a
□	Check for connection errors. If any exist resolve (check last page for troubleshooting tips)
□	*If Needed, Synchronize clock to Computer (Menu>System Settings>Configuration> Sync to PC Time)*
□	*Exhaust Flow Meter*: Perform back purge and then Zero
□	Set filter to Bypass Pump On
□	Connect N2 bottle to EFM Port
□	Got to Menu>System Setup: Leak check, set gas path to Sample
□	Check that O2 goes to <0.1%
	Disconnect N2 bottle from EFM Port and move to Calibration Port
□	Check the following under sample system details UPDATE Sample Humidity < 21% Sample flow rate > 2.5 L/min Dryer inlet 55 +/- 6 degC Htd Filter Temp 100 +/- 6 degC
□	*Particle Mass II > Details:* Check that dilutor sample flow is 1.4 (+/- 0.3) SLPM, and Inlet Pressure is 90kpa (+/-8) *If incorrect, check PM filters are correctly installed*
□	Check delta P (+/-0.02) and Pegasor data mass (<0.5) (Negative is okay)
	If outside desired range, perform the following
	Pressure
	□ *Particle Mass II > Setup:* Scroll down and select "Zero Pressures"
	□ Re-Check delta P (+/-0.02)
	Pegasor
	□ Turn on bypass pump and wait 15 seconds
	□ *Particle Mass II > Setup:* Select "Zero Pegasor"
	□ Re-Check Pegasor data mass (<0.5)
□	On home screen, Check the following under FID Heated Line Average Temp 191 +/- 5 degC
	Start New Test
□	Use information above and name file **DATE_Vehicle_Fuel_Route_Test Number**
□	Switch gas path to Calibration
□	Press Start Test - This must be done prior to starting calibrations
□	Press cancel to leave gas path in Calibration
	PEMS Zero Span (Co-Pilot)
□	Select Menu Zero/Span Calibration
	***NOTE**: Before performing any zero or span always verify you are seeing what you expect for each checked box. When changing gas paths always wait 30 seconds (the visual display will move approximately half way across)
□	Select CO, CO2, NO, NO2 and THC
□	Verify Single FID is set to Range 3
□	Select Zero at bottom of screen
□	**Connect Cal (Quad) bottle to Cal port**
□	Select CO, CO2, NO, and THC
□	Select Span at bottom of screen
□	**Switch the Cal line from the Quad bottle to the NO2 bottle**
□	Select NO2
□	Select span at bottom of screen
□	Pause Test at end of Calibration to mark this ending.
□	Set gas path back to Sample

□	**Switch the Cal line from the NO2 bottle to the Nitrogen bottle**
	Pretest Check
	When Horiba Zero/Span is complete
□	Turn Bypass Pump Off
□	Install PEMS filter in Dyno
□	Turn Bypass Pump On
	When vehicle communications start (after driver keys on vehicle)
□	Check that FID flame is still lit
□	Switch bypass pump to filter 1
	Check Particle Mass II flows Dilutor Sample flow 1.4SLPM Make Up + Inlet + Dilutor Sample flow ~= Filter Flow
□	Reverify there are no warnings on the home screen
□	Re-Start Recording
	End of Test (Co-Pilot)
□	Switch Filter to Pump Bypass
	After Test Zero/Span (Co-Pilot)
□	Select Menu Zero/Span Calibration
	***NOTE**: Before performing any zero or span always verify you are seeing what you expect for each checked box. When changing gas paths always wait 30 seconds (the visual display will move approximately half way across)
□	Select CO, CO2, NO, NO2 and THC
□	Verify Single FID is set to Range 3
□	Select Zero at bottom of screen
□	**Connect Cal (Quad) bottle to Cal port**
□	Select CO, CO2, NO, and THC
□	Select Span at bottom of screen
□	**Switch the Cal line from the Quad bottle to the NO2 bottle**
□	Select NO2
□	Select span at bottom of screen
□	Pause Test at end of Calibration to mark this ending.
□	Set gas path back to Sample
□	Select End Test
□	**Switch the Cal line from the NO2 bottle to the Nitrogen bottle**
	After Test:
□	After last test of the day download files. Can be done in the following ways a. Use USB stick to transfer from PEMS laptop to SwRI Laptop b. Connect SwRI Laptop to PEMS unit WiFi and download directly to computer SSID: SensorTechA19512188 PW: 1b26tzhp2a
□	Place files in CRC data folder
□	Technician Signature: ______________________________

Example of Procedure for On-Road Test

Fuel ID:	**xFuel**
Project:	**25980.01.005**
PM Filter #	
Set #	
Run #	
	PEMS (day prior)
□	Schedule a new test to wake up at least 1 hour prior to desired test time
	PEMS (day of)
□	Take PEMS unit outside at least 1 hour prior to start of test
	Bottle Rack
□	Turn on FID Fuel small bottle and set to 35 PSI (ensure that bottle is disconnected from FID T)
□	Verify flow by purging the end of the line Note: There is a check valve that must be "Reset" position to allow flow
□	Turn on FID Fuel big bottle and set to 45 PSI
□	Connect both bottles to FID T
□	Connect N2 bottle to Purge solenoid and Purge Solenoid to EFM Port
□	Connect Purge Solenoid Wire to EFM left receptacle
	PEMS Setup
□	Boot computer (pw: Crcuserb163)
□	Connect Wifi to SensorTechA19512188 Pw: 1b26tzhp2a
□	Check for connection errors. If any exist resolve (check last page for troubleshooting tips)
□	*Synchronize clock to Computer (Menu>System Settings>Configuration> Sync to PC Time)*
□	*Exhaust Flow Meter*: Perform back purge and then Zero
□	Got to Menu>System Setup: Leak check, set gas path to Sample and perform O2 leak check
□	Set gas path to Ambient
□	Set filter to Bypass Pump On
□	*Particle Mass II > Details:* Check delta P (+/-0.02) and Pegasor data mass (<0.5) (Negative is okay)
	If outside desired range, perform the following
	Pressure
□	*Particle Mass II > Setup:* Scroll down and select "Zero Pressures"
□	Re-Check delta P (+/-0.02)
	Pegasor
□	Turn on bypass pump and wait 15 seconds
□	*Particle Mass II > Setup:* Select "Zero Pegasor"
□	Re-Check Pegasor data mass (<0.5)
□	*Particle Mass II :* Check that dilutor sample flow is 1.4 (+/- 0.3) SLPM, and Inlet Pressure is 90kpa (+/-8) *If incorrect, check PM filters are correctly installed*
□	Check the following under sample system details UPDATE RH < 15%? Sample flow rate > 2.5 L/min Dryer inlet 55 +/- 5 degC Htd Filter Temp 100 +/- 5 degC
	Check the following under FID Heated Line Average Temp 191 +/- 5 degC
	Start New Test
□	Click "New Test"
□	Use information above and name file DATE_Vehicle_Fuel_Route_Test Number
□	Start Recording - This must be done prior to starting calibrations
	PEMS Zero Span
□	Select Menu Zero/Span Calibration
	NOTE: Before performing any zero or span always verify you are seeing what you expect for each checked box. When changing gas paths always wait 30 seconds (the visual display will move approximately half way across)
□	Set gas path to Ambient and visually check O2% - 20.8% (+/- 0.5%)
□	Connect N2 to Cal Port
□	Switch gas path to Calibration
□	Select CO, CO2, NO, NO2 and THC
□	Verify Single FID is set to Range 3
□	Select Zero at bottom of screen
□	Connect Cal gas to Cal port
	Sometimes the FID will not pull the proper THC level. If true perform the following
□	Disconnect the Cal input quick connect (gas will only travel through white tube) Note: Sample flow will go low during this time
□	Select THC only and perform Span

□	Reconnect Cal input on Sensors unit
□	Select CO, CO2, NO, and THC (if applicable)
□	Select Span at bottom of screen
□	Switch the Cal line from the quad bottle to the NO2 bottle
□	Select NO2
□	Select span at bottom of screen
□	Pause Test at end of Calibration to mark this ending.
□	Set gas path back to Sample
□	Remove Purge Valve and communication wire
□	**PEMS Install**
□	Push car outside and connect to PEMS unit (start this while finishing up Zero/Spans)
□	Install PEMS on receiver hitch
□	Tighten Allen bolt lock
□	Install hitch lock
□	Connect exhaust flange to vehicle (lower PEMS prior to connecting)
	Pretest Take Off
□	Record fuel gauge level________________ (>1/4 tank)
□	Record vehicle odometer ____________________.
□	Key-on and check DTCs.
	Record codes here: ____
□	Install New PM Filters (silver side out)
□	Record filter number at top of work request
□	Remove FID Big Bottle Line
□	Disconnect battery from charger and connect to distribution block
□	Disconnect shore power
□	Check for GPS connectivity (1 minute)
□	Check that FID flame is still lit
□	Switch bypass pump to appropriate filter (1 or 2)
□	Check Particle Mass II flows Dilutor Sample flow 1.4SLPM Make Up + Inlet + Dilutor Sample flow ~= Filter Flow
□	Reverify there are no warnings on the home screen
□	Re-Start Recording
□	Verify all vehicle accessories are off
□	Simultaneously start the car and press the green function button on the in cab module
□	Idle for 18 seconds in park before shifting into drive (use stop watch to measure)
	End of Test
□	Stop as designated location
□	Press green function button to denote EOT
□	Switch Filter to Pump Bypass
□	Stop recording
□	Park car in designated location and Key-off vehicle
□	Record codes here: ____
□	**After Test Bottle Rack**
□	Turn on FID Fuel big bottle and set to 45 PSI
□	Connect big bottle to FID T
	After Test Zero/Span
□	Restart recording
□	Select Menu Zero/Span Calibration
	NOTE: Before performing any zero or span always verify you are seeing what you expect for each checked box. When changing gas paths always wait 30 seconds (the visual display will move approximately half way across)
□	Set gas path to Ambient and visually check O2% - 20.8% (+/- 0.5%)
□	Connect N2 to Cal Port
□	Switch gas path to Calibration
□	Select CO, CO2, NO, NO2 and THC
□	Verify Single FID is set to Range 3
□	Select Zero at bottom of screen
□	Connect Cal gas to Cal port
	Sometimes the FID will not pull the proper THC level. If true perform the following
□	Disconnect the Cal input quick connect (gas will only travel through white tube) Note: Sample flow will go low during this time

