CRC Report No. E-122-2

LIGHT DUTY PEMS PHASE 2: ENGINE TECHNOLOGY AND FUEL PROPERTY INVESTIGATION

Final Report

January 2023

COORDINATING RESEARCH COUNCIL, INC.
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Project E-122-2

Submitted to:

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

December 2022

POWERTRAIN ENGINEERING DIVISION

Southwest Research Institute® Final Report
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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-122-2, was conducted between March 19 of 2019 and April of 2022. The project was based on SwRI's technical proposal to CRC dated December 17, 2018, and revised proposal dated May 8, 2019. The internal SwRI project number was 03.24546. 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.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 EXECUTIVE SUMMARY

This report documents a project conducted by SwRI on behalf of Coordinating Research Council (CRC). The project investigated the use of multiple engine technologies and different fuel properties to determine Portable Emission Measurement System (PEMS) performance in measuring exhaust emissions changes during on-road and chassis dynamometer tests. Additional program objectives were:

- Determine the repeatability of the chassis dynamometer testing to compare with the PEMS unit
- Determine the accuracy of a PEMS unit under real on-road driving conditions and changing ambient temperatures
- Compare the significance of fuel Particulate Matter Index (PMI) and Reid Vapor Pressure (RVP) as predictors of gaseous and PM emissions with PEMS data to compare to chassis dynamometer testing
- Determine how exhaust flow measurement from the individual PEMS system correlates with exhaust flow measured by the test cell Constant Volume Sampling (CVS)

This project evaluated exhaust emissions from four light-duty vehicles using five unique test fuels. Four of the fuels were commercially available market fuels and the fifth was an emissions-grade certification fuel. For each fuel-vehicle combination, both on-road and chassis dynamometer tests were used to evaluate exhaust emissions and both testing techniques used the E-122 set route. For chassis dynamometer tests, exhaust emissions were measured simultaneously by certification-grade laboratory equipment and a PEMS. For on-road tests, the PEMS was the sole measurement device.

Statistical analysis of the results was conducted to examine PEMS repeatability in measuring exhaust emissions. The emissions parameters were transformed based on a Box-Cox approach prior to analysis to remove any level-dependency. For oxides of nitrogen (NO_x), total hydrocarbon (THC), and nonmethane hydrocarbon (NMHC), variability was determined to be significantly different between vehicles, and therefore was analyzed on a per-vehicle basis. Comparisons were made between laboratory measurements from chassis dynamometer tests (denoted in this report as Dilute), PEMS measurements from chassis dynamometer tests (denoted as PEMS_Dyno), and PEMS measurements from on-road tests (denoted as PEMS_Road). Whereas repeatability generally refers to results run in back-to-back fashion or in close proximity in time to one another, the design of experiments (DOE) allowed evaluation of repeated results run at different points in time. Particulate Matter (PM) was the only emission parameter that showed a significant increase in variability when considering on-road tests run at different points in time with the PEMS. For all parameters except for carbon monoxide (CO), the PEMS on-road testing variability was significantly higher than the chassis dynamometer dilute testing, based on a F-test for variances. Table 1 summarizes the repeatability conclusions by parameter and provides the estimated increase in testing standard deviation of the PEMS on-road tests compared to dilute chassis dynamometer tests. Further detail, including the repeatability of PEMS measurements on a chassis dynamometer, are discussed in the body of this report.

TABLE 1. REPEATABILITY SUMMARY COMPARING PEMS ON-ROAD TESTING TO DILUTE CHASSIS DYNO TESTING

Parameter	Variability Vehicle-Dependent?	Variability Significantly Increased Over Time?	Estimated Standard Deviation Increase Over Dilute
CubeRoot(PM, mg/mi)	No	Yes, PEMS_Road only	80%
Ln(NO_x, g/mi)	Yes	No	190% (Vehicle A) 100% (Vehicle B)
Ln(CO_2, g/mi) and Ln(Fuel Economy, mpg)	No	No	180%
Ln(THC, g/mi) and Ln(NMHC, g/mi)	Yes	No	70% (Vehicle B)
Ln(CO, g/mi)	No	No	No significant differences

PEMS results were also analyzed for accuracy. PEMS accuracy is defined here as the difference between measurements made by the PEMS and measurements made by laboratory analyzers (Dilute). Since the PEMS was run on the chassis dynamometer, a direct paired comparison of PEMS vs. Dilute was available for each test. The "PEMS_Dyno – Dilute" difference was calculated for each chassis dynamometer test. Because of previous work in CRC project E-122 detailing variability and bias across multiple PEMS units, the bias estimates by themselves for this single unit were not a primary interest of this study. The estimates were necessary, however, to remove the instrument bias when estimating the additional variability and bias that is attributable to on-road testing with the PEMS unit. Therefore, bias-corrected road results were obtained in which the median bias observed for each vehicle-parameter combination was subtracted out of each road test result. Next, the result

$$\%\ \text{Delta} = \frac{\text{PEMS\_Road\_BiasCorrected} - \text{Dilute}}{\text{Dilute}} * 100$$

was calculated for every possible pairwise comparison of a road result and a corresponding Dilute result for the same vehicle-fuel combination. Quantiles of the distribution of results, including the 5^{th}, 10^{th}, 50^{th} (median), 90^{th}, and 95^{th} percent, were calculated and plotted, along with 95% confidence intervals of each quantile. To serve as a baseline for comparison, all possible pairwise comparisons of two Dilute measurements were also calculated and the distribution of these percent differences plotted. An example comparing the distributions of percent deltas is shown for PM below in Figure 1.

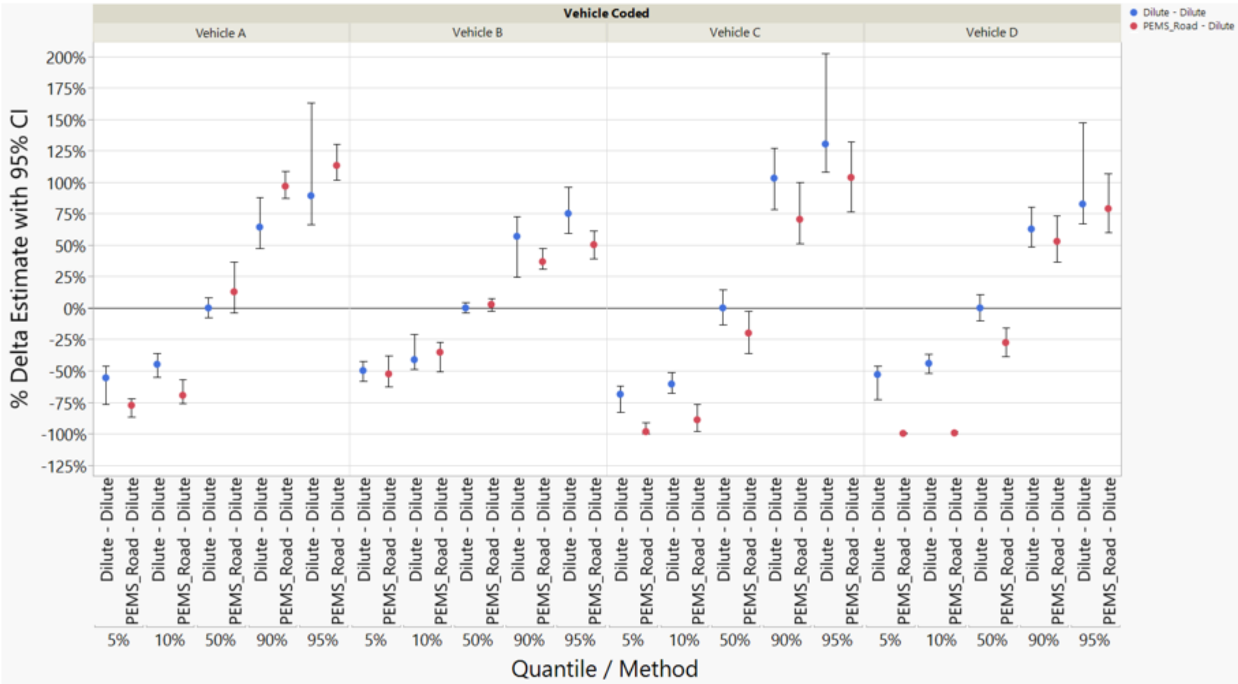


FIGURE 1. DISTRIBUTION OF PERCENT DIFFERENCES COMPARING PM USING PEMS ON-ROAD WITH BIAS-CORRECTION VS. PM WITH DILUTE

Some key takeaways relating to the accuracy of the PEMS based on this analysis were the following:

- For all parameters, conclusions about the comparison of the PEMS on-road testing results with chassis dyno results were vehicle-dependent.
- Even after the instrument bias correction, the median comparison of PEMS on-road results was significantly different from zero for at least three of four vehicles on all parameters except PM, where it was different for two of the vehicles.
- CO_2 was the most inaccurate of the parameters when comparing to dilute chassis dyno testing. Three of four vehicles had a median bias of 5-15% higher CO_2 on the road, while two of those vehicles had no overlap whatsoever in the distribution of results (PEMS_Road always gave higher CO_2).
- Based on the quantiles representing the tails of the distribution (5%, 10%, 90%, and 95%), PEMS tended to give more extreme results than would be expected with chassis dyno testing. For each parameter, there was at least one instance, though often several, where the lower quantiles were significantly lower, or the upper quantiles were significantly higher than the baseline comparison.

Detailed results of each parameter can be found in Section 4.5. Results are provided for both the percentage difference described here using untransformed units, and for direct difference comparisons using transformed values.

Finally, the viability of fuel PMI and RVP as predictors of emissions was assessed. To this end, a regression model was run for each emission parameters with predictor variables Vehicle, PMI, RVP, and two-way interactions between these variables. Backwards variable selection was used to reduce each model to include only statistically significant predictors. Correlations between PMI and RVP with other fuel properties was expected for both coincidental and intrinsic reasons. In cases where PMI and/or RVP are determined to be statistically significant predictors, one must keep in mind all other highly correlated parameters as being potential replacement predictors. A targeted fuel property design of experiments would be needed to unconfound the effects of PMI and RVP from these other properties and quantify their effects independently. For these fuels, PMI was shown to be highly correlated with T90, T95, FBP, 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. A full correlation matrix is provided in Section 4.6. An example of two of the stronger correlations with fuel RVP is plotted below in Figure 2.

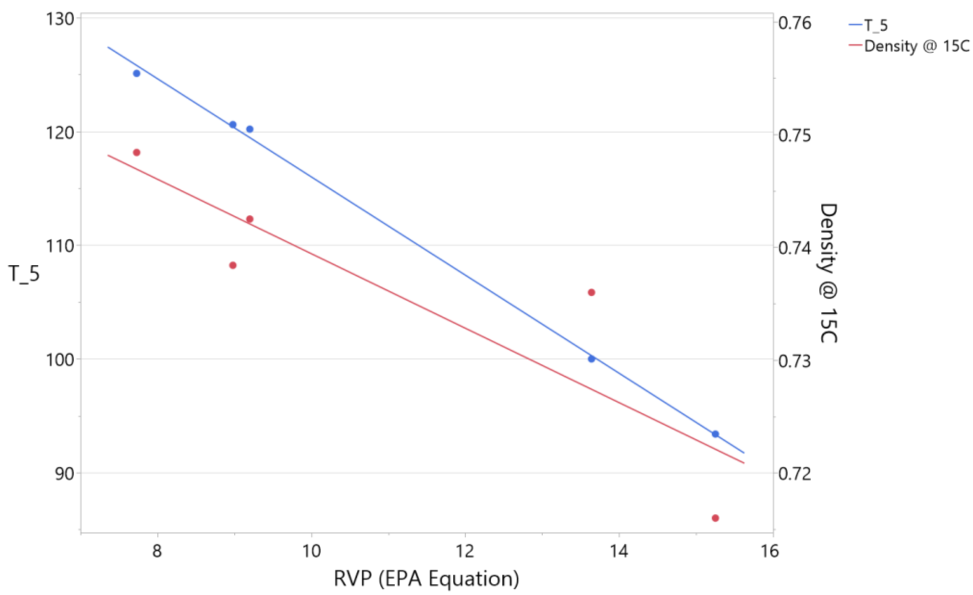


FIGURE 2. T5 AND DENSITY VS. RVP

For all prediction models, lab dilute measurement data was modeled separately from PEMS data to determine whether the two models would yield similar conclusions regarding PMI and RVP as predictors. For all parameters except CO_2, modeling of Dilute results came to the same conclusions as a model using PEMS_Dyno results, indicating that the measurement technique was not a factor. There were several parameters for which PMI and RVP were significant predictors. However, in all cases the effect was vehicle dependent, with certain vehicles not observing any significant change in the predicted emissions with changes in PMI and RVP. The list of conclusions by parameter is summarized below in Table 2. A dashed line (-) on the table means that the fuel property was not statistically significant for that emissions parameter. There are a couple of instances where statistically significant model results are shown as insignificant in the table (dashed lines) when model estimates are felt to be unstable and unreliable, such as a PMI effect for NO_x with Vehicle D. These instances are detailed in Section 4.6 of this report.

TABLE 2. CONCLUSIONS REGARDING FUEL PMI AND FUEL RVP AS PREDICTORS OF EMISSIONS

Parameter	Fuel PMI a Significant Predictor? (Vehicle)	Fuel RVP 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)
PM (mg/mi)	Yes (Vehicles A, B)	-	A - 0.20 B – 1.00	A – 0.35 (+75%) B – 2.44 (+144%)	-
NO_x (g/mi)	-	-	-	-	-
CO_2 (g/mi)	-	Yes (Vehicle A)	A - 315.0	-	308.1 (-2.2%)
THC (g/mi)	Yes (Vehicles A, C)	-	A - 0.0150 C – 0.0075	A – 0.0013 (-24%) C – 0.0041 (-46%)	-
NMHC (g/mi)	Yes (Vehicles A, C)	-	A - 0.0150 C – 0.0075	A – 0.0013 (-24%) C – 0.0040 (-47%)	-
CO (g/mi)	Yes (Vehicles A, C)	Yes (Vehicles B, C)	A - 0.500 B – 0.300 C – 0.200	A – 0.202 (-60%) C – 0.147 (-26%)	B – 0.393 (+31%) C – 0.271 (+35%)

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

2.0 INTRODUCTION

With Europe adopting the use of portable emissions measurement systems (PEMS) to determine light-duty vehicle real-world emissions, there is a greater interest in PEMS functionality and use. The California Air Resources Board (CARB) and the Environmental Protection Agency (EPA) are also conducting tests in the United States with light duty vehicles to determine their ability to measure real-world on-road emissions. This is in addition to the normal Federal Test Procedure (FTP-75), Highway Fuel Economy Test (HWFET), and US06 Supplemental Federal Test Procedures (SFTP) chassis dynamometer testing. There are several PEMS manufacturers producing these units and some studies have been conducted to understand how they perform compared to normal chassis dynamometer testing. This project investigated how PEMS emission measurements were affected by various engine technologies and fuel properties.

The project evaluated the exhaust emissions from several light-duty vehicle engine technologies. Test fuels with different properties were used to investigate how well a portable emission measuring system (PEMS) could detect fuel property impacts on exhaust emissions. Additional program objectives were:

- Determine the repeatability of the chassis dynamometer testing to compare with the PEMS unit.

- Determine the accuracy of a PEMS unit under real on-road driving conditions and changing ambient temperatures.
- Compare the significance of fuel Particulate Matter Index (PMI) and Reid Vapor Pressure (RVP) as predictors of gaseous and PM emissions with PEMS data to compare to chassis dynamometer testing.
- Determine how exhaust flow measurement from the individual PEMS system correlates with exhaust flow measured by the test cell Constant Volume Sampling (CVS).

A project kickoff meeting was held at SwRI on May 2 and 3, 2019. Of the many project tasks, locating and procuring test fuels required more time and effort than originally anticipated. The first test fuel was located and arrived in May of 2020, one year after the kickoff meeting. The last fuel took another year to locate and arrived at SwRI in June of 2021. Official testing began in October of 2020 and was completed in October 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 five fuels were located and procured for this program. Four were market fuels, comprised of summer and winter grades, each having a low and high Particulate Matter Index (PMI). Emissions-grade certification fuel was also procured for testing alongside the market fuels. 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. This PUL fuel was supplied by a CRC member company unadditized but was additized to match TOP TIER® performance before use. The acquisition of the fuels occurred over a one-year period since no winter fuels of the desired PMI level were located within the 2020 high vapor pressure season.

With assistance from CRC members, appropriate fuels were identified at specific fuel terminals. SwRI then arranged to transport each fuel from the terminal using a tanker truck that was steam-cleaned, dried, and inspected before being sealed and dispatched to acquire the fuel. Figure 3 shows seals installed on one of the tanker trucks. When the truck arrived at SwRI, a sample of fuel was drawn and analyzed for key fuel properties. After approval, the fuel was offloaded into pre-inspected epoxy-phenolic lined drums and stored at 70°F. Results of the key properties from each fuel are shown in Table 3, and detailed analysis results are given in Appendix A. Appendix A also includes a detailed description of the fuel procurement process. Certification Tier 3 gasoline was purchased by SwRI from Haltermann Solutions. It was used for vehicle checkout tests and for E-122 tests. Certification fuel was shipped from the supplier in drums and the supplier's certificate of analysis is given in Appendix A. SwRI provided Tier 2 certification fuel for checkout tests on one vehicle because it was originally certified using Tier 2 protocol. This Tier 2 fuel is also given in Appendix A.

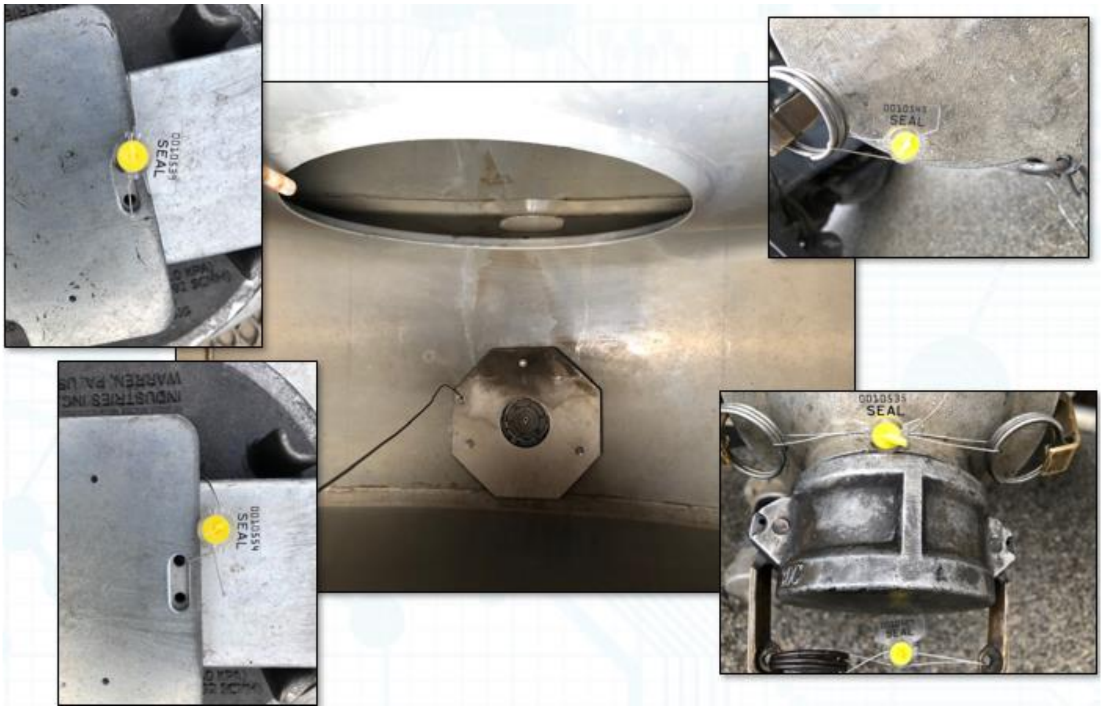


FIGURE 3. FUEL TANKER INSPECTION AND SEALS

TABLE 3. ANALYSIS RESULTS OF KEY FUEL PROPERTIES

Fuel ID	Code	Name	Ethanol vol%	PMI	RVP psi	FBP °F	Total Aromatics wt %	Notes
Fuel A	EM-10967	Certification E10	9.7	1.8	9.2	388	28	EPA Tier 3 EEE
Fuel B	GA-10940	Summer Low PMI E10	9.7	1.1	9.0	367	24	
Fuel C	GA-10920	Summer High PMI E10	9.5	1.9	7.7	408	33	
Fuel D	GA-11027	Winter Low PMI E10	9.6	0.7	15.3	344	26	
Fuel E	CGB-11093	Winter High PMI E10	10.2	1.8	13.6	392	33	PUL

3.2 Test Vehicles

Four vehicles were used in this project. CRC supplied one vehicle and SwRI purchased the other vehicles from local dealerships. Table 4 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. All technical issues involved with vehicles are given in Appendix B.

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
- Hybrid battery State of Charge (SOC) and hybrid mode while testing
- Vehicle load considerations due to the mass and aerodynamic drag of the PEMS

TABLE 4. 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 regular unleaded gasoline (RUL).
- 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 (NMHC, CO, CO_2, NO_X, and PM) were measured and provided to the CRC technical panel for final approval of the vehicle. All vehicles produced emissions well below their certification level. Table 5 gives the results from each checkout test.

TABLE 5. 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

3.2.2 SOC Investigation

In January 2020, development tests were conducted with the plug-in hybrid vehicle (Vehicle D) to investigate how the battery state of charge (SOC) was managed over the preconditioning and test procedures planned for this program. Results from these initial tests were discussed on January 14, 2020, in a project review meeting held at SwRI. During the meeting, a repeat of the test sequence was requested to investigate the consistency and repeatability of the results. Major steps in the E-122-2 test sequence are listed below.

E-122-2 Test Sequence:

1. Sulfur purge
2. Coast downs
3. 12-hour soak
4. Urban Dynamometer Driving Schedule (UDDS) + Highway Fuel Economy Test (HwFET) + HwFET + US06 Supplemental Federal Test Procedure (US06)
5. 12-hour soak
6. Cold-start LA92
7. 12-hour soak
8. Hot 505
9. 12-hour soak
10. E-122 test on chassis dyno
11. 12-hour soak
12. E-122 test on public road

For this SOC investigation, the high-voltage battery was connected to the vehicle's 120V plug-in hybrid charger and the vehicle's 12-volt battery was connected to a battery maintainer during overnight soaks. For each chassis dynamometer test, the vehicle was set to 2WD certification mode. Hybrid Vehicle (HV) mode was manually activated for on-road tests.

Table 6 summarizes the engine duty cycle and change in battery SOC (recorded from OBD) for each step of the procedure. The change in battery SOC was very small for each drive cycle. Both the initial and repeat test are given to assess repeatability. As expected, the engine runs for a larger percentage of time during high speed and high load cycles, such as the US06 and HwFET. Figure 4 shows the SOC over the entire test sequence and results from individual cycles are given in Appendix C. Engine operation differed between the two E-122 on-road cycles due to variability in traffic conditions. However, SOC remained consistent for these tests so SOC was not expected to negatively influence fuel economy measurements in the actual test matrix. Engine operation and SOC were very consistent when comparing the E-122 dyno cycles. As a result of these findings, all dyno tests in the project were operated with the vehicle in 2WD certification mode and all on-road tests were operated in HV mode.

TABLE 6. SUMMARY OF ENGINE RUN TIME AND SOC WITH VEHICLE D

	Checkout 1		Checkout 2	
	Engine Time On	ΔSOC	Engine Time On	ΔSOC
	[%]	[%]	[%]	[%]
Sulfur Purge & Coastdowns	24.5%	-0.39	24.0%	2.35
UDDS	25.8%	0.78	29.7%	0.39
2xHwFET	55.4%	-0.78	52.4%	-1.18
US06	67.5%	-1.57	68.8%	-1.96
LA92*	30.7%	0.39	29.7%	-1.18
H505	59.4%	-0.78	57.6%	0.00
E-122 On-Dyno	51.3%	1.18	51.0%	0.78
E-122 On-Road	42.8%	-0.78	42.9%	-0.39

*Not including soak

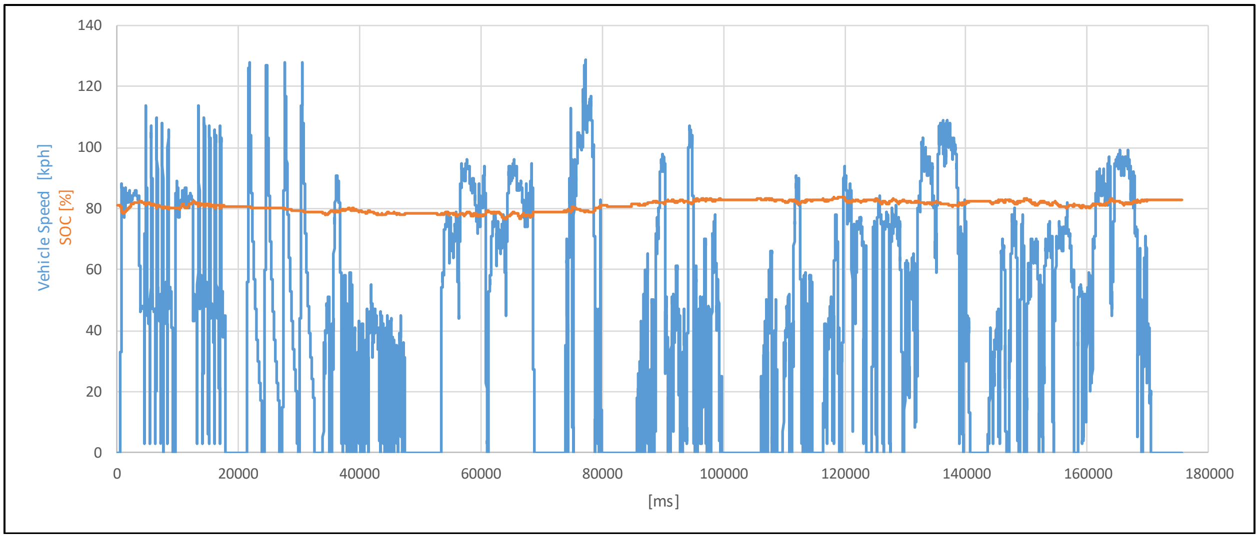


FIGURE 4. VEHICLE D STATE OF CHARGE OVER COMPLETE E-122-2 FUEL CHANGE AND TEST SEQUENCE

3.2.3 Vehicle Loading Due to PEMS

To investigate the change in vehicle road-load and inertia forces due to the PEMS, on-road coastdowns were conducted both with and without the PEMS attached to Vehicle A. Coastdowns were completed in January 2020, at Texas A&M's Rellis campus. Due to the limited length of the runway at Rellis, coastdowns were split into two speed ranges as described in SAE J2263. Figure 5 shows how the road load changed due to the addition of the PEMS.

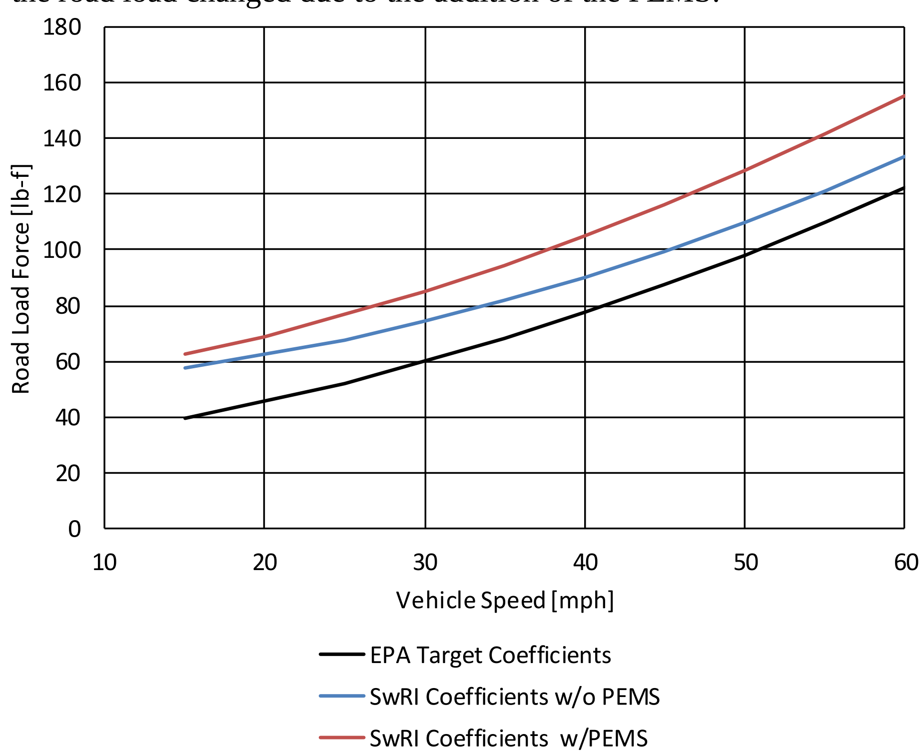


FIGURE 5. ON-ROAD COASTDOWN COMPARISON WITH VEHICLE A

To better understand the PEMS impact on vehicle loading, SAE J2951 driver metrics were calculated using the E-122 cycle and the measured on-road coast down results. Road load coefficients and inertia of the vehicle, with and without the PEMS, were fed into the J2951 method which calculates the energy required to drive a specific cycle. The coefficients found in EPA's Test Car List (TCL) were also fed into the method for comparison. Table 7 gives the results of these calculations showing a required total energy increase of 13% when the PEMS is mounted compared to the stock vehicle. Total energy is composed of inertial energy and road load energy. The increase in road load energy of 18% dominated the increase in inertia of 7%. To investigate the influence of this additional load on criteria pollutants, Vehicle A was tested on the dynamometer using the target settings measured with the PEMS attached. These "Heavy" tests were conducted with three of the test fuels.

TABLE 7. SAE J2951 DRIVE CYCLE METRICS RESULTS

	Dyno Target Settings				SAE J2951 Calculations		
Vehicle Configuration	Inertia (lbm)	A (lbf)	B (lbf/mph)	C (lbf/mph^2)	Total Energy (MJ)	Inertial Energy (MJ)	Road Load Energy (MJ)
EPA Test Car List	4750	26.79	0.6021	0.0166	25.7	12.08	13.62
Vehicle A without PEMS*	4828	49.94	0.2286	0.0195	27.8	12.28	15.49
Vehicle A with PEMS*	5172	48.03	0.6853	0.0185	31.5	13.16	18.31
Change due to PEMS, abs	344	-1.91	0.4567	-0.001	3.7	0.88	2.81
Change due to PEMS, %	7%	-4%	200%	-5%	13%	7%	18%
*Dyno target settings measured from SwRI on-road coastdowns							

PM and emissions results from dynamometer tests using the EPA coefficients and "heavy" coefficients were compared with on-road results. Only chassis dynamometer results measured via the PEMS was used in the comparison, as to not confound the comparison with measurement instrument differences. Box plots of the emissions data are shown in Figure 6 to Figure 11. To summarize the results, a model was run to account for fuel differences with variables "fuel" and "test type," where the latter was a three-level categorical variable with levels "Road Test," "Dyno EPA Coefficients," and "Dyno Heavy Coefficients." The model accounts for the fuel differences and then calculates a least squares (LS) mean for each test type. The LS means summary table is given below in Table 8**.** In the table, relative differences are also provided showing the relative differences of each set of coefficients when compared to the road test results.