□	Select THC only and perform Span
□	Reconnect Cal input on Sensors unit
□	Select CO, CO2, NO, and THC (if applicable)
□	Select Span at bottom of screen
□	Switch the Cal line from the quad bottle to the NO2 bottle
□	Select NO2
□	Select span at bottom of screen
□	Select End Test
	After Test:
□	After last test of the day download files. Can be done in the following ways a. Use USB stick to transfer from PEMS laptop to SwRI Laptop b. Connect SwRI Laptop to PEMS unit WiFi and download directly to computer SSID: SensorTechA19512188 PW: 1b26tzhp2a
□	Place files in CRC data folder
□	Turn off N2, Cal and NO2 bottles (FID at end of week of testing)
	Driver's Signature: ____
	Co-Pilot Signature: ____

APPENDIX F

SUPPLEMENTAL PLOTS FOR STATISTICAL ANALYSIS RESULTS

This appendix includes the full set of plots for each emissions parameter. Each section includes the raw data plot in original units, including any outliers denoted with asterisks. Additionally, each emissions parameter is plotted in transformed units vs. PMI, RVP, and Ethanol.

F.1 PM

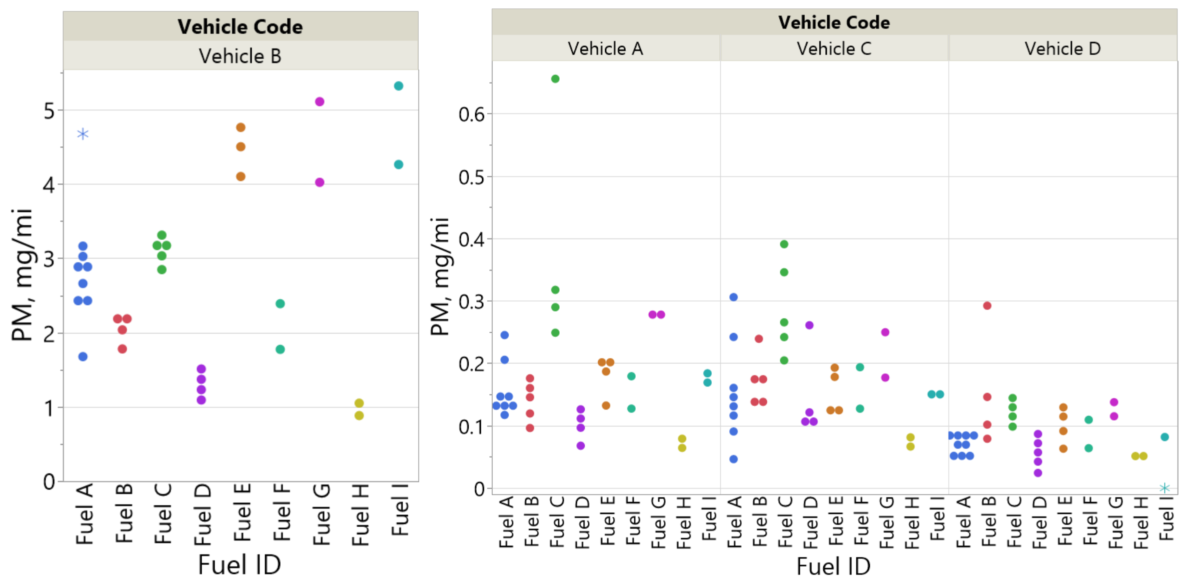


FIGURE 21. RAW DATA PLOT OF PM (MG/MI) BY VEHICLE

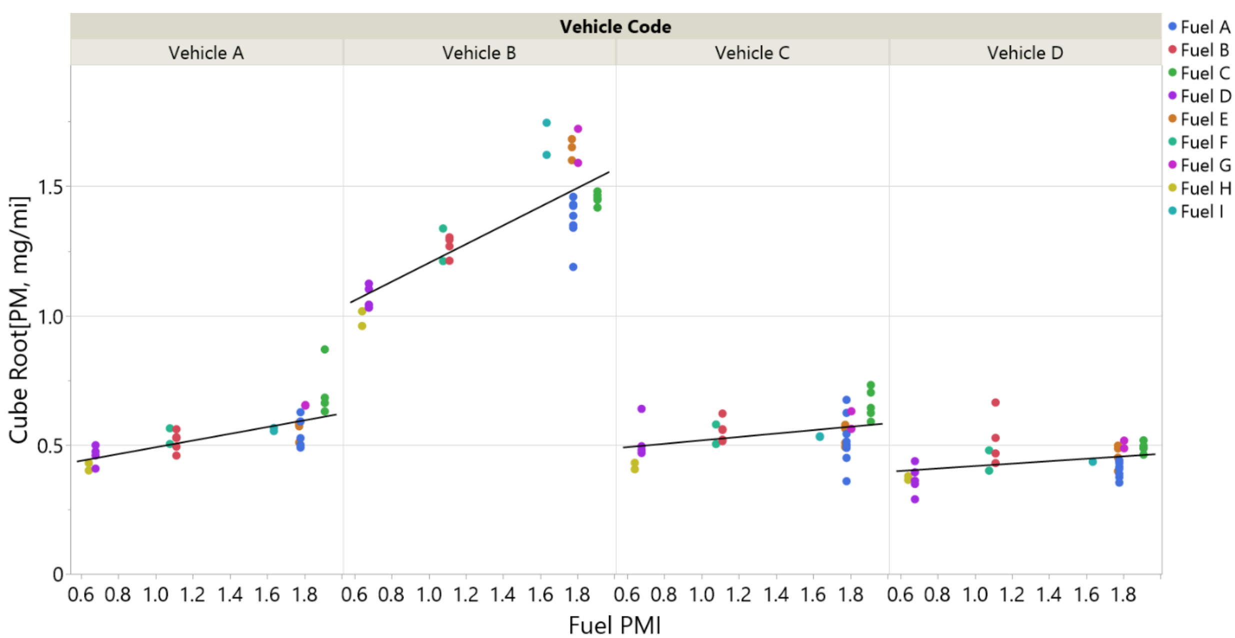


FIGURE 22. PLOT OF CUBE ROOT (PM) VS. FUEL PMI BY VEHICLE

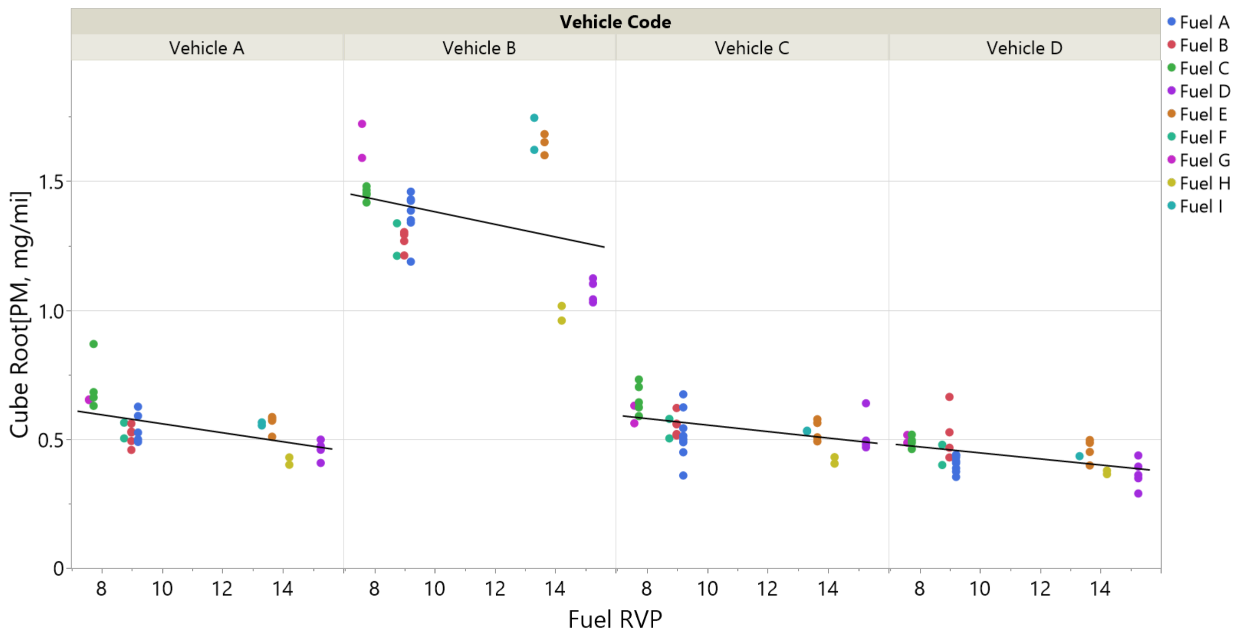


FIGURE 23. PLOT OF CUBE ROOT (PM) VS. FUEL RVP BY VEHICLE

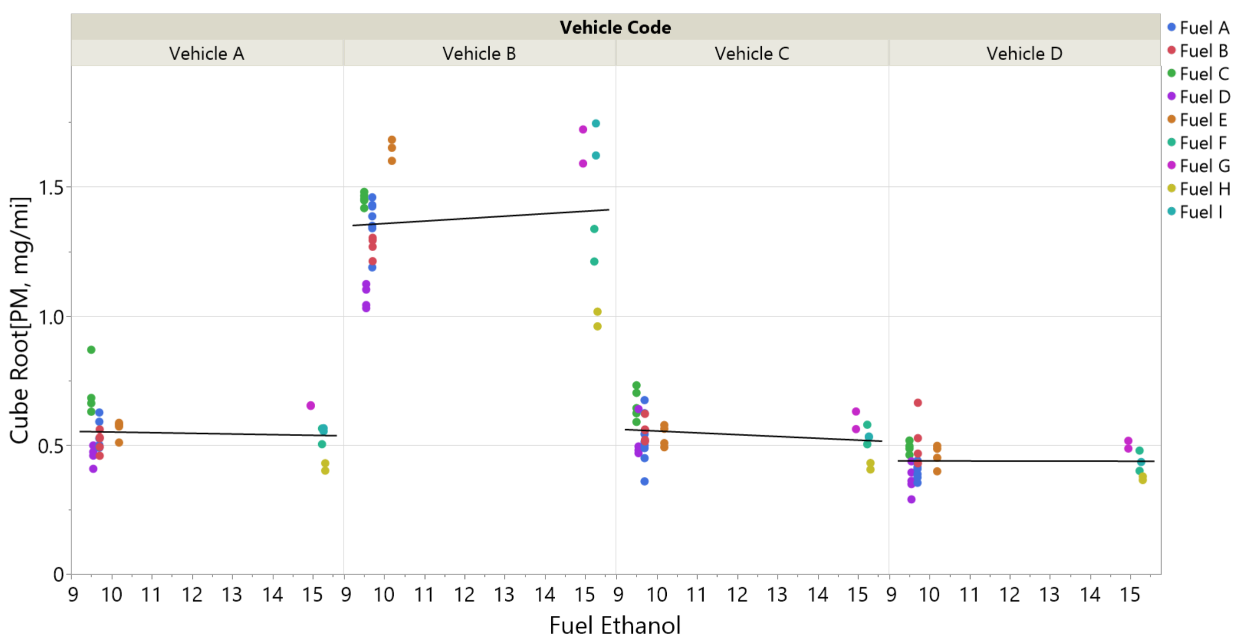


FIGURE 24. PLOT OF CUBE ROOT (PM) VS. FUEL ETHANOL BY VEHICLE

F.2 NO_x

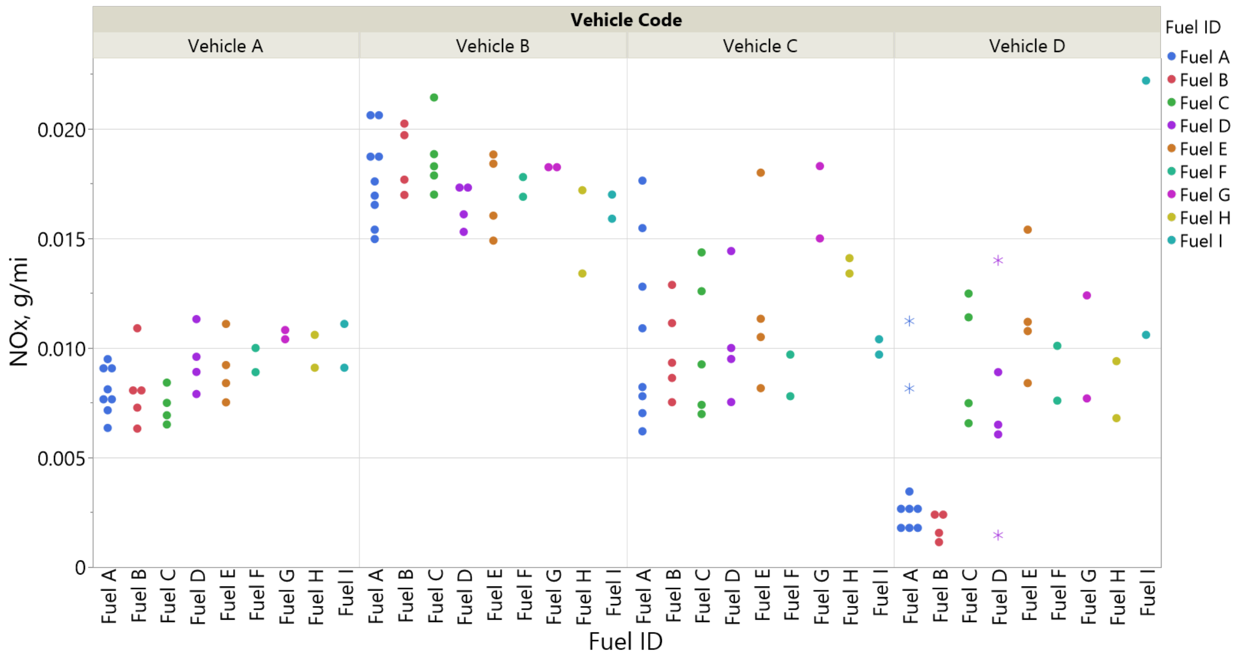


FIGURE 25. RAW DATA PLOT OF NO_X (G/MI) BY VEHICLE

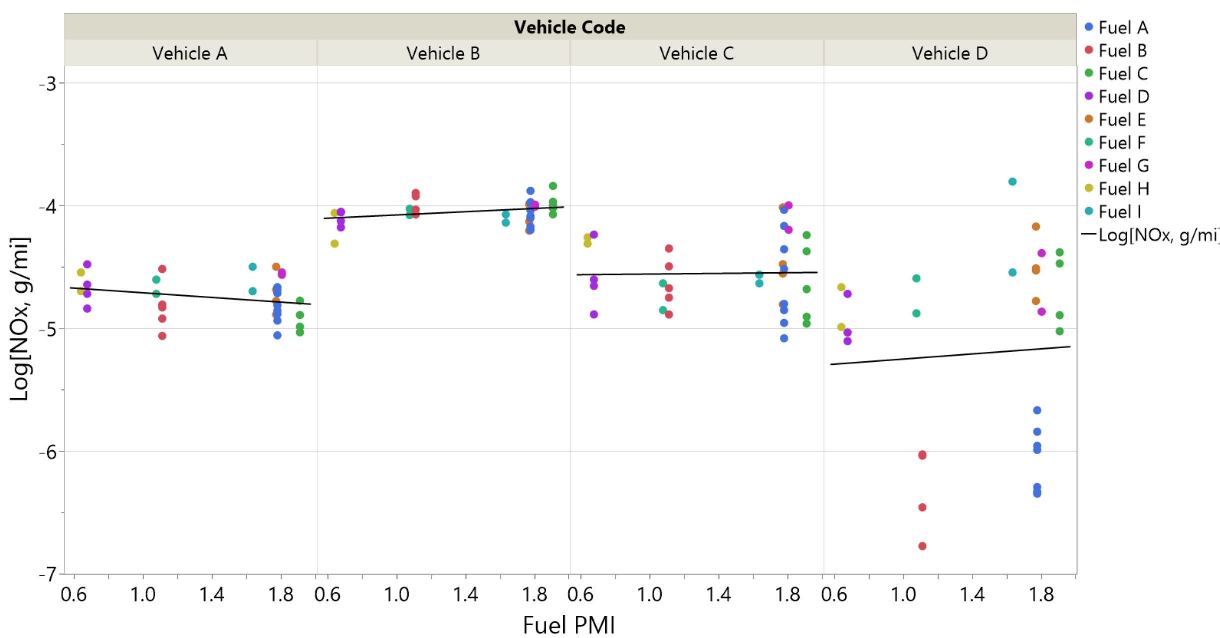


FIGURE 26. PLOT OF LN (NO_X) VS. FUEL PMI BY VEHICLE

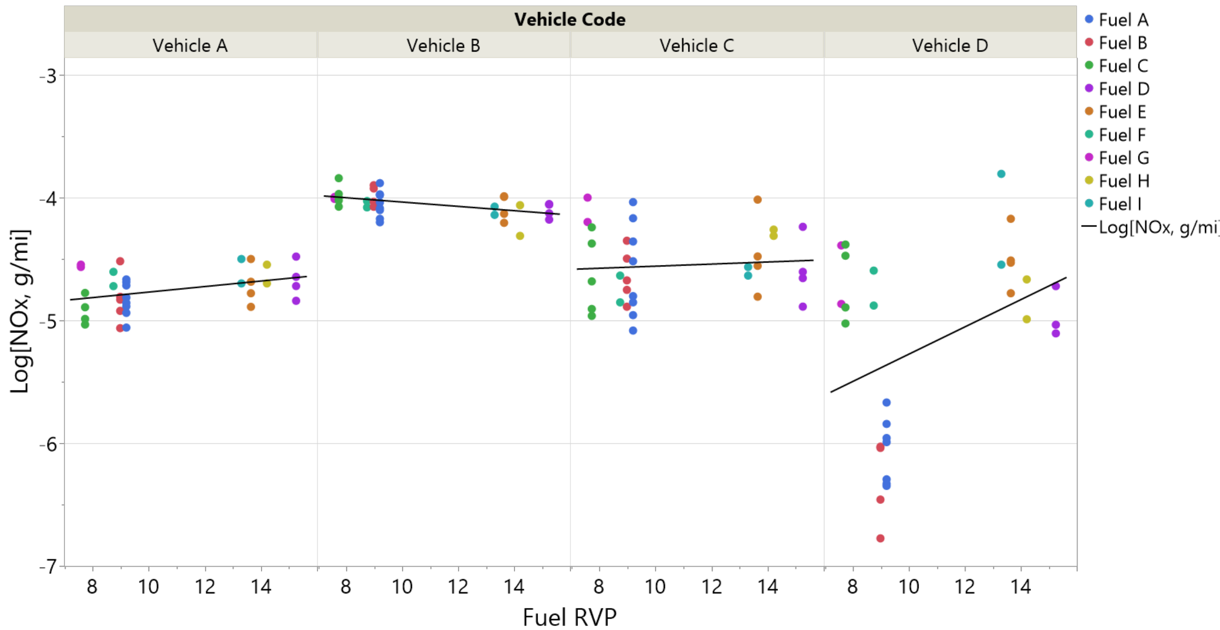


FIGURE 27. PLOT OF LN (NO_X) VS. FUEL RVP BY VEHICLE

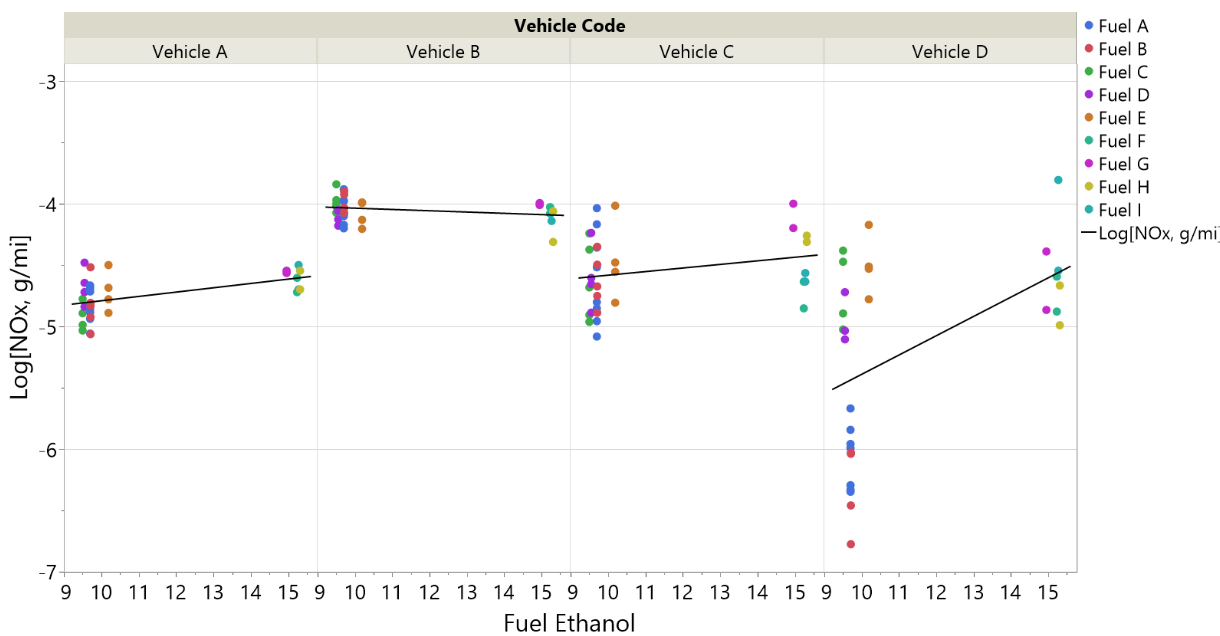


FIGURE 28. PLOT OF LN (NO_X) VS. FUEL ETHANOL BY VEHICLE

F.3 CO_2

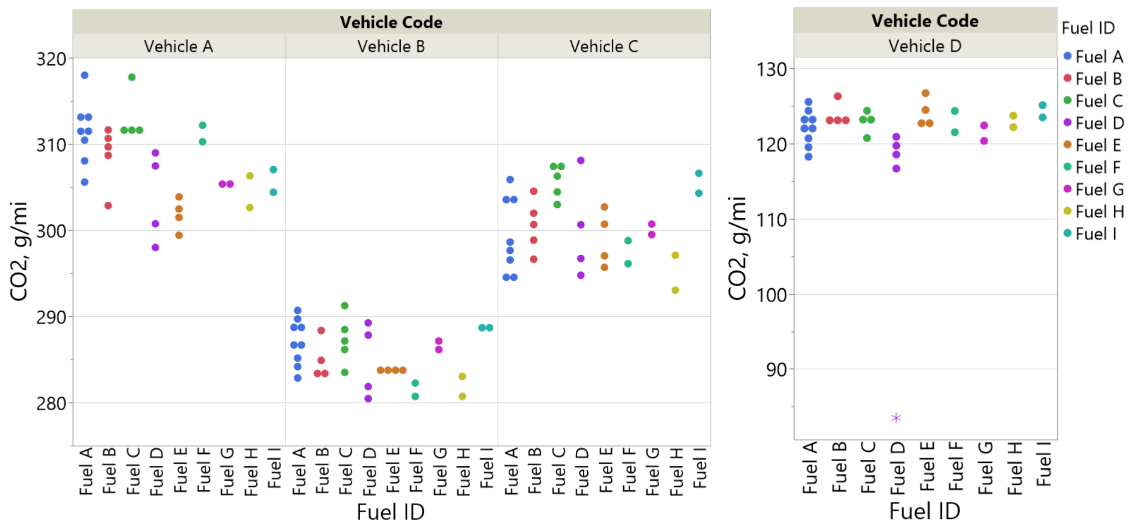


FIGURE 29. RAW DATA PLOT OF CO_2 (G/MI) BY VEHICLE

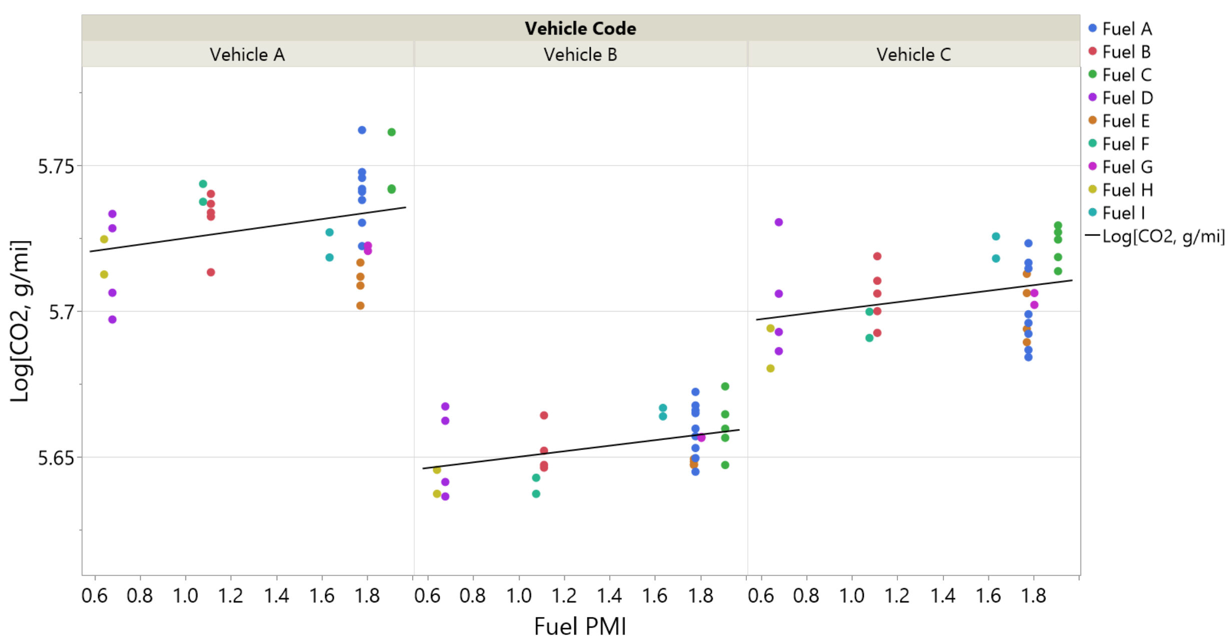


FIGURE 30. PLOT OF LN (CO_2) VS. FUEL PMI BY VEHICLE FOR VEHICLES A,B,C