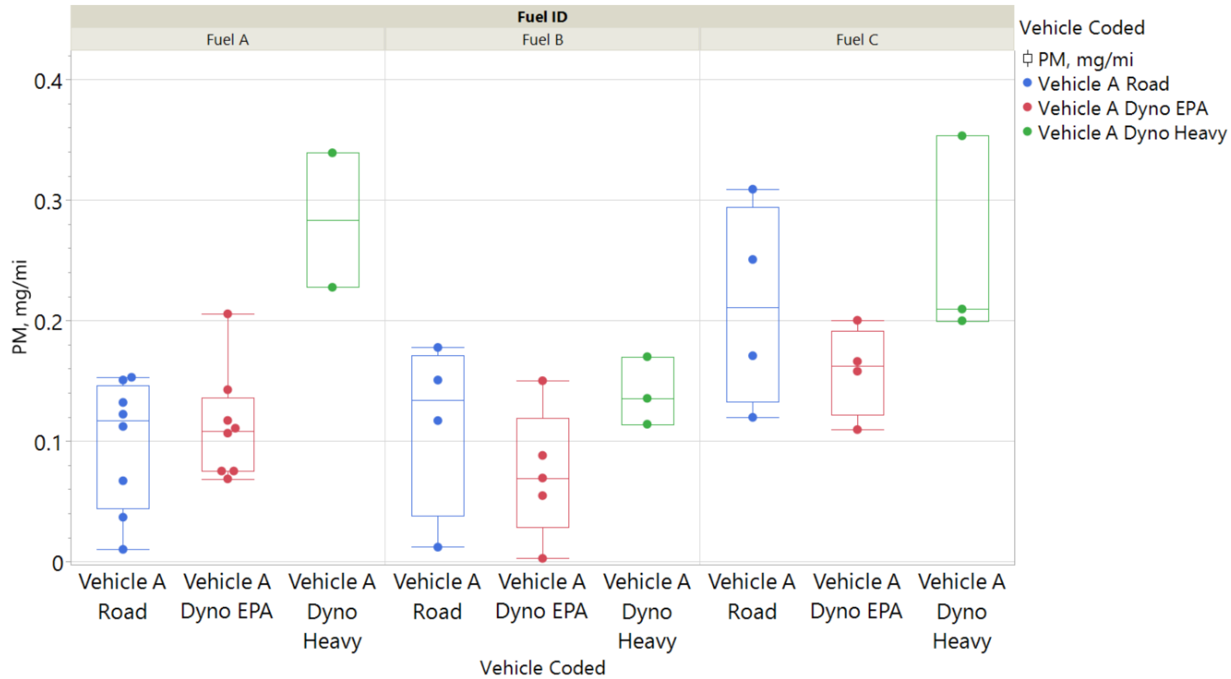


FIGURE 6. VEHICLE A PM DATA COMPARING ROAD TESTS TO SIMILAR DYNO TESTS WITH DIFFERENT COEFFICIENT SETS

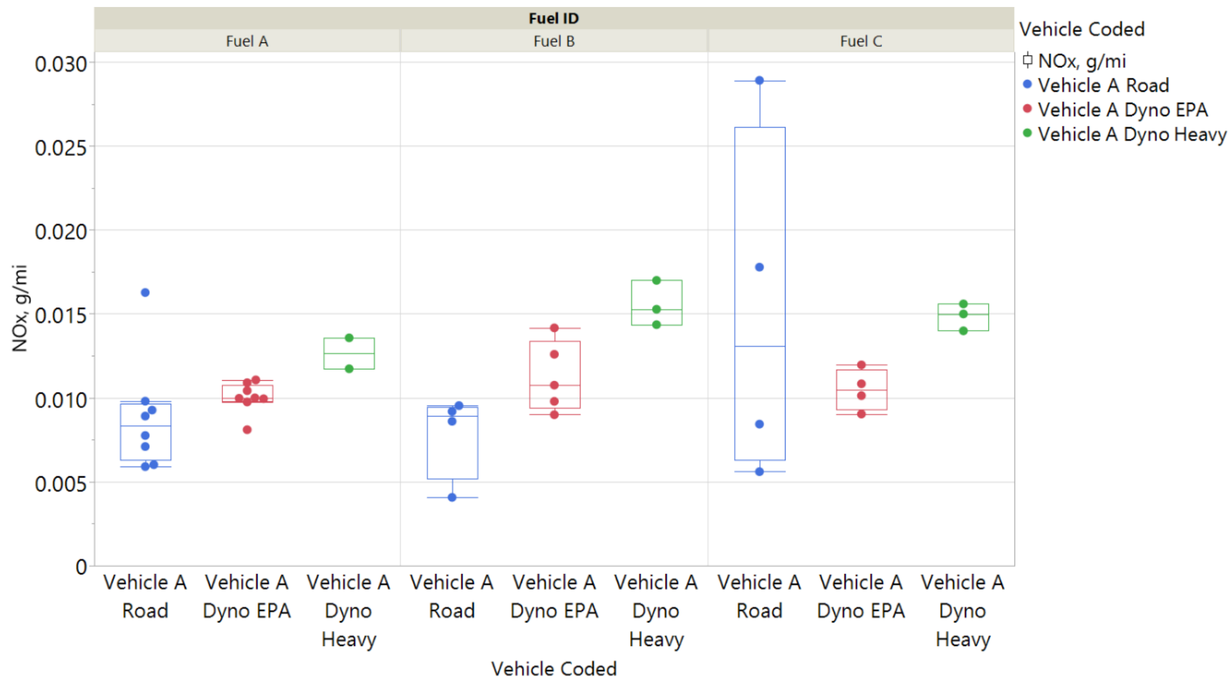


FIGURE 7. VEHICLE A NO_X DATA COMPARING ROAD TESTS TO SIMILAR DYNO TESTS WITH DIFFERENT COEFFICIENT SETS

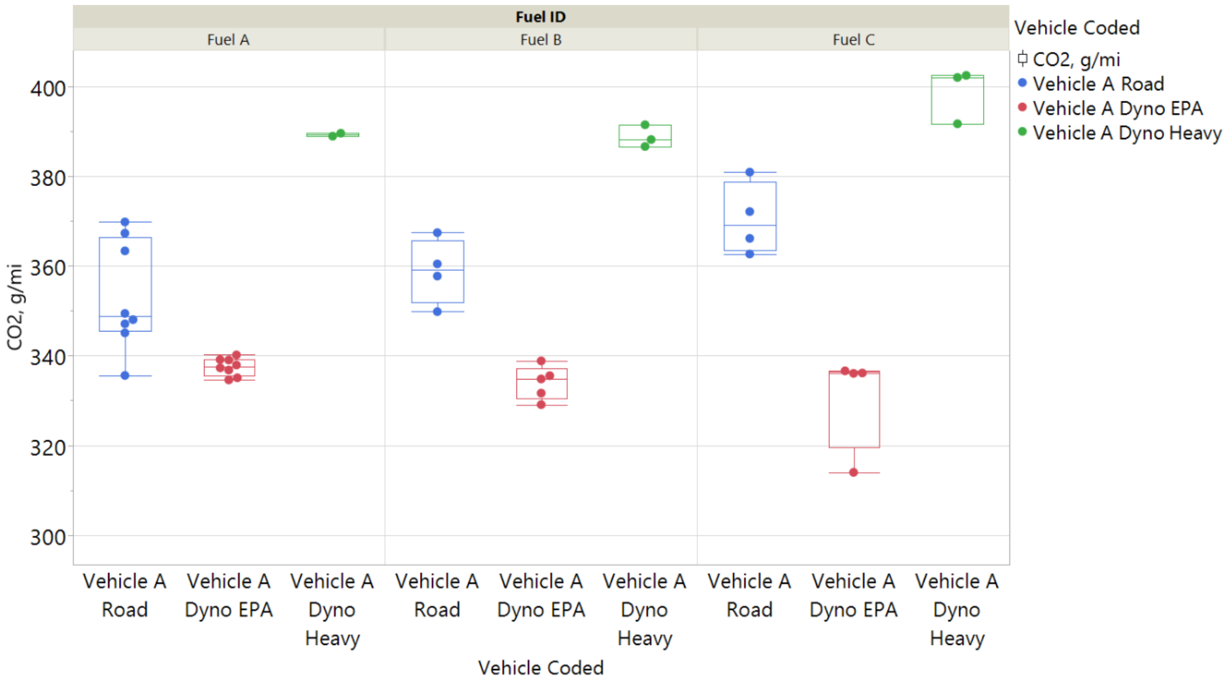


FIGURE 8. VEHICLE A CO_2 DATA COMPARING ROAD TESTS TO SIMILAR DYNO TESTS WITH DIFFERENT COEFFICIENT SETS

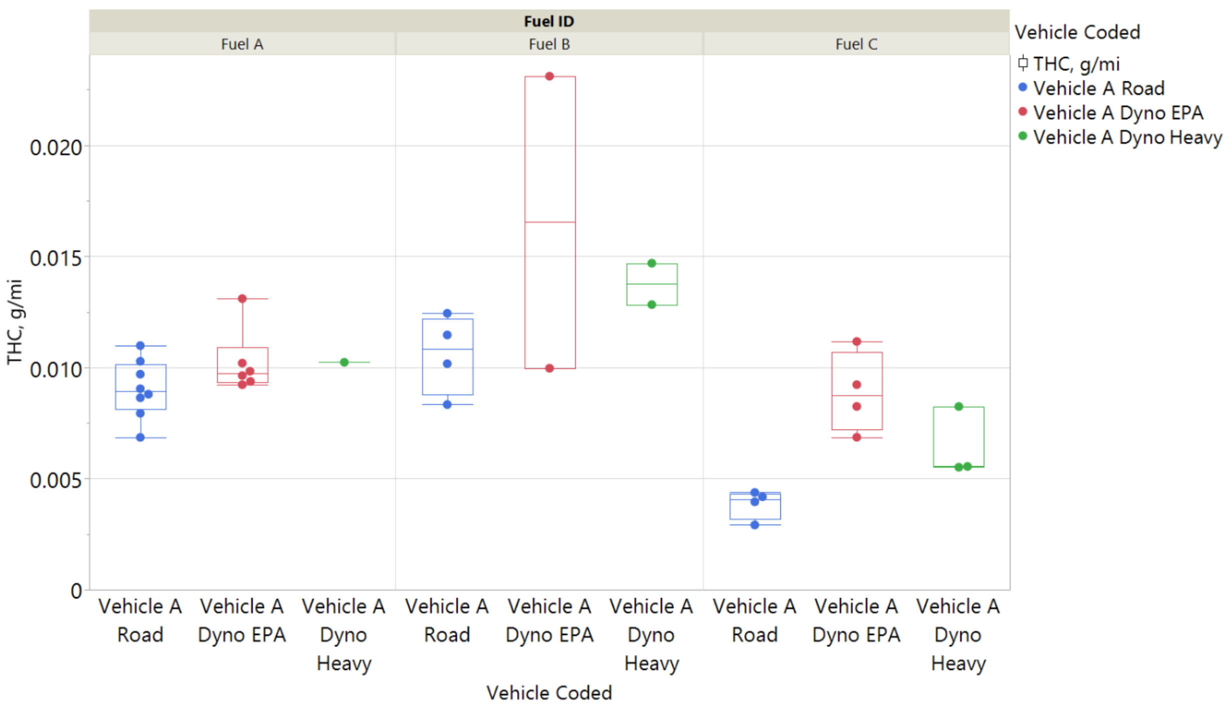


FIGURE 9. VEHICLE A THC DATA COMPARING ROAD TESTS TO SIMILAR DYNO TESTS WITH DIFFERENT COEFFICIENT SETS

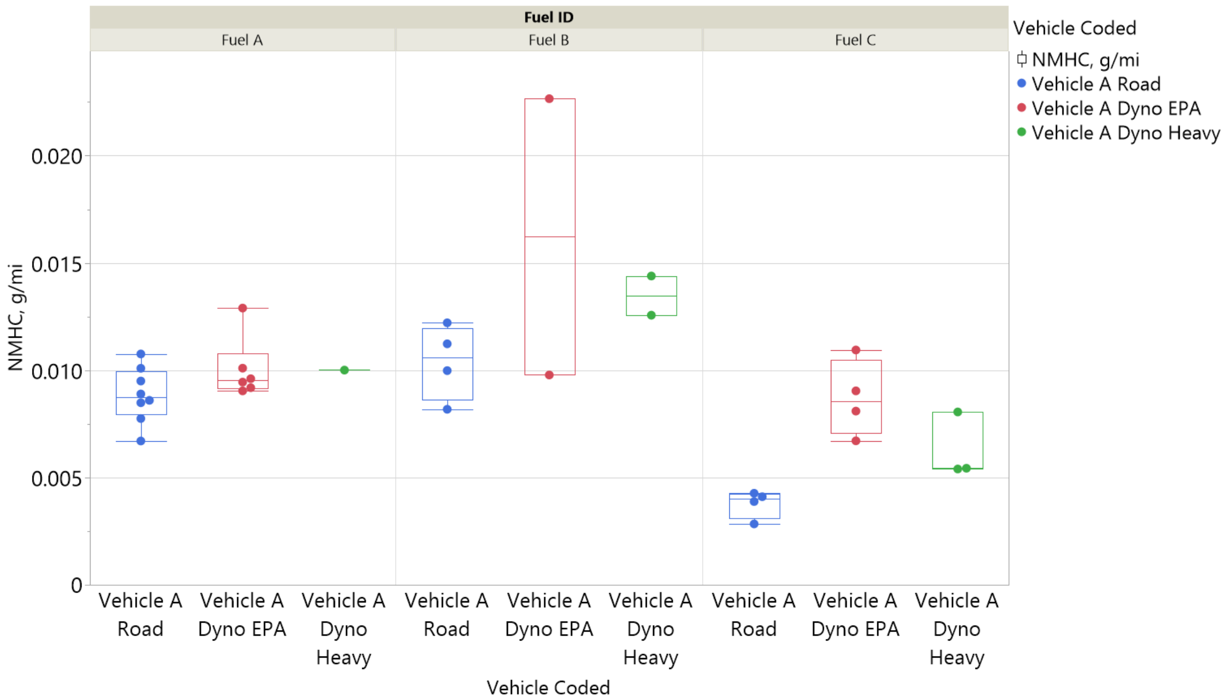


FIGURE 10. VEHICLE A NMHC DATA COMPARING ROAD TESTS TO SIMILAR DYNO TESTS WITH DIFFERENT COEFFICIENT SETS

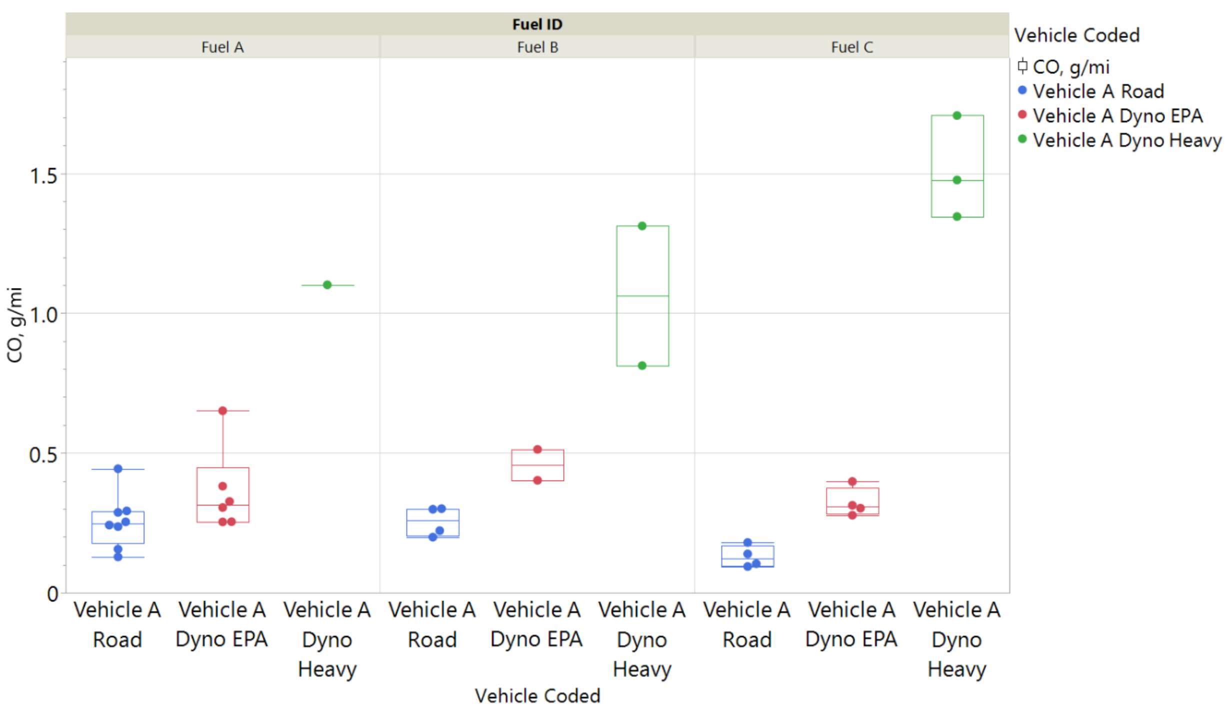


FIGURE 11. VEHICLE A CO DATA COMPARING ROAD TESTS TO SIMILAR DYNO TESTS WITH DIFFERENT COEFFICIENT SETS

TABLE 8. LEAST SQUARES (LS) MEANS COMPARING DYNO COEFFICIENTS TO ROAD TESTS

Parameter	Road Test LS Mean	EPA Coef. LS Mean (Relative change from Road)	Heavy Coef. LS Mean (Relative change from Road)
PM (mg/mi)	0.133	0.117 (-12%)	0.217 (63%)
NO_x (g/mi)	0.0105	0.0108 (3%)	0.0144 (37%)
CO_2 (g/mi)	359.5	335.5 (-7%)	392.3 (9%)
THC (g/mi)	0.0081	0.0114 (40%)	0.0101 (24%)
NMHC (g/mi)	0.0080	0.0112 (40%)	0.0099 (24%)
CO (g/mi)	0.222	0.361 (62%)	1.291 (481%)

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 11, 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.

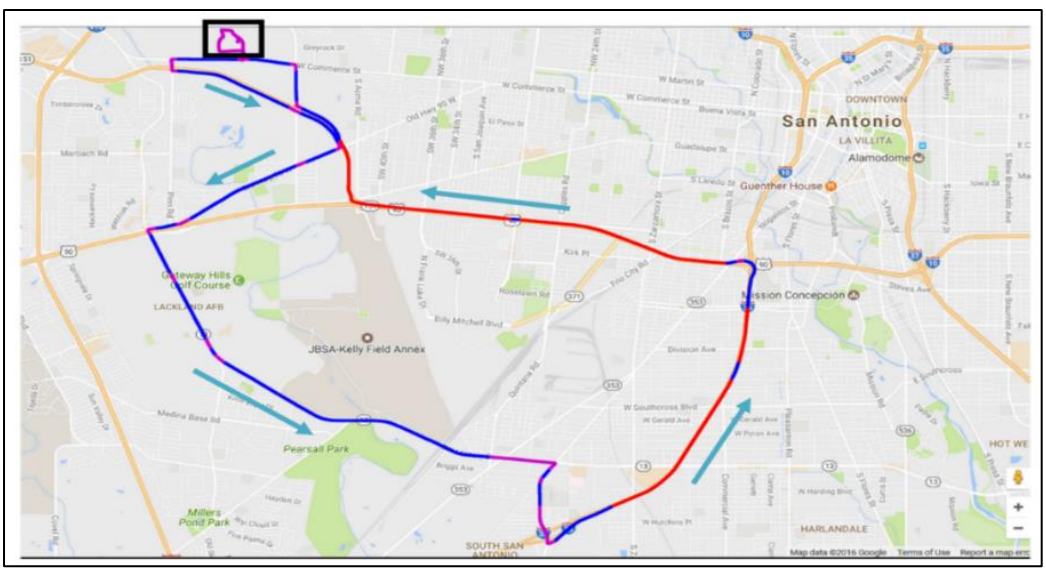


FIGURE 12. E-122 TEST ROUTE

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. Figure 13 shows the modified E-122-2 cycle that includes the additional idle time. The modified cycle was used for all tests in this project.

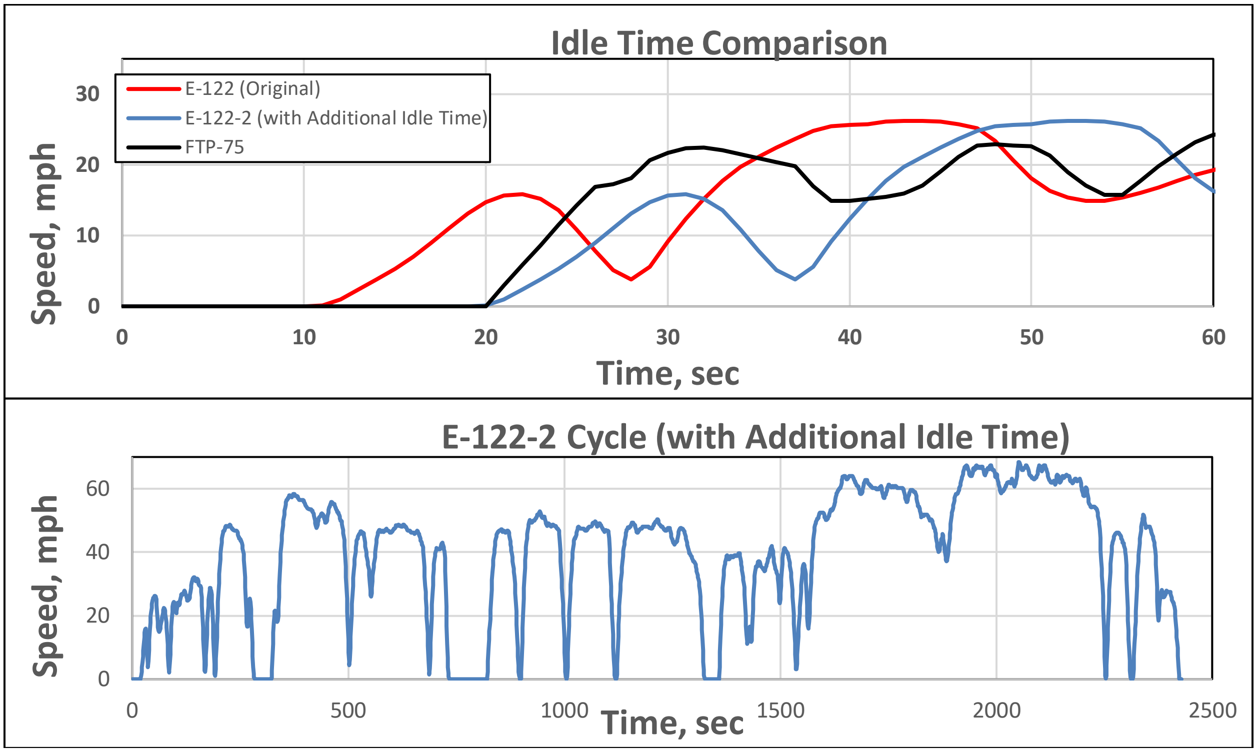


FIGURE 13. MODIFIED E-122 CYCLE TO INCLUDE TEN ADDITIONAL SECONDS OF IDLE

3.3.1 Route Consistency

To assess consistency of the on-road route, four repeats were driven with Vehicle B. Start-times were chosen to mimic testing with the full, four-vehicle fleet. Twenty-one parameters were logged from the vehicle's CAN bus including vehicle speed, accelerator pedal position and engine run time. Table 9 summarizes data from the four tests and compares against the E-122 dyno schedule.

Distance was very consistent for each run. Drive time, average speed, and fuel economy were also reasonably consistent for three out of the four runs. During the last run, a pedestrian on the highway and an active school zone slowed traffic. This run appeared to be an outlier compared to the runs conducted earlier in the day.

TABLE 9. VEHICLE B, ON-ROAD TEST DATA

		1st Run	2nd Run	3rd Run	4th Run	**Average**	E-122 Dyno Schedule
Start Time		9:09:55 AM	10:37:14 AM	12:59:37 PM	2:39:49 PM		
Distance (dash)	mi	26.3	26.3	26.3	26.3	**26.3**	26.7
Engine-on time (OBD)	s	2495	2543	2504	2752	**2574**	n/a
Avg. Speed (dash)	mph	39	38	39	35	**38**	39.6
# of Stops	int	15	13	14	16	**14.5**	8
% idle	%	8.1	9.3	8.3	11.3	**9.3**	8
Avg. Fuel Economy (dash)	mpg	29	28.5	29.7	27.6	**28.7**	n/a
Notes			Had to aggressively pass 18-wheeler on IH-35 onramp		School Zone Traffic stopped on IH-35: pedestrian on the highway picking up lost load		

Three items stood out as impacting the consistency of the driving route:

1. After turning onto some roads of the route, the speed limit is not posted until a few miles down the road. The driver does not know the speed limit, which causes variability in the driving route. To mitigate this, the on-road route was loaded into Google Maps, which provides real-time speed limit and traffic information. This information was used to improve consistency for future on-road tests.

2. On all runs, the test vehicle was frequently caught behind bus route 102 on W Military Dr. To mitigate this, future runs stayed in the middle lane of that road. Figure 14 shows this bus route; the E-122 cycle stretches from point A to roughly point C on this map.

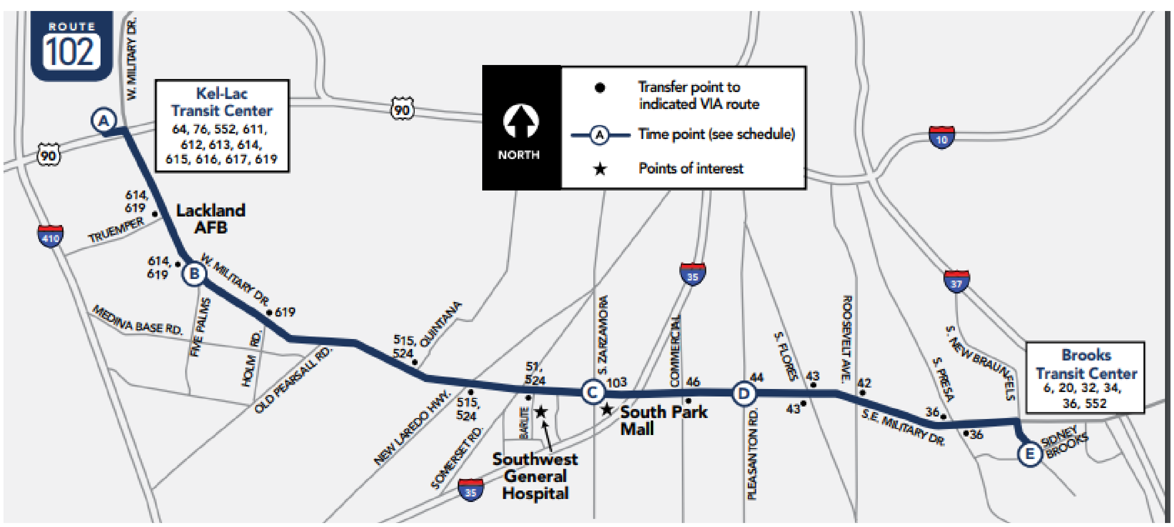


FIGURE 14. BUS ROUTE 102

3. In the last run, a school zone was active on Palo Alto road just before the turn-off onto IH-35 for an elementary and high school. This added a significant amount time to the driving route. To mitigate the impact of the school zone, the start time for future tests was targeted between 9:00AM and 2:00PM.

Figure 15 and Figure 16 show the four on-road tests superimposed on the E-122 dyno drive cycle. The 1st and 2nd runs were split up from the 3rd and 4th runs to make these plots easier to visualize. All four on-road tests took longer than the dyno drive cycle, with the 4th run being an outlier due to a school zone and stopped traffic on IH-35.

FIGURE 15. 1ST AND 2ND ON-ROAD TESTS WITH VEHICLE B

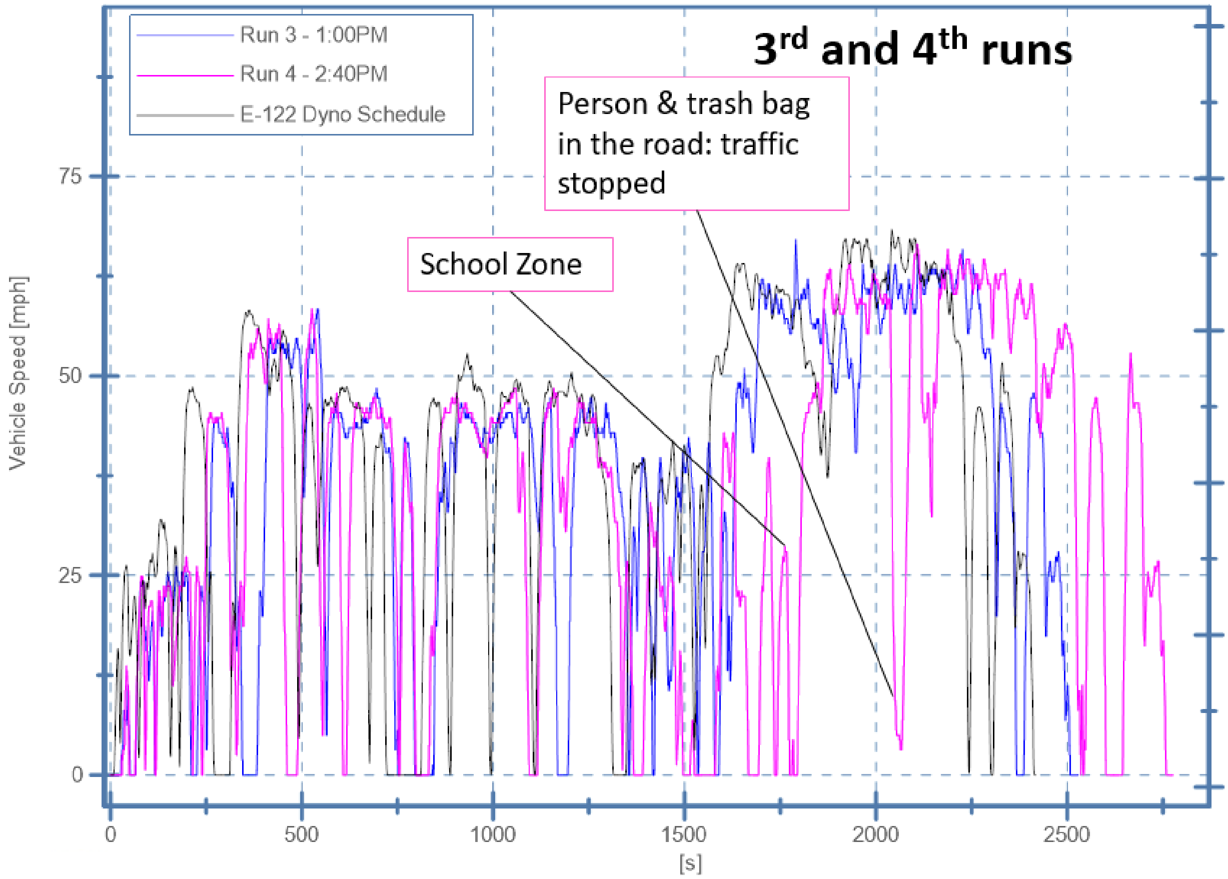


FIGURE 16. 3RD AND 4TH ON-ROAD TESTS WITH VEHICLE B

3.3.2 Route Changes and Road Closures

Two route issues were identified before road testing began. The first issue 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 constancy for all on-road tests, an alternate gate was selected. This did not add any additional distance to the route. Figure 17 shows both route changes.

FIGURE 17. ROUTE CHANGES DUE TO CONSTRUCTION AND COVID

Three of the test vehicles encountered a temporary road closure during official testing and were forced to take a detour as shown in Figure 18. The road reopened prior to the fourth vehicle test that day. The driver used the shortest possible detour for these tests which resulted in approximately 1.5 additional miles. The detour did not have a significant effect on the emission results. No repeat tests were conducted for these tests.

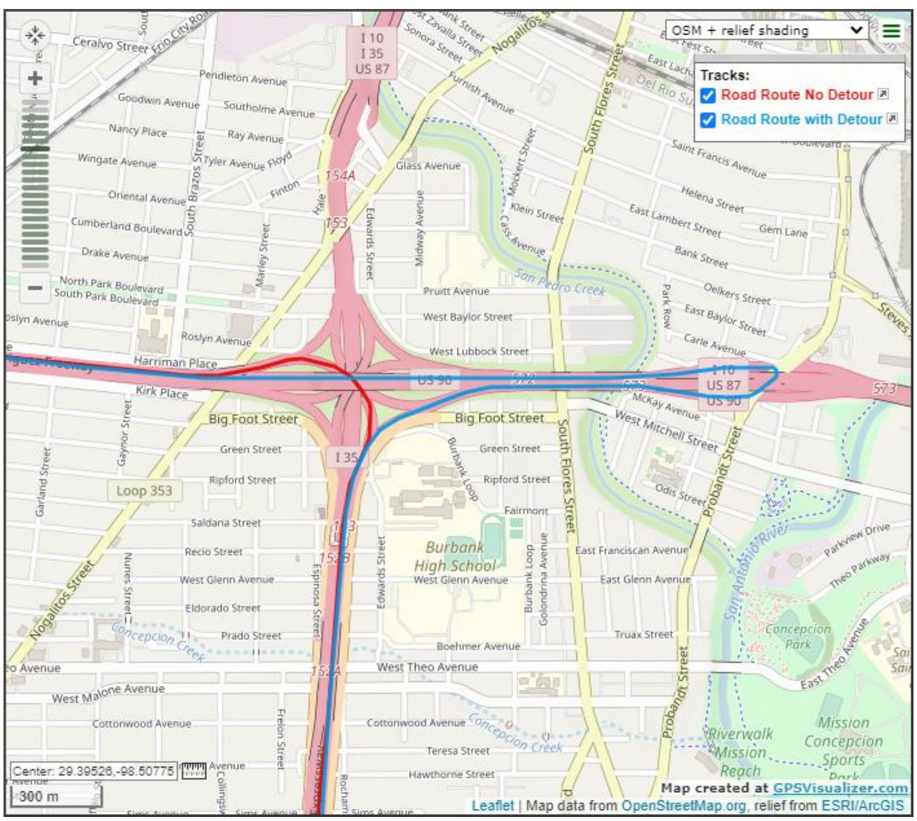


FIGURE 18. ROAD ROUTE WITH AND WITHOUT DETOUR

3.4 PEMS

CRC purchased a new Sensors LDV PEMS for this program. The system was shipped directly to SwRI from the manufacturer and arrived 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 19 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 19. PEMS INITIAL INSPECTION AND ASSEMBLY

All PEMS components were mounted external to the vehicle on a carrier rack shown in Figure 20. The PEMS, battery power supply, FID fuel, and mounting rack weighed 344 pounds. To investigate the influence of the additional weight and aerodynamic drag added by the PEMS, one of the vehicles was tested with dynamometer settings that simulated the additional PEMS loading. These "heavy" tests were conducted using three fuels and results were compared to tests using dynamometer settings given in the vehicle's EPA certification document.

FIGURE 20. PEMS MOUNTED TO TEST VEHICLE

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 D. 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 21 shows pictures taken during the LFE portion of the verification.

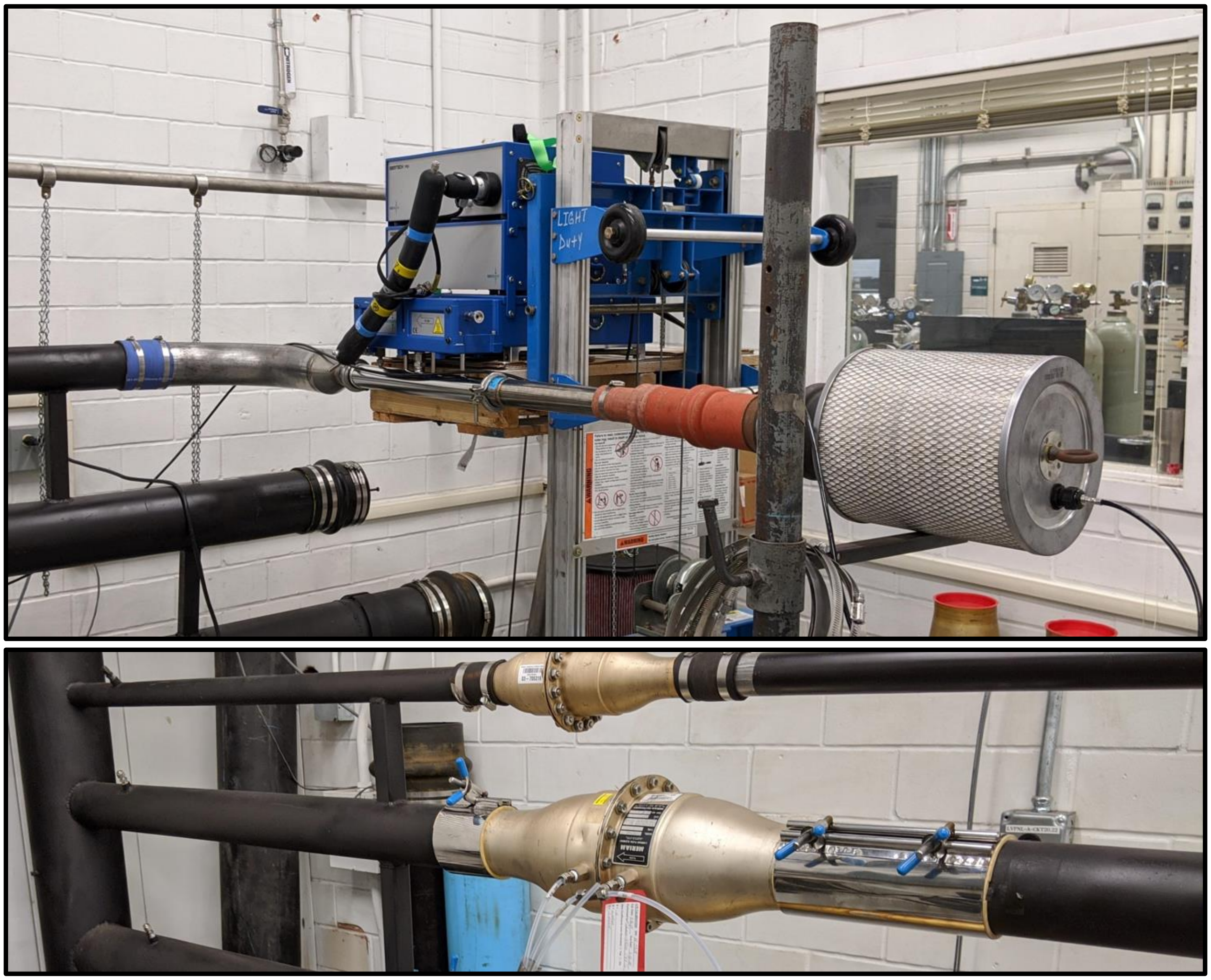


FIGURE 21. EFM CALIBRATION

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 slope. Figure 22 and Table 10 give the individual data points and the resulting 1065 linearization results and pass/fail criteria from the initial verification. Red data points were measured with an LFE, and blue data points were measured with a Micromotion.

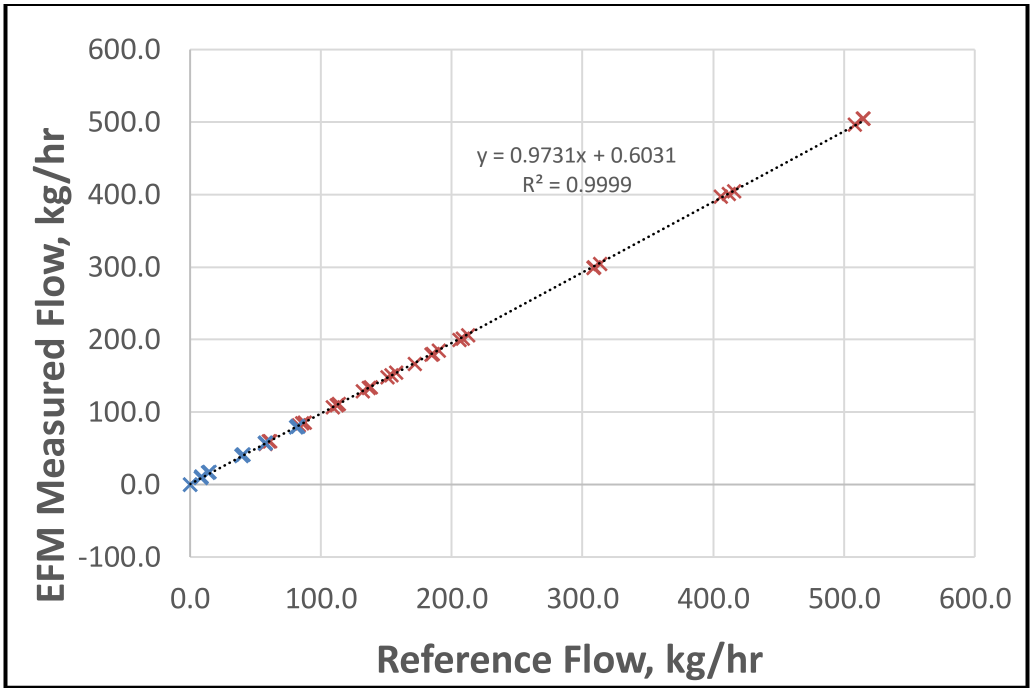


FIGURE 22. REFERENCE VS. MEASURED FLOW FROM INITIAL EFM VERIFICATION

TABLE 10. 1065 ACCEPTANCE CRITERIA FROM INITIAL EFM VERIFICATION

Statistic	Result	1065 Criteria	Pass/Fail
Slope (M)	0.97	0.98-1.02	Fail
Intercept (%)	0.117%	≤ 1 % Max	Pass
SEE (%)	0.258%	≤ 2 % Max	Pass
R2	1.000	≥ 0.990	Pass
NPoints	49	≥ 10	Pass

SwRI sent these 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 23 and Table 11 give the new results showing compliance with 1065 criteria.

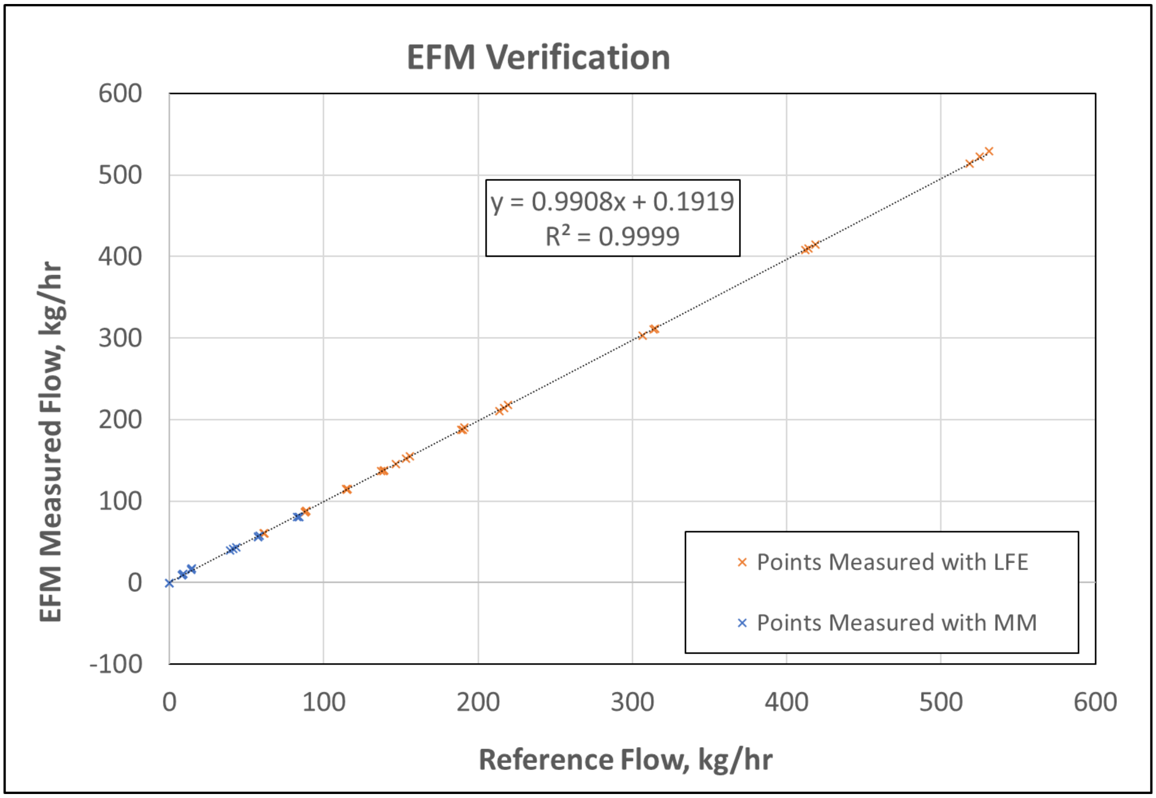


FIGURE 23. REFERENCE VS. MEASURED FROM SECOND EFM VERIFICATION

TABLE 11. 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

The PEMS EFM was also compared to the exhaust flow measured by the chassis dynamometer's Constant Volume Sampler (CVS) after correcting the EFM's linear discharge coefficient. Figure 24 shows the exhaust flow measured by both systems during an E-122 test with the plug-in hybrid vehicle. The figure shows measured instantaneous flow and cumulative exhaust volume over the entire cycle. The test-total accumulated volume measured by the PEMS was approximately five percent higher compared to the CVS for this particular run. The accumulated volume measured by the two systems matched within one percent for the first half of the test and began to diverge during the high-speed portion of the cycle. Agreement between instantaneous exhaust flow measurements was good during steady-state conditions and moderate exhaust flow rates. Disagreement between the measurements was greatest during flow spikes and transient conditions. Mass emission results are calculated using the instantaneous exhaust flow and instantaneous pollutant concentration at each time step. Pollutant concentrations are generally higher during the cold-start phase of a test where the exhaust flow measurements agreed.

Therefore, a general correlation was not identified to link the differences in exhaust flow measurement to final mass emission results.

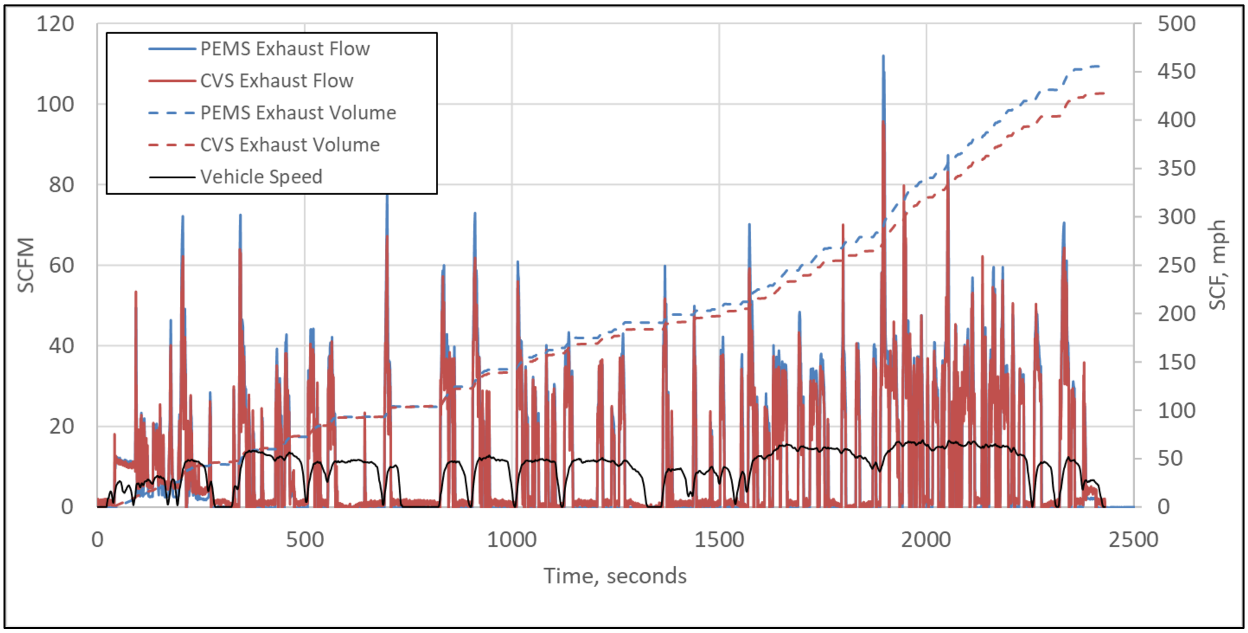


FIGURE 24. PEMS VS CVS EXHAUST FLOW MEASUREMENT

3.4.2 PEMS Sensitivity to Temperature

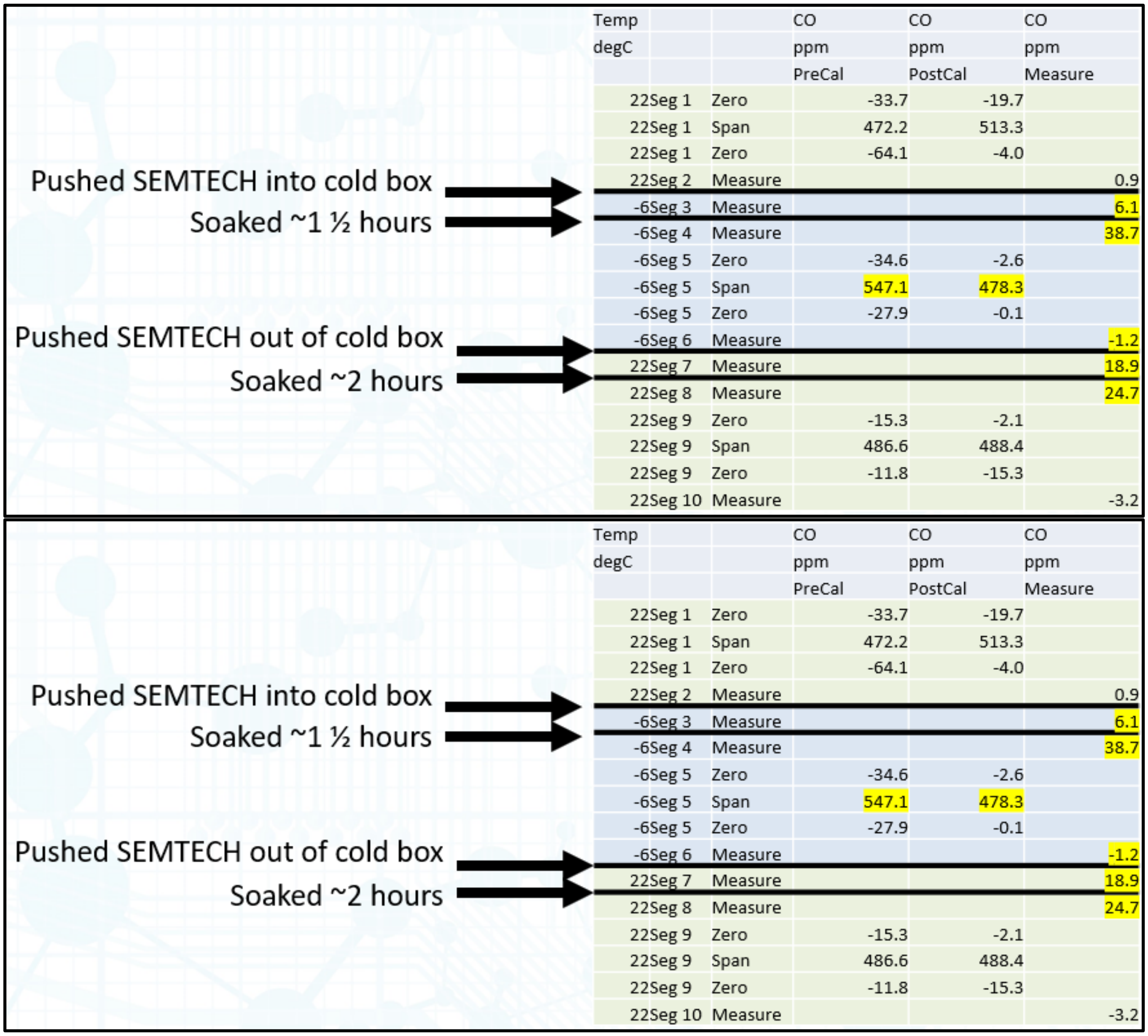
There was concern from the CRC committee that changes in ambient temperature might induce significant drift in the PEMS analyzer response. The original test plan called for soaking the PEMS and vehicle inside the temperature-controlled soak space overnight, pushing the vehicle outside, and immediately starting a cold-start on-road test. If outdoor conditions are significantly hotter or colder than soak conditions, the ambient temperature of the PEMS would change suddenly, possibly causing drift in the emission measurements.