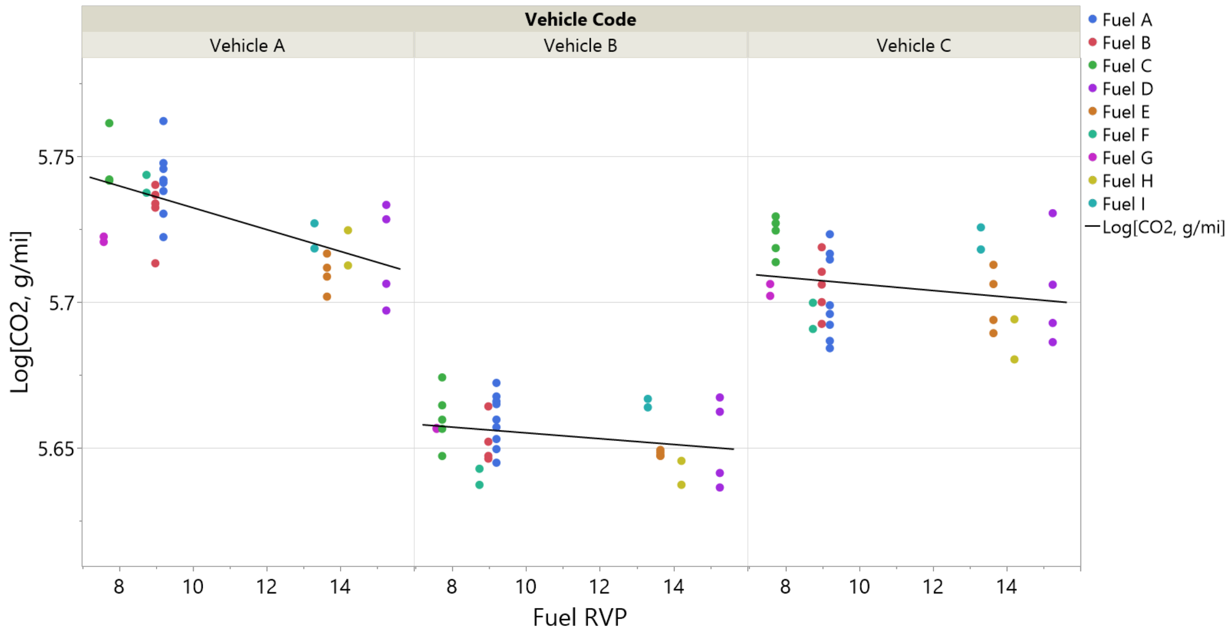


FIGURE 31. PLOT OF LN (CO_2) VS. FUEL RVP BY VEHICLE FOR VEHICLES A,B,C

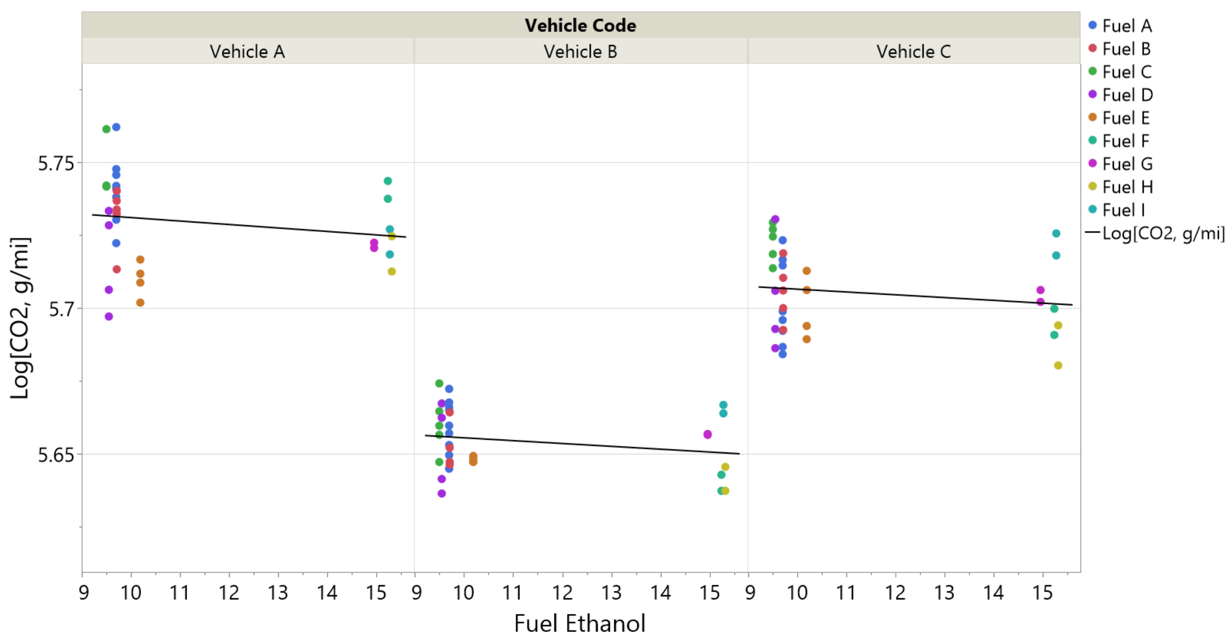


FIGURE 32. PLOT OF LN (CO_2) VS. FUEL ETHANOL BY VEHICLE FOR VEHICLES A,B,C

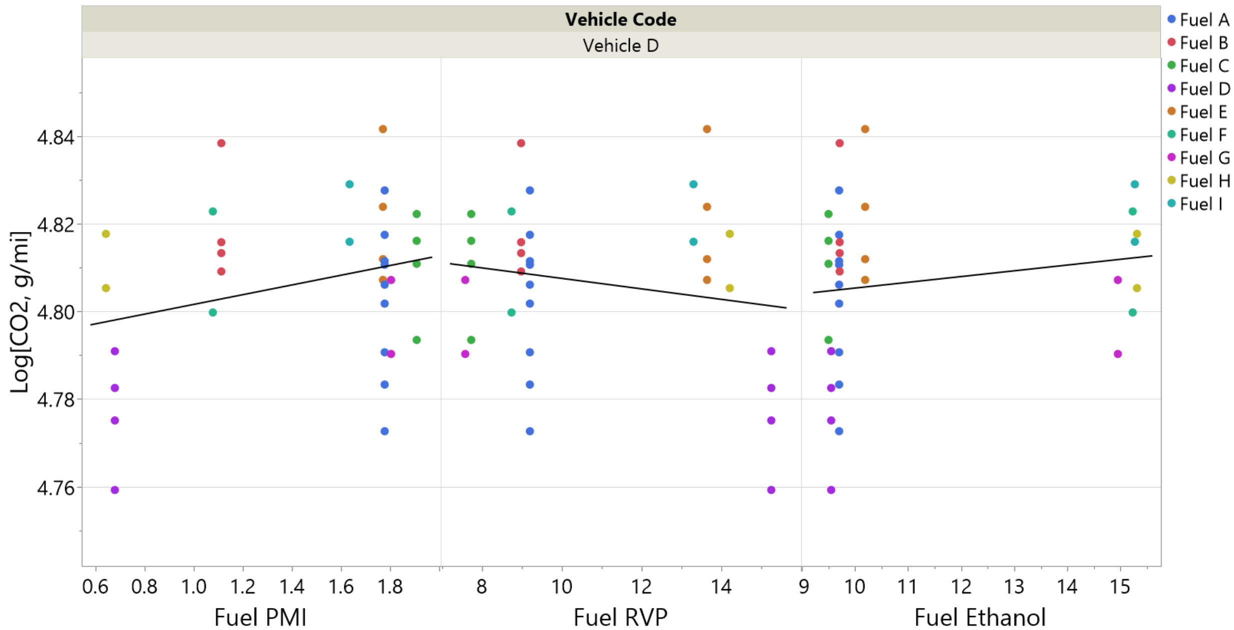


FIGURE 33. PLOT OF LN (CO_2) VS. FUEL PMI, RVI, AND ETHANOL BY FOR VEHICLE D

F.4 THC

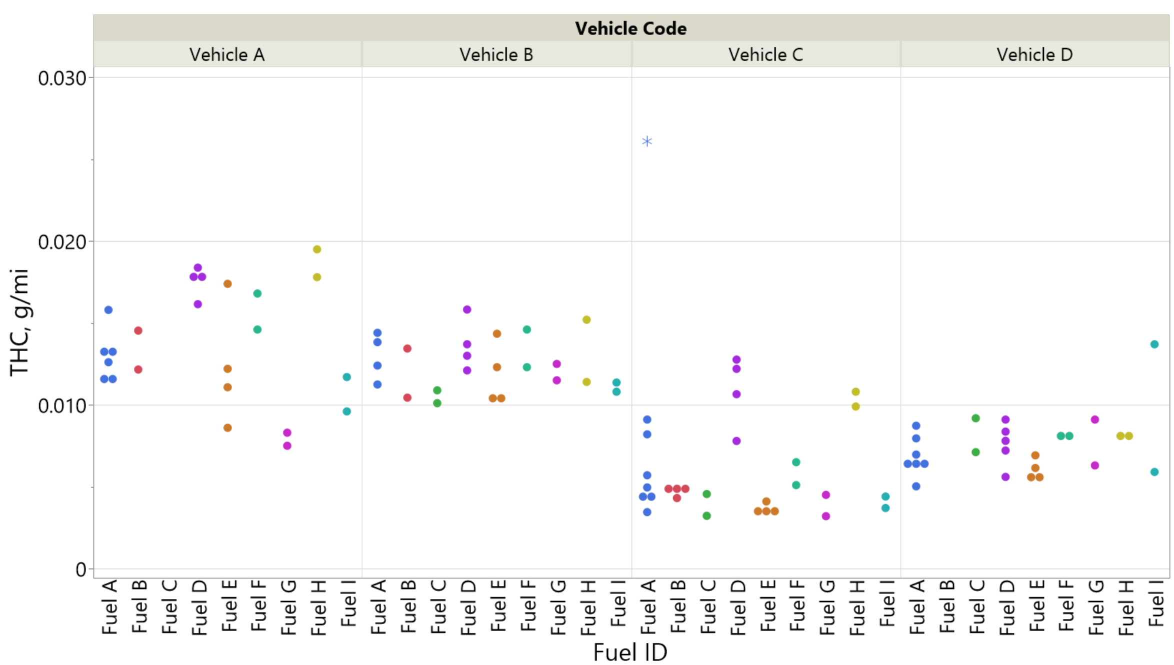


FIGURE 34. RAW DATA PLOT OF THC (G/MI) BY VEHICLE

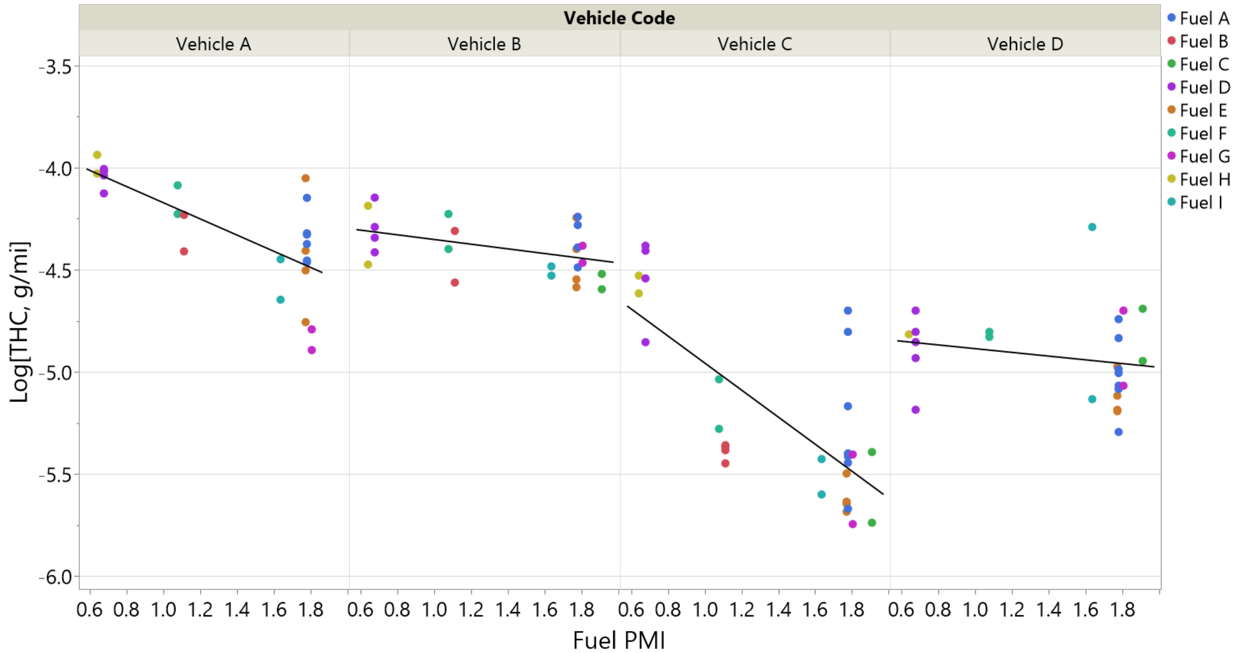


FIGURE 35. PLOT OF LN (THC) VS. FUEL PMI BY VEHICLE

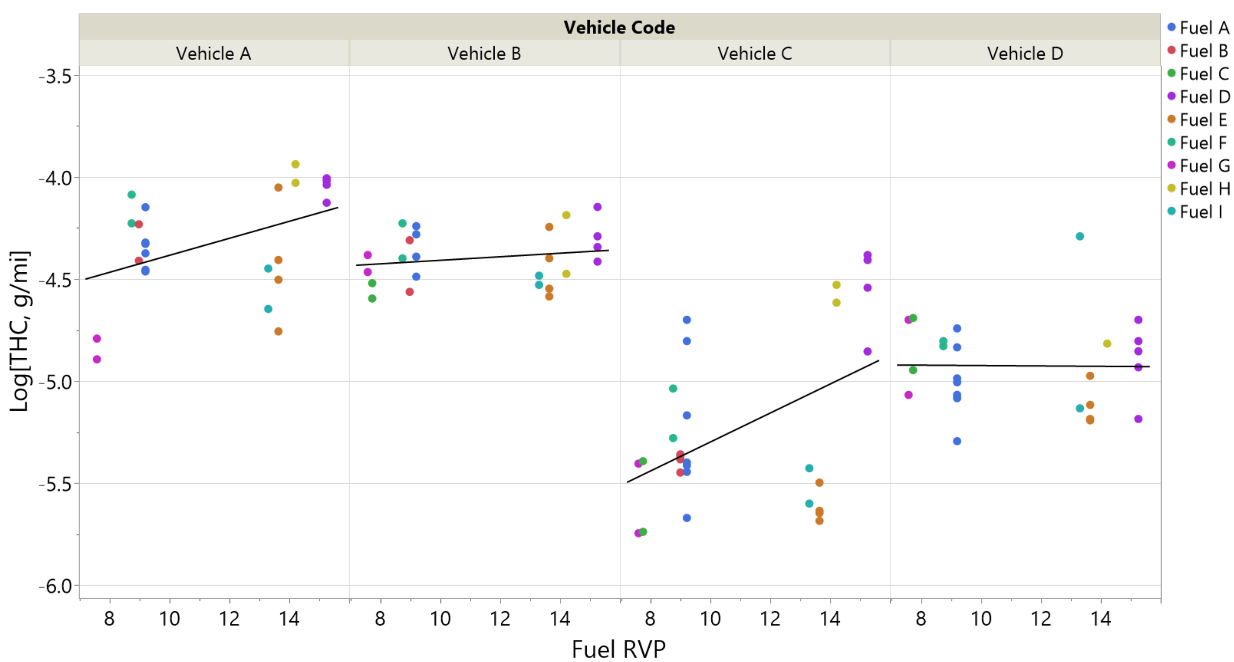


FIGURE 36. PLOT OF LN (THC) VS. FUEL RVP BY VEHICLE

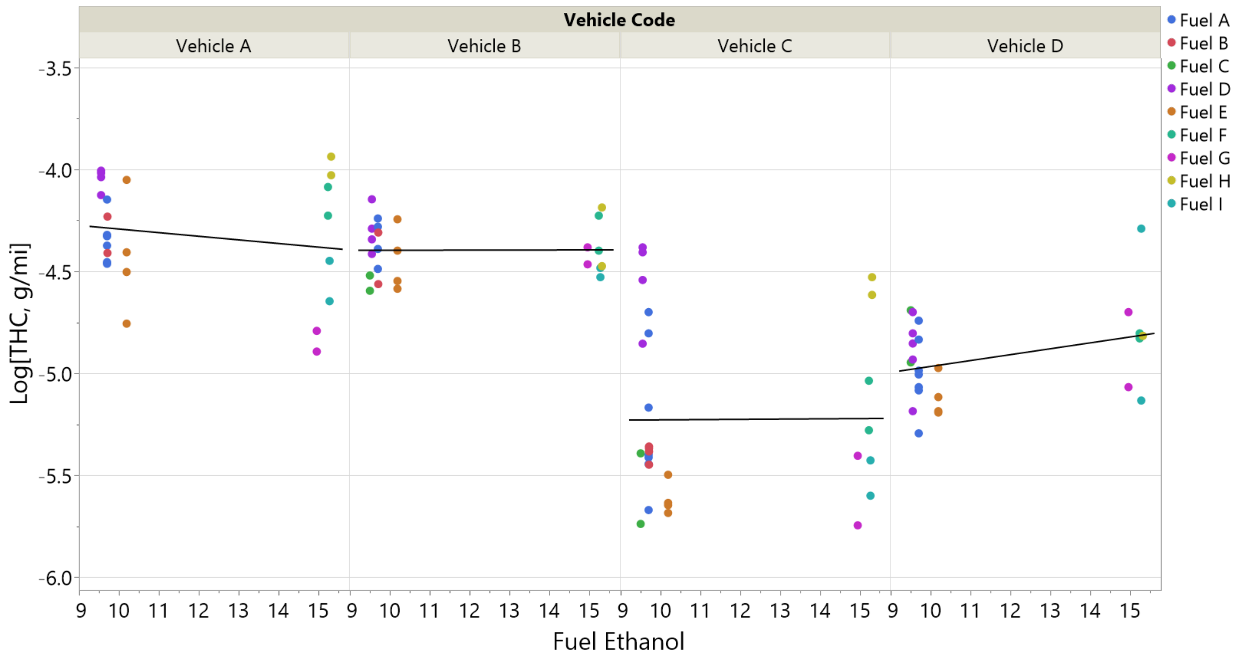


FIGURE 37. PLOT OF LN (THC) VS. FUEL ETHANOL BY VEHICLE

F.5 NMHC

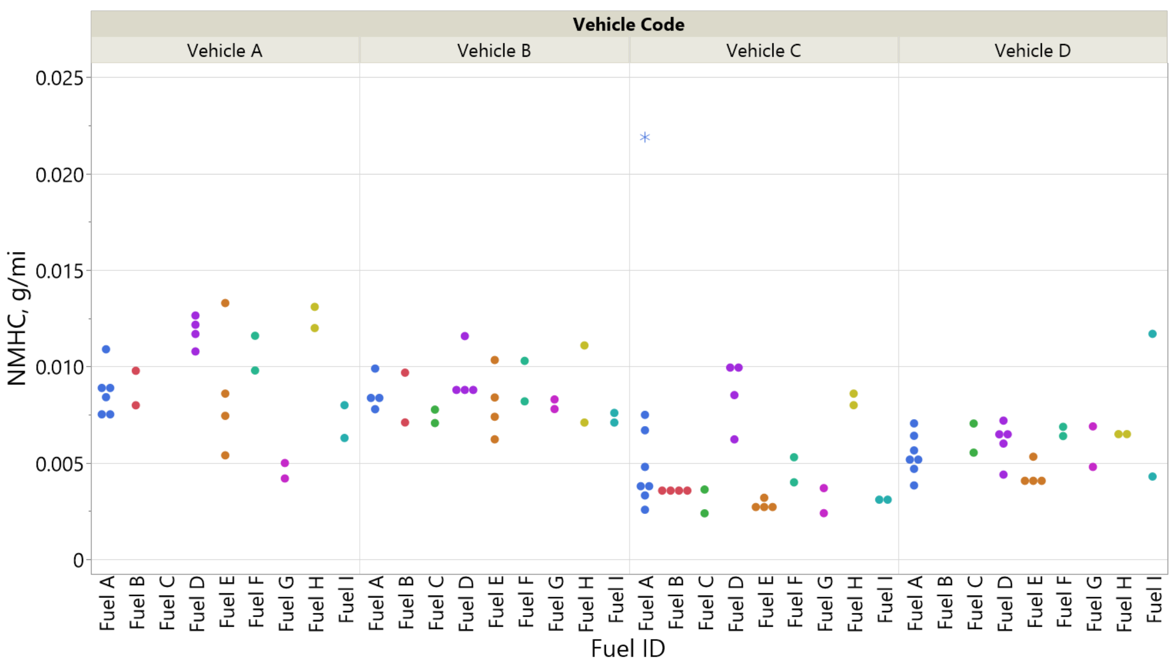


FIGURE 38. RAW DATA PLOT OF NMHC (G/MI) BY VEHICLE

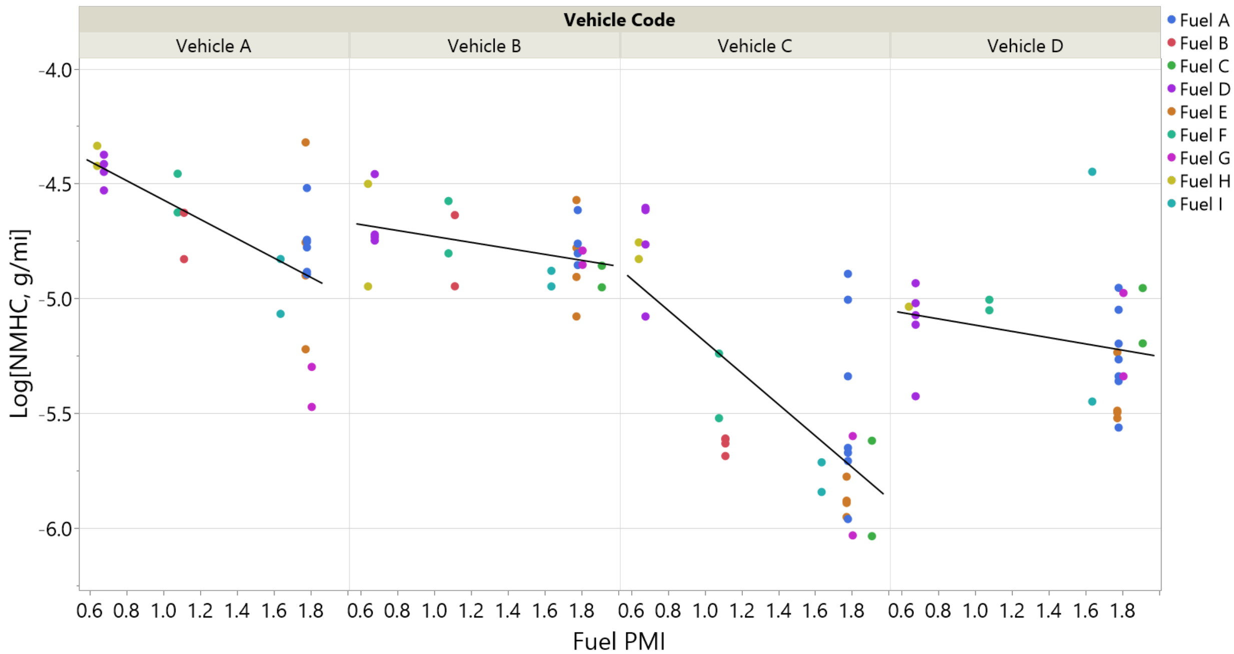


FIGURE 39. PLOT OF LN (NMHC) VS. FUEL PMI BY VEHICLE

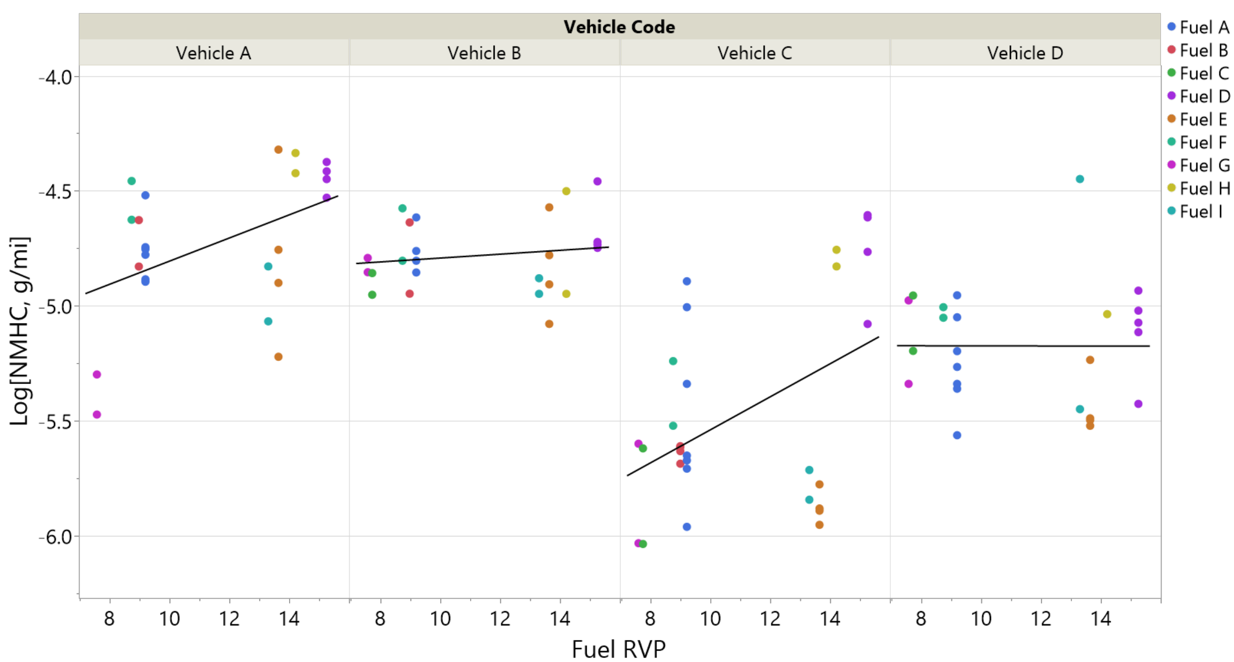