To investigate this concern, the PEMS was tested for drift by exposing the unit to a hot and cold step changes from ambient temperature. SwRI's temperature-controlled enclosure (TCEE) was used to induce a step change from 22°C to 35°C and from 22°C to -6°C. For each step change, the following sequence was conducted:

1. Soak PEMS at 22 °C
2. Conduct zero-span-zero procedure
3. Sample ambient air for 5 minutes
4. Push PEMS into TCEE (stabilized at 35 °C or -6 °C)
5. Immediately sample ambient air for 5 minutes
6. Allow PEMS to soak at TCEE temperature (35 °C or -6 °C) for 1-2 hours
7. Sample ambient air for 5 minutes
8. Conduct zero-span-zero procedure
9. Sample ambient air for 5 minutes

10. Push PEMS into 22 °C soak space
11. Immediately sample ambient air for 5 minutes

A 38-ppm increase in CO ambient air measurement was observed when the PEMS was calibrated at ambient temperature and then moved to cold temperature. A 60-ppm decrease in THC ambient air measurement was observed when the PEMS was calibrated at the cold temperature and then moved back to ambient. No major shifts were observed with the hot temperature step changes. The detailed results from this study are shown in Figure 25 through Figure 28.

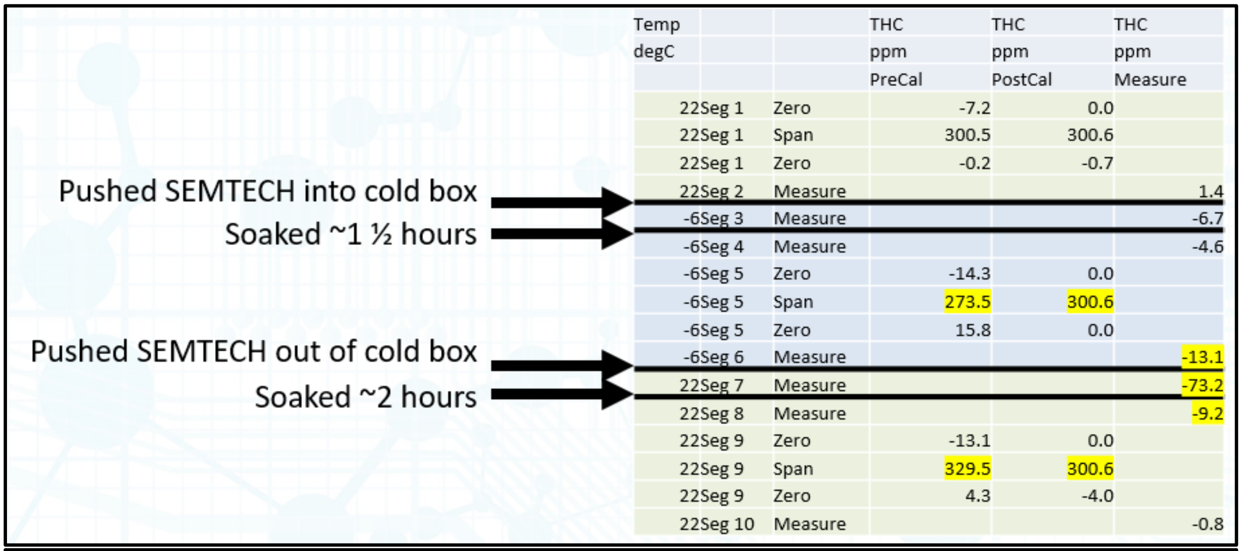


Temp degC			CO ppm PreCal	CO ppm PostCal	CO ppm Measure
22	Seg 1	Zero	-33.7	-19.7	
22	Seg 1	Span	472.2	513.3	
22	Seg 1	Zero	-64.1	-4.0	
22	Seg 2	Measure			0.9
-6	Seg 3	Measure			6.1
-6	Seg 4	Measure			38.7
-6	Seg 5	Zero	-34.6	-2.6	
-6	Seg 5	Span	547.1	478.3	
-6	Seg 5	Zero	-27.9	-0.1	
-6	Seg 6	Measure			-1.2
22	Seg 7	Measure			18.9
22	Seg 8	Measure			24.7
22	Seg 9	Zero	-15.3	-2.1	
22	Seg 9	Span	486.6	488.4	
22	Seg 9	Zero	-11.8	-15.3	
22	Seg 10	Measure			-3.2

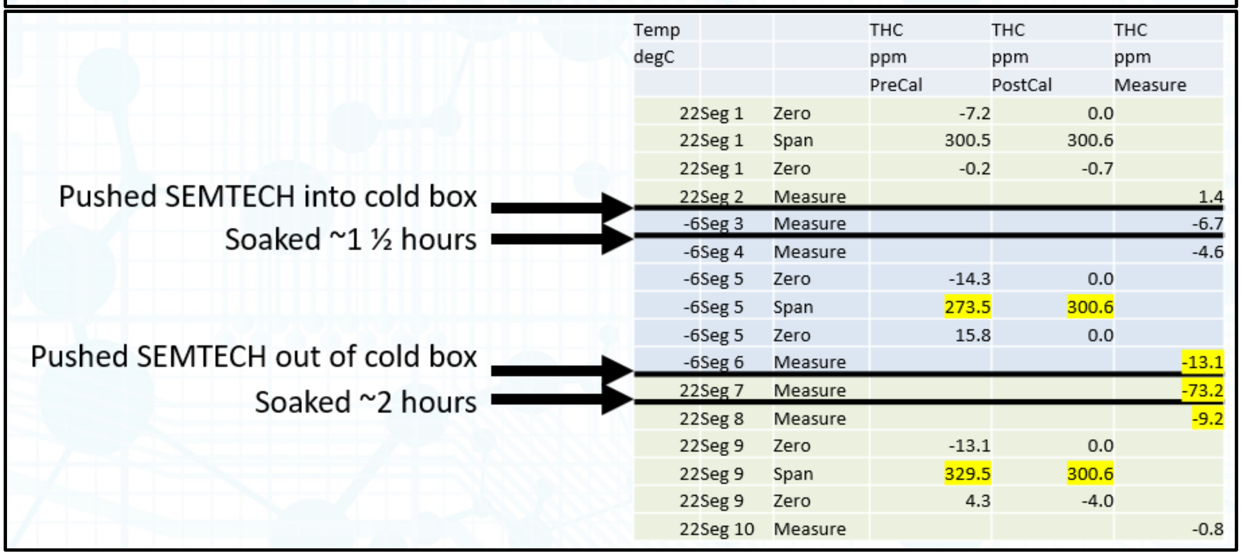
Pushed SEMTECH into cold box
Soaked ~1 ½ hours
Pushed SEMTECH out of cold box
Soaked ~2 hours

Temp degC			CO ppm PreCal	CO ppm PostCal	CO ppm Measure
22	Seg 1	Zero	-33.7	-19.7	
22	Seg 1	Span	472.2	513.3	
22	Seg 1	Zero	-64.1	-4.0	
22	Seg 2	Measure			0.9
-6	Seg 3	Measure			6.1
-6	Seg 4	Measure			38.7
-6	Seg 5	Zero	-34.6	-2.6	
-6	Seg 5	Span	547.1	478.3	
-6	Seg 5	Zero	-27.9	-0.1	
-6	Seg 6	Measure			-1.2
22	Seg 7	Measure			18.9
22	Seg 8	Measure			24.7
22	Seg 9	Zero	-15.3	-2.1	
22	Seg 9	Span	486.6	488.4	
22	Seg 9	Zero	-11.8	-15.3	
22	Seg 10	Measure			-3.2

FIGURE 25. CO STEP CHANGE: -6 °C

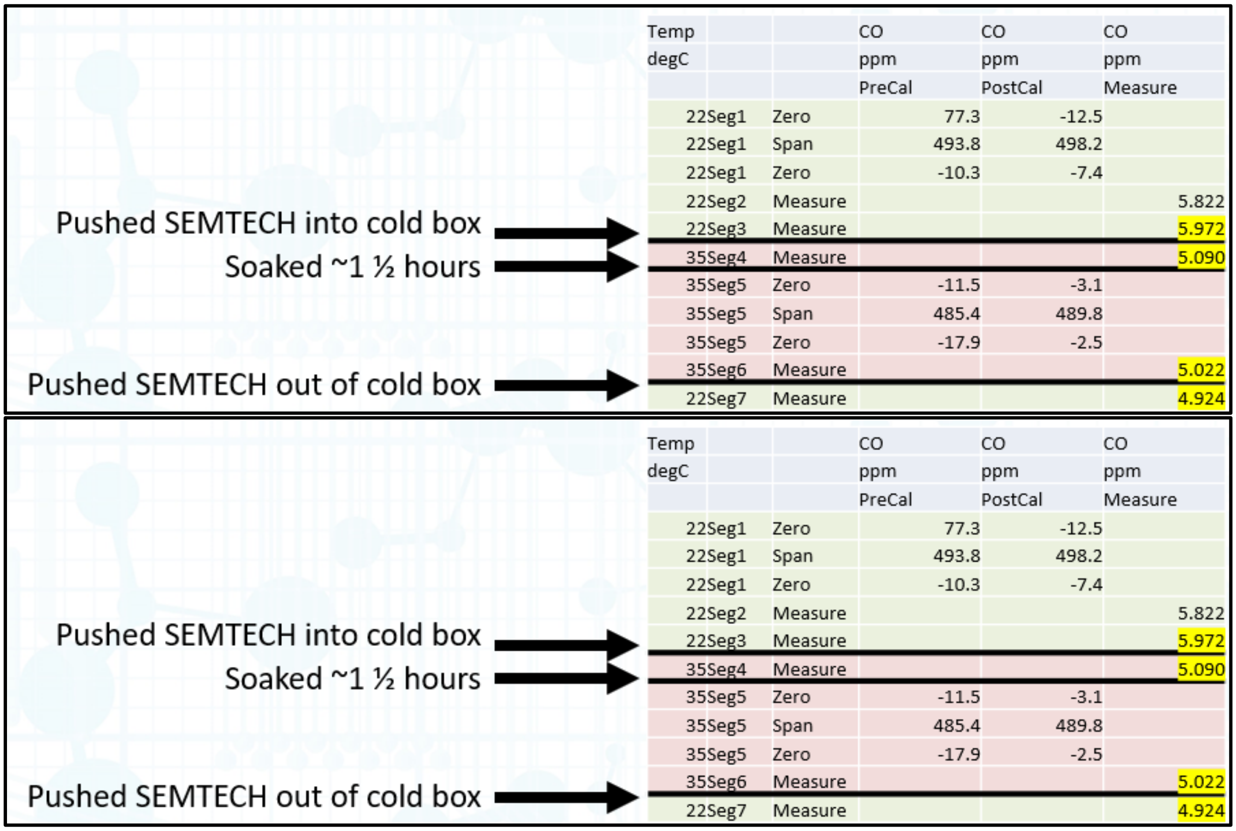


Temp degC			THC ppm PreCal	THC ppm PostCal	THC ppm Measure
22	Seg 1	Zero	-7.2	0.0	
22	Seg 1	Span	300.5	300.6	
22	Seg 1	Zero	-0.2	-0.7	
22	Seg 2	Measure			1.4
-6	Seg 3	Measure			-6.7
-6	Seg 4	Measure			-4.6
-6	Seg 5	Zero	-14.3	0.0	
-6	Seg 5	Span	273.5	300.6	
-6	Seg 5	Zero	15.8	0.0	
-6	Seg 6	Measure			-13.1
22	Seg 7	Measure			-73.2
22	Seg 8	Measure			-9.2
22	Seg 9	Zero	-13.1	0.0	
22	Seg 9	Span	329.5	300.6	
22	Seg 9	Zero	4.3	-4.0	
22	Seg 10	Measure			-0.8


Pushed SEMTECH into cold box
Soaked ~1 ½ hours
Pushed SEMTECH out of cold box
Soaked ~2 hours

Temp degC			THC ppm PreCal	THC ppm PostCal	THC ppm Measure
22	Seg 1	Zero	-7.2	0.0	
22	Seg 1	Span	300.5	300.6	
22	Seg 1	Zero	-0.2	-0.7	
22	Seg 2	Measure			1.4
-6	Seg 3	Measure			-6.7
-6	Seg 4	Measure			-4.6
-6	Seg 5	Zero	-14.3	0.0	
-6	Seg 5	Span	273.5	300.6	
-6	Seg 5	Zero	15.8	0.0	
-6	Seg 6	Measure			-13.1
22	Seg 7	Measure			-73.2
22	Seg 8	Measure			-9.2
22	Seg 9	Zero	-13.1	0.0	
22	Seg 9	Span	329.5	300.6	
22	Seg 9	Zero	4.3	-4.0	
22	Seg 10	Measure			-0.8

FIGURE 26. THC STEP CHANGE: -6 °C

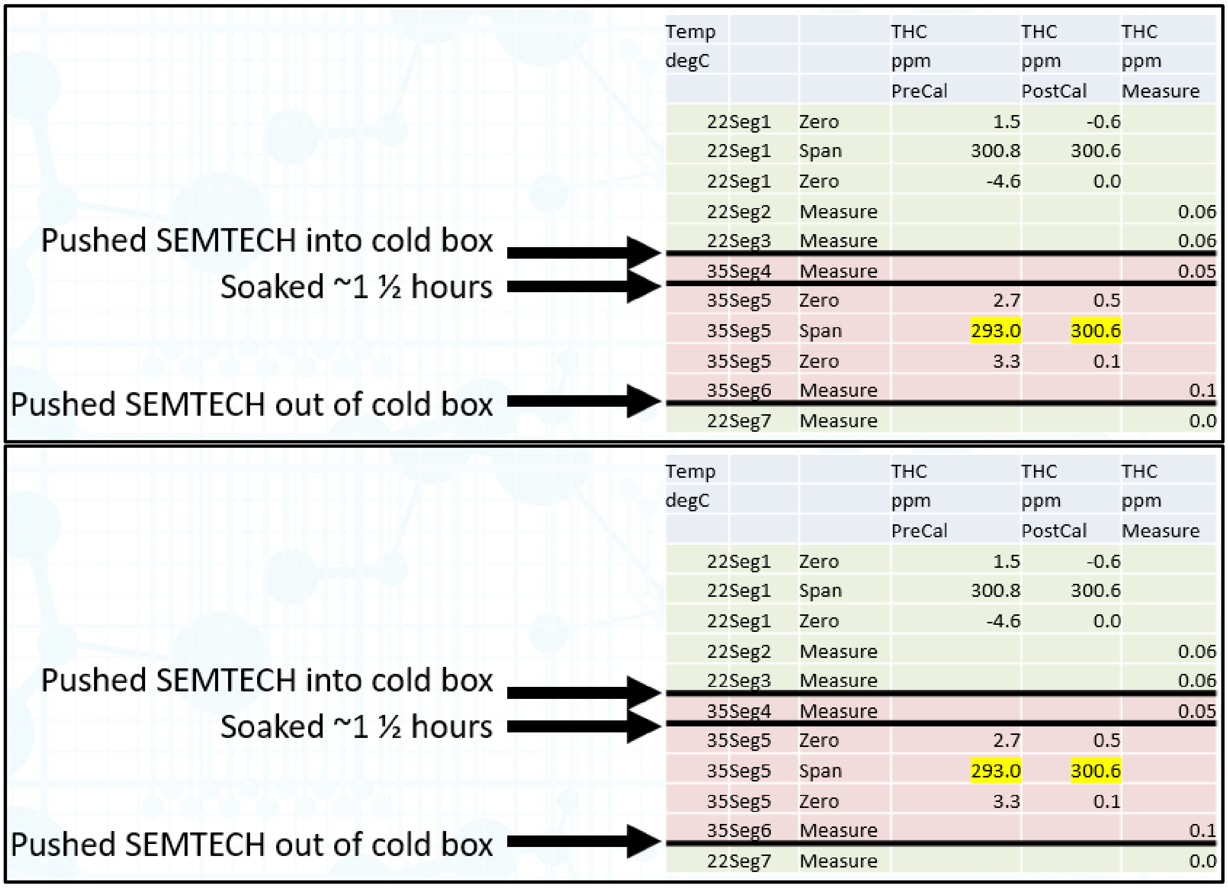


Temp degC		CO ppm PreCal	CO ppm PostCal	CO ppm Measure
22Seg1	Zero	77.3	-12.5	
22Seg1	Span	493.8	498.2	
22Seg1	Zero	-10.3	-7.4	
22Seg2	Measure			5.822
22Seg3	Measure			5.972
35Seg4	Measure			5.090
35Seg5	Zero	-11.5	-3.1	
35Seg5	Span	485.4	489.8	
35Seg5	Zero	-17.9	-2.5	
35Seg6	Measure			5.022
22Seg7	Measure			4.924

Pushed SEMTECH into cold box
Soaked ~1 ½ hours
Pushed SEMTECH out of cold box

Temp degC		CO ppm PreCal	CO ppm PostCal	CO ppm Measure
22Seg1	Zero	77.3	-12.5	
22Seg1	Span	493.8	498.2	
22Seg1	Zero	-10.3	-7.4	
22Seg2	Measure			5.822
22Seg3	Measure			5.972
35Seg4	Measure			5.090
35Seg5	Zero	-11.5	-3.1	
35Seg5	Span	485.4	489.8	
35Seg5	Zero	-17.9	-2.5	
35Seg6	Measure			5.022
22Seg7	Measure			4.924

FIGURE 27. CO STEP CHANGE: 35 °C



Temp degC			THC ppm PreCal	THC ppm PostCal	THC ppm Measure
22	Seg1	Zero	1.5	-0.6	
22	Seg1	Span	300.8	300.6	
22	Seg1	Zero	-4.6	0.0	
22	Seg2	Measure			0.06
22	Seg3	Measure			0.06
35	Seg4	Measure			0.05
35	Seg5	Zero	2.7	0.5	
35	Seg5	Span	293.0	300.6	
35	Seg5	Zero	3.3	0.1	
35	Seg6	Measure			0.1
22	Seg7	Measure			0.0

Pushed SEMTECH into cold box
Soaked ~1 ½ hours
Pushed SEMTECH out of cold box

Temp degC			THC ppm PreCal	THC ppm PostCal	THC ppm Measure
22	Seg1	Zero	1.5	-0.6	
22	Seg1	Span	300.8	300.6	
22	Seg1	Zero	-4.6	0.0	
22	Seg2	Measure			0.06
22	Seg3	Measure			0.06
35	Seg4	Measure			0.05
35	Seg5	Zero	2.7	0.5	
35	Seg5	Span	293.0	300.6	
35	Seg5	Zero	3.3	0.1	
35	Seg6	Measure			0.1
22	Seg7	Measure			0.0

FIGURE 28. THC STEP CHANGE: 35 °C

Sensors Inc. was contacted and stated that part of the PEMS system specification is to limit temperature changes to less than 10 C° per hour. The analyzers within the PEMS unit are heated to a constant temperature. When ambient temperature changes, the heaters automatically adjust to maintain a constant analyzer temperature. However, very sudden changes in ambient temperature cause the heater controls to over or undershoot their temperature setpoint manifesting as drift or a shift in the concentration response. The manufacturer's recommended practice is to allow both the vehicle and PEMS to soak outdoors for 1-2 hours before beginning an on-road test. However, the proposed E-122-2 test procedure specified starting each on-road test at a constant vehicle temperature; therefore, vehicles must soak indoors before each on-road test.

Through discussions with CRC, the test plan was modified to allow vehicles to soak indoors at 22°C while soaking the PEMS outdoors. Just prior to a cold-start on-road test, vehicles were pushed out of the laboratory and the PEMS was installed as quickly as possible. This allowed vehicles to soak indoors and begin each test with a consistent temperature while allowing the PEMS to acclimate to outdoor ambient conditions.

3.4.3 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 29 shows the final assembly along with a hydraulic jack that was modified to mount and dismount the assembly from each vehicle.

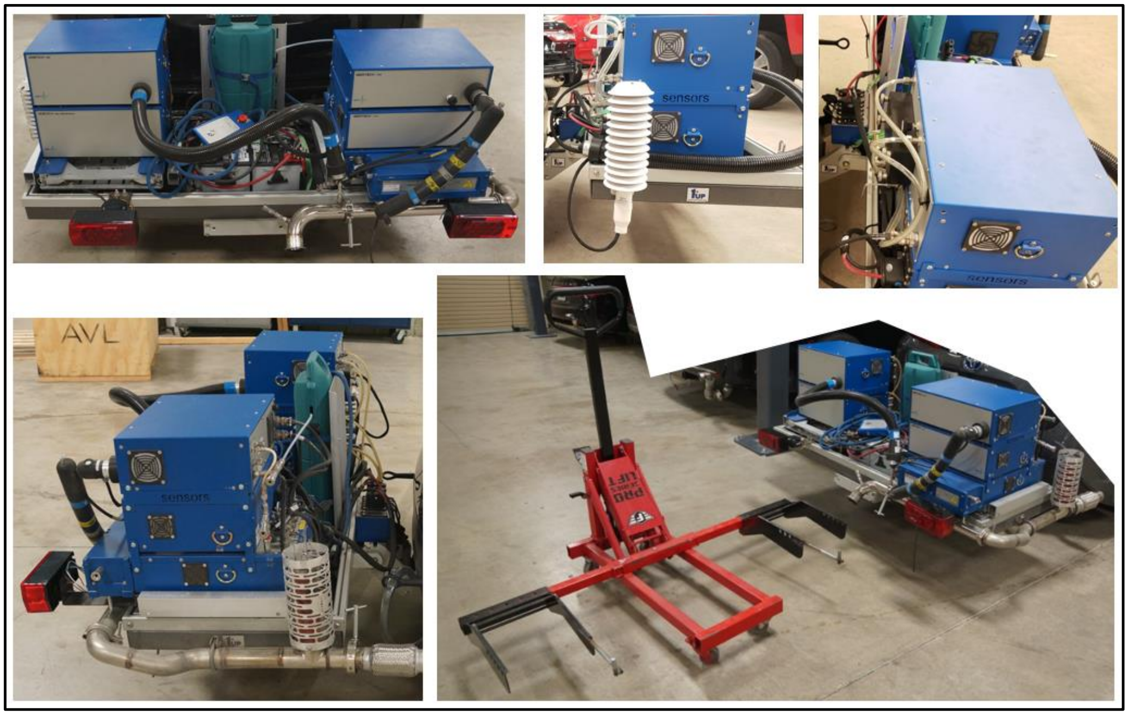


FIGURE 29. PEMS COMPONENT MOUNTING

3.4.4 PEMS Issues

This section describes problems encountered with the PEMS during this project. The PEMS manufacturer was very helpful and offered remote support for minor problems and repaired components at their facility for major problems. Both hardware failures and failures caused by operator error are discussed.

3.4.4.1 Exhaust Flow Meter Communication

A new two-inch EFM flow tube was purchased by CRC for this project. Upon arrival, it was found that the new tube, shown in Figure 30, would not communicate properly with the EFM5 PEMS module. SwRI sent the tube back to the factory for inspection. Sensors replaced a communication cable and returned the tube, but the problem persisted. Upon further investigation, it was found that the EFM5 Module and flow tube were of two different generations. Sensors updated the EFM5 module and two additional flow tubes to the latest generation to fix the problem.

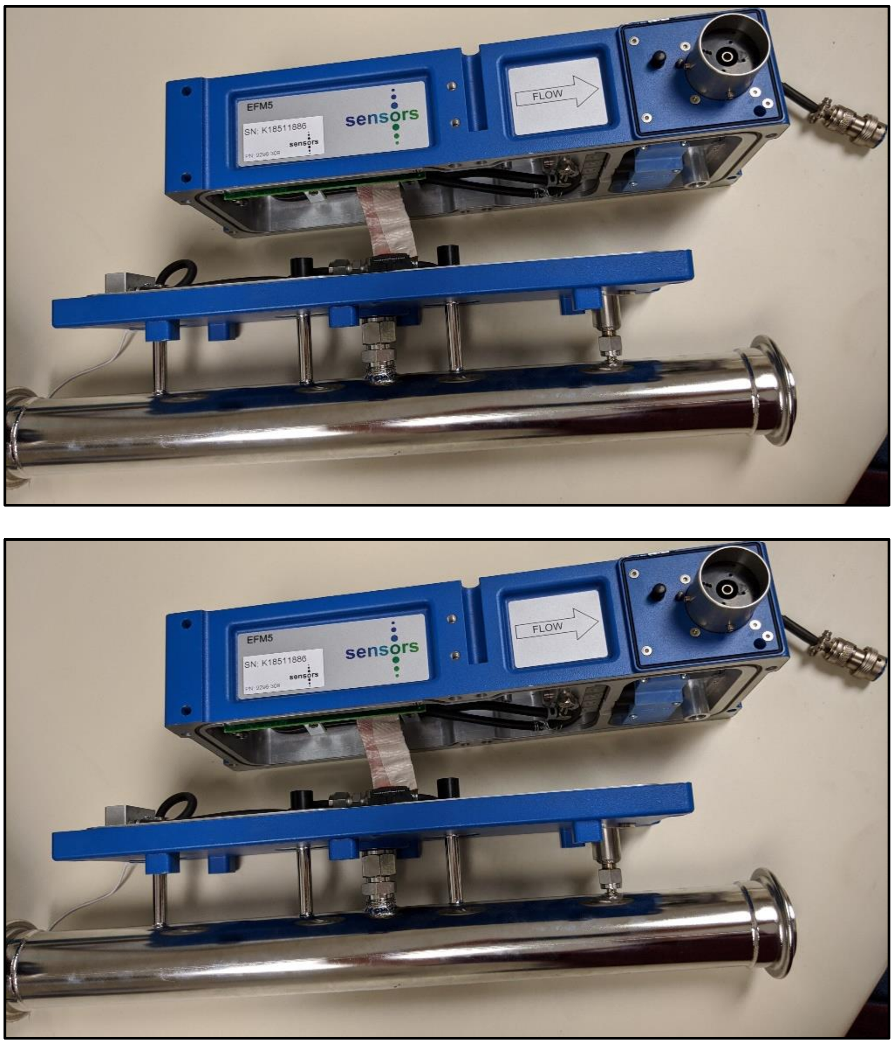


FIGURE 30. FLOW TUBE AND EMF5 MODULE ON TEST BENCH

3.4.4.2 Lithium Battery Failure

Lithium-ion batteries and a battery charger were specified by CRC and purchased for this program to power the PEMS. During an early road test, one of the lithium-ion batteries dropped to nine volts and forced the PEMs to shut down before the test completed. SwRI investigated the problem and found that the charger's battery management system indicated a full battery charge even though the actual battery state of charge was approximately 50%. The charger also showed a tendency to overheat if connected to 120-volt power while not being connected to a battery. A possible faulty cell in one of the battery packs was also identified.

To prevent testing delays, two AGM lead acid batteries were purchased and installed on the PEMs rack in place of the lithium-ion battery. A second set of lead-acid batteries was purchased to allow fully charged batteries to be used for each test. No further battery issues were encountered.

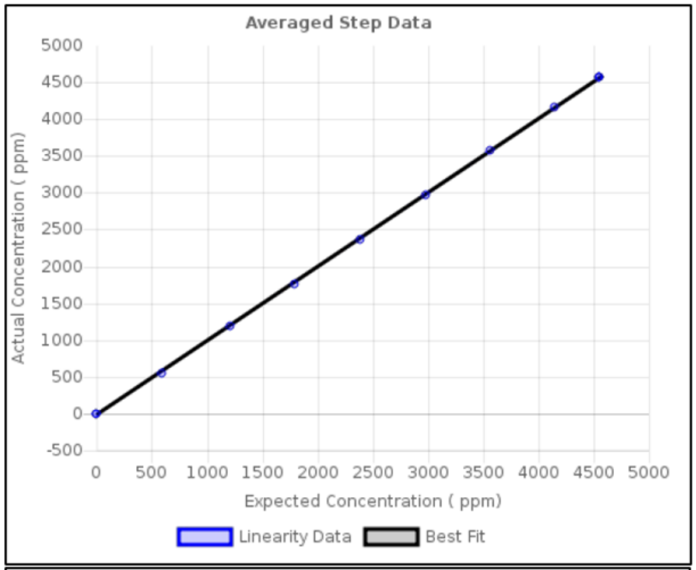
3.4.4.3 PEMS FID Failure

While preparing to conduct a test, the laboratory Flame Ionization Detector (FID) fuel bottle was depleted. FID fuel is used by the THC analyzer and is a mixture of 40 percent hydrogen and 60 percent helium. The SwRI operator mistakenly replaced the bottle with 100 percent hydrogen. This resulted in over heating and failure of the FID chimeny shown in Figure 31.

FIGURE 31. FAILED CHIMNEY FROM FID ANALYZER

The PEMS THC analyzer was damaged on March 11, 2021 and was sent to the manufacturer in Ann Arbor and ultimately to Germany for repair. The shipment was held in German customs from March 26th until April 20th. The unit was repaired and sent back to Ann Arbor for complaince testing prior to being sent to SwRI. The unit arrived at SwRI on May 11th. SwRI paid for the shipping and repair of the analyzer due to operator error.

Once received, the SwRI team conducted a full linearization check on the unit and the linearization report is shown in Figure 32. To further confirm the repair, an E-122 dyno test was performed with the last vehicle tested before the PEMS failure. The test measured emission levels very similar to previous tests with this vehicle indicating that the system was properly repaired. Table 12 gives vehicle emission results before and after the PEMS repair.



	Value	Criteria	Result
Slope	1.01	0.99 ≤ m ≤ 1.01	Pass
Intercept	-0.545	|b| ≤ 1.000%	Pass
SEE	0.362	SEE ≤ 1.000%	Pass
R^2	1	$R^2 \geq 0.998$	Pass
Overall			**Pass**

FIGURE 32. THC LINEARIZATION REPORT AFTER FID REPAIR

TABLE 12. THC AND CO2 BEFORE AND AFTER PEMS FAILURE

Date	Measurement Method	THC (g/mi)	CO2 (g/mi)
3/10/2021	PEMS_Dyno	0.033	325.5740
5/25/2021	PEMS_Dyno	0.033	325.5265
	Difference	**0.000**	**0.0475**

3.4.4.4 PM2 Pump Module Failure

While performing a chassis dynamometer test in June 2021, a failure of the PM2 Pump Module occurred. On the web interface, the PM2 module showed a channel fault, indicating the power distribution board had failed. After onsite troubleshooting, the unit was sent to the manufacturer in Ann Arbor for repair. Sensors helped to quickly turn around the unit, confirming the board had failed, and replaced it with a new board. They then tested and sent the unit back to SwRI. Upon re-installation the unit was only intermittently operational. A Sensors representative was on-site for a different project and helped to troubleshoot. It was found that the PM2 module (a separate module where the PM measurements occur) was the cause of the overpowering of the power distribution board. Both the PM2 Pump Module and PM2 Module were sent back to Sensors for a full evaluation. Figure 33 shows the location of both components. Sensors reported that a loose screw was found in the PM2 module, and this could have caused the “Channel in Fault” errors that were observed.

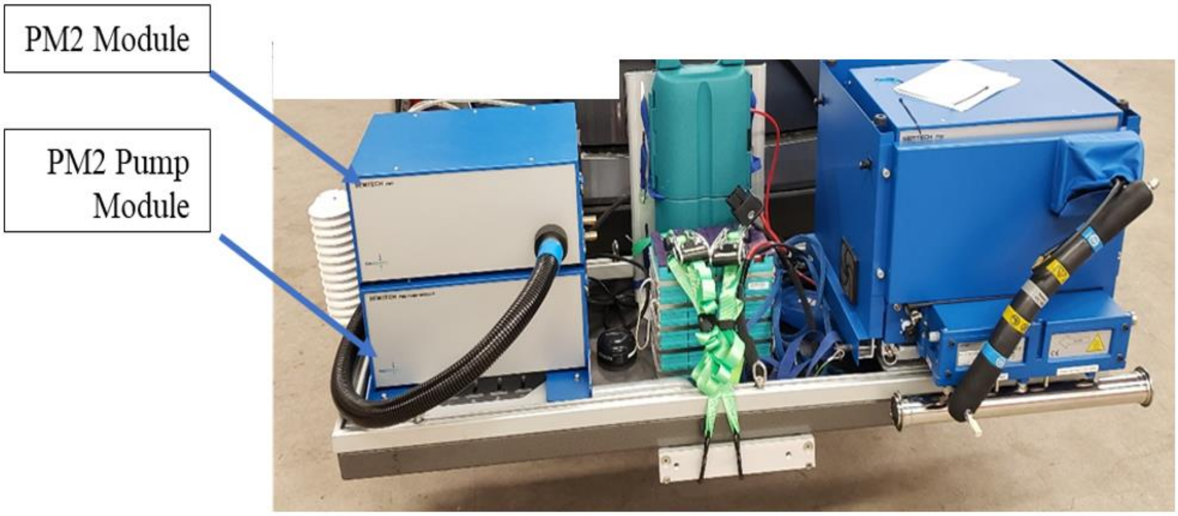


FIGURE 33. PM2 AND PM2 PUMP MODULE INSTALLED ON VEHICLE

After receiving the unit back at SwRI, it was inspected and appeared to be working properly. However, after a road test, the PM2 module lost connection to the control interface. With the help of Sensors, the team was able to diagnose that the network switch that provides communication between the PM2 module and the main unit was not working. To avoid additional down time associated with sending the unit back to Sensors, SwRI sourced and installed a replacement 12-volt network switch. With the system operational, CRC instructed to continue using the aftermarket switch rather than sending the unit to Sensors for installation of an OEM switch.

3.4.4.5 PEMS GPS Failure

During two E-122 on-road tests in October 2021, the PEMS GPS signal dropped out for a portion of the test. Emission results from on-road tests are calculated using the distance measured by the PEMS' GPS. An example of the GPS failure is shown below in Figure 34. For these two tests, vehicle speed captured by the ECM was used to calculate the distance-weighted emissions results.

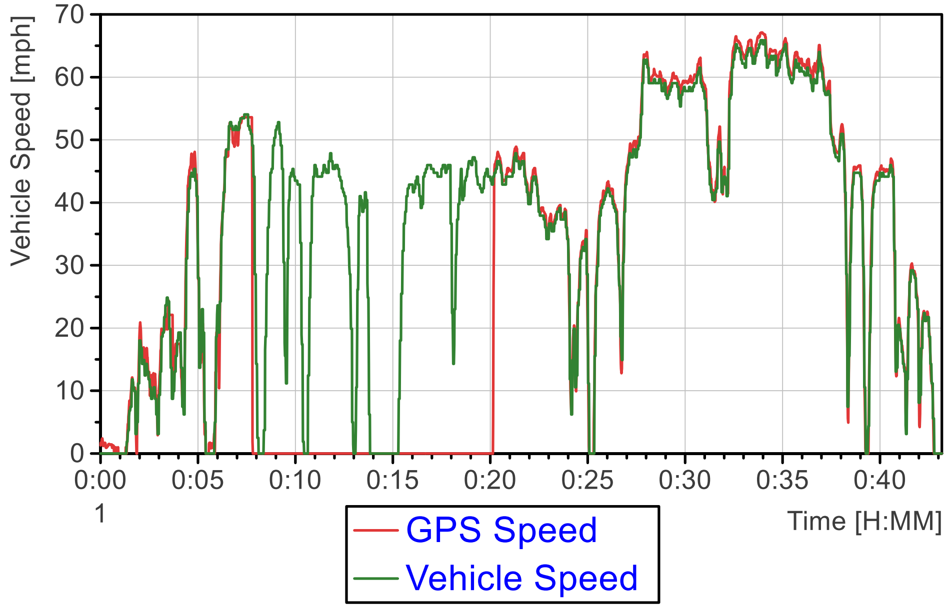


FIGURE 34. GPS FAILURE DURING ON-ROAD TEST

3.4.4.6 PEMS Weather Station Failure

During October of 2021, the PEMS weather probe dislodged itself from the protective housing during the 2nd on-road test of the day. The probe was destroyed and weather data from that test was not captured. A new probe was ordered from Sensors and arrived one week later. While waiting for the new probe, temperature and humidity data from SwRI's on-site weather station was substituted by post processing the results. Only four road tests were affected. The new PEMS probe was installed using a light glue at the press fit interface to keep the new probe from dislodging. The new probe remained properly secured for the remainder of the project.

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 13 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 was connected to a level two charger during soak periods as previously discussed.

TABLE 13. 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 or Tedlar bags. For the determination of PM emissions, a proportional sample of dilute exhaust was drawn through a 47mm Whatman Teflon membrane filter. Partway through the project, in September 2021, measurement of exhaust soot was added as a cross check for PM. Soot was 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 gaseous pollutant. The laboratory dilute and raw exhaust pollutants 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 (added Sept 2021)	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 35 shows the test cell layout for this project.

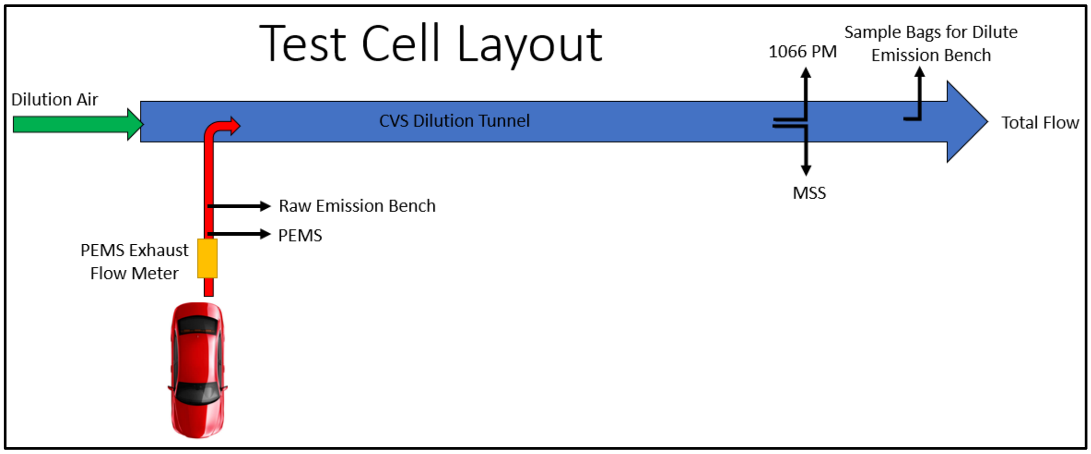


FIGURE 35. TEST CELL LAYOUT

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 Experimental Design

Prior to conducting any testing, several meetings were held with SwRI's statistician to discuss the experimental design for this project. Some of the questions discussed included:

1. How many vehicles and how many runs on each vehicle-fuel combination?
2. How to monitor long-term drift?
3. What randomization strategy will be used to avoid other potential systematic effects?

4. Is there value in obtaining a duplicate vehicle of the same make and model?
5. Should we repeat vehicle-fuel combinations at different points in time?

Due to the seasonal nature of the availability of the fuels, it was determined that summer fuels would all be run in one matrix and winter fuels would be run in a second matrix. To monitor long-term test drift, a control vehicle was considered which would run on a single summer fuel during the summer test matrix and a single winter fuel for the duration of the winter matrix. This solution only provided drift monitoring within the summer and winter matrices but gave no mechanism for comparing the summer and winter matrices together. Additionally, the additional testing would provide little contribution to the project goals. As an alternative approach, the inclusion of EPA Tier 3 EEE Certification Fuel in both the winter and summer test matrices would allow test drift monitoring across the entire program. This option was ultimately selected for drift monitoring.

To help determine the number of vehicles and tests per vehicle-fuel combination, statistical power calculations were obtained. Several different models were examined. One such model examined with main effects and two-way interactions is

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \beta\gamma_{jk} + \varepsilon_{ijkl},$$

Where,

α_i is the vehicle, $i = 1,2,3,4$
β_j is the fuel, $j = 1,2,3,4,5$
γ_k is the method, $k = 1,2$
ε_l is the residual error for the run number, $l = 1,2,3,4$ (up to 8 for cert. fuel).

Power calculations were provided for effect sizes in units of standard deviations, often also called “sigmas”. Table 14 below shows an example of power numbers for first-order and second-order terms involving measurement method, either PEMS or Dilute, using a four-test vehicle and five fuel experimental design. In most variations, including the example shown, four tests per vehicle-fuel-method combination was sufficient to achieve good statistical power for all terms with effect sizes of one standard deviation or greater.