FIGURE 40. PLOT OF LN (NMHC) VS. FUEL RVP BY VEHICLE

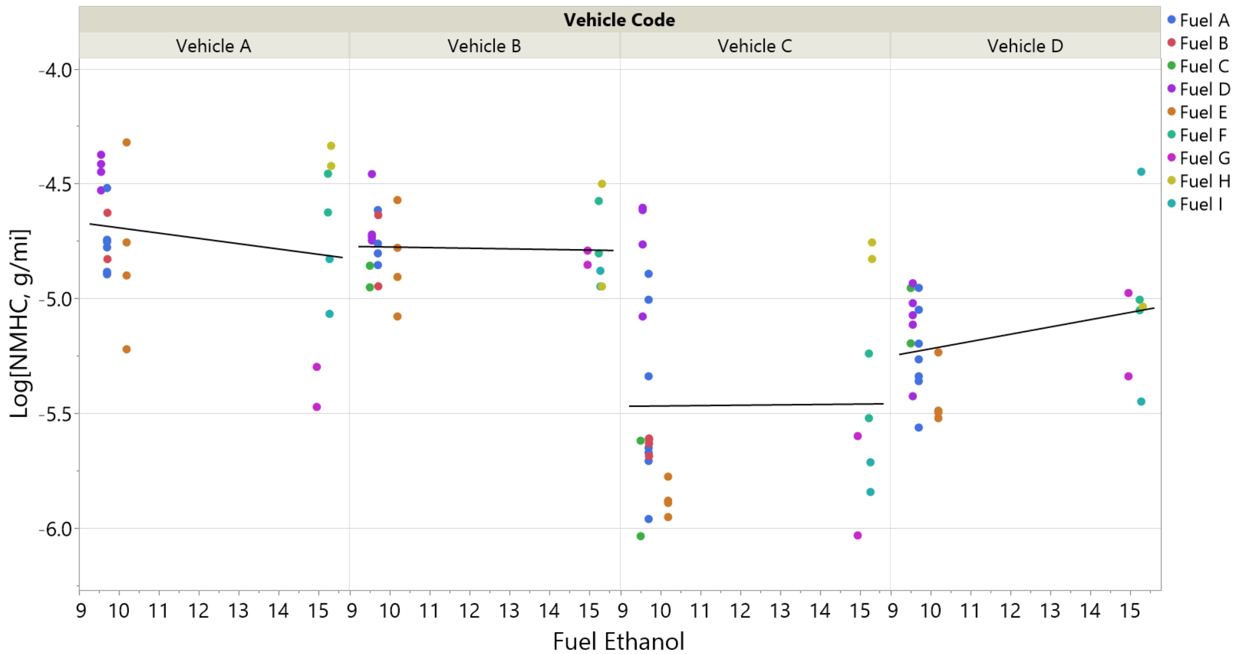


FIGURE 41. PLOT OF LN (NMHC) VS. FUEL ETHANOL BY VEHICLE

F.7 CO

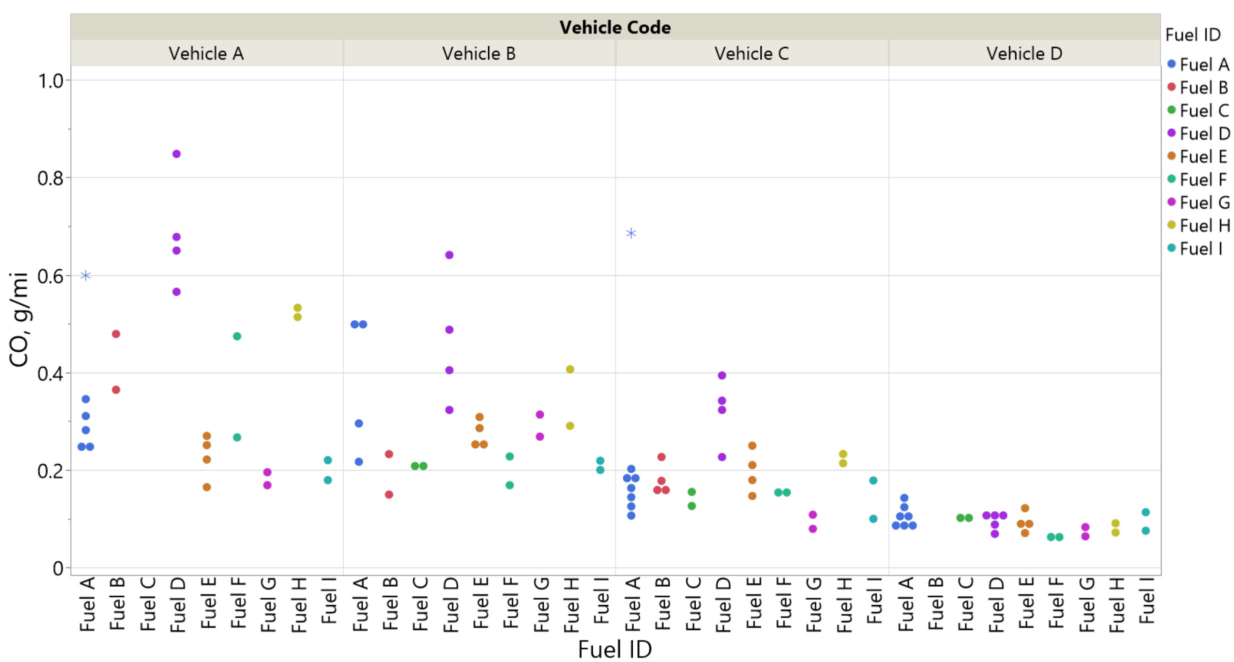


FIGURE 42. RAW DATA PLOT OF CO (G/MI) BY VEHICLE

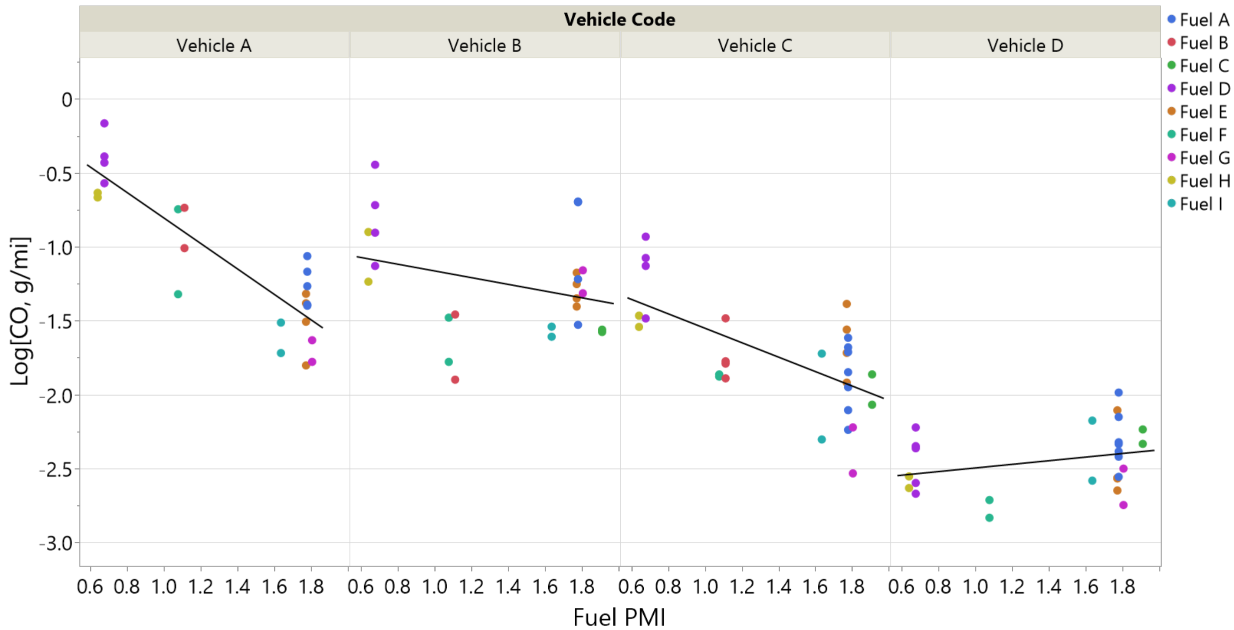


FIGURE 43. PLOT OF LN (CO) VS. FUEL PMI BY VEHICLE

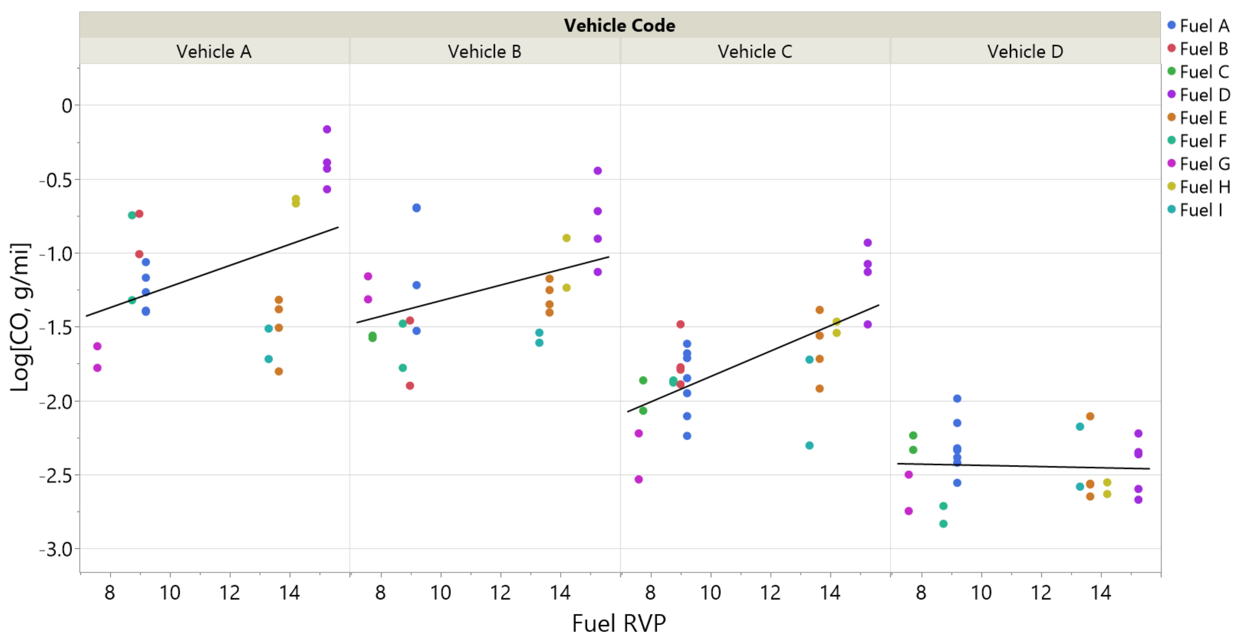


FIGURE 44. PLOT OF LN (CO) VS. FUEL RVP BY VEHICLE

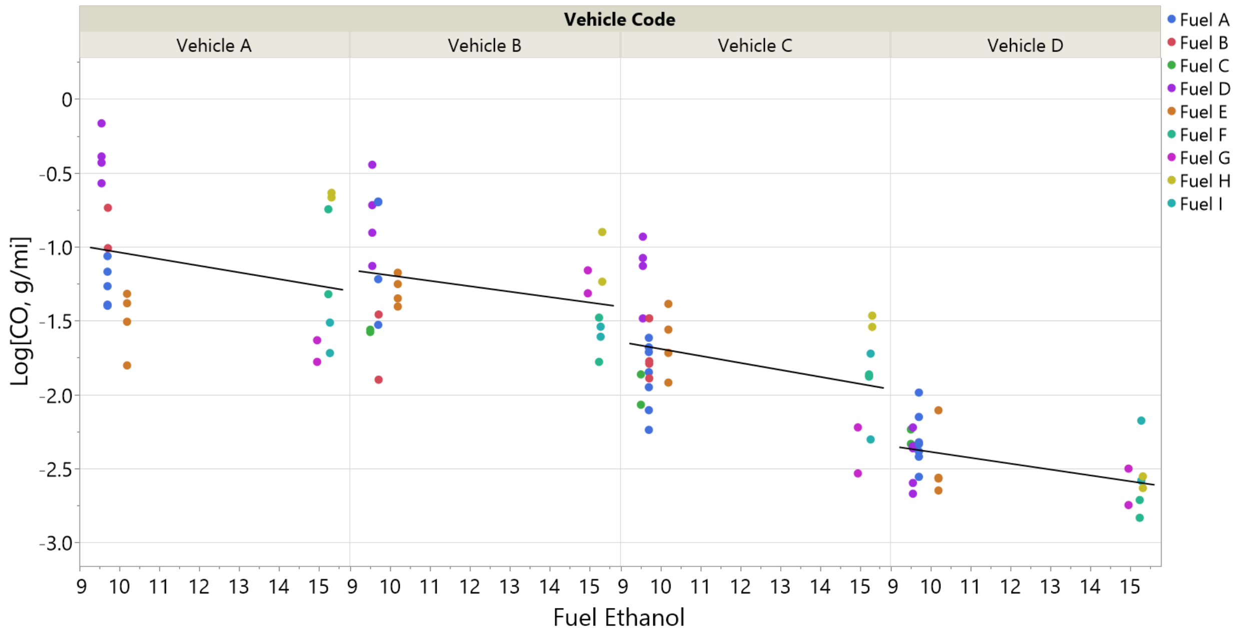


FIGURE 45. PLOT OF LN (CO) VS. FUEL ETHANOL BY VEHICLE