TABLE 14. POWER CALCULATIONS FOR MODELS TERMS INCLUDING MEASUREMENT METHOD, 4 TEST VEHICLES

Parameter	Number of Tests Per Vehicle-Fuel-Method	2 Standard Deviations	1 Standard Deviation	0.5 Standard Deviation
method_k	6	100%	100%	93%
	5	100%	100%	88%
	4	100%	100%	80%
$\text{vehicle}_i * \text{method}_k$	6	100%	98%	51%
	5	100%	95%	44%
	4	100%	90%	37%
$\text{fuel}_j * \text{method}_k$	6	100%	98%	51%
	5	100%	95%	44%
	4	100%	90%	37%

Estimates of standard deviations were obtained from some initial checkout test data generated under CRC project E-122-2b for CO, CO_2, NO_x, and THC. These estimates are shown below in Table 15.

TABLE 15. ESTIMATED STANDARD DEVIATIONS BASED ON CHECKOUT TESTS

Parameter, g/mi	2 Sigma	1 Sigma	0.5 Sigma
CO_2	6.28	3.14	1.57
CO	0.0992	0.0496	0.0248
NO_x	0.0046	0.0023	0.0012
THC	0.0094	0.0047	0.0024

Power calculations were also provided for experimental designs using five vehicles, as there was consideration being given to adding another vehicle technology. In addition, one question being considered was whether there was value in adding a duplicate vehicle of the same make and model of one of the four test vehicles. This was seen to add little value, since only one duplicate would not be enough to provide a reliable estimate of vehicle-to-vehicle variation within a particular vehicle make and model. Ultimately, only four test vehicles were chosen, and based on the power analysis results, four tests per vehicle-fuel-method combination.

There was also a desire to understand long-term variability and repeatability of results from PEMS as compared with chassis dynamometer tests. Therefore, it was decided that each vehicle-fuel-method combination would be duplicated at different points in time of the test matrix. The final design chosen is shown below in Table 16. As opposed to full randomization which can still lead to undesired outcomes, the test order was strategically constructed to balance factor levels appropriately to avoid systematic bias. Each block represents two chassis dyno tests and two road tests. Each vehicle-fuel block is therefore shown twice for each of the summer and winter tests fuels, and four times for the Tier 3 Certification Fuel (twice in the summer matrix, and twice in the winter matrix).

TABLE 16. ORIGINAL TEST MATRIX DESIGN

Test Matrix						Winter Fuel Matrix					
Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9	Set 10	Set 11	Set 12
Veh. A	Veh. B	Veh. C	Veh. C	Veh. D	Veh. C	Veh. C	Veh. D	Veh. A	Veh. C	Veh. B	Veh. C
Veh. D	Veh. C	Veh. D	Veh. D	Veh. B	Veh. A	Veh. A	Veh. B	Veh. D	Veh. D	Veh. C	Veh. D
Veh. C	Veh. A	Veh. B	Veh. A	Veh. A	Veh. D	Veh. D	Veh. A	Veh. C	Veh. B	Veh. A	Veh. A
Veh. B	Veh. D	Veh. A	Veh. B	Veh. C	Veh. B	Veh. B	Veh. C	Veh. B	Veh. A	Veh. D	Veh. B

Fuels	
	Fuel A
	Fuel B
	Fuel C
	Fuel D
	Fuel E

3.9 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 E. Each fuel-vehicle combination was tested twice following steps 1-16 below. Table 17 gives the final test matrix that was followed for this project. This matrix includes several modifications that were required to capture repeat tests as previously discussed. Steps 1-16 below represent a single block in the matrix. The summer matrix began in November 2020 and was followed by the winter matrix which began in July 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 17. FINAL TEST MATRIX CONDUCTED

Test Matrix								Winter Fuel Matrix					
Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9	Set 10	Set 11	Set 12	Set 13	Set 14
Veh. A	Veh. B	Veh. C	Veh. C	Veh. D	Veh. C	Veh. C	Veh. C	Veh. C	Veh. D	Veh. A	Veh. C	Veh. B	Veh. C
Veh. D	Veh. C	Veh. D	Veh. D	Veh. B	Veh. A	Veh. B	Veh. B	Veh. A	Veh. B	Veh. D	Veh. D	Veh. C	Veh. D
Veh. C	Veh. A	Veh. B	Veh. A	Veh. A	Veh. D	Veh. A		Veh. D	Veh. A	Veh. C	Veh. B	Veh. A	Veh. A
Veh. B	Veh. D	Veh. A	Veh. B	Veh. C	Veh. B			Veh. B	Veh. C	Veh. B	Veh. A	Veh. D	Veh. B

Fuels	
	Fuel A
	Fuel B
	Fuel C
	Fuel D
	Fuel E

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 F gives examples of step-by-step check lists developed for this project.

3.9.1 Chassis Dynamometer Test Procedure Change

Early in the program, high CO and THC results were measured from some chassis dynamometer tests. While investigating the unexpected results, it was found that although the driver was waiting the correct amount of time between starting the vehicle and beginning to accelerate, he was shifting into drive for dynamometer tests much earlier compared to on-road tests.

The E-122 dyno test procedure was modified to match the E-122 road test procedure. For initial dyno tests, the vehicle was shifted into drive immediately after starting the engine. For dynamometer tests after the change, the shift from park to drive was scheduled for 18 seconds after starting the engine to closely match the procedure used for road tests.

Tests conducted with the new dyno test procedure resulted in much lower emissions of THC and CO. In Figure 36, the THC concentration traces of four different tests are shown for the first minute of an E-122 dyno test. The blue vertical line indicates when the vehicle initially starts to accelerate to follow the target vehicle speed. Tests conducted with the new procedure, "idle in park", gave significantly lower concentrations of THC during the cold-start period. Figure 37 shows the THC concentration over the entire test and clearly illustrates that the majority of THC emissions are generated during the first minute of operation. As expected, the overall test result is greatly affected by the procedural change.

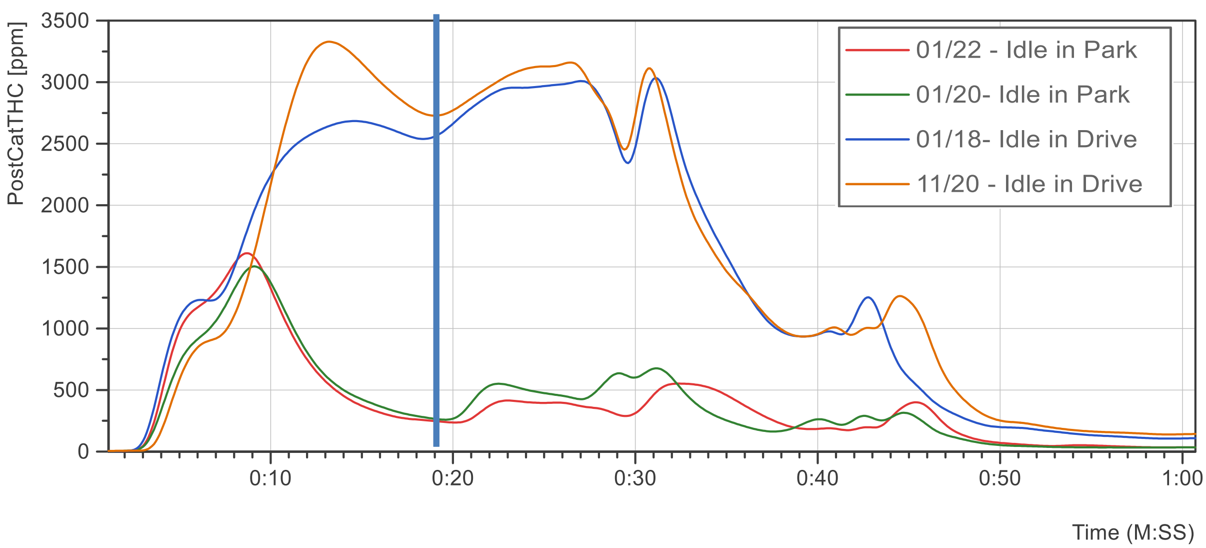


FIGURE 36. COLD-START THC CONCENTRATION WITH NEW SHIFT PROCEDURE

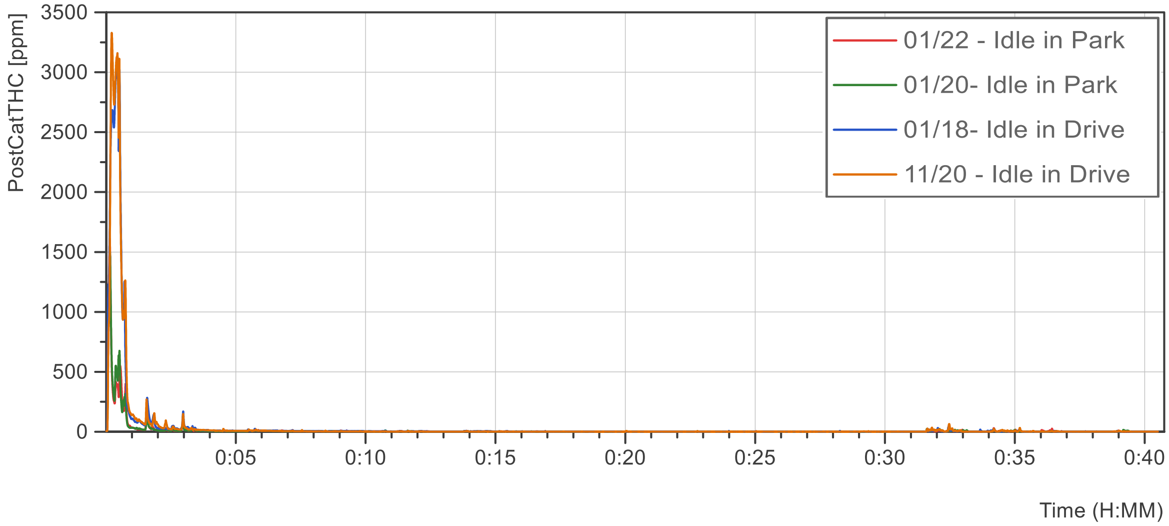


FIGURE 37. THC CONCENTRATION OVER THE ENTIRE TEST WITH NEW SHIFT PROCEDURE

Figure 38 shows CO mass emissions during the first minute of operation. Like THC, the new procedure produces significantly less CO in the first minute compared to the old procedure. Figure 39 gives the cumulative CO mass and shows that the cold-start phase greatly influences the final CO result.

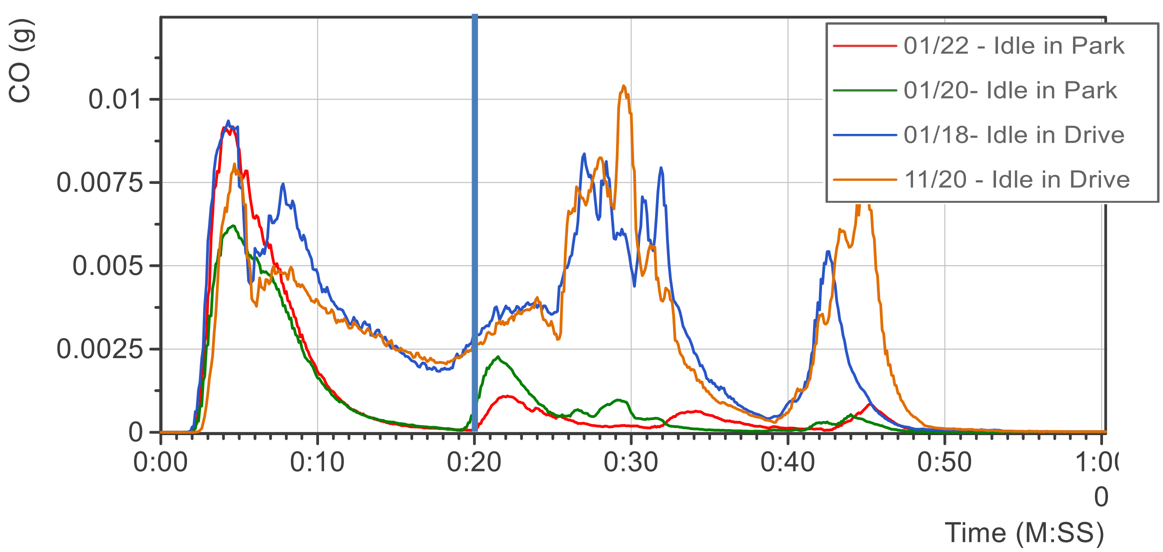


FIGURE 38. REAL TIME CO FIRST MINUTE

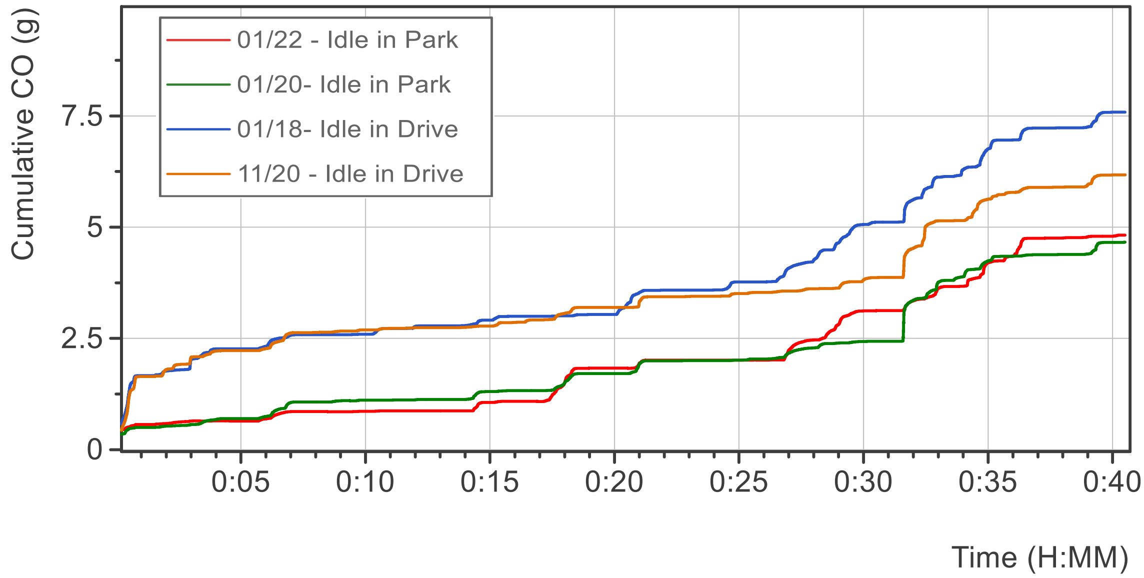


FIGURE 39. CUMULATIVE CO FULL TEST

The procedural change did not have the same effect on NOx emissions. No clear trend was identified in NOx emissions between the two procedures. Vehicle D (plug-in hybrid) was unaffected by the procedure change because the engine remains off until the vehicle is accelerated.

4.0 STATISTICAL ANALYSIS OF RESULTS

Statistical analysis was conducted to evaluate the variability of PEMS measurements compared to traditional emission measurements taken from dilute exhaust. Repeatability estimates were obtained for each emissions measurement technique. Additionally, bias estimates were calculated for the PEMS unit used in this study. Bias estimates were then subtracted out in order to understand PEMS road testing accuracy and variability unrelated to instrument-specific bias when compared with dilute testing on the chassis dynamometer. Finally, viability of fuel PMI and RVP as predictors of PM and gaseous emissions was assessed. Data measured via the dilute method was modeled separately from results measured with the PEMS to understand if conclusions regarding fuel property effects were sensitive to measurement method.

4.1 Data Transformations

To properly compare variability between measurement methods across vehicles of varying emissions levels, data transformations were necessary. Whenever variability is naturally a function of emissions levels, it is necessary to apply a data transformation to results when comparing variability between methods to ensure that any conclusions made about differences in variability are not due to differences in absolute level, but instead can be attributed to the measurement methods themselves. In addition, the regression models used to predict emissions changes with changes in fuel PMI and RVP require that the residuals of the model be normally distributed with mean zero and a constant variance which is not level dependent. This is necessary to conduct the t-tests to determine predictor variable significance. Box-Cox power transformation analyses were conducted on each of the emissions variables. The model used was

Y ~ Vehicle-Fuel-MeasurementMethod-Set

Since it was not of interest to determine predictor variable significance in this exercise, this single predictor variable used is a concatenation of all factor differences tested. At each unique level, there were only two data points, so this allows us to understand the best transformation to apply for repeated values across all levels. 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 40, and the summary of transformations for all parameter is given in Table 18. 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 $\lambda = 0.292$.

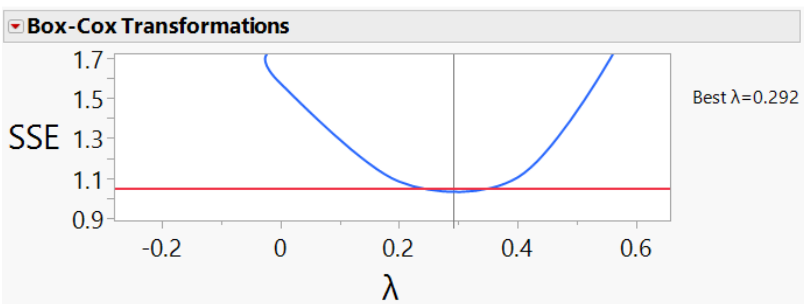


FIGURE 40. BOX-COX ANALYSIS FOR PARTICULATE MATTER

TABLE 18. TRANSFORMATION SUMMARY

Parameter	Transformation
PM	CubeRoot(PM)
NOx	Ln (NOx), separate by vehicle
CO2	Ln (CO2)
Fuel Economy	Ln (Fuel Economy)
THC	Ln (THC)
NMHC	Ln (NMHC)
CH4	Ln (CH4)

NO_x was the only parameter for which variability was dependent not only on level, but also on vehicle. As can be seen in Figure 41, Vehicles A, C, and D have similar NO_x levels, but Vehicle A clearly has much lower variability than Vehicle C or Vehicle D. Therefore, the transformation of Ln (NO_x) was verified to be acceptable for each vehicle individually. For all other parameters, homogeneity across factor levels was verified by visual inspection of model residuals.

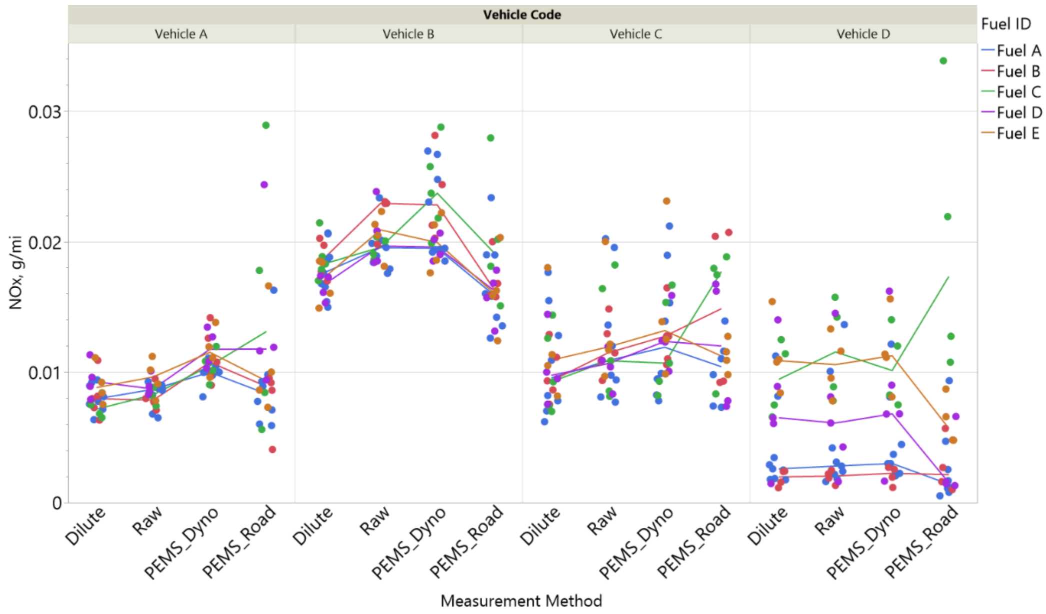


FIGURE 41. RAW DATA PLOT OF NOX (G/MI) BY MEAUREMENT METHOD AND VEHICLE, COLORED BY FUEL

4.2 Outliers and Data Removed

The data was inspected for outliers using studentized residuals from the predictor variable used in the transformation analysis and the response variable using the selected transformation. Residuals are the difference between the actual value and the model predicted value, and studentized means that this difference was 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, since variability estimates are a primary project goal, only extreme outliers were considered appropriate for removal, and therefore +/- 3 was chosen as the cut-off. Figure 42 shows two data points which were removed from Vehicle D for CO_2 and fuel economy, which are indicated with an asterisk. The asterisks in Figure 43 indicate points which were removed as outliers for THC, NMHC, and CO on Vehicle C.

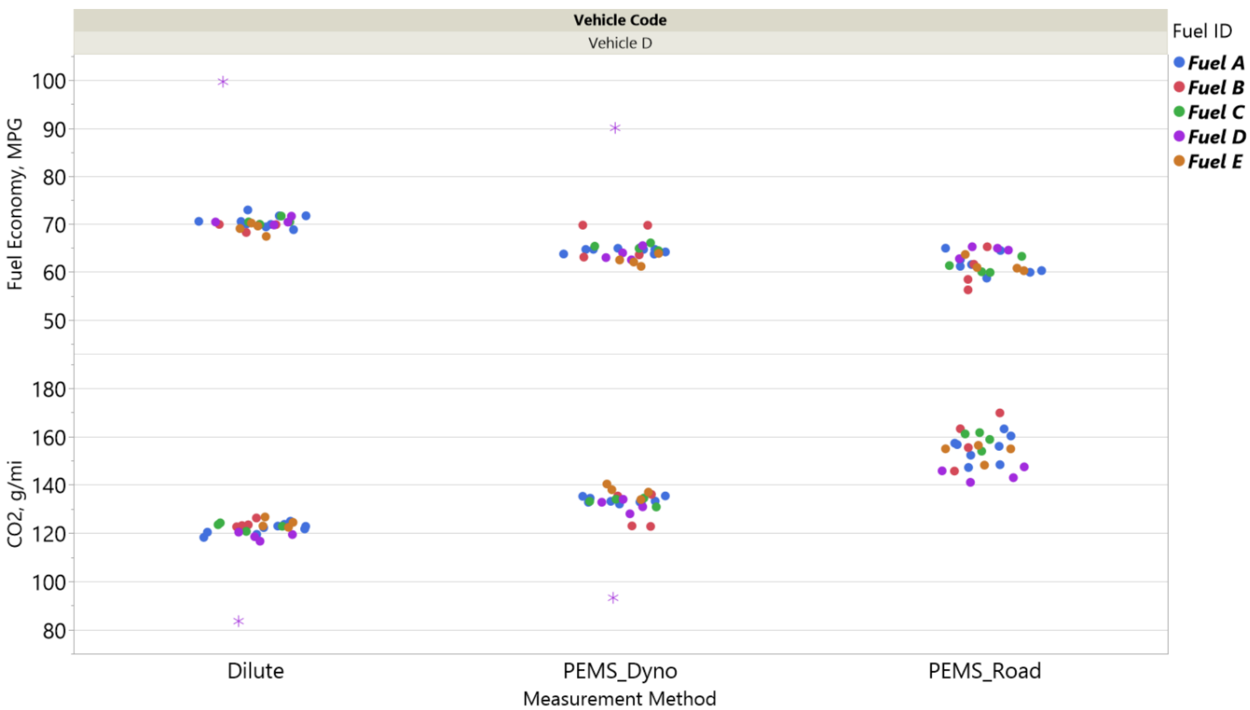


FIGURE 42. OUTLIER DATA POINTS FOR FUEL ECONOMY AND CO_2

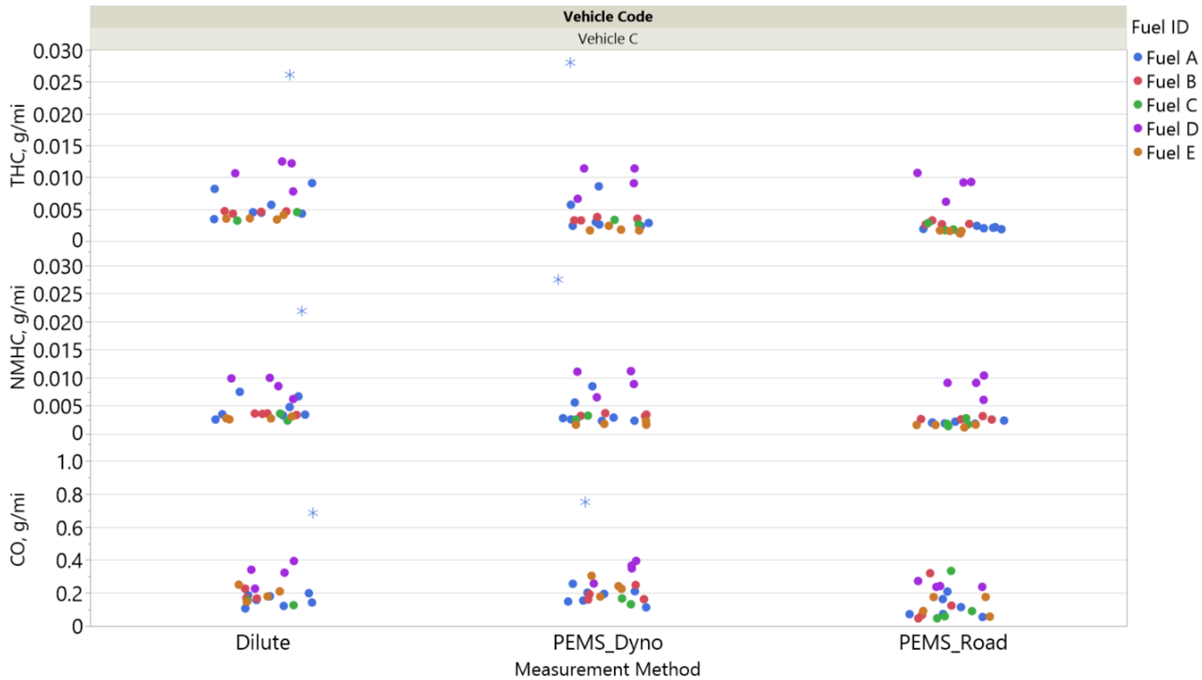


FIGURE 43. OUTLIER DATA POINTS FOR THC, NMHC, AND CO

Idling with the vehicle in park compared to idling the vehicle in drive was discovered to impact THC, NMHC, and CO results. Around the mid-point of the summer fuels test matrix, the new "idle in park" method was adopted for chassis dynamometer tests as discussed in section 3.9.1. Data from tests run before the change was excluded from the analysis of THC, NMHC, and CO. All data points were included in the analysis of all other parameters not impacted by the change.

4.3 Repeatability of PEMS Compared with Chassis Dynamometer Dilute Testing

Repeatability is defined as the maximum difference one can expect to see between two results, run under identical test conditions, with 95% confidence, within a short period of time. It can also be expressed as the difference between repeated results which will only be exceeded in 1 out of 20 cases in the long run. This value is calculated by scaling the repeatability standard deviation by a factor from the t-distribution, or for large sample sizes, the standard deviation is multiplied by $1.96 * \text{sqrt}(2) = 2.77$, based on the convergence of the t-distribution to the normal distribution. A complete discussion on the calculation of repeatability can be found in ASTM D6300 "Standard Practice for Determination of Precision and Bias Data for Use in Test Methods for Petroleum Products and Lubricants."

For this analysis, we define both a short-term repeatability and long-term repeatability. The former is the traditional definition for two results, run under identical conditions, in a back-to-back manner. However, for PEMS results, we are also interested in repeatability at different points in time, with changing ambient conditions, and changes in driving conditions such as traffic. To understand how different two results can be at different points in time there are two variance components which need estimation; the spread of results around the sample mean for a given test set, and how much the sample means are expected to change over time from one test set to another. To help visualize this, consider the hypothetical data in Figure 44. In this example, the results were all run on identical test material but conducted at three different points in time represented by the different test sets. There is clearly significant set-to-set, or long-term variation in this example. If the effect were absent, one would expect to see the sample means of each set all very similar to one another and thus also close to the grand mean.

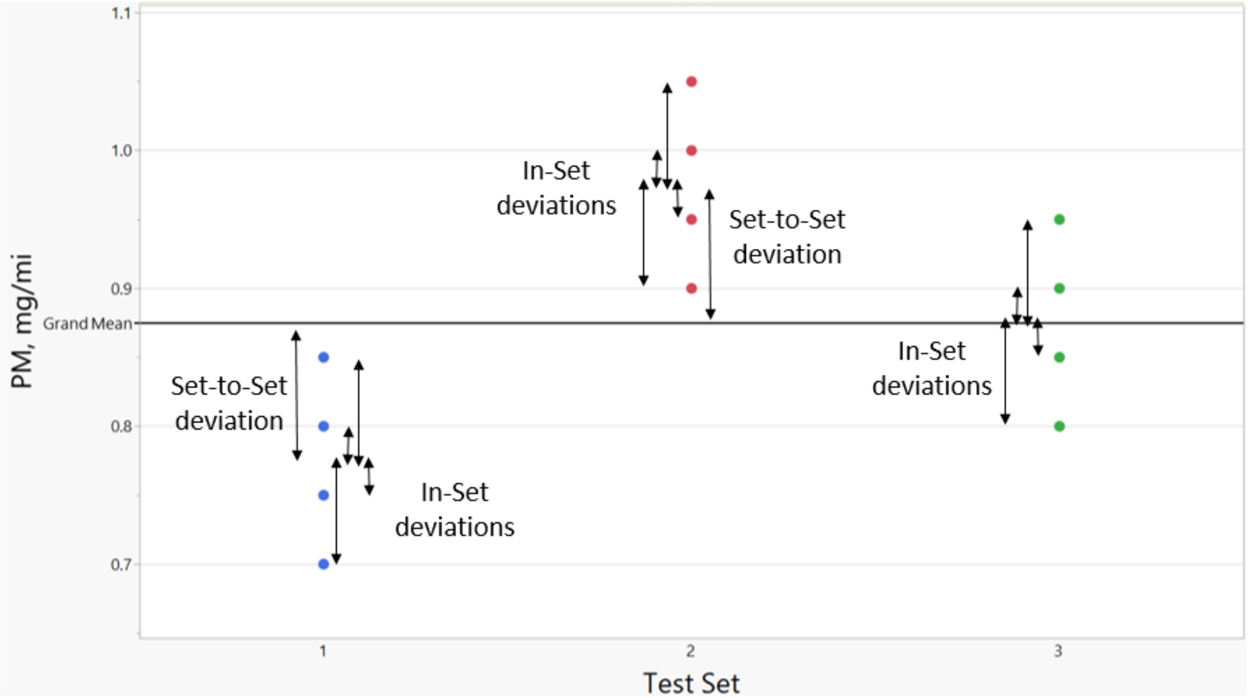


FIGURE 44. HYPOTHETICAL DATA COMPARING IN-SET DEVIATION TO SET-TO-SET DEVIATIONS

For this project, the design of experiments was structured to allow identification of a set-to-set variance component. Significance of this variance was tested using a mixed effects model. For each transformed parameter Y_i, the mixed effects model was

$$Y_{ijkl} = \mu_i + \alpha_{ij} + \gamma_{ik} + \varepsilon_{ijkl},$$

where:

μ_i =Overall Mean

α_{ij} =Fixed effect of the vehicle-fuel combination, j=1,2,…,20

γ_{ik} =Random Effect of the test set, k=1,2,…,sum of all test sets run on all vehicles

$$\gamma_{ik} \sim \mathrm{Normal}(0, \sigma^2_{set-to-set})$$

ε_{ijkl} =Random Effect for the irreducible test error, l=1,2,…,total runs on the vehicle-fuel combination

$$\varepsilon_{ijkl} \sim \text{Normal}(0, \sigma^2_{\text{In-set}})$$

Prior to running any of the mixed effects models, the term for "set" was included in the model as a fixed effect. Least square (LS) means plots were inspected for any vehicle drift and /or outlier test sets. This was done separately for each measurement method to check for measurement drift.

After checking for drift and outlier test sets, the mixed effects model was run and a Wald's test was used to determine if there was a significant set-to-set variance component present for the particular measurement method and emissions parameter. If the set-to-set variance component was not statistically significant, the term was dropped, and the model was re-run as a standard ANOVA model with only fixed effects.

In the sections that follow, the full repeatability analysis is provided for PM as an example of the process followed, but only select data plots and final results are provided for NO_x, CO_2, fuel economy, THC, NMHC, and CO. The plots and tables corresponding to parameters not shown are available in Appendix G.

4.3.1 Particulate Matter (PM) Repeatability of PEMS Compared with Chassis Dyno Dilute Testing

Figure 45 and Figure 46 show the untransformed and transformed PM values, respectively. Due to the higher untransformed PM values of Vehicle B, note that this vehicle is plotted on the left-hand side using a different scaling. Each trend line represents a different fuel and runs through the median result of each measurement method. A small random scatter along the x-axis is added to aid in visualizing all data points.

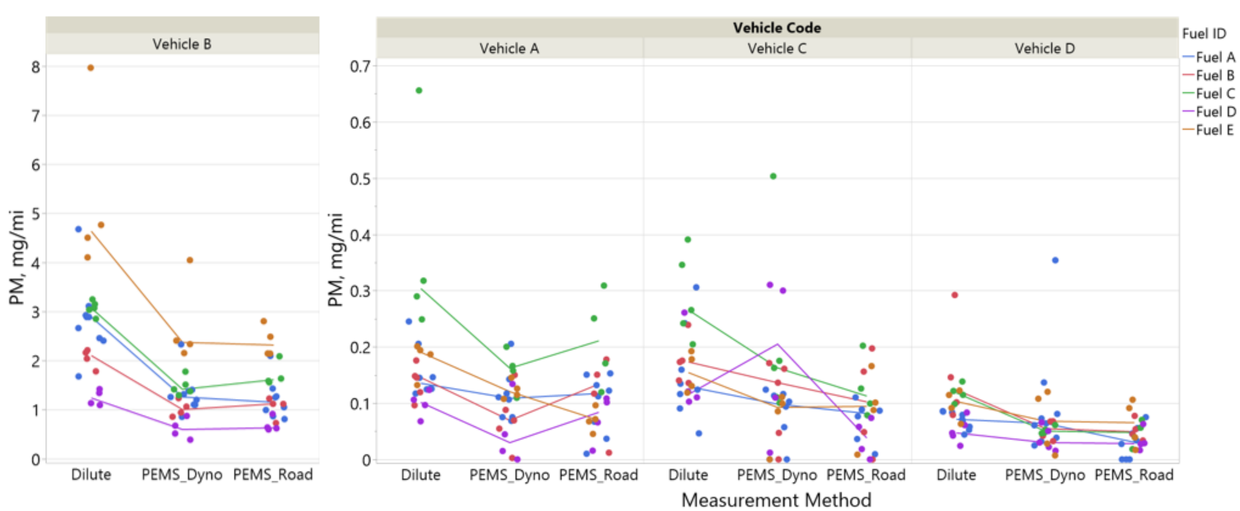


FIGURE 45. RAW DATA PLOT OF PM (MG/MI) BY MEASUREMENT METHOD AND VEHICLE, COLORED BY FUEL

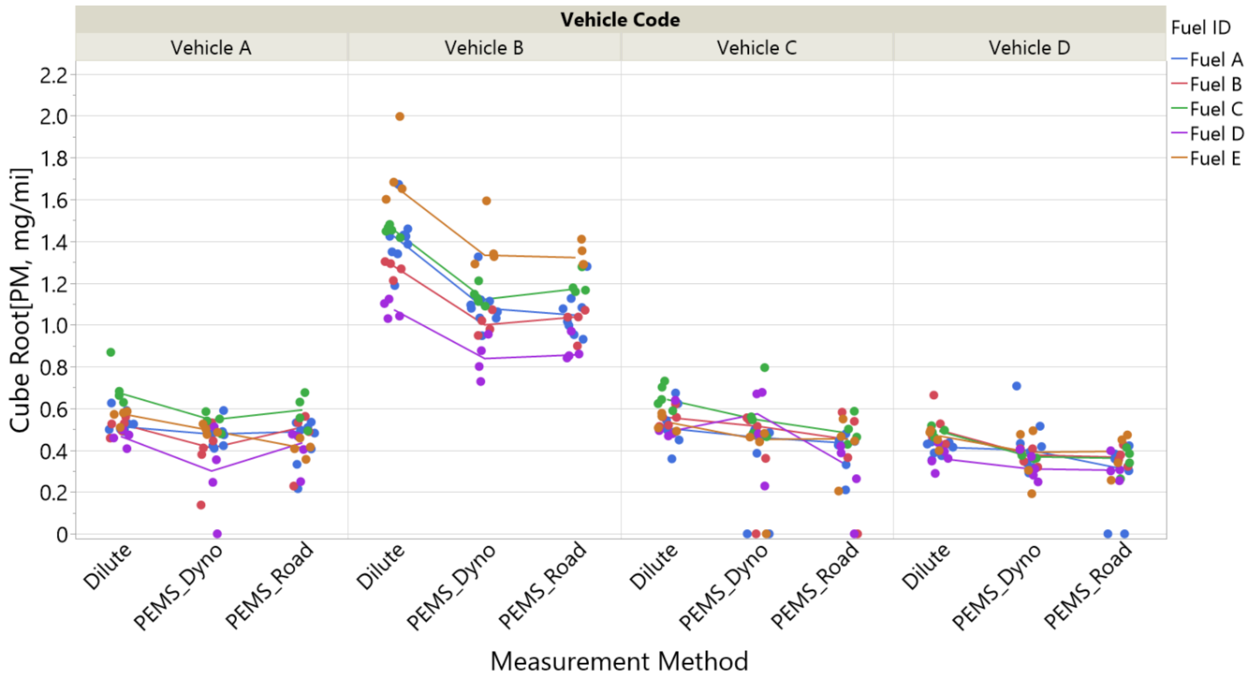


FIGURE 46. RAW DATA PLOT OF CUBE ROOT PM (MG/MI) BY MEASUREMENT METHOD AND VEHICLE, COLORED BY FUEL

The drift check graphs are shown below in Figure 47. Set 8 was a make-up set where only Vehicle C was tested. It was conducted to supplement two previous sets containing single valid chassis dynamometer results per set. Additionally, the PEMS road data from Set 8 was not in good agreement with previous data. The Vehicle C Fuel B data is plotted below in Figure 48. The inconsistencies in this vehicle-fuel combination along with the single data point test sets used to estimate set-to-set variability led to the exclusion of all Vehicle C Fuel B data from estimation of typical variability. Set 11 also tested as significantly different from all other test sets for the Dilute and PEMS_Dyno models, and was therefore removed from the variance estimates, since the goal was to estimate normal expected variability of each method.

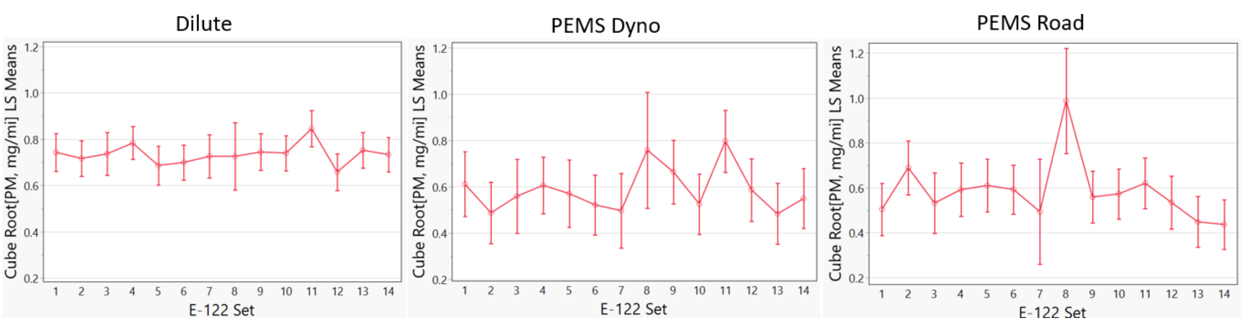


FIGURE 47. DRIFT CHECK FOR DILUTE, PEMS DYNO, AND PEMS ROAD MODELS

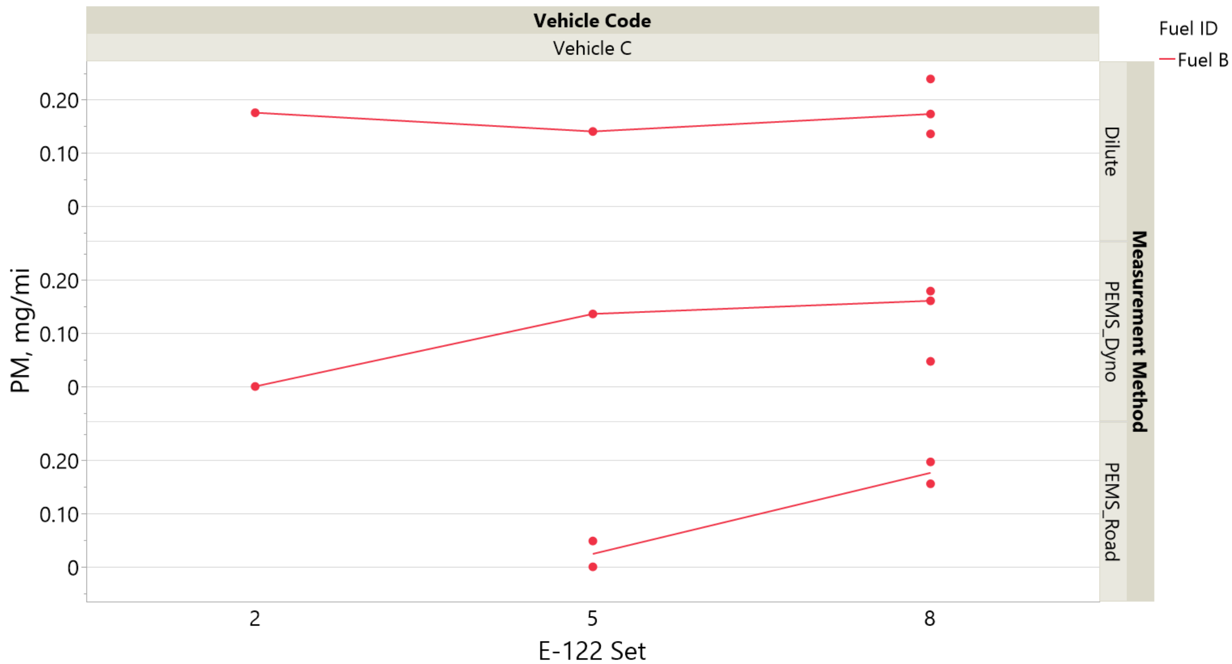


FIGURE 48. PM RESULTS (MG/MI) FOR VEHICLE C USING FUEL B BY TEST SET AND MEASUREMENT METHOD

Next, the mixed effects model was run to test for a significant set-to-set variance component. With the Vehicle C Fuel B data excluded from all three models and Set 11 removed from the Dilute and PEMS_Dyno models, the results are shown below in Table 19.

TABLE 19. WALD'S TESTS FOR A SIGNIFICANT SET-TO-SET VARIANCE COMPONENT OF PM

Dilute

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.010547	-5.466e-5	-0.001685	0.0015761	0.9476	0.000
Residual		0.0051826	0.0036251	0.0080186		100.000
Total		0.0051826	0.0036251	0.0080186		100.000

PEMS Dyno

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.077322	-0.001172	-0.006029	0.0036854	0.6363	0.000
Residual		0.0151547	0.0104635	0.0239102		100.000
Total		0.0151547	0.0104635	0.0239102		100.000

PEMS Road

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.7586683	0.0061819	0.0003581	0.0120057	0.0375*	43.139
Residual		0.0081484	0.0056058	0.0129265		56.861
Total		0.0143303	0.0099139	0.0225419		100.000

The results indicate that only PEMS_Road data appears to be showing a statistically significant set-to-set variance component. With this in mind, the standard deviation summary, short-term repeatability summary, and long-term repeatability summary are provided in Table 20. The numbers shown in transformed units are based on the selected transformation of CubeRoot (PM, mg/mi). For Dilute testing and PEMS_Dyno testing, the short-term and long-term repeatability estimates will be the same due to the absence of a significant set-to-set variance component, indicating the passage of time and fuel changes did not affect the repeatability of the chassis dyno testing. Because the short-term repeatability variances for PEMS_Dyno and PEMS_Road were not statistically distinguishable based on an F-Test, these values were also pooled together to create a better estimate of short-term PEMS repeatability. The PEMS_Pooled short-term pooled standard deviation was used with the PEMS_Road set-to-set standard deviation to create a "PEMS_Road_Pooled" estimate of long-term repeatability. This estimate is considered to be the best estimate of PEMS repeatability over time.

The key takeaway from this analysis is that the PEMS_Road_Pooled long-term standard deviation of 0.132 is 80% greater than the long-term standard deviation estimates for Dilute chassis dynamometer testing and this difference was statistically significant different based on an F-test for variances.

TABLE 20. PARTICULATE MATTER STANDARD DEVIATIONS AND REPEATABILITY SUMMARIES BY METHOD

Std. Dev. Summary of Transformed Data

Measurement Method	Std. Dev. (Within-Set)	Std. Dev. (Set-to-Set)	Std. Dev. (Total)
Dilute	0.072	-	0.072
PEMS_Dyno	0.129	-	0.129
PEMS_Road	0.090	0.079	0.120

Short-Term Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Short-Term Repeatability, mg/mi[1]
Dilute	0.072	$= 0.216x^{\frac{2}{3}}$
PEMS_Dyno	0.120	$= 0.360x^{\frac{2}{3}}$
PEMS_Road	0.090	$= 0.270x^{\frac{2}{3}}$
PEMS_Pooled	0.106	$= 0.318x^{\frac{2}{3}}$

Long-Term Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Long Term Repeatability, mg/mi[1]
Dilute	0.072	$= 0.216x^{\frac{2}{3}}$
PEMS_Dyno	0.120	$= 0.360x^{\frac{2}{3}}$
PEMS_Road	0.120	$= 0.360x^{\frac{2}{3}}$
PEMS_Road_Pooled	0.132	$= 0.396x^{\frac{2}{3}}$

Note 1: "x" represents the average of two results being compared, in mg/mi.

4.3.2 NO_x, Repeatability of PEMS Compared with Chassis Dyno Dilute Testing

For NO_x emissions, the variability was determined to be vehicle dependent. This is clearly seen from the raw data plot shown below in Figure 49.

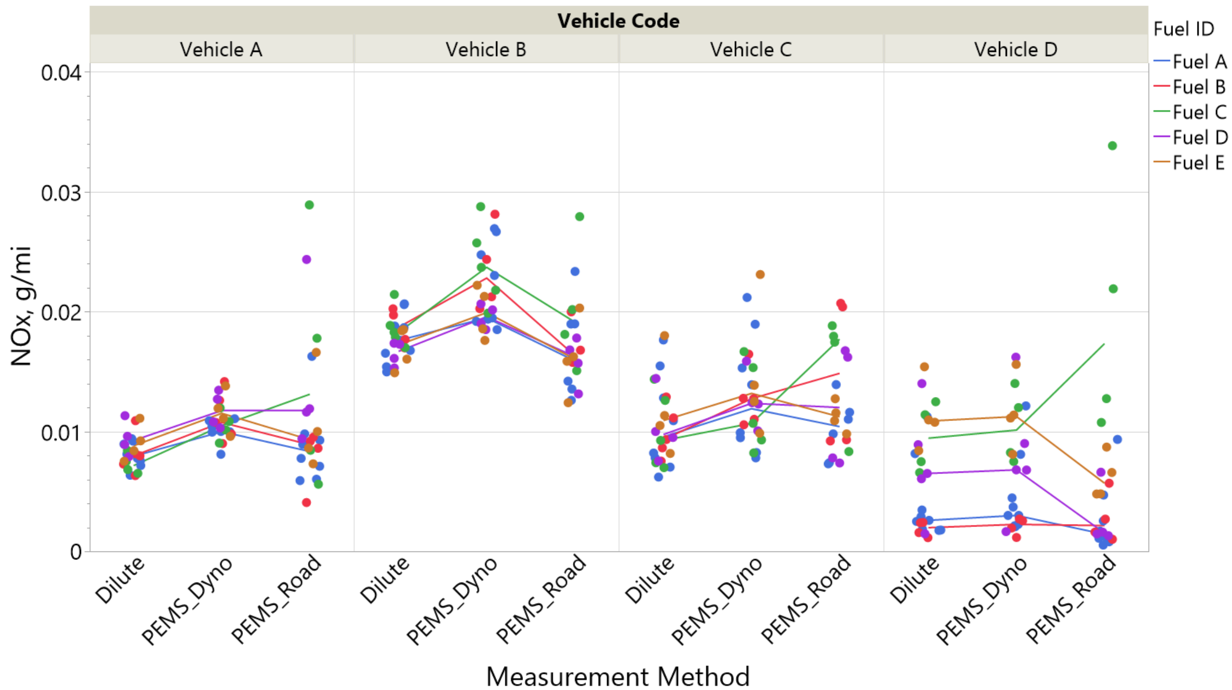


FIGURE 49. RAW DATA PLOT OF NOX (G/MI) BY MEASUREMENT METHOD AND VEHICLE, COLORED BY FUEL

A separate mixed effects model was run for each vehicle/method combination, and no statistically significant set-to-set variance component was observed, and therefore the short- and long-term repeatability summaries are the same and combined into a single table shown below in Table 21. F-tests for variances run separately by method indicated that PEMS_Road repeatability standard deviation is statistically different from Dilute for Vehicles A and B and are estimated to be a 190% increase and 100% increase, respectively. PEMS_Road and Dilute repeatability for NO_x were not statistically distinguishable for Vehicles C and D.

TABLE 21. NO_X REPEATABILITY SUMMARY BY VEHICLE

Vehicle A

Repeatability Summary

Measurement Method	Std. Dev. , Transformed Units	Repeatability, g/mi[1]
Dilute	0.1544	$0.4280 * X$
PEMS_Dyno	0.1341	$0.3717 * X$
PEMS_Road	0.4445	$1.2321 * X$

Vehicle B

Repeatability Summary

Measurement Method	Std. Dev. , Transformed Units	Repeatability, g/mi[1]
Dilute	0.0987	$0.2736 * X$
PEMS_Dyno	0.1344	$0.3725 * X$
PEMS_Road	0.1930	$0.5350 * X$

Vehicle C

Repeatability Summary

Measurement Method	Std. Dev. , Transformed Units	Repeatability, g/mi[1]
Dilute	0.3415	$0.9466 * X$
PEMS_Dyno	0.3345	$0.9272 * X$
PEMS_Road	0.3187	$0.8834 * X$

Vehicle D

Repeatability Summary

Measurement Method	Std. Dev. , Transformed Units	Repeatability, g/mi[1]
Dilute	0.5907	$1.6373 * X$
PEMS_Dyno	0.5687	$1.5764 * X$
PEMS_Road	0.7549	$2.0925 * X$

Note 1: “X” represents the average of two results being compared, in g/mi.

4.3.3 CO_2 and Fuel Economy, Repeatability of PEMS Compared with Chassis Dyno Dilute Testing

A plot of CO_2 emissions is given below in Figure 50, followed by fuel economy in Figure 51. The mixed effects model was run to test for a statistically significant set-to-set variance component, and only the Dilute method came back as statistically significant. This can be attributed to the highly repeatable nature of CO_2 via the Dilute method on the chassis dynamometer. The standard deviation between sets was estimated to be 1 g/mi, and therefore not practically significant. Therefore, though the variance components were estimated separately for Dilute, the summary provided in Table 22 is only the long-term repeatability summary combining both variance components, since the magnitude of the difference for dilute does not warrant a separate table.

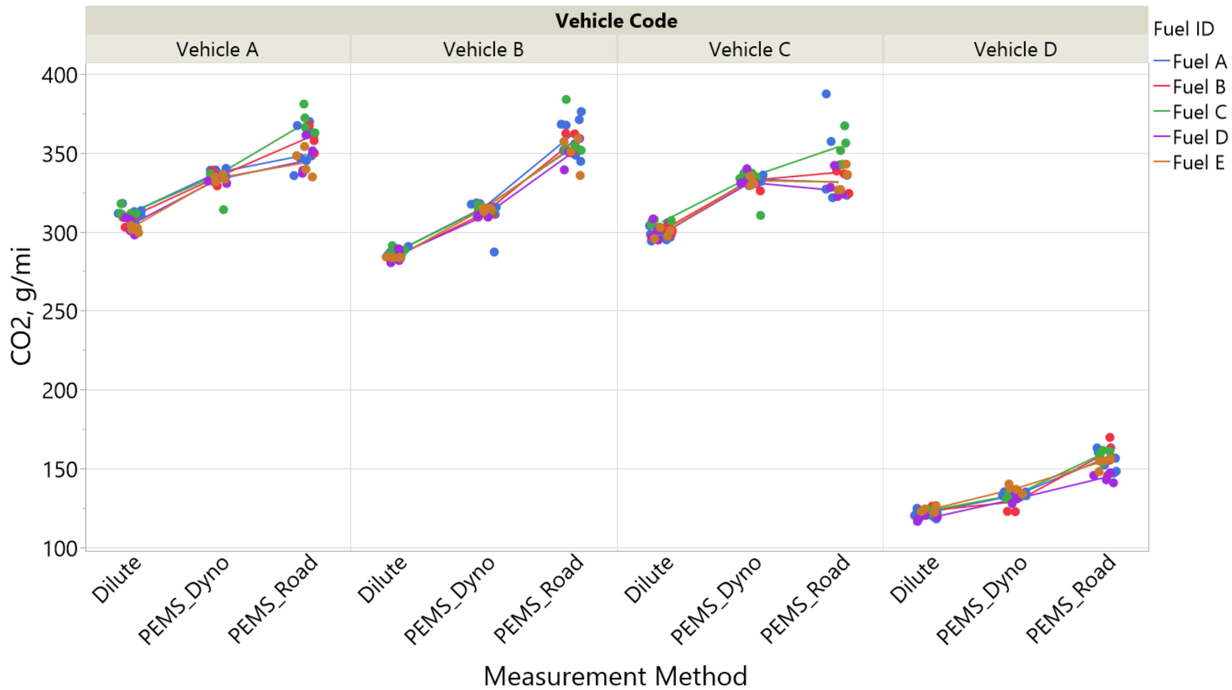


FIGURE 50. RAW DATA PLOT OF CO2 (G/MI) BY MEASUREMENT METHOD AND VEHICLE, COLORED BY FUEL

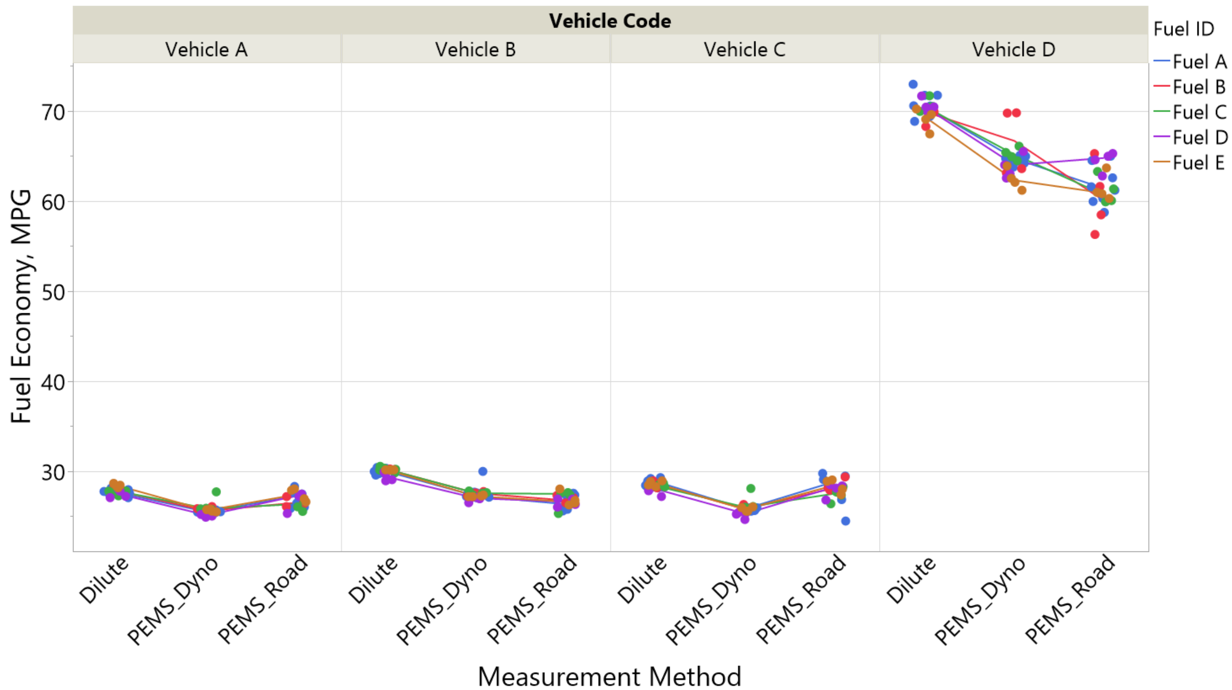


FIGURE 51. RAW DATA PLOT OF FUEL ECONOMY (MPG) BY MEASUREMENT METHOD AND VEHICLE, COLORED BY FUEL

No vehicle differences in variability were seen with the transformed data. Therefore, only a single repeatability table is needed which covers short- and long-term repeatability estimates for all vehicles. The values for both the CO_2 (Table 22) and fuel economy (Table 23) are, in fact, the same, and were re-run to verify there was not an oversight. The key takeaway from these values is that the standard deviation ranking of Dilute < PEMS_Dyno < PEMS_Road is statistically significant based on pairwise F-tests, with PEMS_Dyno repeatability standard deviation estimated to be 50% higher than Dilute, and PEMS_Road repeatability standard deviation estimated to be 180% higher than Dilute.

TABLE 22. CO_2 REPEATABILITY SUMMARY

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.013	$0.0360 * X$
PEMS_Dyno	0.020	$0.0554 * X$
PEMS_Road	0.036	$0.0998 * X$

Note 1: "X" represents the average of two results being compared, in g/mi.

TABLE 23. FUEL ECONOMY REPEATABILITY SUMMARY

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability, mpg[1]
Dilute	0.013	$0.0360 * X$
PEMS_Dyno	0.020	$0.0554 * X$
PEMS_Road	0.036	$0.0998 * X$

Note 1: "X" represents the average of two results being compared, in mpg.

4.3.4 THC and NMHC, Repeatability of PEMS Compared with Chassis Dyno Dilute Testing

Figure 52 and Figure 53 give plots of the THC and NMHC data, respectively.

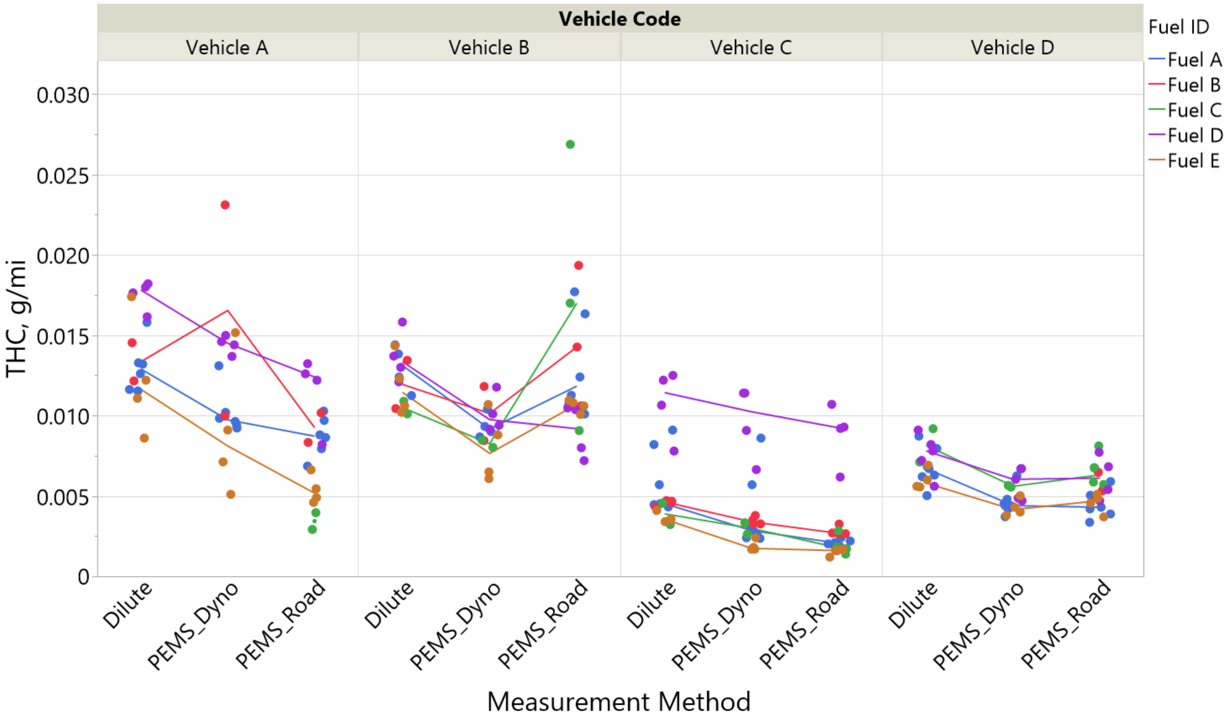


FIGURE 52. RAW DATA PLOT OF THC (G/MI) BY MEASUREMENT METHOD AND VEHICLE, COLORED BY FUEL

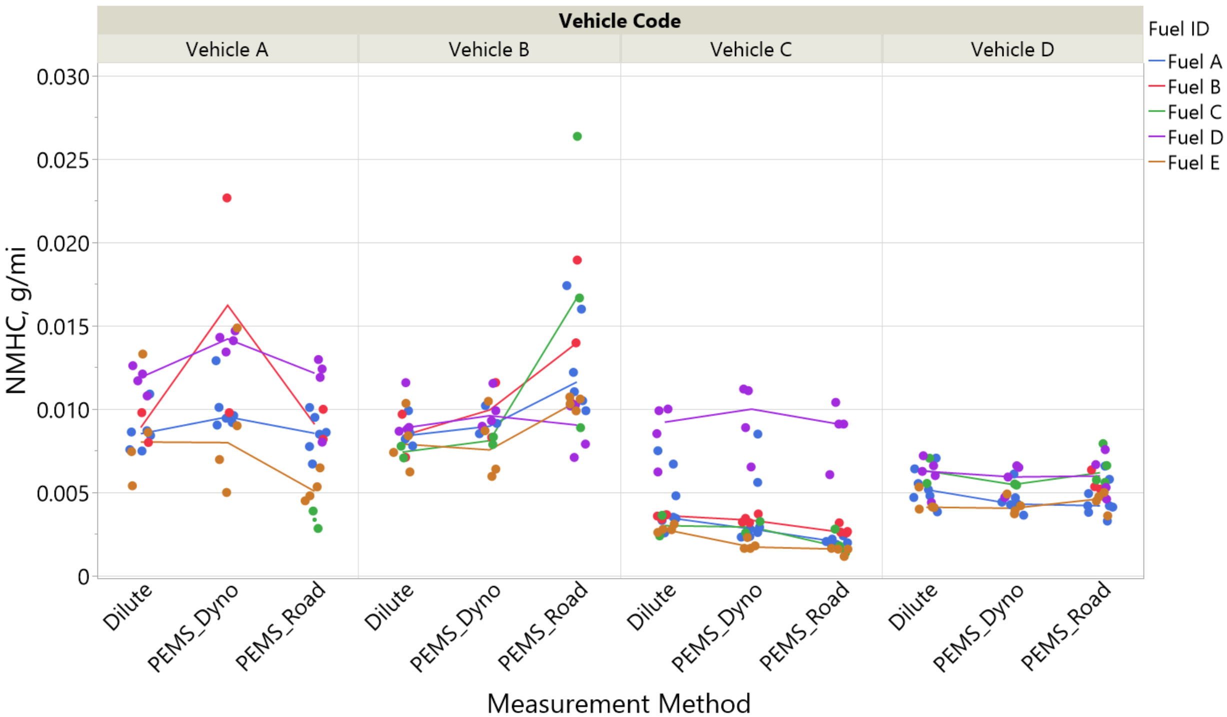


FIGURE 53. RAW DATA PLOT OF NMHC (G/MI) BY MEASUREMENT METHOD AND VEHICLE, COLORED BY FUEL

Variability was determined to be vehicle dependent for this parameter, and therefore a separate mixed model was run for each vehicle/method combination. None of the models indicated a significant set-to-set variance component. The repeatability summaries by vehicle are given in Table 24 and Table 25 for THC and NMHC, respectively. Under the assumption that PEMS on-road standard deviation cannot be smaller than chassis dyno testing with the PEMS, in cases where the observed PEMS_Road testing standard deviation was estimated to be smaller than PEMS_Dyno, the two estimates were considered appropriate to pool together for an improved estimate of the PEMS standard deviation. This was done for Vehicles A and C for both THC and NMHC. In these cases, the pooled PEMS estimate was statistically compared against Dilute. PEMS_Road repeatability standard deviation vs. Dilute for Vehicle B is the only significant difference, estimated to be a 70% increase.

TABLE 24. THC REPEATABILITY SUMMARY

Vehicle A

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.1699	$0.4706 * X$
PEMS_Dyno	0.2991	$0.8285 * X$
PEMS_Road	0.1698	$0.4703 * X$
PEMS_Pooled	0.2432	$0.6737 * X$

Vehicle B

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.1290	$0.3573 * X$
PEMS_Dyno	0.1715	$0.4751 * X$
PEMS_Road	0.2220	$0.6149 * X$

Vehicle C

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.2758	$0.7640 * X$
PEMS_Dyno	0.3730	$1.0332 * X$
PEMS_Road	0.1774	$0.4914 * X$
PEMS_Pooled	0.2921	$0.8091 * X$

Vehicle D

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.1668	$1.6373 * X$
PEMS_Dyno	0.1504	$1.5764 * X$
PEMS_Road	0.2136	$2.0925 * X$

Note 1: “X” represents the average of two results being compared, in g/mi.

TABLE 25. NMHC REPEATABILITY SUMMARY

Vehicle A

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.2132	$0.5906 * X$
PEMS_Dyno	0.2996	$0.8299 * X$
PEMS_Road	0.1750	$0.4848 * X$
PEMS_Pooled	0.2454	$0.6798 * X$

Vehicle B

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.1591	$0.4407 * X$
PEMS_Dyno	0.1709	$0.4734 * X$
PEMS_Road	0.2773	$0.7681 * X$

Vehicle C

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.2726	$0.7551 * X$
PEMS_Dyno	0.3359	$0.9304 * X$
PEMS_Road	0.1867	$0.5172 * X$
PEMS_Pooled	0.2717	$0.7526 * X$

Vehicle D

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.1837	$0.5088 * X$
PEMS_Dyno	0.1481	$0.4102 * X$
PEMS_Road	0.1907	$0.5282 * X$

Note 1: “X” represents the average of two results being compared, in g/mi.

4.3.5 CO, Repeatability of PEMS Compared with Chassis Dyno Dilute Testing

For CO, there was no vehicle dependence in variability after the natural log transformation was applied. Additionally, none of the methods indicated a significant set-to-set variance component based on the Wald's test from the mixed model. A raw plot of the data is shown below in Figure 54, followed by the repeatability summary table in Table 26.

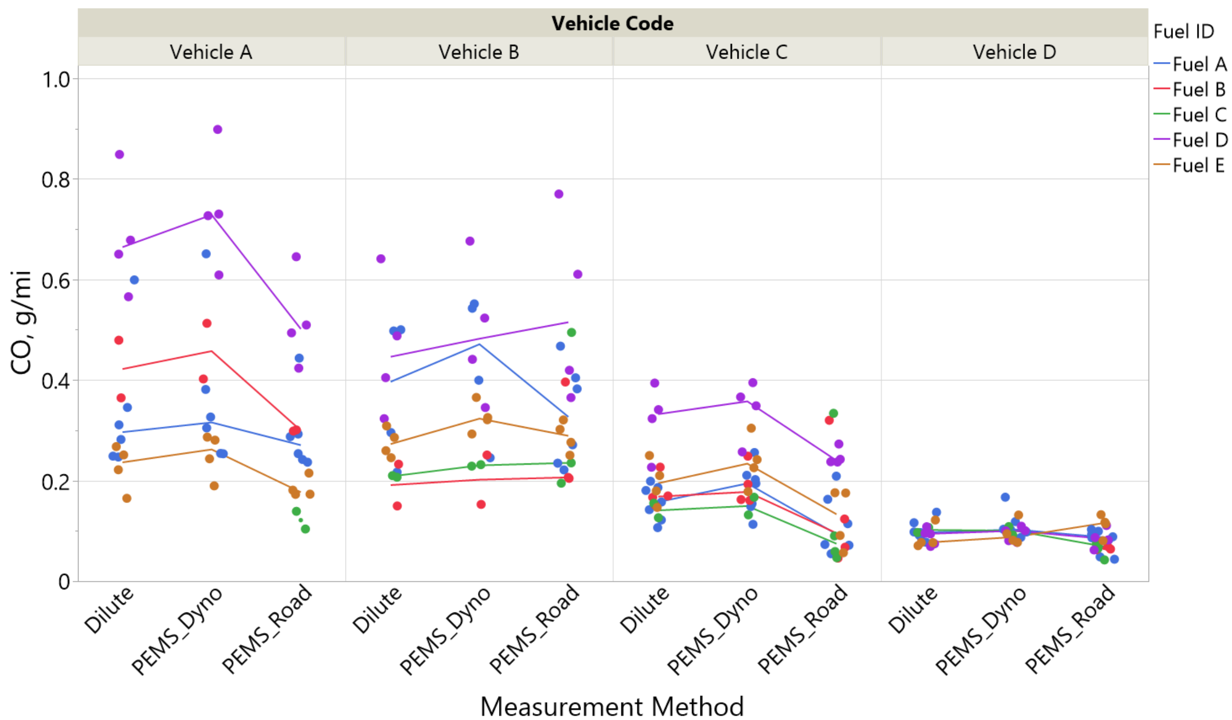


FIGURE 54. RAW DATA PLOT OF CO (G/MI) BY MEASUREMENT METHOD AND VEHICLE, COLORED BY FUEL

TABLE 26. CO REPEATABILITY SUMMARY

Repeatability Summary

Measurement Method	Std. Dev., Transformed Units	Repeatability g/mi[1]
Dilute	0.1954	$0.5416 * X$
PEMS_Dyno	0.2654	$0.7357 * X$
PEMS_Road	0.1964	$0.5444 * X$
PEMS_Pooled	0.2335	$0.6472 * X$

Note 1: "X" represents the average of two results being compared, in g/mi.

4.4 PEMS Accuracy

PEMS results were also analyzed for accuracy. For this analysis PEMS accuracy was defined as the difference between the PEMS results and the Dilute results. Since the PEMS unit was run on the chassis dynamometer, a direct paired result of PEMS results vs. Dilute results was available for each test. "PEMS_Dyno – Dilute" was calculated using all the chassis dynamometer tests. The differences were calculated after applying the appropriate transformations. A plot of the transformed PM data is shown below in Figure 55. The trend lines connect the median result for each fuel/method and are separated by vehicle. The PEMS results tended to be lower than the chassis-dyno dilute results.

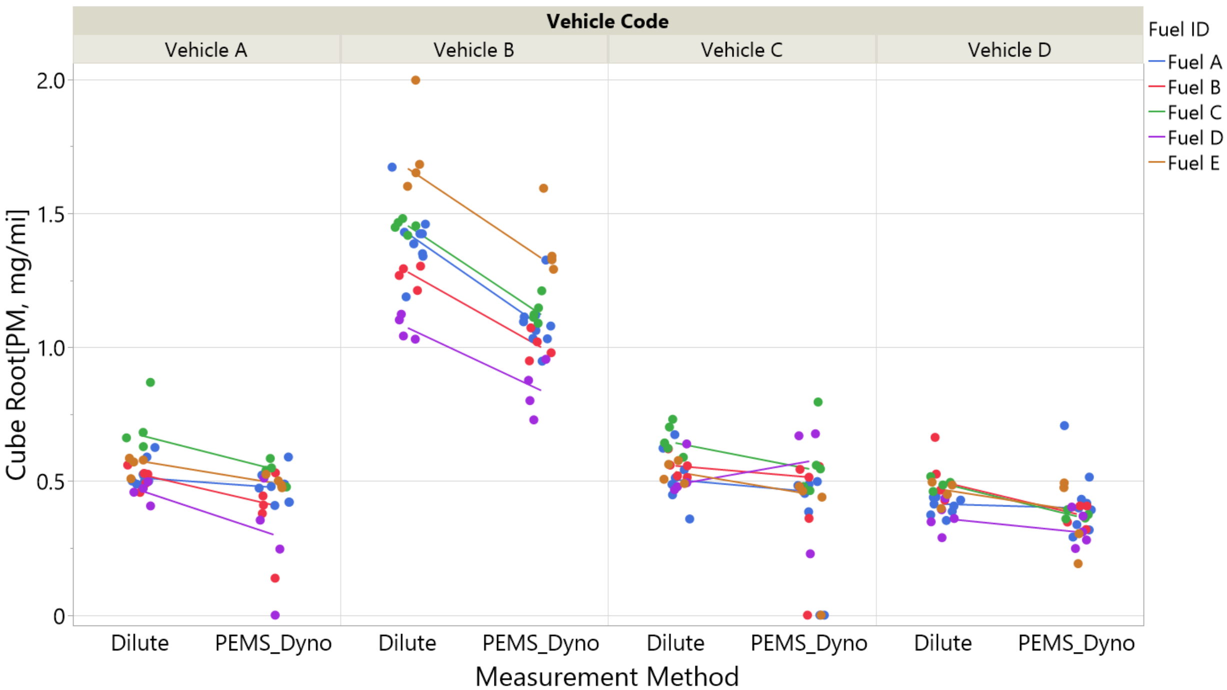


FIGURE 55. SIDE-BY-SIDE COMPARISON OF DILUTE VS. PEMS_DYNO BY VEHICLE, COLORED BY FUEL

Histograms showing the distribution of the differences of "PEMS_Dyno – Dilute" were also created for each vehicle. Figure 56 shows that for PM, the PEMS had a larger bias (more negative) for Vehicle B than for the other three vehicles. Though Vehicle B was a Tier 2 vehicle with higher PM than the other Tier 3 vehicles, even on a percentage basis, Vehicle B still exhibited the largest bias.

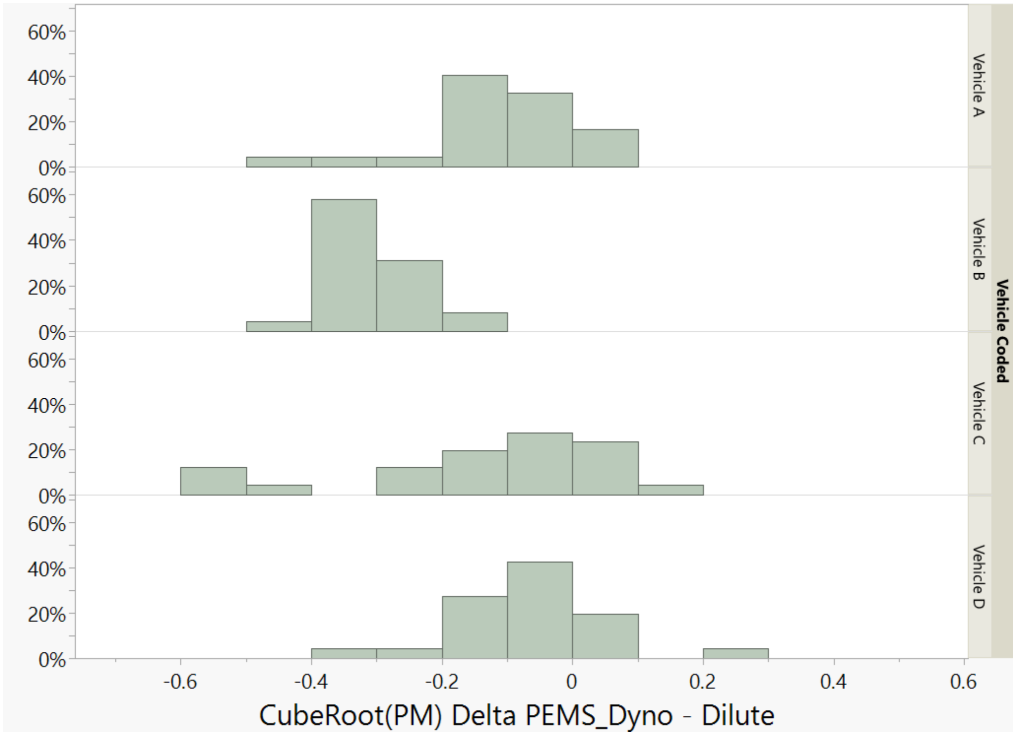


FIGURE 56. HISTOGRAM OF PEMS_DYNO – DILUTE, DISTRIBUTION BY VEHICLE

For each vehicle, the median bias was obtained, along with a 95% confidence interval using the transformed data. These differences were then back transformed into units of mg/mi. Finally, the relative bias was obtained for each vehicle by dividing the estimates by the median PM level. Results from these three steps are shown below in Table 27, Table 28, and Table 29.

TABLE 27. MEDIAN BIAS FOR CUBE ROOT (PM), PEMS_DYNO - DILUTE

Vehicle	PEMS Median Bias Estimate, $\sqrt[3]{PM}$	Lower 95%	Upper 95%
Vehicle A	-0.100	-0.125	-0.068
Vehicle B	-0.307	-0.332	-0.278
Vehicle C	-0.092	-0.169	-0.026
Vehicle D	-0.056	-0.103	-0.014

TABLE 28. PEMS MEDIAN BIAS ESTIMATE FOR PM (MG/MI)

Vehicle	Median Dilute PM, mg/mi	PEMS Median Bias Estimate, mg/mi	Lower 95%	Upper 95%
Vehicle A	0.146	-0.068	-0.081	-0.049
Vehicle B	2.867	-1.486	-1.577	-1.375
Vehicle C	0.166	-0.070	-0.111	-0.022
Vehicle D	0.083	-0.028	-0.046	-0.008

TABLE 29. PEMS MEDIAN RELATIVE BIAS ESTIMATE (%)

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	-46.9%	-55.7%	-34.0%
Vehicle B	-51.8%	-55.0%	-48.0%
Vehicle C	-42.3%	-66.8%	-13.5%
Vehicle D	-33.7%	-55.4%	-9.3%

Table 29 shows that the range of median PEMS relative bias was -52% to -34% depending on the vehicle. The median relative bias ranges seen on the other tested parameters following the same procedure are shown in Table 30. The same plots and tables shown above for PM are given for other parameters in Appendix G.

TABLE 30. MEDIAN RELATIVE BIAS RANGES ACROSS VEHICLES BY PARAMETER

Parameter	Median Relative Bias Range
PM, mg/mi	-52% to -34%
NO_x, g/mi	11% to 30%
CO_2, g/mi	8.7% to 10.5%
Fuel Economy, mpg	-9.5% to -8.2%
THC, g/mi	-29% to -20%
NMHC, g/mi	-9 to 17.0%
CO, g/mi	6.5% to 10.5%

4.5 PEMS Road-Testing Accuracy and Variability After Instrument Bias Correction

Only a single PEMS unit was tested in this study. Results pertaining to variability and bias across multiple PEMS units are detailed in the report for CRC project E-122. Because of this previous work, the bias estimates by themselves for this single unit were not a primary interest of this study. The estimates were necessary, however, to remove the instrument bias when estimating the additional variability and bias that is attributable to road testing with the PEMS unit. Therefore, bias-corrected road results were also obtained in which the median bias observed for each vehicle-parameter combination was subtracted out of each road test result. Next, the distribution of "PEMS_Road_BiasCorrected – Dilute" was obtained by calculating every possible pairwise difference of a road result and a corresponding Dilute result for the same vehicle-fuel combination. The difference calculated is referred to as either "Delta" or "% Delta." The Delta values are calculated differences using the transformed parameters, while percentage Delta values are calculated as percent differences in original units. For example, for PM,

$$Delta = \sqrt[3]{PM\_PEMS\_Road} - \sqrt[3]{PM\_Dilute}$$

$$\%\ Delta = \frac{PM\_PEMS\_Road - PM\_Dilute}{PM\_Dilute} * 100$$

Quantiles of these distributions were calculated and plotted, along with 95% confidence intervals. To serve as a baseline for comparison, all possible pairwise differences of two Dilute measurements were also calculated and the distribution of these differences plotted. Therefore, the true “change” by using PEMS on the road can be understood by the side-by-side comparison. The 5th, 10th, 50th (median), 90th, and 95th percent quantiles are shown for each distribution.

4.5.1 PEMS Road-Testing Accuracy and Variability After Bias Correction for Particulate Matter

For Particulate Matter, the quantiles of the distributions of “Delta” and “% Delta” are shown below in Figure 57 and Figure 58, respectively. The key takeaway is that after the instrument bias correction, there were no quantiles where a PEMS_road test would be expected to produce a higher PM result compared to a typical Dilute chassis dynamometer test variability. There is a slight negative median bias that is attributed to the on-road testing for Vehicles C and D. PEMS on-road testing sometimes resulted in abnormally low PM result compared to normal dilute testing variability as seen by the 5th and 10th percent quantiles for all vehicles but Vehicle B.

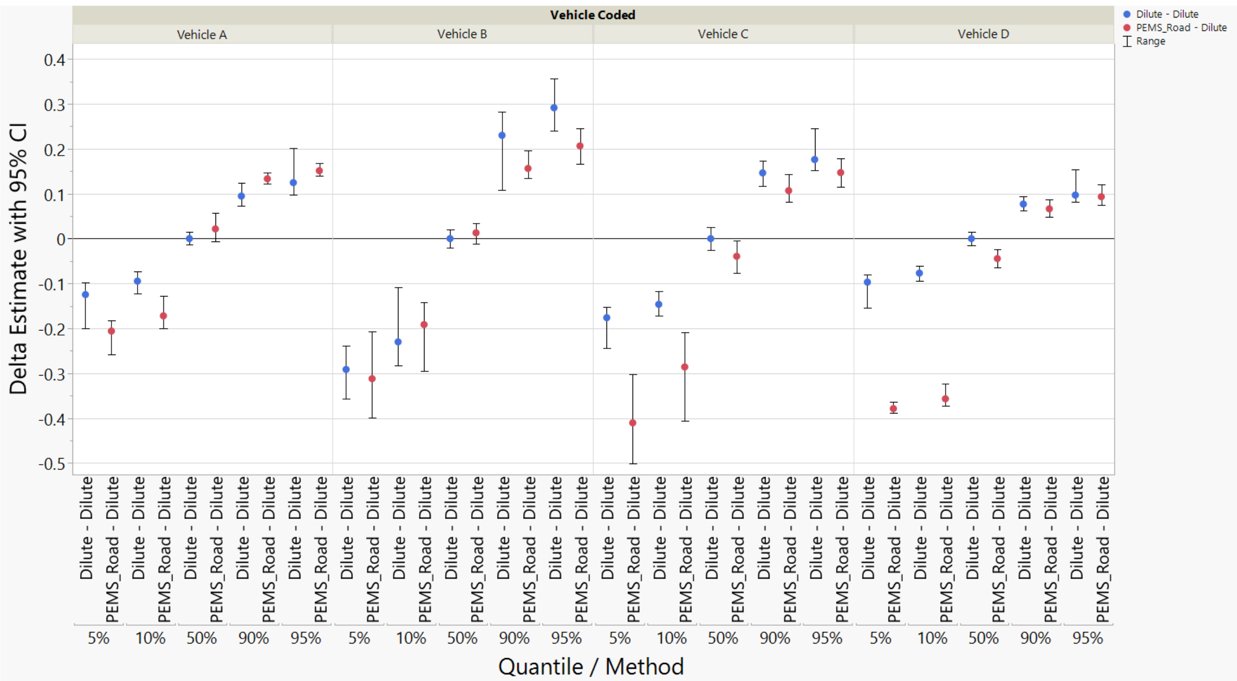


FIGURE 57. QUANTILES OF DELTA PM WITH 95% CONFIDENCE INTERVALS

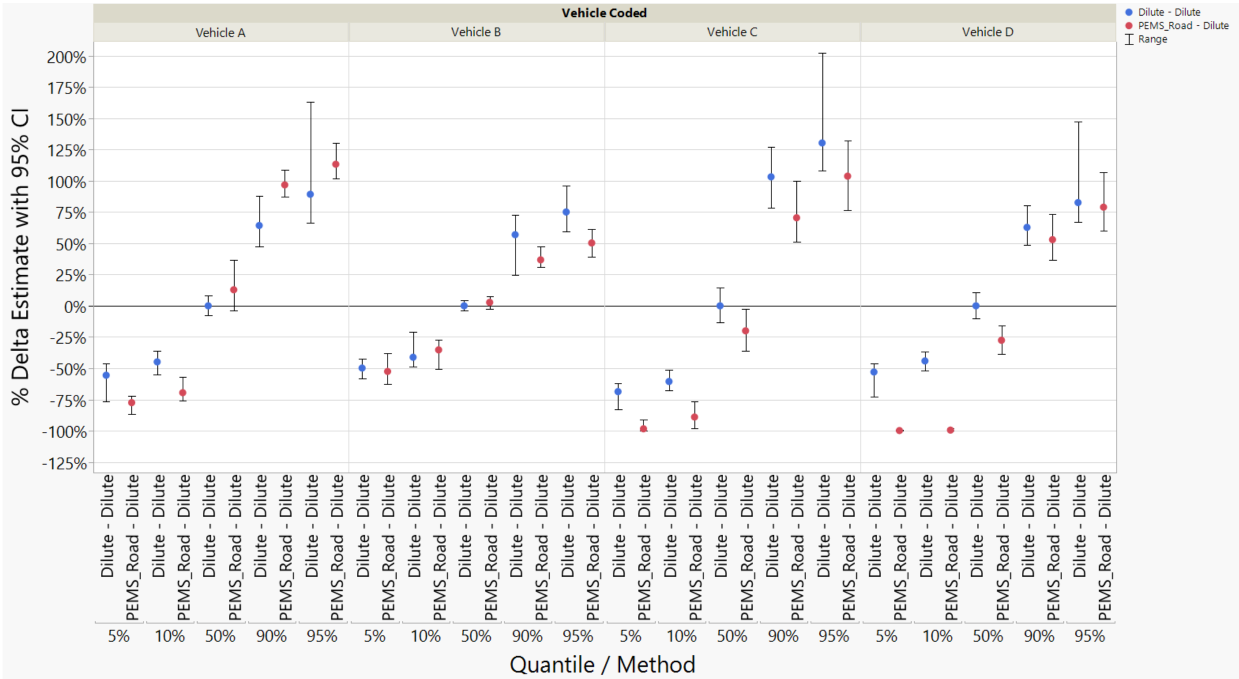


FIGURE 58. QUANTILES OF % DELTA PM WITH 95% CONFIDENCE INTERVALS

4.5.2 PEMS Road-Testing Accuracy and Variability After Bias Correction for NO_x

For NO_x, the quantiles of the distributions of "Delta" and "% Delta" are shown below in Figure 59 and Figure 60, respectively. The conclusions varied by vehicle. Vehicle A showed much more variability, seeing some instances of higher than normal NO_x along with other instances of lower than normal NO_x. For Vehicles B and D, NO_x levels only tended to be lower than normal, while no significant differences are seen for Vehicle C.

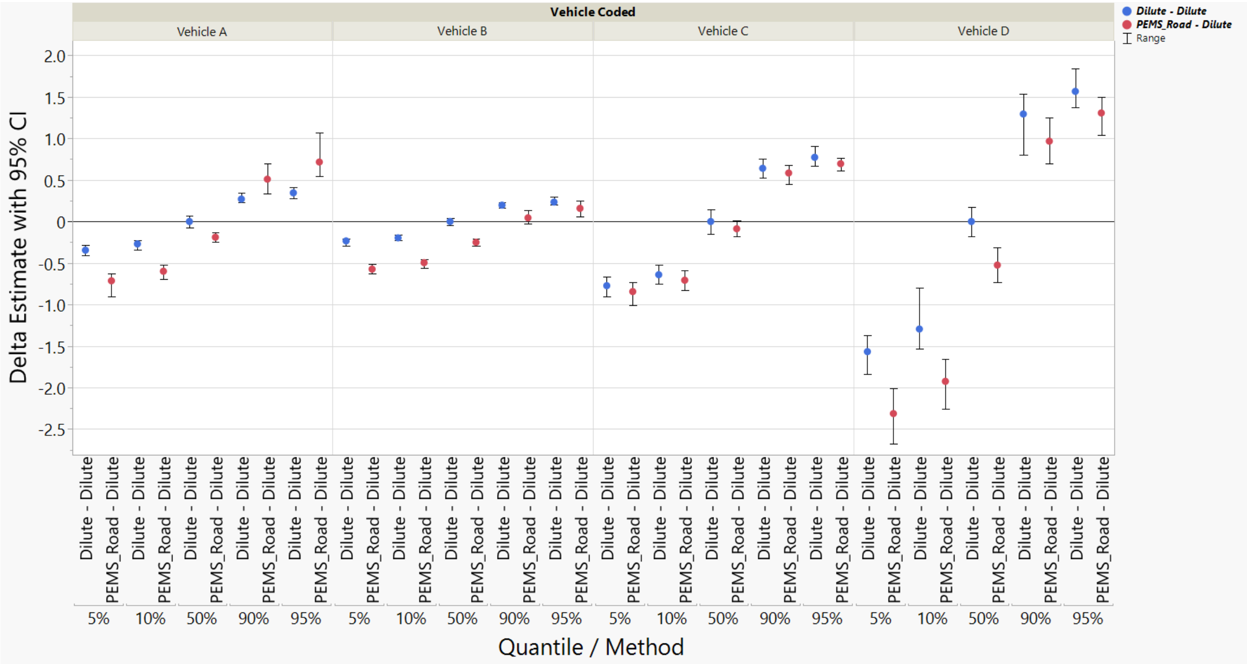


FIGURE 59. QUANTILES OF DELTA NO_X WITH 95% CONFIDENCE INTERVALS

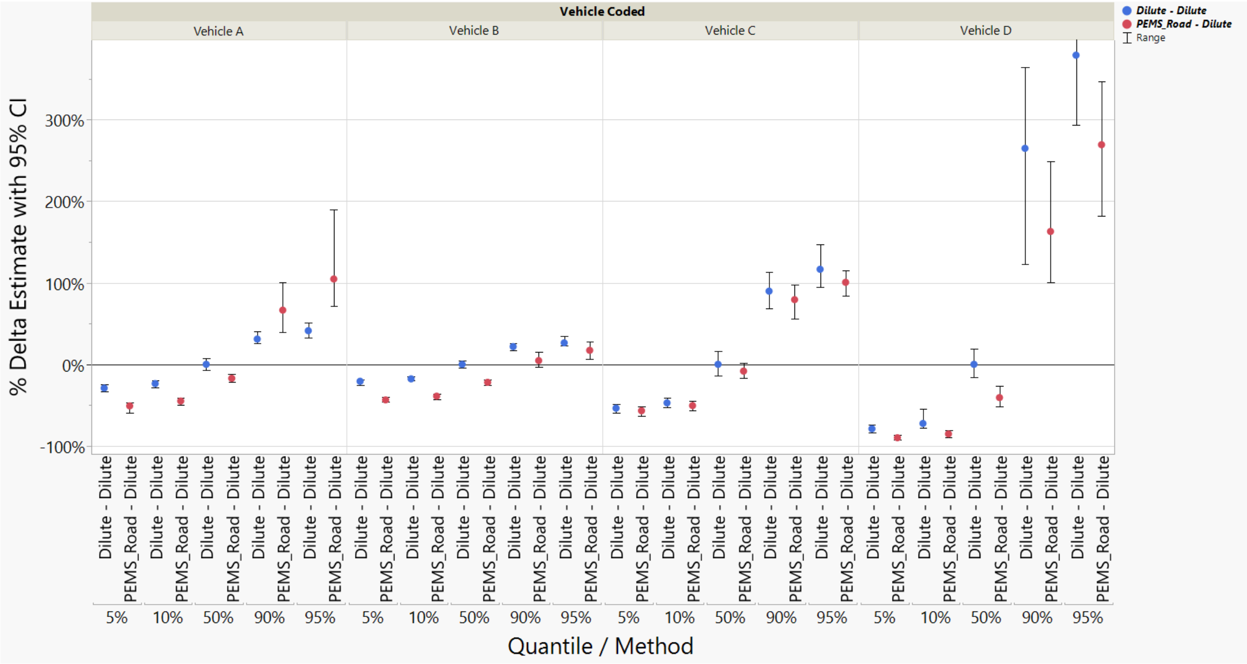


FIGURE 60. QUANTILES OF % DELTA NO_X WITH 95% CONFIDENCE INTERVALS

4.5.3 PEMS Road-Testing Accuracy and Variability After Bias Correction for CO_2

For CO_2, the quantiles of the distributions of "Delta" and "% Delta" are shown below in Figure 61 and Figure 62, respectively. For all vehicles, CO_2 levels were higher on the road compared with Dilute chassis dynamometer levels, even after the instrument bias correction.

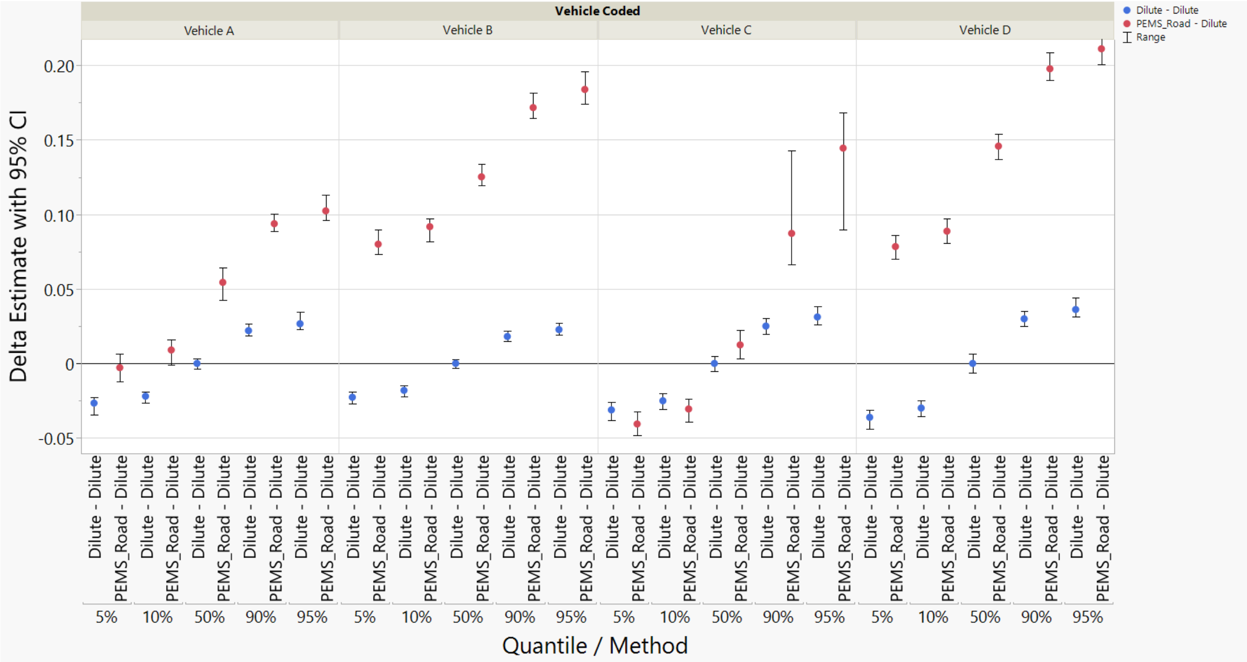


FIGURE 61. QUANTILES OF DELTA CO_2 WITH 95% CONFIDENCE INTERVALS

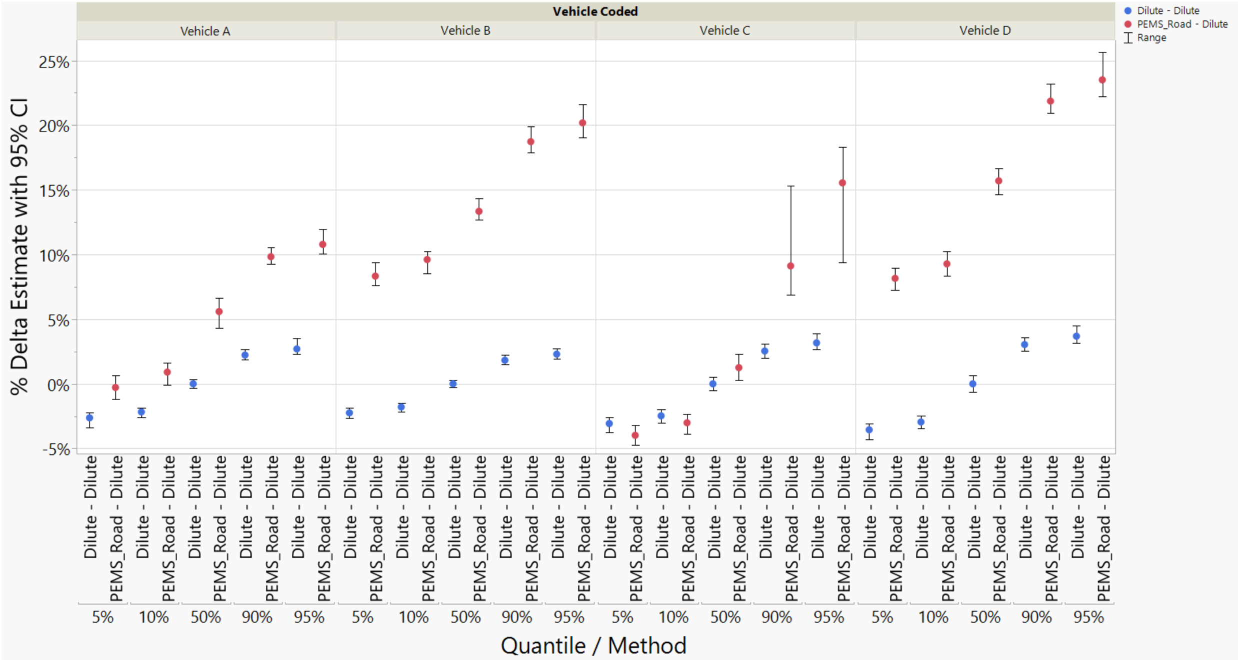


FIGURE 62. QUANTILES OF % DELTA CO_2 WITH 95% CONFIDENCE INTERVALS

4.5.4 PEMS Road-Testing Accuracy and Variability After Bias Correction for Fuel Economy

For fuel economy, the quantiles of the distributions of "Delta" and "% Delta" are shown in Figure 63 and Figure 64, respectively. Vehicles A and C tended to show higher fuel economy from on-road tests compared to chassis dynamometer tests. Vehicle B and D show the opposite trend.

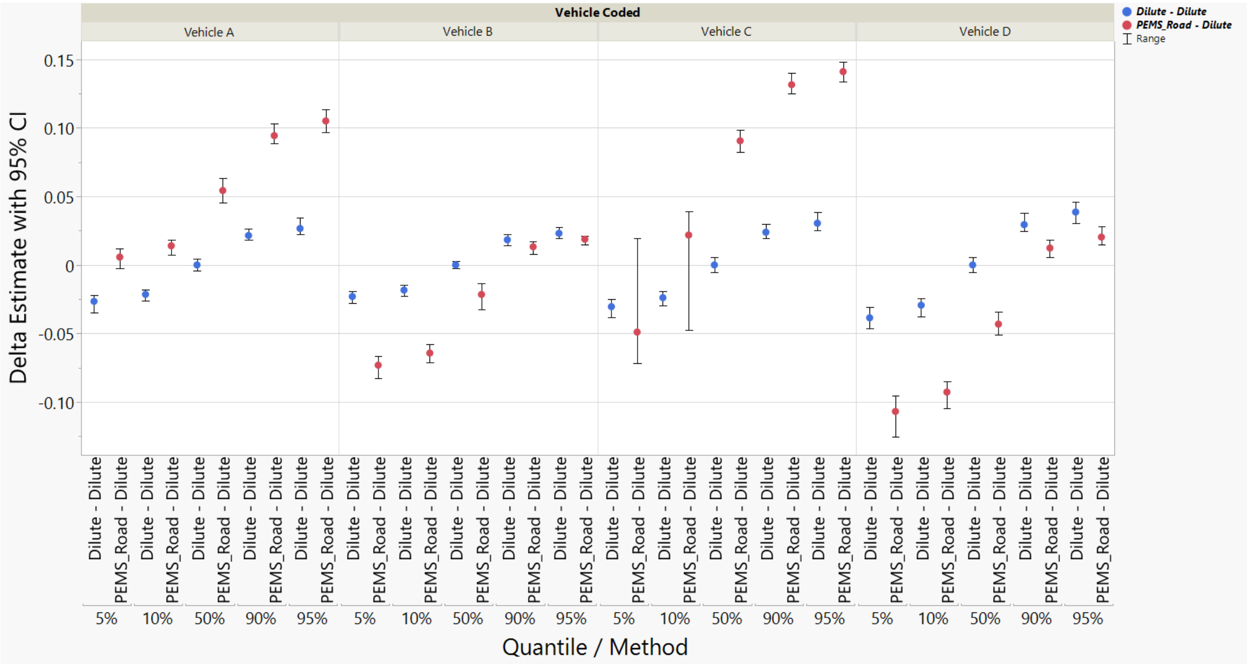


FIGURE 63. QUANTILES OF DELTA FUEL ECONOMY WITH 95% CONFIDENCE INTERVALS

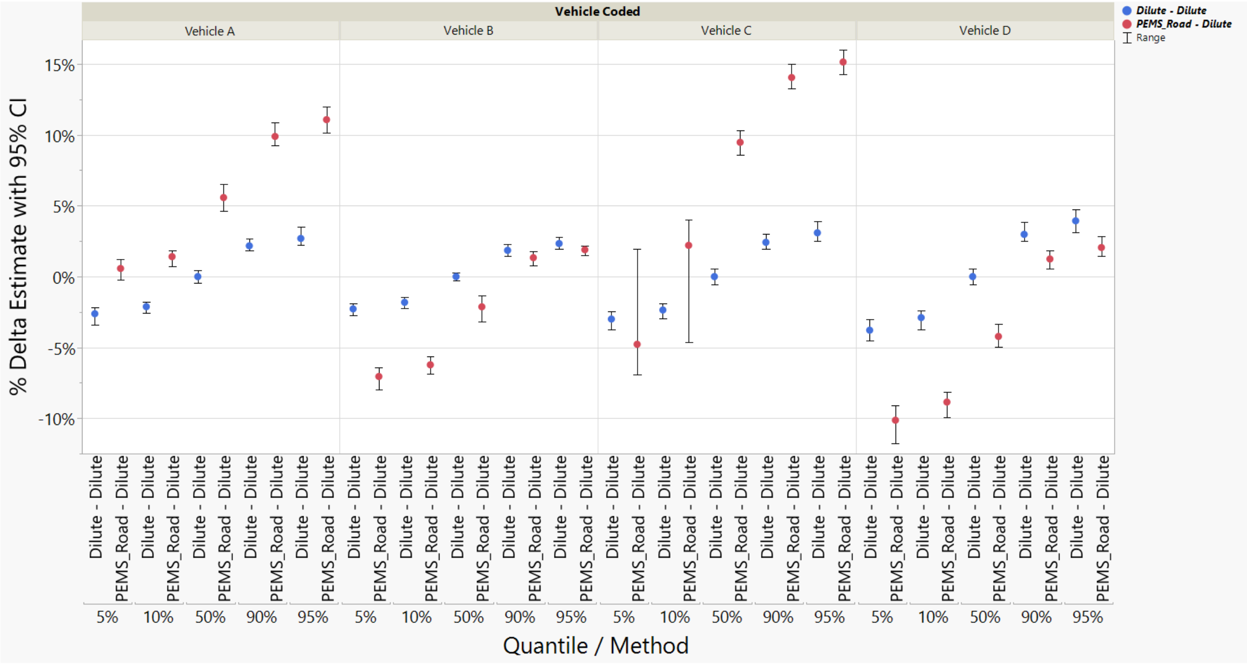


FIGURE 64. QUANTILES OF % DELTA FUEL ECONOMY WITH 95% CONFIDENCE INTERVALS

4.5.5 PEMS Road-Testing Accuracy and Variability After Bias Correction for THC

For THC, the quantiles of the distributions of "Delta" and "% Delta" are shown below in Figure 65 and Figure 66, respectively. Vehicles A and C had lower than normal THC levels, Vehicle B tended to have higher THC, and Vehicle D exhibited no differences in the distribution.

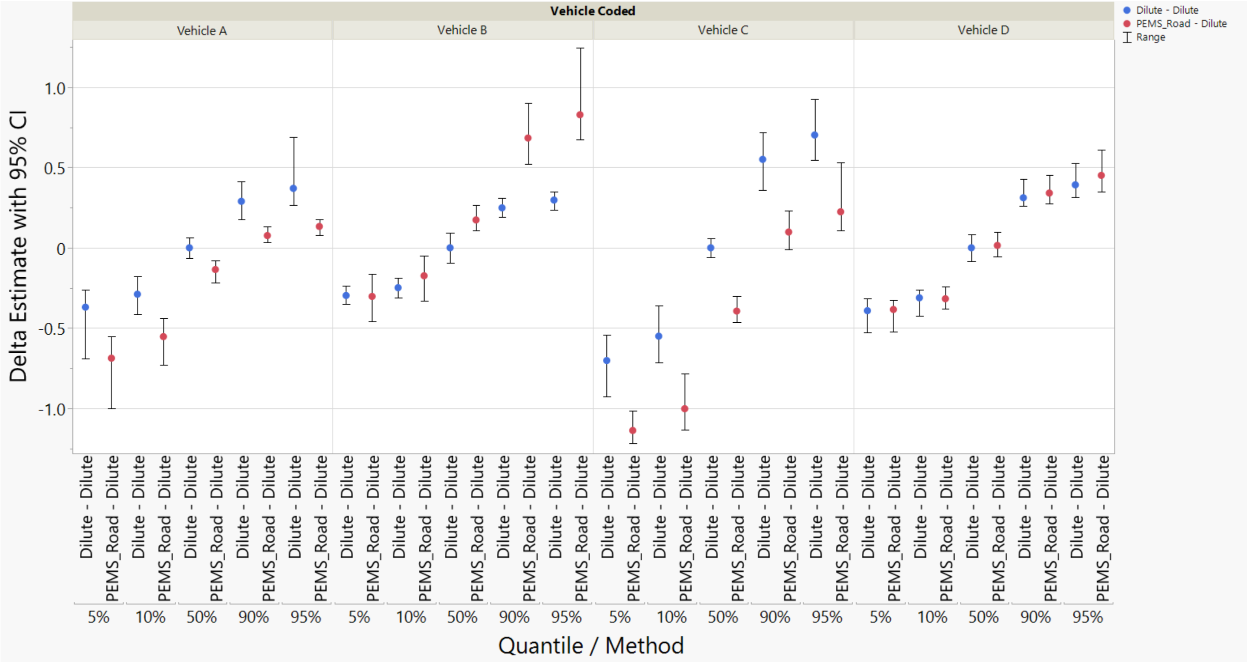


FIGURE 65. QUANTILES OF DELTA THC WITH 95% CONFIDENCE INTERVALS

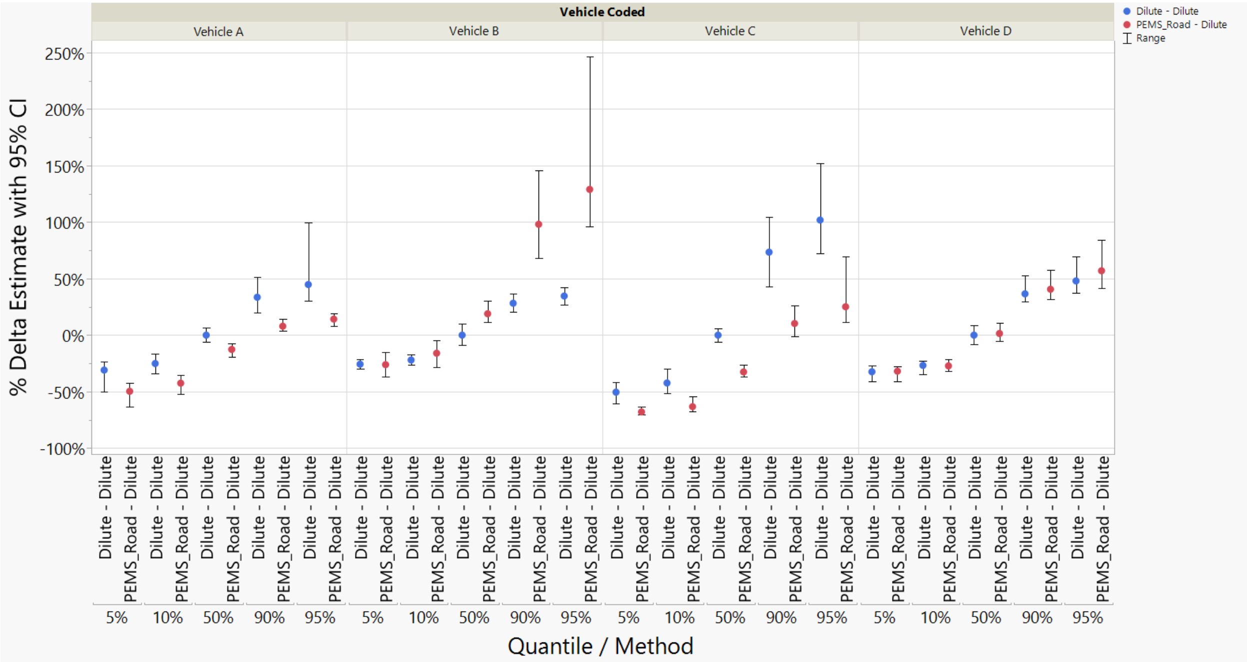


FIGURE 66. QUANTILES OF % DELTA THC WITH 95% CONFIDENCE

INTERVALS

4.5.6 PEMS Road-Testing Accuracy and Variability After Bias Correction for NMHC

For NMHC, the quantiles of the distributions of "Delta" and "% Delta" are shown below in Figure 67 and Figure 68, respectively. The conclusions are the same as with THC.

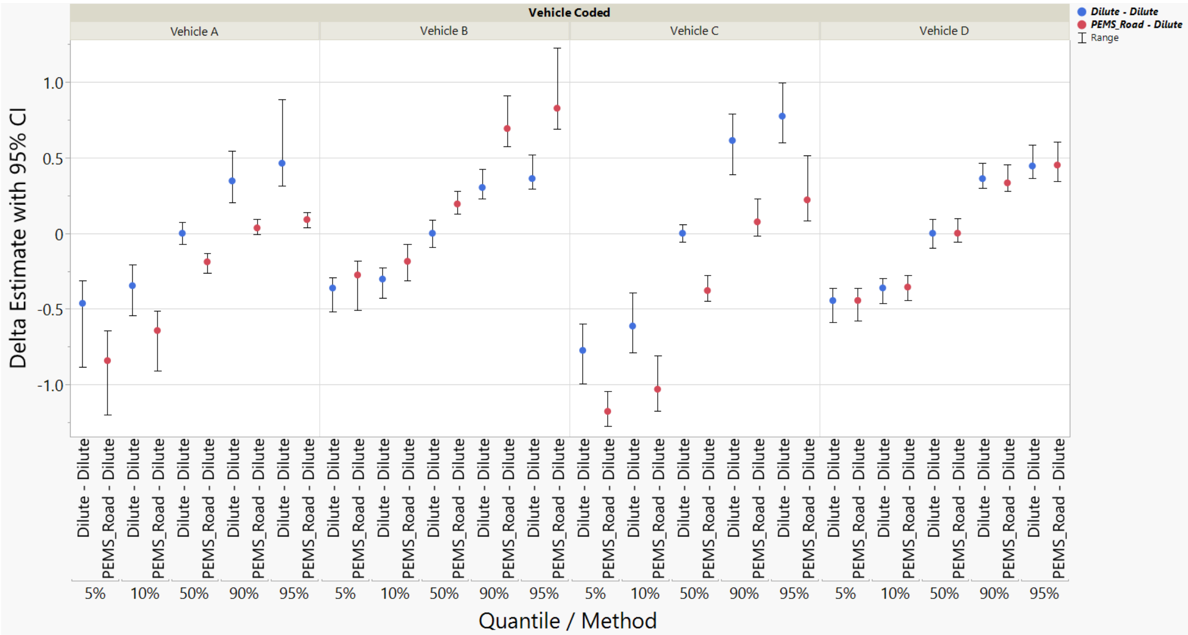


FIGURE 67. QUANTILES OF DELTA NMHC WITH 95% CONFIDENCE INTERVALS

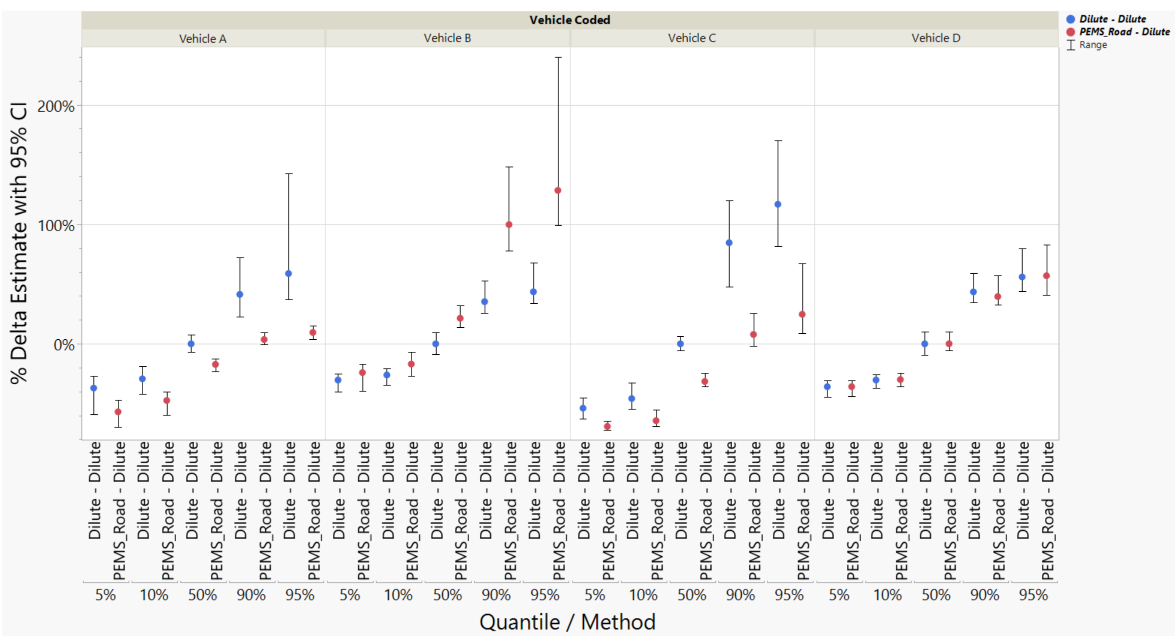


FIGURE 68. QUANTILES OF % DELTA NMHC WITH 95% CONFIDENCE

4.5.7 PEMS Road-Testing Accuracy and Variability After Bias Correction for CO

For CO, the quantiles of the distributions of "Delta" and "% Delta" are shown below in Figure 69 and Figure 70, respectively. Vehicles C and D had distributions with a negative bias and longer tails in the lower end, but no differences in the upper end. Vehicle A showed a slight negative bias in the upper half of the distribution, while Vehicle B showed no differences.

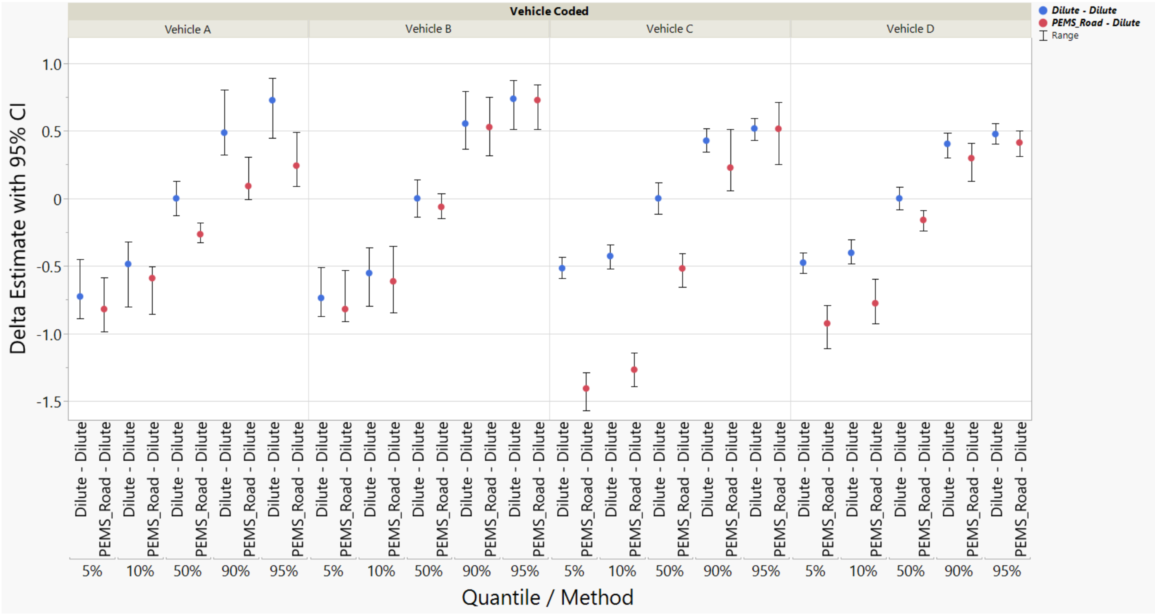


FIGURE 69. QUANTILES OF DELTA CO WITH 95% CONFIDENCE INTERVALS

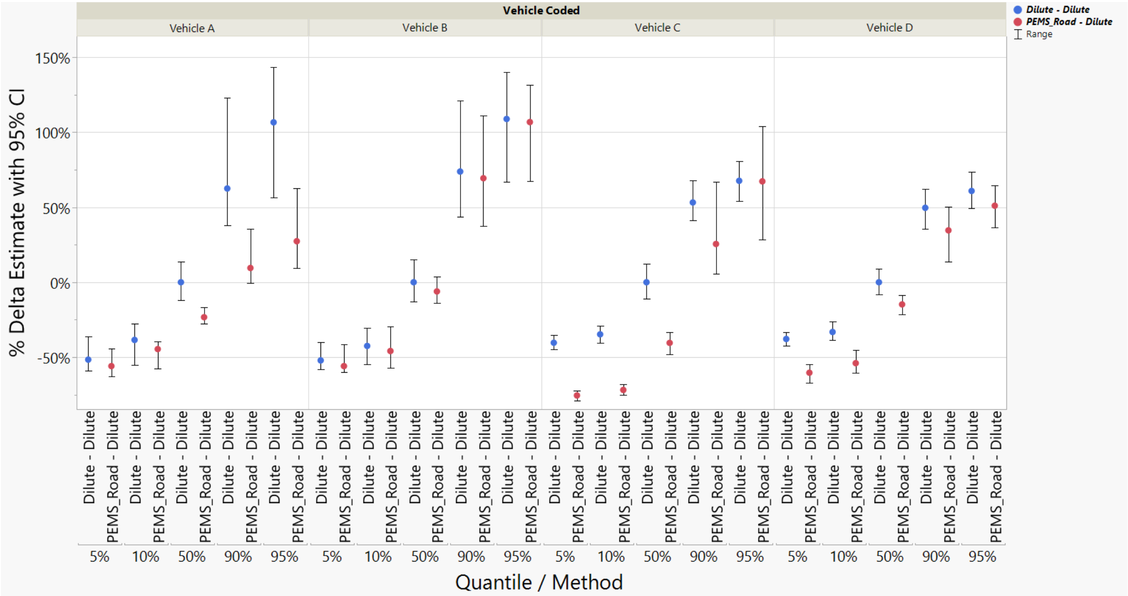


FIGURE 70. QUANTILES OF % DELTA CO WITH 95% CONFIDENCE INTERVALS

4.6 Fuel PMI and Fuel RVP as predictors of PM and Gaseous Emissions

The test fuels for this program were chosen to include high and low PMI fuels, along with high and low RVP fuels. Values of PMI and RVP by fuel were given in Table 3. There were two objectives related to these fuel properties.

1. Determine if fuel PMI and fuel RVP are statistically significant predictors of PM and gaseous emissions.
2. Is PEMS testing impacted similarly to dilute chassis-dyno testing by the changes in fuel properties?

Correlations between PMI and RVP with other fuel properties was expected for both coincidental and intrinsic reasons. In cases where PMI and/or RVP are determined to be statistically significant predictors, one must keep in mind all other highly correlated parameters as being potential replacement predictors. A targeted fuel property design of experiments would be needed to unconfound the effects of PMI and RVP from these other properties and quantify their effects independently. For these fuels, PMI was shown to be highly correlated with T90, FBP, T95, 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. A correlation matrix is provided below in Table 31. Cells are formatted to show a darker green color as the correlation strength increases, regardless of direction. Plots of some of the stronger correlations are shown for PMI in Figure 71 and RVP in Figure 72.

TABLE 31. PMI AND RVP CORRELATIONS WITH OTHER FUEL PROPERTIES

	PMI	RVP
PMI	1.000	-0.551
RVP (EPA Equation)	-0.551	1.000
IBP	0.408	-0.963
T_5	0.541	-0.999
T_10	0.503	-0.994
T_20	0.461	-0.977
T_30	0.528	-0.915
T_40	0.498	-0.678
T_50	0.535	-0.961
T_60	0.902	-0.550
T_70	0.951	-0.473
T_80	0.933	-0.434
T_90	0.954	-0.428
T_95	0.894	-0.357
FBP	0.976	-0.617
Total Aromatics	0.782	-0.112
Recovered	0.458	-0.628
Residue	-0.182	-0.487
Loss	-0.434	0.720
Net Heat of Combution	-0.896	0.793
RON	0.373	0.323
MON	0.394	0.348
API Gravity	-0.863	0.880
Density @ 15C	0.861	-0.883
Ethanol (vol%)	0.307	0.362
Total Oxygen	0.009	0.584
Carbon Content	0.545	-0.598
Hydrogen Content	-0.807	0.733
H/C Ratio	-0.779	0.727
Sulfur by UV	-0.694	0.378

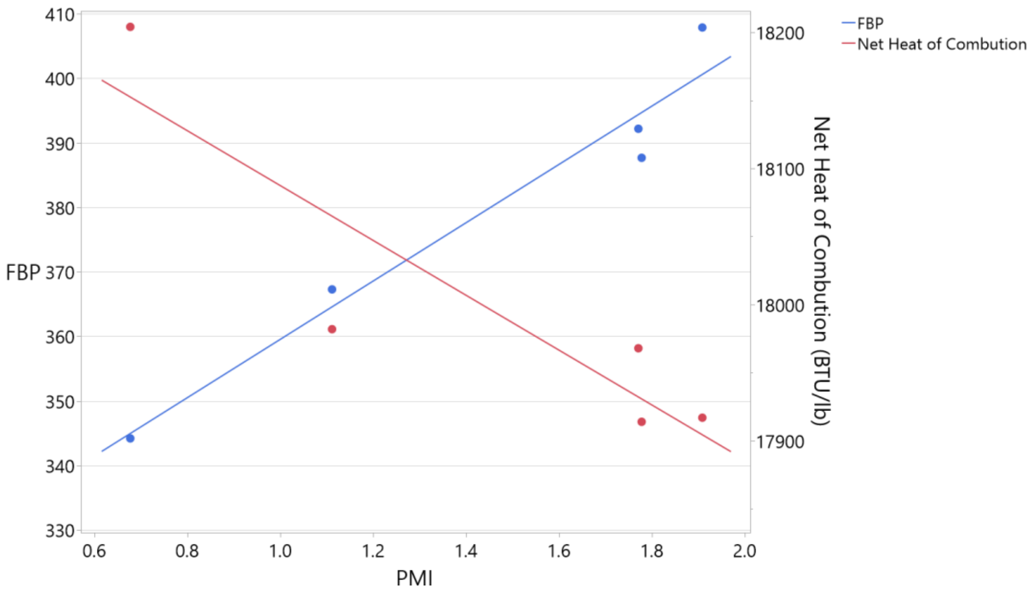


FIGURE 71. FBP AND NET HEAT OF COMBUSTION VS. PMI

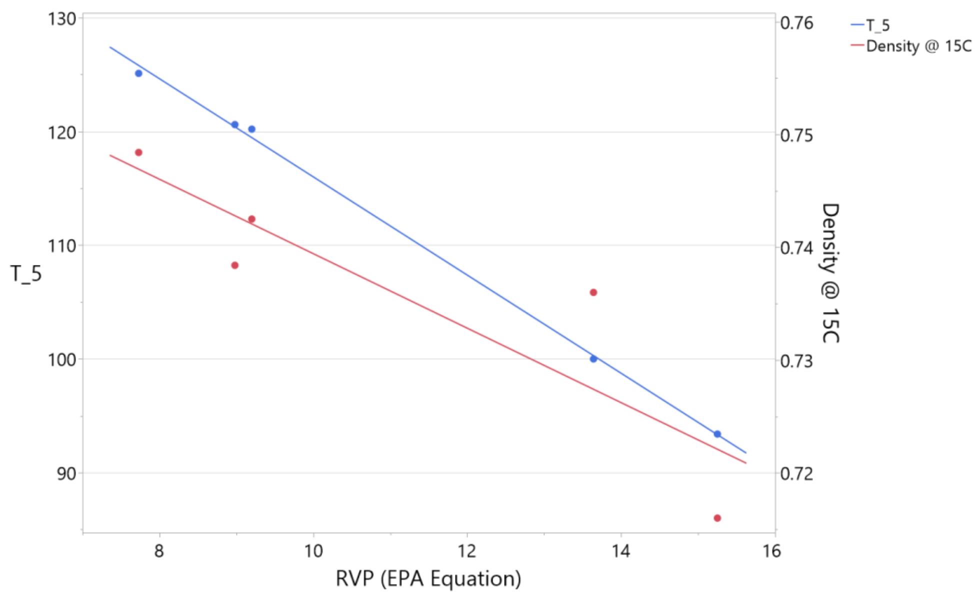


FIGURE 72. T5 AND DENSITY VS. RVP

For each of the emissions results, a regression model was built using Dilute chassis dynamometer data, and separately using the PEMS_Dyno data. PEMS_Dyno data was chosen over PEMS_Road data to reduce the variability in day-to-day results and provide more statistical power for detecting changes in results due to the fuel properties with the PEMS. The model included the categorical variable for vehicle, the continuous variables PMI and RVP, 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.

4.6.1 Fuel PMI and Fuel RVP as Predictors of Particulate Matter

The output from the PM models is shown in Table 32. The significant effects are the same for the Dilute model and the PEMS model. The results indicate that the fuel PMI variable is statistically significant but is vehicle dependent. The models indicate the PMI variable is significant for Vehicles A and B, but not for Vehicles C and D. Based on the dilute model coefficients, a fuel PMI increase of 1 is predicted to see an increase in PM from Vehicle A and Vehicle B PM by 75% and 144%, when the original PM level is 0.20 mg/mi and 1.00 mg/mi, respectively. A plot of the transformed PM data vs. PMI is given in Figure 73.

TABLE 32. CUBE ROOT (PM) ~ VEHICLE + FUEL PMI + (VEHICLE * FUEL PMI)

Dilute Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Vehicle Code	3	3	14.868272	463.6705	<.0001*
Fuel PMI	1	1	0.388206	36.3189	<.0001*
Fuel PMI*Vehicle Code	3	3	0.328619	10.2481	<.0001*

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	0.5279059	<.0001*	0.457593	0.5982188
Vehicle Code[Vehicle A]	-0.180677	<.0001*	-0.216075	-0.145278
Vehicle Code[Vehicle B]	0.6517174	<.0001*	0.6167418	0.6866931
Vehicle Code[Vehicle C]	-0.177539	<.0001*	-0.212467	-0.142611
Vehicle Code[Vehicle D]	-0.293501	<.0001*	-0.328448	-0.258555
Fuel PMI	0.1361129	<.0001*	0.0912747	0.1809512
(Fuel PMI-1.50149)*Vehicle Code[Vehicle A]	-0.016142	0.6847	-0.094828	0.062544
(Fuel PMI-1.50149)*Vehicle Code[Vehicle B]	0.2099395	<.0001*	0.1316344	0.2882447
(Fuel PMI-1.50149)*Vehicle Code[Vehicle C]	-0.093589	0.0189*	-0.171404	-0.015774
(Fuel PMI-1.50149)*Vehicle Code[Vehicle D]	-0.100209	0.0101*	-0.176019	-0.024398

PEMS Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Vehicle Code	3	3	8.7550999	133.5933	<.0001*
Fuel PMI	1	1	0.2983820	13.6590	0.0004*
Fuel PMI*Vehicle Code	3	3	0.2851902	4.3517	0.0064*

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	0.4038261	<.0001*	0.3033072	0.504345
Vehicle Code[Vehicle A]	-0.14174	<.0001*	-0.192346	-0.091134
Vehicle Code[Vehicle B]	0.5024956	<.0001*	0.4524946	0.5524966
Vehicle Code[Vehicle C]	-0.158297	<.0001*	-0.20823	-0.108364
Vehicle Code[Vehicle D]	-0.202458	<.0001*	-0.252418	-0.152499
Fuel PMI	0.1193313	0.0004*	0.0552309	0.1834318
(Fuel PMI-1.50149)*Vehicle Code[Vehicle A]	0.069188	0.2251	-0.043301	0.1816772
(Fuel PMI-1.50149)*Vehicle Code[Vehicle B]	0.1481548	0.0100*	0.0362103	0.2600993
(Fuel PMI-1.50149)*Vehicle Code[Vehicle C]	-0.157134	0.0061*	-0.268378	-0.04589
(Fuel PMI-1.50149)*Vehicle Code[Vehicle D]	-0.060209	0.2729	-0.168587	0.0481695

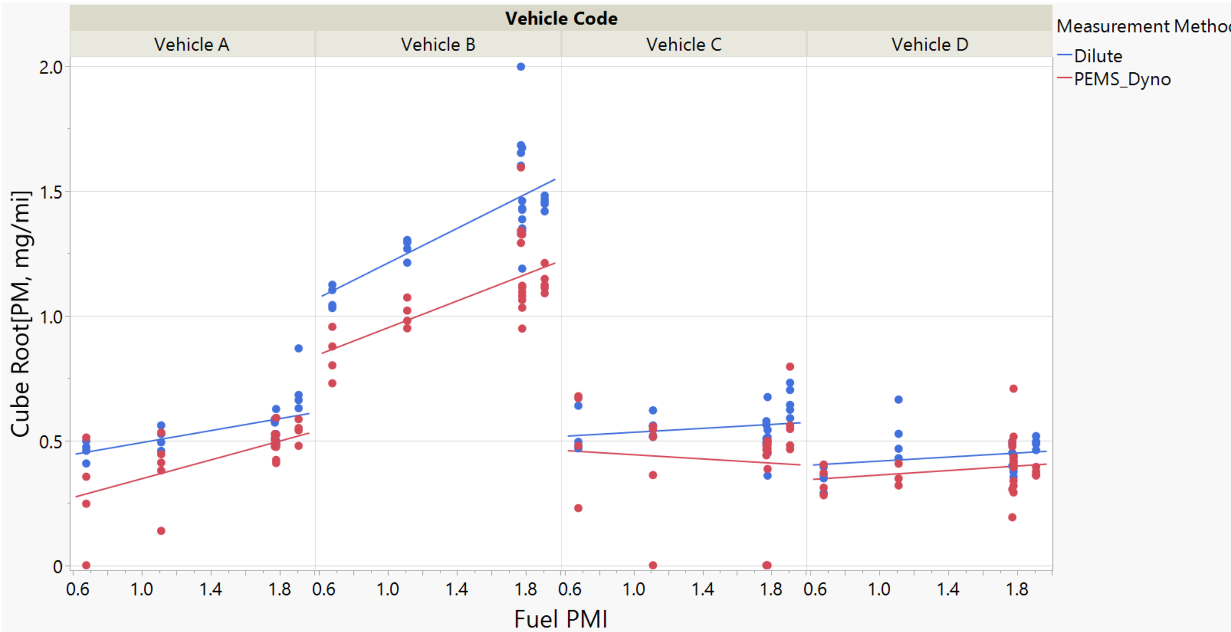


FIGURE 73. PLOT OF CUBE ROOT (PM) VS. FUEL PMI BY VEHICLE, COLORED BY METHOD

4.6.2 Fuel PMI and Fuel RVP as Predictors of NO_x

The variability in NO_x was much higher for Vehicle D than for the other three vehicles. Vehicle D data was modeled separately from the other vehicles, and it was the only vehicle to show any significant effects. For this vehicle, PMI and RVP coefficients were statistically different from zero, as shown in Table 33. However, from Figure 74 and Figure 75, we see that the significant effect seems driven by clusters of data with high leverage on the slope, rather than being reflected consistently across fuels. Therefore, the predicted changes in NO_x by the model are felt to be unstable and unreliable.

TABLE 33. LN (NO_X) ~ FUEL PMI + FUEL RVP

Vehicle D Dilute Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Fuel PMI	1	1	3.8614209	7.5727	0.0114*
Fuel RVP	1	1	5.2136879	10.2246	0.0040*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-9.157687	1.152935	-7.94	<.0001*
Fuel PMI	1.0656855	0.387261	2.75	0.0114*
Fuel RVP	0.2052078	0.064176	3.20	0.0040*

Vehicle D PEMS Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Fuel PMI	1	1	3.6001529	7.6605	0.0110*
Fuel RVP	1	1	4.5078674	9.5920	0.0051*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-8.842964	1.106848	-7.99	<.0001*
Fuel PMI	1.0290014	0.371781	2.77	0.0110*
Fuel RVP	0.1908125	0.06161	3.10	0.0051*

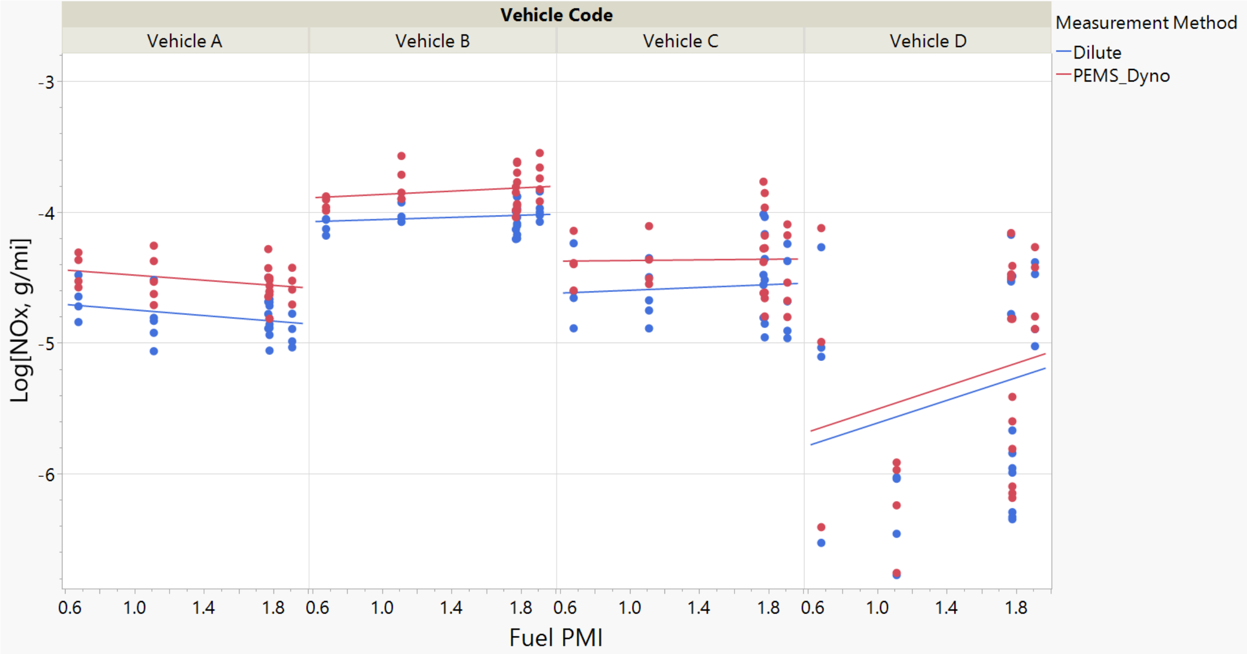


FIGURE 74. PLOT OF LN (NO_X) BY FUEL PMI, COLORED BY METHOD

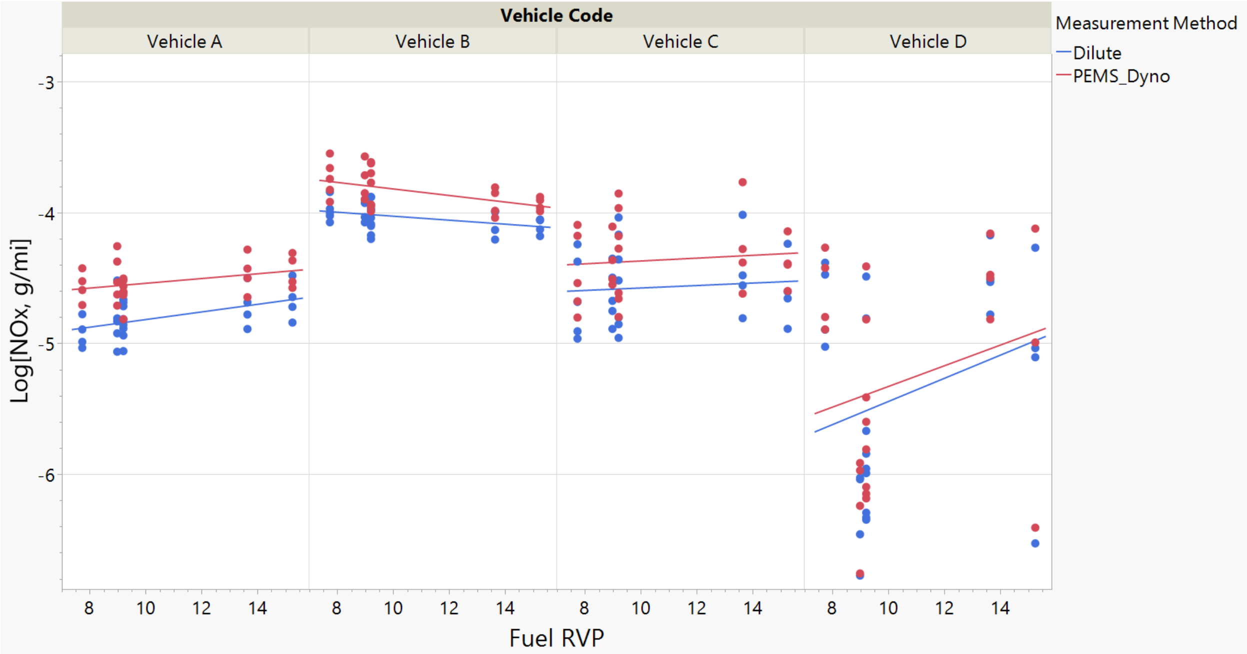


FIGURE 75. PLOT OF LN (NO_X) BY FUEL RVP, COLORED BY METHOD

4.6.3 Fuel PMI and Fuel RVP as Predictors of CO_2

The output from the CO_2 models are shown below in Table 34. The models do result in different sets of predictor variables. However, further inspection reveals that these two models are not much different. The Dilute model indicates RVP is a significant predictor of CO_2, but largely only for Vehicle A (though the interaction term is not significant, all other vehicles have confidence intervals containing zero when adding their confidence intervals with the main effect). Though the Vehicle A coefficient is not statistically significant in the PEMS model, the coefficients from the two models are overlapping. Evaluating at 315 g/mi, the dilute model indicates an estimated drop of 2.2% in CO_2 with an increase in Fuel RVP of 5 for Vehicle A. The plot of CO_2 by Fuel RVP is shown in Figure 76, with Vehicle D excluded due to the vastly different CO_2 levels to improve plot resolution.

For the Dilute model Fuel PMI is not a statistically significant predictor. For the PEMS model vehicle coefficients indicate PMI and RVP are both significant, but in both cases only for Vehicle D. The plots of CO_2 by fuel PMI and fuel RVP for Vehicle D are shown in Figure 77. One can see from the figures that both fuel property effects seem questionable. For RVP, the two highest RVP fuels gave the highest and lowest CO_2 values. There are clearly some high leverage points, in combination with the highly repeatable data from the other vehicles, which is leading this vehicle to the statistical significance claim. For fuel PMI, there again appears to be leverage from some high results on the certification fuel. The data from the highest and lower PMI fuels is similar.

In summary, the highly repeatable nature of CO_2 leads to highly sensitive models. After closer inspection of all vehicles, only the Vehicle A RVP effects seems to hold up visually and not be influenced by high leverage clusters of data. This effect was not significant in the PEMS models, but the coefficient is not statistically different from the significant coefficient in the dilute model.

TABLE 34. LN (CO_2) ~ VEHICLE + FUEL PMI + FUEL RVP + (VEHICLE * FUEL PMI) + (VEHICLE * FUEL RVP)

Dilute Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Vehicle Code	3	3	15.066106	24369.38	<.0001*
Fuel PMI	1	1	0.000189	0.9170	0.3408
Fuel RVP	1	1	0.002188	10.6195	0.0016*
Fuel PMI*Vehicle Code	3	3	0.000521	0.8431	0.4738
Fuel RVP*Vehicle Code	3	3	0.001023	1.6541	0.1826

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	5.490958	<.0001*	5.4685603	5.5133558
Vehicle Code[Vehicle A]	0.2565639	<.0001*	0.2516347	0.2614931
Vehicle Code[Vehicle B]	0.1809154	<.0001*	0.1760503	0.1857805
Vehicle Code[Vehicle C]	0.2317887	<.0001*	0.2269252	0.2366522
Vehicle Code[Vehicle D]	-0.669268	<.0001*	-0.674196	-0.66434
Fuel PMI	0.0037245	0.3408	-0.004002	0.0114512
Fuel RVP	-0.002079	0.0016*	-0.003346	-0.000811
(Fuel PMI-1.50957)*Vehicle Code[Vehicle A]	-0.004146	0.5347	-0.017361	0.0090699
(Fuel PMI-1.50957)*Vehicle Code[Vehicle B]	-0.002725	0.6905	-0.016279	0.0108291
(Fuel PMI-1.50957)*Vehicle Code[Vehicle C]	-0.003934	0.5549	-0.01712	0.0092519
(Fuel PMI-1.50957)*Vehicle Code[Vehicle D]	0.0108045	0.1173	-0.002767	0.0243764
(Fuel RVP-10.5473)*Vehicle Code[Vehicle A]	-0.002427	0.0292*	-0.004602	-0.000252
(Fuel RVP-10.5473)*Vehicle Code[Vehicle B]	0.0008343	0.4559	-0.001379	0.0030475
(Fuel RVP-10.5473)*Vehicle Code[Vehicle C]	0.0005623	0.6070	-0.001602	0.0027266
(Fuel RVP-10.5473)*Vehicle Code[Vehicle D]	0.0010305	0.3601	-0.001195	0.0032561

PEMS Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Vehicle Code	3	3	15.258407	13016.29	<.0001*
Fuel PMI	1	1	0.003088	7.9018	0.0061*
Fuel RVP	1	1	0.001642	4.2016	0.0433*
Fuel PMI*Vehicle Code	3	3	0.005162	4.4033	0.0062*
Fuel RVP*Vehicle Code	3	3	0.003259	2.7800	0.0456*

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	5.5217395	<.0001*	5.4908979	5.5525812
Vehicle Code[Vehicle A]	0.2490052	<.0001*	0.2422177	0.2557927
Vehicle Code[Vehicle B]	0.1819622	<.0001*	0.175263	0.1886614
Vehicle Code[Vehicle C]	0.242612	<.0001*	0.235915	0.249309
Vehicle Code[Vehicle D]	-0.673579	<.0001*	-0.680365	-0.666794
Fuel PMI	0.0150544	0.0061*	0.0044148	0.0256941
Fuel RVP	0.0018003	0.0433*	5.5416e-5	0.0035451
(Fuel PMI-1.50957)*Vehicle Code[Vehicle A]	-0.011877	0.1981	-0.030074	0.0063209
(Fuel PMI-1.50957)*Vehicle Code[Vehicle B]	-0.007325	0.4376	-0.025989	0.011339
(Fuel PMI-1.50957)*Vehicle Code[Vehicle C]	-0.014598	0.1137	-0.032755	0.0035588
(Fuel PMI-1.50957)*Vehicle Code[Vehicle D]	0.0337996	0.0005*	0.0151112	0.0524881
(Fuel RVP-10.5473)*Vehicle Code[Vehicle A]	-0.001732	0.2537	-0.004728	0.0012635
(Fuel RVP-10.5473)*Vehicle Code[Vehicle B]	-0.001521	0.3240	-0.004569	0.0015262
(Fuel RVP-10.5473)*Vehicle Code[Vehicle C]	-0.001189	0.4300	-0.004169	0.001791
(Fuel RVP-10.5473)*Vehicle Code[Vehicle D]	0.0044426	0.0050*	0.001378	0.0075072

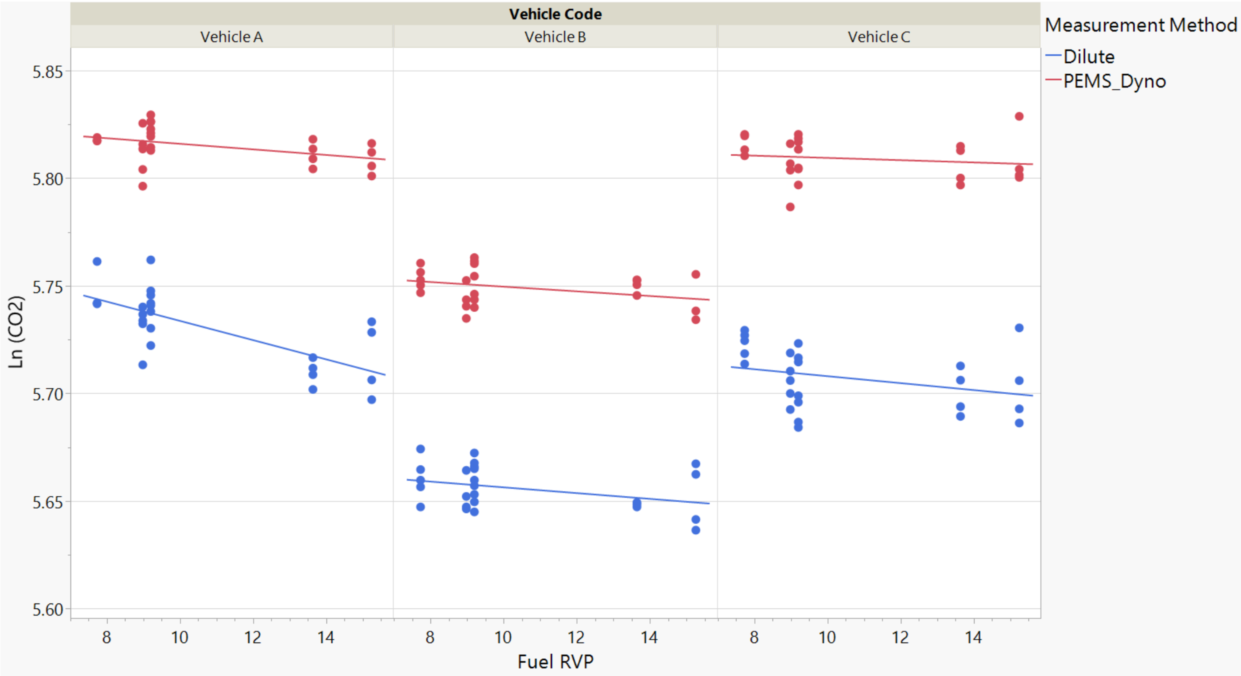


FIGURE 76. PLOT OF LN (CO_2) BY FUEL RVP, COLORED BY METHOD

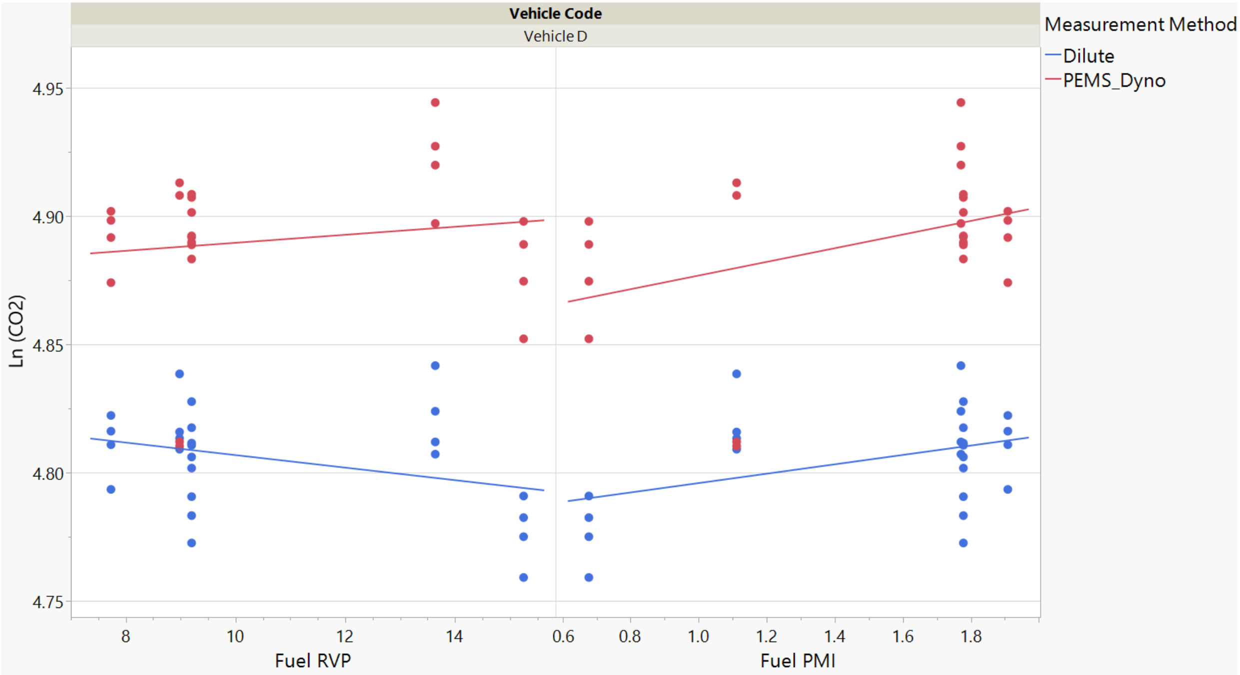


FIGURE 77. PLOT OF LN (CO_2) BY FUEL RVP AND PMI FOR VEHICLE D, COLORED BY METHOD

4.6.4 Fuel PMI and Fuel RVP as Predictors of THC and NMHC

The output from the THC models are shown below in Table 35. The NMHC models and plots are extremely similar to THC and are included in Appendix G. Both the Dilute and PEMS models agree that Fuel PMI is a statistically significant predictor, and the variable is vehicle dependent. Vehicles A and C are the vehicles where the PMI variable is significant. The dilute model estimates that at 0.015 g/mi, Vehicle A would see a decrease in THC of 24% with an increase of 1 in Fuel PMI. Vehicle C, evaluated at 0.0075 g/mi, would see a decrease of 46% for the same increase in PMI. A plot of the transformed THC data vs. PMI is given in Figure 78.

TABLE 35. LN (THC) ~ VEHICLE + FUEL PMI + (VEHICLE * FUEL PMI)

Dilute Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Vehicle Code	3	3	10.980845	69.7231	<.0001*
Fuel PMI	1	1	1.208968	23.0291	<.0001*
Fuel PMI*Vehicle Code	3	3	0.754509	4.7908	0.0045*

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	-4.332187	<.0001*	-4.504607	-4.159767
Vehicle Code[Vehicle A]	0.4275699	<.0001*	0.3297096	0.5254301
Vehicle Code[Vehicle B]	0.327003	<.0001*	0.229254	0.424752
Vehicle Code[Vehicle C]	-0.506504	<.0001*	-0.595887	-0.41712
Vehicle Code[Vehicle D]	-0.248069	<.0001*	-0.342152	-0.153987
Fuel PMI	-0.271682	<.0001*	-0.384815	-0.158548
(Fuel PMI-1.4487)*Vehicle Code[Vehicle A]	-0.007996	0.9377	-0.211598	0.1956062
(Fuel PMI-1.4487)*Vehicle Code[Vehicle B]	0.1624469	0.1089	-0.037158	0.3620514
(Fuel PMI-1.4487)*Vehicle Code[Vehicle C]	-0.336425	0.0008*	-0.527346	-0.145503
(Fuel PMI-1.4487)*Vehicle Code[Vehicle D]	0.1819741	0.0593	-0.00735	0.3712977

PEMS Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Vehicle Code	3	3	14.048887	51.2608	<.0001*
Fuel PMI	1	1	2.865903	31.3708	<.0001*
Fuel PMI*Vehicle Code	3	3	1.555514	5.6757	0.0017*

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	-4.428563	<.0001*	-4.656014	-4.201113
Vehicle Code[Vehicle A]	0.522226	<.0001*	0.3931322	0.6513199
Vehicle Code[Vehicle B]	0.3249	<.0001*	0.1959529	0.453847
Vehicle Code[Vehicle C]	-0.568792	<.0001*	-0.686704	-0.45088
Vehicle Code[Vehicle D]	-0.278334	<.0001*	-0.402445	-0.154223
Fuel PMI	-0.418296	<.0001*	-0.567538	-0.269054
(Fuel PMI-1.4487)*Vehicle Code[Vehicle A]	-0.005018	0.9703	-0.273603	0.2635672
(Fuel PMI-1.4487)*Vehicle Code[Vehicle B]	0.2562333	0.0563	-0.007078	0.5195446
(Fuel PMI-1.4487)*Vehicle Code[Vehicle C]	-0.486646	0.0003*	-0.738503	-0.234789
(Fuel PMI-1.4487)*Vehicle Code[Vehicle D]	0.2354302	0.0642	-0.014319	0.4851792

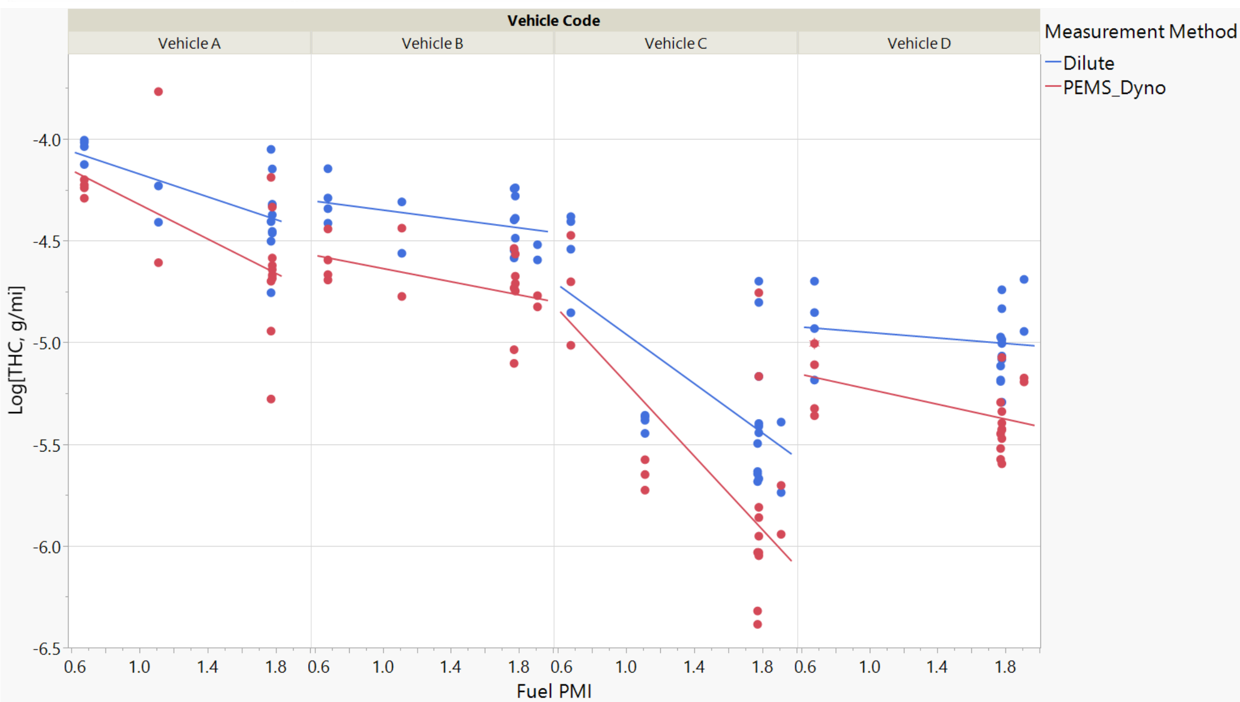


FIGURE 78. PLOT OF LN (THC) VS. FUEL PMI BY METHOD

4.6.5 Fuel PMI and Fuel RVP as Predictors of CO

The output from the CO models are shown in Table 36. Both models agree that there are vehicle-dependent effects from both fuel PMI and fuel RVP. The plots of CO vs. PMI and RVP are shown below in Figure 79 and Figure 80, respectively. Evaluated at 0.50 g/mi, the Dilute model estimates that Vehicle A would have a 60% decrease in CO with an increase of 1 in PMI. Vehicle C, evaluated at 0.20 g/mi, would have a decrease of 20% with the same increase in PMI. Fuel PMI was not statistically significant for Vehicles B and D. The Dilute model also predicts that an increase of 5 in Fuel RVP would see to an increase in CO for Vehicle B of 31% when evaluated at 0.30 g/mi, and an increase in CO of 35% for Vehicle C when evaluated at 0.20 g/mi.

TABLE 36. LN (CO) ~ VEHICLE + FUEL PMI + FUEL RVP + (VEHICLE * FUEL PMI) + (VEHICLE * FUEL RVP)

Dilute Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Vehicle Code	3	3	18.036357	84.9567	<.0001*
Fuel PMI	1	1	1.178347	16.6511	0.0001*
Fuel RVP	1	1	0.036796	0.5200	0.4737
Fuel PMI*Vehicle Code	3	3	1.057898	4.9830	0.0038*
Fuel RVP*Vehicle Code	3	3	0.739529	3.4834	0.0213*

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	-1.172979	<.0001*	-1.712133	-0.633826
Vehicle Code[Vehicle A]	0.5347479	<.0001*	0.4203151	0.6491806
Vehicle Code[Vehicle B]	0.3630774	<.0001*	0.2490448	0.4771099
Vehicle Code[Vehicle C]	-0.088094	0.1004	-0.193715	0.0175269
Vehicle Code[Vehicle D]	-0.809731	<.0001*	-0.920943	-0.698518
Fuel PMI	-0.3504	0.0001*	-0.522226	-0.178574
Fuel RVP	0.0106006	0.4737	-0.018816	0.0400171
(Fuel PMI-1.4487)*Vehicle Code[Vehicle A]	-0.554422	0.0004*	-0.846816	-0.262028
(Fuel PMI-1.4487)*Vehicle Code[Vehicle B]	0.2413076	0.1042	-0.051301	0.533916
(Fuel PMI-1.4487)*Vehicle Code[Vehicle C]	0.0426786	0.7547	-0.229358	0.3147154
(Fuel PMI-1.4487)*Vehicle Code[Vehicle D]	0.2704356	0.1068	-0.059975	0.6008464
(Fuel RVP-11.5001)*Vehicle Code[Vehicle A]	-0.047264	0.0689	-0.098314	0.003786
(Fuel RVP-11.5001)*Vehicle Code[Vehicle B]	0.0432908	0.0857	-0.006271	0.092853
(Fuel RVP-11.5001)*Vehicle Code[Vehicle C]	0.0501073	0.0324*	0.004353	0.0958616
(Fuel RVP-11.5001)*Vehicle Code[Vehicle D]	-0.046134	0.1095	-0.10295	0.0106812

PEMS Model

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Vehicle Code	3	3	18.737458	85.8435	<.0001*
Fuel PMI	1	1	0.723868	9.9489	0.0025*
Fuel RVP	1	1	0.141849	1.9496	0.1679
Fuel PMI*Vehicle Code	3	3	1.294125	5.9289	0.0013*
Fuel RVP*Vehicle Code	3	3	0.795137	3.6428	0.0177*

Expanded Estimates

Nominal factors expanded to all levels

Term	Estimate	Prob>|t|	Lower 95%	Upper 95%
Intercept	-1.304517	<.0001*	-1.851204	-0.757831
Vehicle Code[Vehicle A]	0.5160964	<.0001*	0.4000648	0.632128
Vehicle Code[Vehicle B]	0.3846356	<.0001*	0.2690098	0.5002614
Vehicle Code[Vehicle C]	-0.061746	0.2533	-0.168843	0.0453505
Vehicle Code[Vehicle D]	-0.838986	<.0001*	-0.951752	-0.726219
Fuel PMI	-0.274636	0.0025*	-0.448862	-0.100409
Fuel RVP	0.0208134	0.1679	-0.009014	0.0506409
(Fuel PMI-1.4487)*Vehicle Code[Vehicle A]	-0.616467	0.0001*	-0.912946	-0.319987
(Fuel PMI-1.4487)*Vehicle Code[Vehicle B]	0.2788188	0.0650	-0.017878	0.5755155
(Fuel PMI-1.4487)*Vehicle Code[Vehicle C]	0.0816379	0.5560	-0.1942	0.3574756
(Fuel PMI-1.4487)*Vehicle Code[Vehicle D]	0.2560099	0.1316	-0.079017	0.5910372
(Fuel RVP-11.5001)*Vehicle Code[Vehicle A]	-0.052216	0.0481*	-0.103979	-0.000453
(Fuel RVP-11.5001)*Vehicle Code[Vehicle B]	0.0435818	0.0879	-0.006673	0.0938364
(Fuel RVP-11.5001)*Vehicle Code[Vehicle C]	0.0523655	0.0276*	0.0059719	0.098759
(Fuel RVP-11.5001)*Vehicle Code[Vehicle D]	-0.043731	0.1341	-0.101341	0.013878

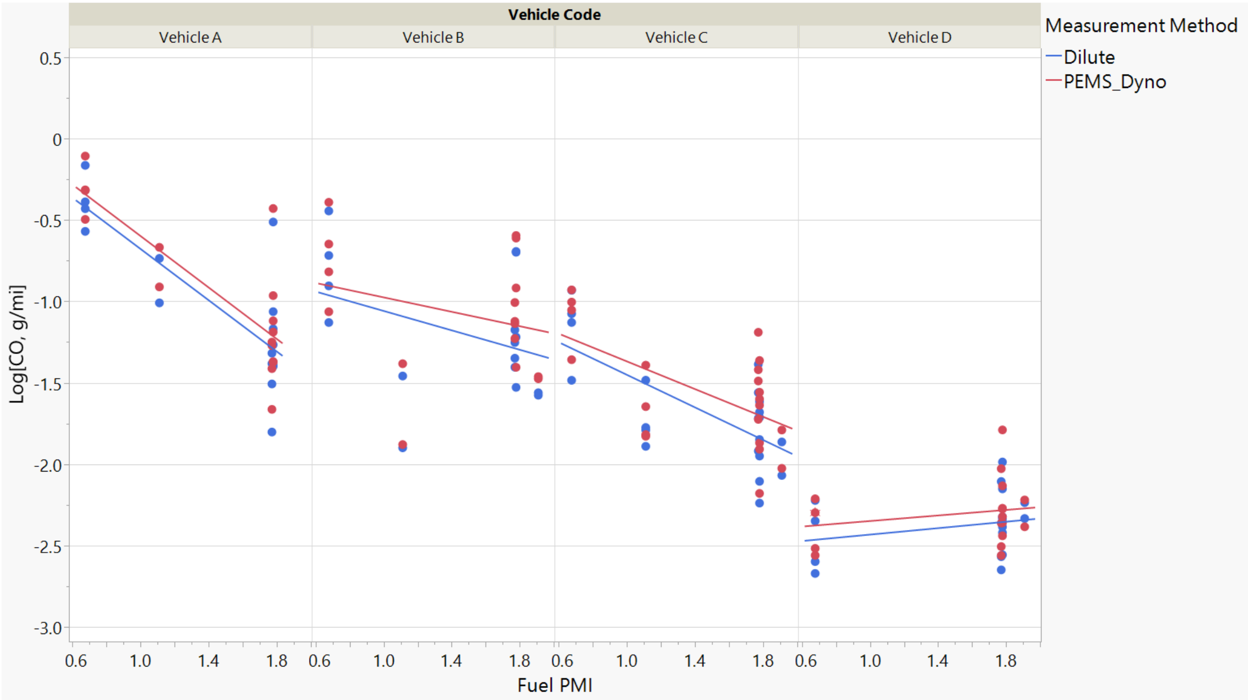


FIGURE 79. PLOT OF LN (CO) VS. FUEL PMI BY METHOD

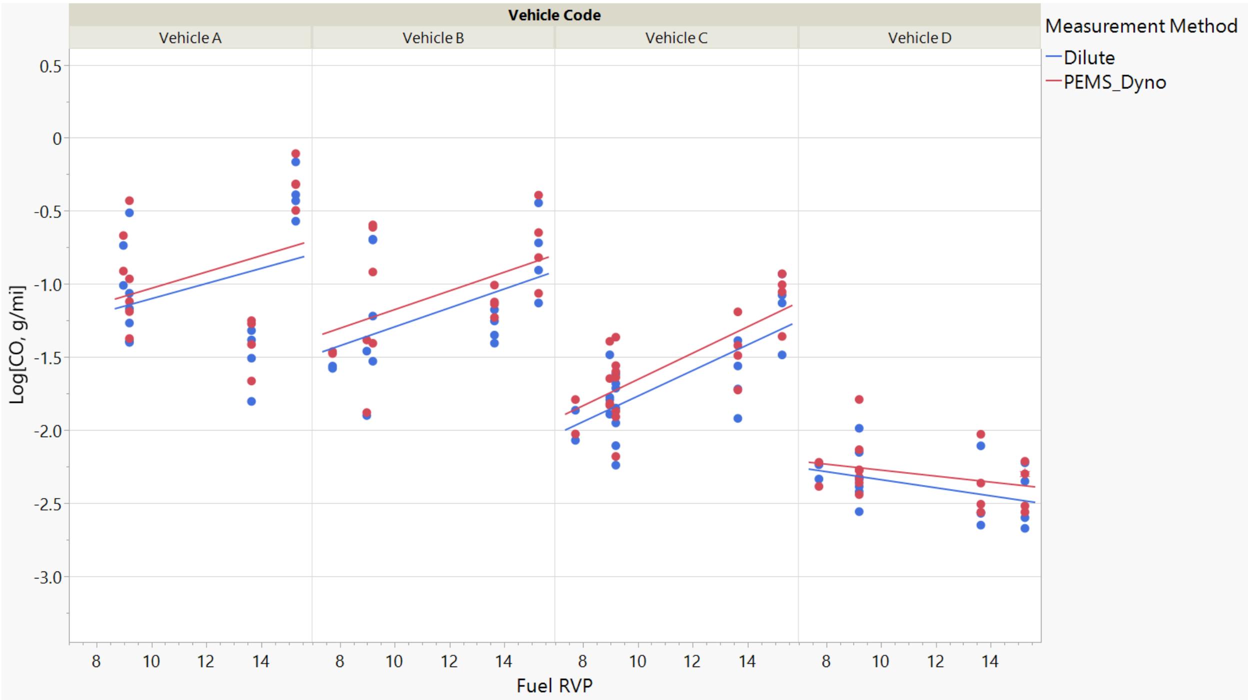


FIGURE 80. PLOT OF LN (CO) VS. FUEL RVP BY METHOD

5.0 CONCLUSIONS

This project investigated the use of multiple engine technologies and different fuel properties to determine Portable Emission Measurement System (PEMS) performance in measuring exhaust emissions changes during on-road and chassis dynamometer tests. The following are some of the key takeaways:

- Regarding PEMS repeatability, for PM, CO_2, and fuel economy, the PEMS on-road testing variability was statistically significantly higher than the chassis dynamometer dilute testing. For NO_x, THC, and NMHC, the higher PEMS variability was only significant for a subset of the vehicles. There was no significant change in variability using PEMS for CO.
- On-road testing with PEMS yielded different results, both in terms of median differences, and in terms of overall variability when compared with chassis dynamometer testing. This project looked at the distribution resulting from a comparison of on-road results to lab measured results (dilute) on the chassis dynamometer. Below are the findings:
    - Even after the instrument bias correction, the median comparison of PEMS on-road result was significantly different from zero for at least three of four vehicles on all parameters except PM, where it was different for two of the vehicles.
    - CO_2 was the most inaccurate of the parameters when comparing to dilute chassis dyno testing. Three of four vehicles had a median bias of 5-15% higher CO_2 on the road, while two of those vehicles had no overlap whatsoever in the distribution of results (PEMS_Road always gave higher CO_2).
    - Based on the quantiles representing the tails of the distribution (5%, 10%, 90%, and 95%), PEMS tended to give more extreme results than would be expected with chassis dyno testing. For each parameter, there was at least one instance, though often several, where the lower quantiles were significantly lower, or the upper quantiles were significantly higher than what was shown to be expected for chassis dyno testing.
- When looking at responsiveness to changes in fuel properties, PEMS emissions results changed similar to lab dilute measurements.
    - Though potential replacement predictors exist given the observed correlations among fuel properties of these five test fuels, PMI and RVP were significant predictors of several emissions parameters, but always only for one or two of the vehicles.
        - Fuel PMI was a statistically significant predictor of PM for Vehicles A and B, along with THC, NMHC, and CO for Vehicles A and C.
        - Fuel RVP was a statistically significant predictor of CO_2 for Vehicle A, along with CO for Vehicles B and C.
        - Fuel PMI and RVP were not significant predictors of any emissions for the plug-in hybrid Vehicle D, except for PMI predicting NO_x, which was thought to be driven by a few extreme results.

6.0 NEXT STEPS

This report covers PEMS testing in mild ambient conditions. Although an experiment was conducted to investigate the PEMS response to step-changes in ambient temperature, no actual vehicle tests were conducted at hot or cold temperature extremes. 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

TEST FUEL ACQUISITION and ANALYSES

Appendix A. Test Fuel Acquisition and Analyses

Four commercial test fuels were obtained by SwRI 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 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 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
- D4814 DI Index

			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)	Chevron 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	10.58	<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 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)	Chevron 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	10.58	<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

EM-10967-F

haltermannsolutions

Telephone: (800) 969-2542

Certificate of Analysis

FAX: (281) 457-1469

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			RESULTS
			MIN	TARGET	MAX	
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

Page 1 of 1

haltermannsolutions

Telephone: (800) 969-2542

Certificate of Analysis

FAX: (281) 457-1469

PRODUCT: EPA TIER II EEE FEDERAL REGISTER

PRODUCT CODE: HF0437

EM-9978-F

Batch No.: FJ0321GP10

Tank No.: Drums

Date: 11/8/2017

TEST	METHOD	UNITS	HALTERMANN Specs MIN	TARGET	MAX	RESULTS
Distillation - IBP	ASTM D86[2]	°F	75		95	87
5%		°F				109
10%		°F	120		135	123
20%		°F				141
30%		°F				162
40%		°F				190
50%		°F	200		230	217
60%		°F				231
70%		°F				242
80%		°F				260
90%		°F	305		325	318
95%		°F				341
Distillation - EP		°F			415	398
Recovery		vol %		Report		97.2
Residue		vol %		Report		0.9
Loss		vol %		Report		1.9
Gravity	ASTM D4052[2]	°API	58.7		61.2	59.0
Density	ASTM D4052[2]	kg/l	0.734		0.744	0.743
Reid Vapor Pressure	ASTM D5191[2]	psi	8.7		9.2	9.0
Carbon	ASTM D3343[2]	wt fraction		Report		0.8656
Carbon	ASTM D5291[2]	wt fraction		Report		0.8684
Hydrogen	ASTM D5291[2]	wt fraction		Report		0.1316
Hydrogen/Carbon ratio	ASTM D5291[2]	mole/mole		Report		1.806
Stoichiometric Air/Fuel Ratio				Report		14.520
Oxygen	ASTM D4815[2]	wt %			0.05	None Detected
Sulfur	ASTM D5453[2]	wt %	0.0025		0.0035	0.0029
Lead	ASTM D3237[2]	g/gal			0.01	None Detected
Phosphorous	ASTM D3231[2]	g/gal			0.005	None Detected
Silicon	ASTM 5184[2]	mg/kg			4	None Detected
Composition, aromatics	ASTM D1319[2]	vol %			35	29
Composition, olefins	ASTM D1319[2]	vol %			10	0
Composition, saturates	ASTM D1319[2]	vol %		Report		71
Particulate matter	ASTM D5452[2]	mg/l			1	0
Oxidation Stability	ASTM D525[2]	minutes	240			1000+
Copper Corrosion	ASTM D130[2]				1	1a
Gum content, washed	ASTM D381[2]	mg/100mls			5	0.5
Fuel Economy Numerator/C Density	ASTM D5291[2]		2401		2441	2436
C Factor	ASTM D5291[2]			Report		1.0014
Research Octane Number	ASTM D2699[2]		96.0			97.2
Motor Octane Number	ASTM D2700[2]			Report		88.6
Sensitivity	D2699/2700[2]		7.5			8.6
Net Heating Value, btu/lb	ASTM D3338[1]	btu/lb		Report		18465
Net Heating Value, btu/lb	ASTM D240[2]	btu/lb		Report		18608
Color	VISUAL			Report		Undyed

Quality Assurance Technician _[signature]_

[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.

Gasoline and diesel specialty fuels from Haltermann Solutions shall remain within specifications for a minimum of 3 years from the date on the COA so long as the drums are sealed and unopened in their original container and stored in a warehouse at ambient conditions. Specialty fuels that have been intentionally modified for aggressive or corrosive properties are excluded.

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

Page 1 of 1

APPENDIX B

VEHICLE ISSUES

Vehicle Issues

Several issues were encountered with individual vehicles early in the program. All issues were overcome, and void tests were repeated when necessary. This section describes each problem and resulting solutions.

During the first test set, Vehicle D did not operate correctly in Hybrid Vehicle (HV) mode as originally planned. Instrumentation installed to measure tractive battery voltage triggered a fault code and forced the vehicle to operate in charge depleting mode (EV) rather than HV. Those tests were repeated during the second interval with that specific fuel. Additionally, the Vehicle D experienced an HEV fault during one of the LA92 tests and could not complete the cycle. This test was also repeated.

Vehicle C's engine start/stop feature did not function properly for the first set of tests. The team investigated and found that start/stop would not operate correctly when driven on a two-wheel drive chassis dynamometer. SwRI installed circuitry to measure the wheel speed from the drive wheels and emulate the measured speed to the ECU, in place of the non-drive wheel speed sensors. This temporarily allowed start/stop to function correctly; however, start/stop reverted to being inoperable after one or two tests on the dynamometer. This problem was remedied by using OEM software to initiate vehicle rolls mode. This allowed start/stop to operate correctly on the dynamometer. Tests conducted with start/stop inoperable were rerun at the end of the summer test matrix.

APPENDIX C

STATE OF CHARGE FOR INDIVIDUAL TEST CYCLES WITH VEHICLE D

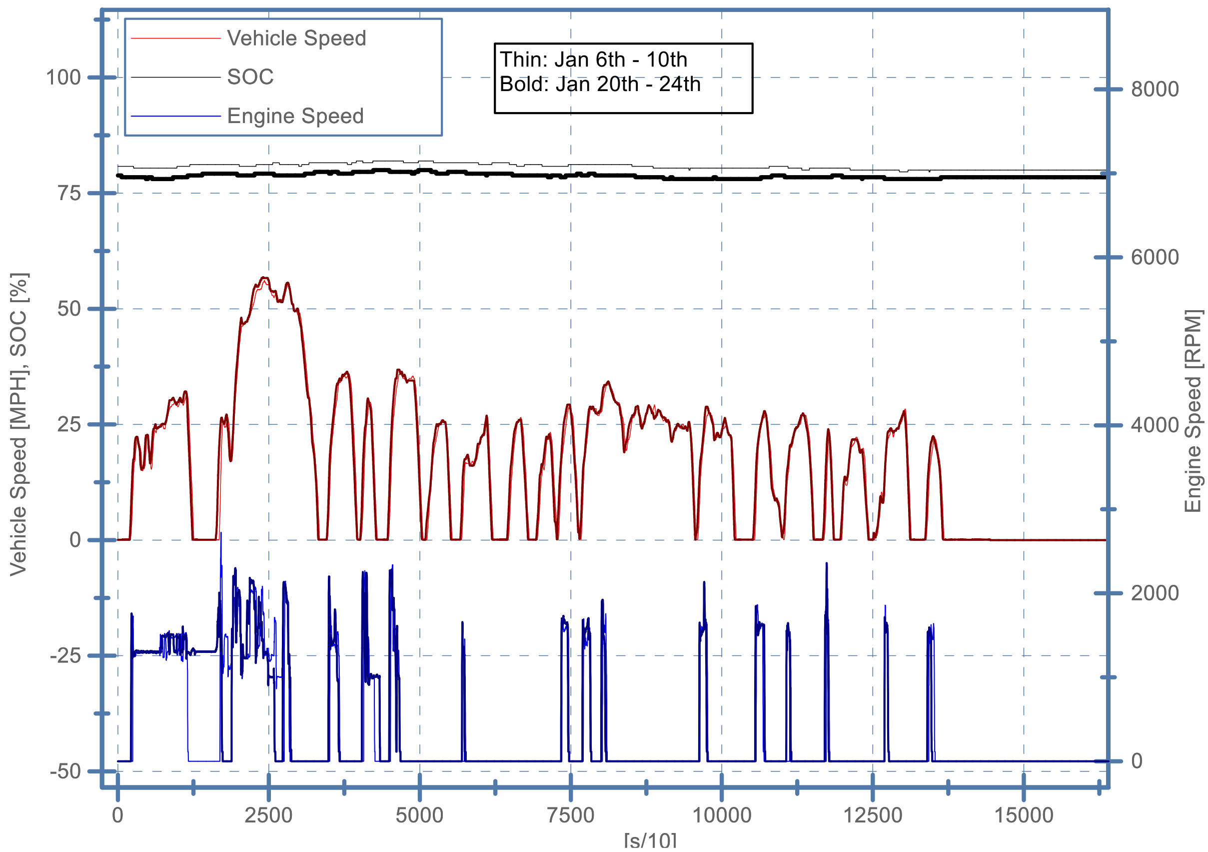


FIGURE 81. SOC AND DUTY CYCLE COMPARISON OF DUPLICATE TEST SEQUENCES: UDDS

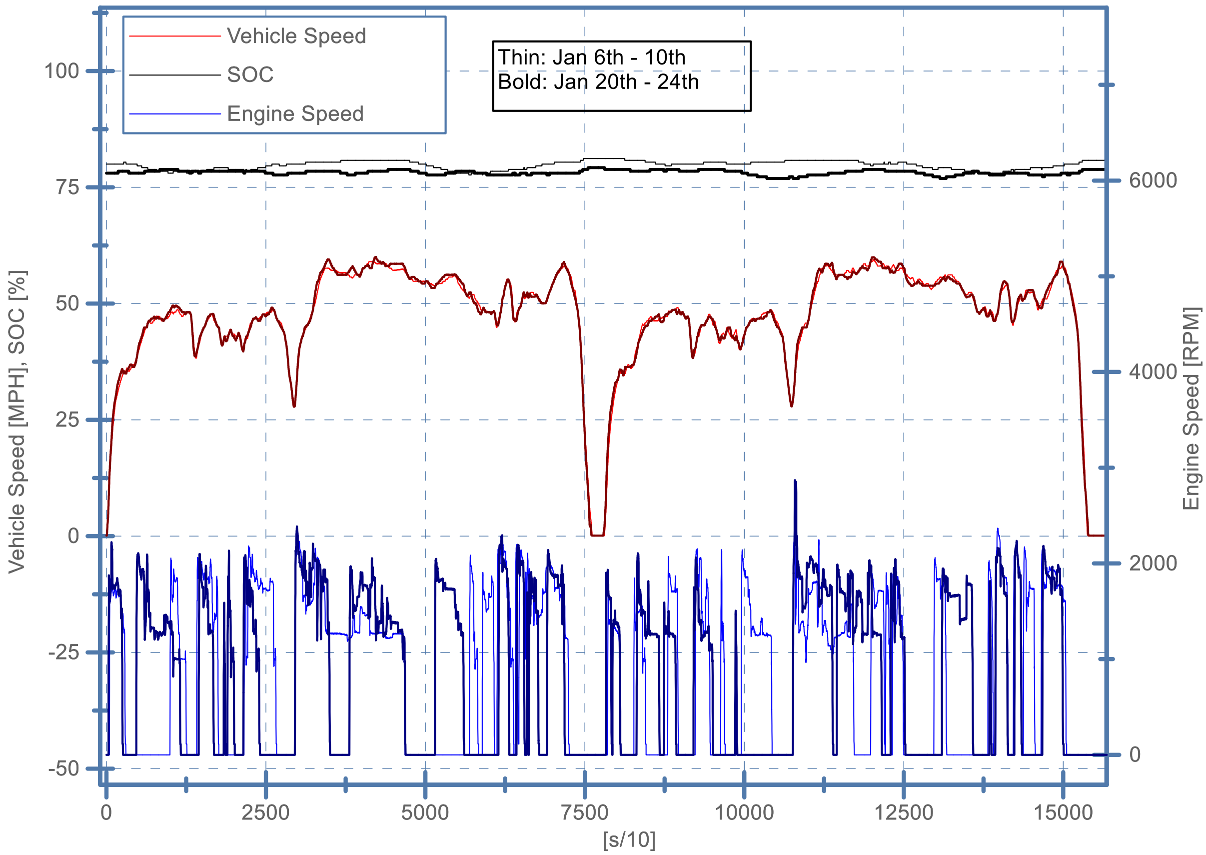


FIGURE 82. SOC AND DUTY CYCLE COMPARISON OF DUPLICATE TEST SEQUENCES: 2XHWFET

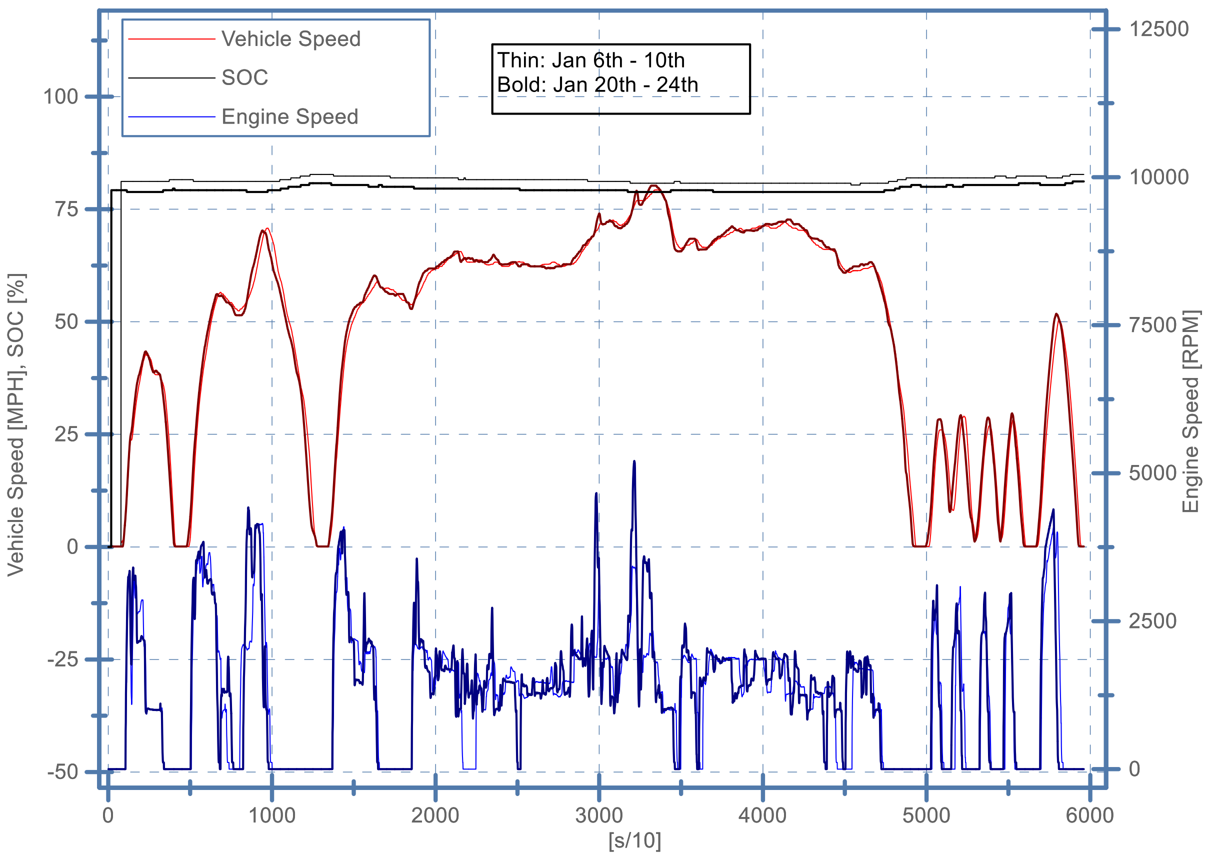


FIGURE 83. SOC AND DUTY CYCLE COMPARISON OF DUPLICATE TEST SEQUENCES: US06

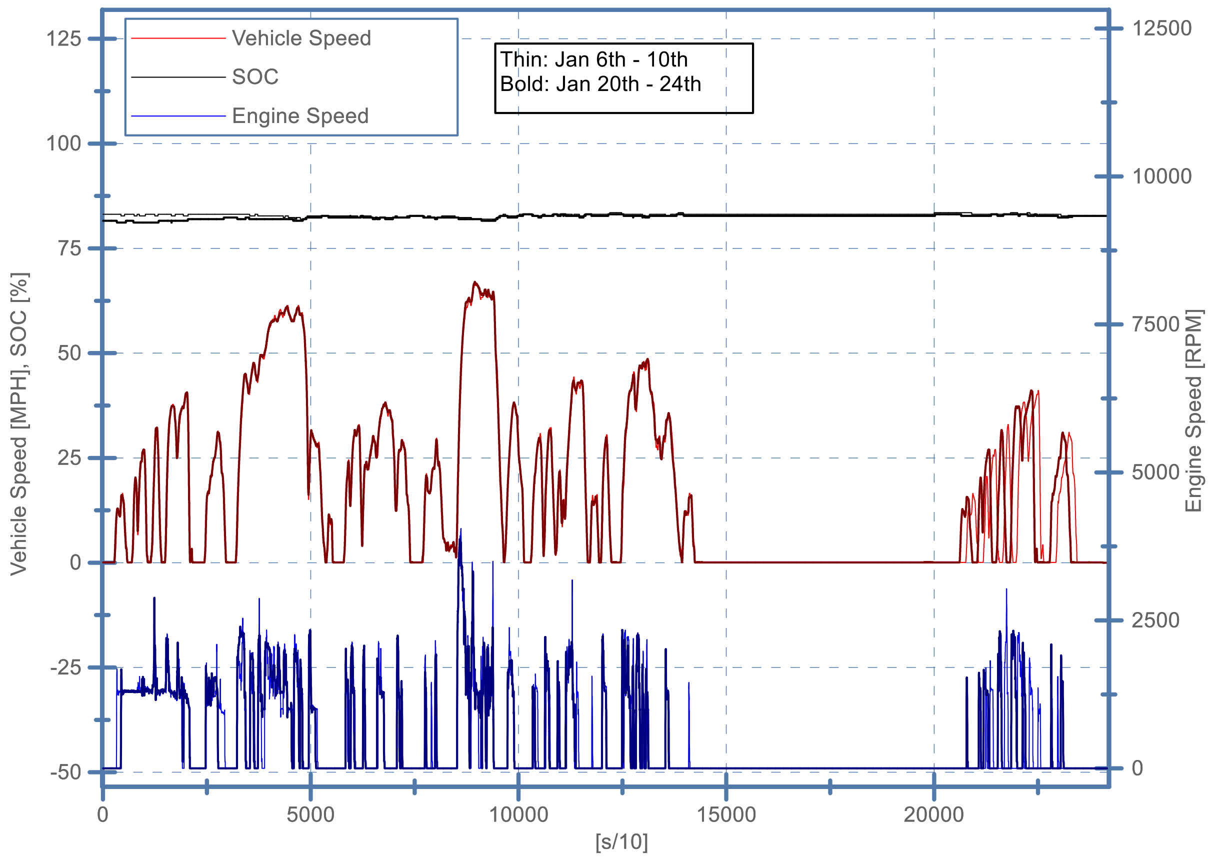


FIGURE 84. SOC AND DUTY CYCLE COMPARISON OF DUPLICATE TEST SEQUENCES: LA92

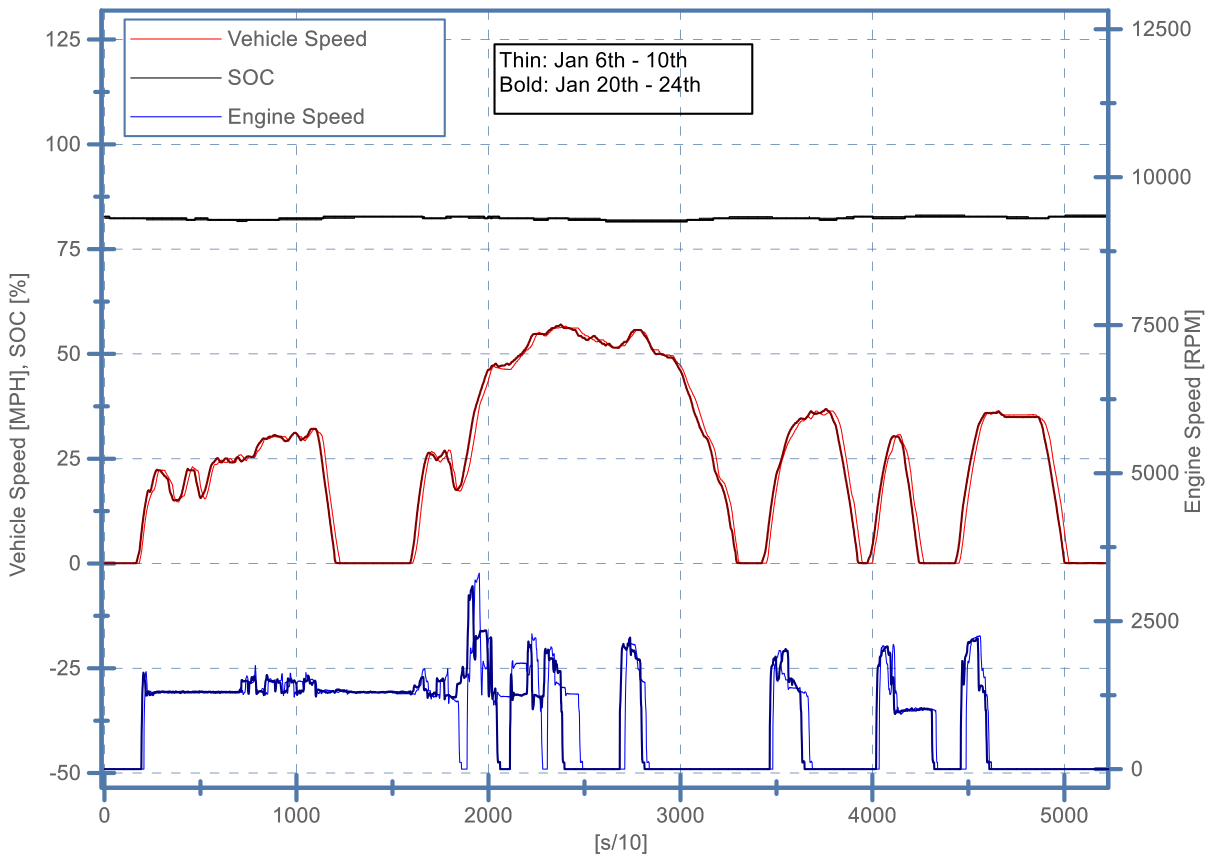


FIGURE 85. SOC AND DUTY CYCLE COMPARISON OF DUPLICATE TEST SEQUENCES: HOT 505

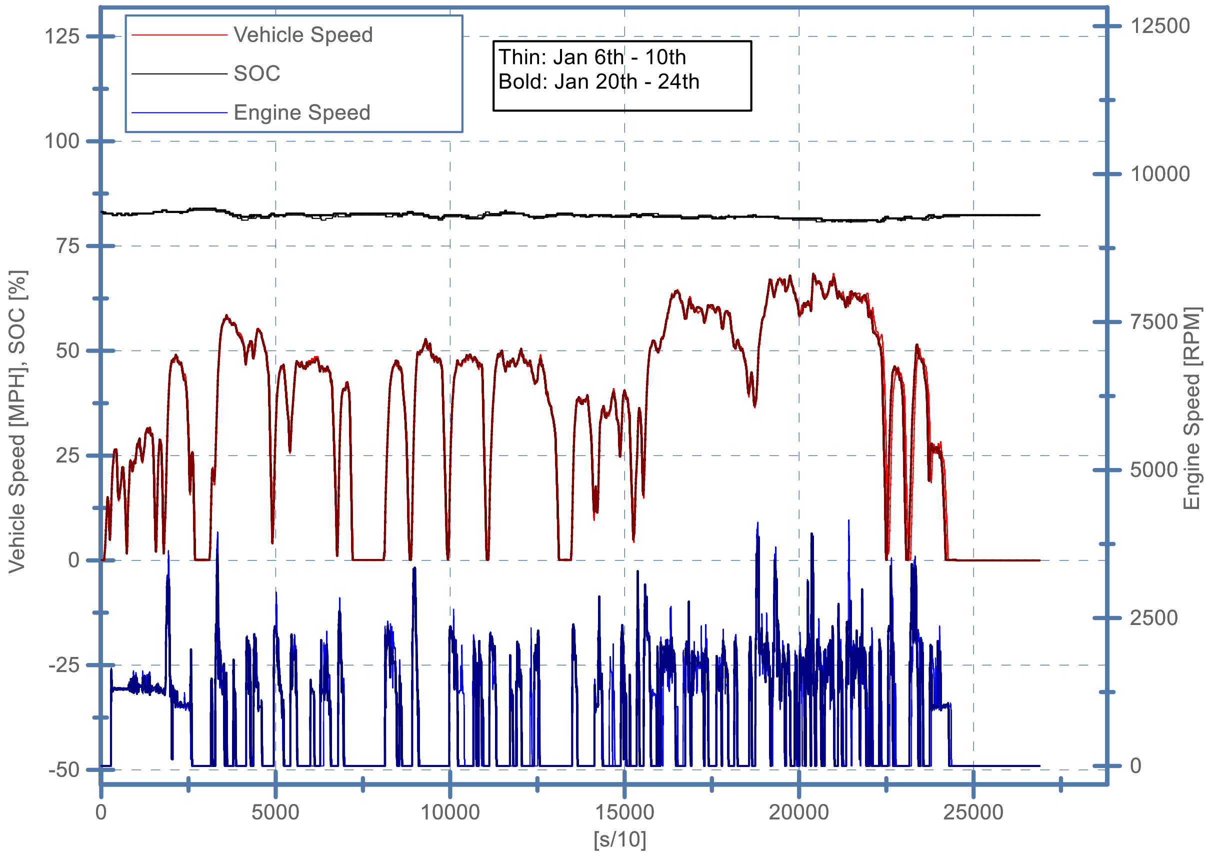


FIGURE 86. SOC AND DUTY CYCLE COMPARISON OF DUPLICATE TEST SEQUENCES: E-122-DYNO

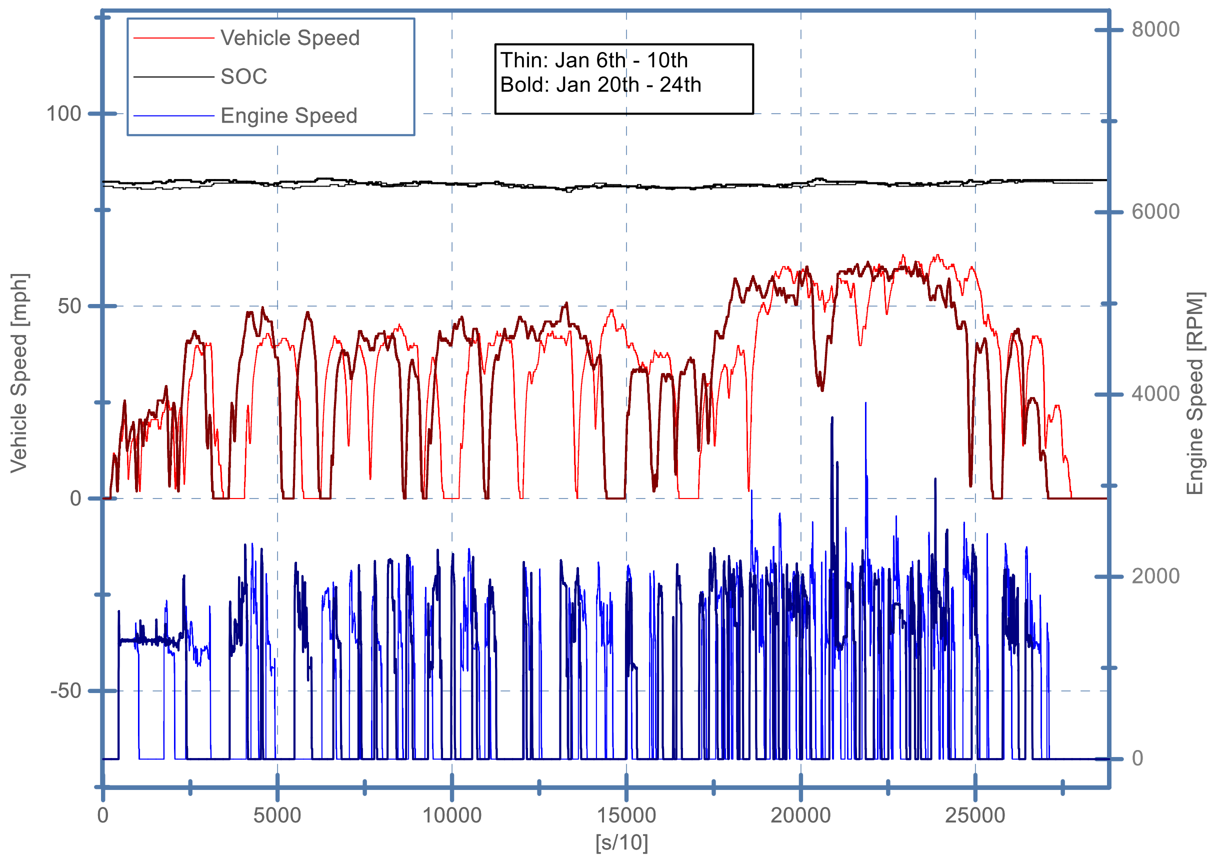


FIGURE 87. SOC AND DUTY CYCLE COMPARISON OF DUPLICATE TEST SEQUENCES: E-122-ROAD

APPENDIX D

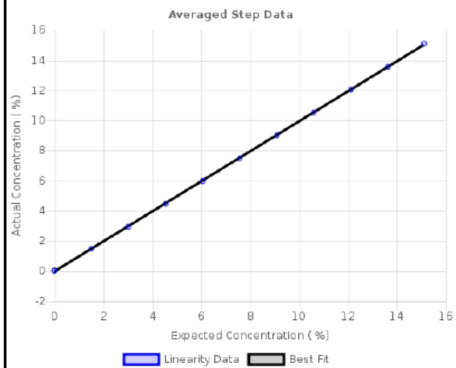
INITIAL PEMS CALIBRATION RESULTS

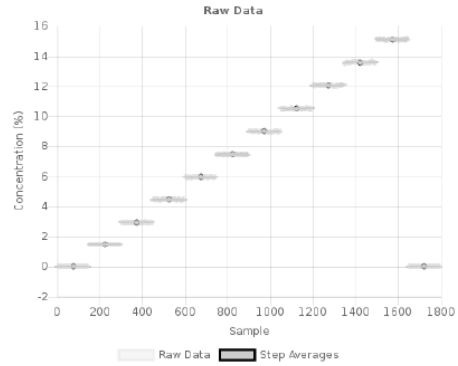
Linearity Certificate

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**





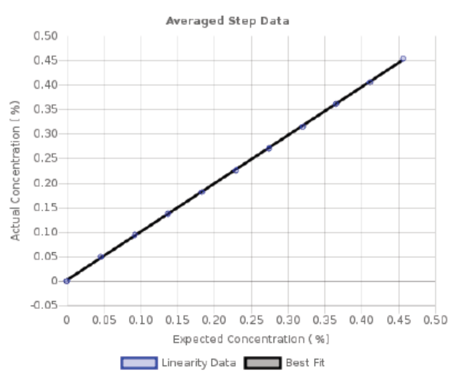
This document certifies that the PEMS listed below meets the linearization requirements listed in Table 1 of CFR40 Part 1065.307. Linearization testing was performed using procedures specified in CFR40 Part 1065.307 with gas standards traceable to the National Institute of Standards (NIST). The PEMS 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.

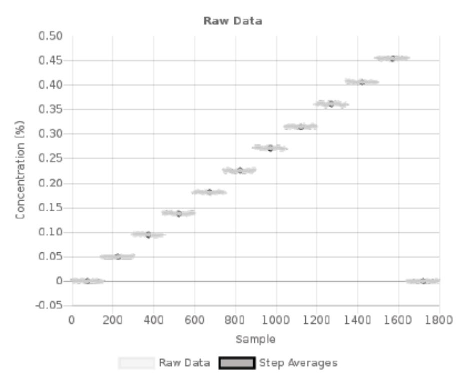
Linearity Certificate

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**





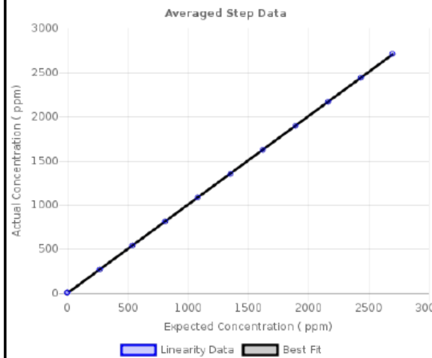
This document certifies that the PEMS listed below meets the linearization requirements listed in Table 1 of CFR40 Part 1065.307. Linearization testing was performed using procedures specified in CFR40 Part 1065.307 with gas standards traceable to the National Institute of Standards (NIST). The PEMS 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.

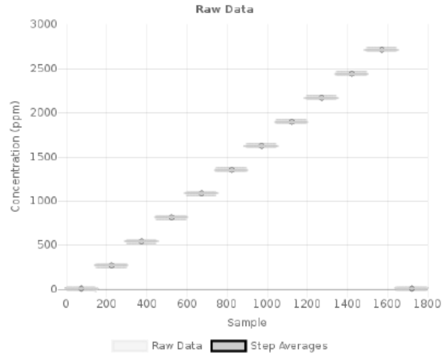
Linearity Certificate

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

Test Information	
Analyzer	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**





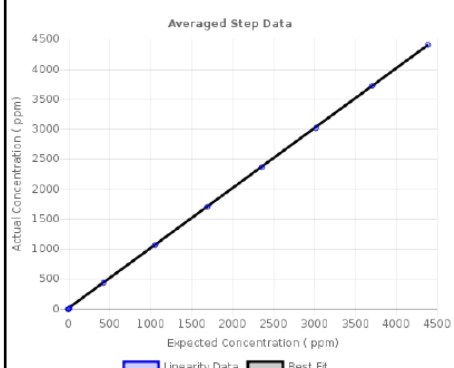
This document certifies that the PEMS listed below meets the linearization requirements listed in Table 1 of CFR40 Part 1065.307. Linearization testing was performed using procedures specified in CFR40 Part 1065.307 with gas standards traceable to the National Institute of Standards (NIST). The PEMS 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.

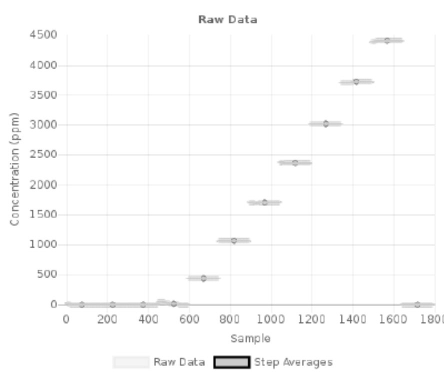
Linearity Certificate

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

Test Information	
Analyzer	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.

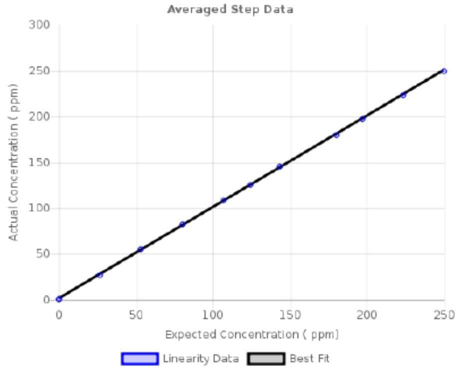
sensors

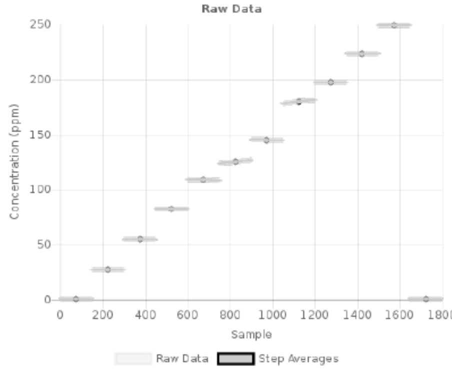
Linearity Certificate

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 ≤ m ≤ 1.01	Pass
Intercept	0.575	|b| ≤ 1.000%	Pass
SEE	0.377	SEE ≤ 1.000%	Pass
R^2	1	R^2 ≥ 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 E

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. 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 F

STEP-BY-STEP CHECK LISTS

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, if not, call Michael @ 281-382-6561**
□	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./mph²
☐	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**
	<u>PEMS (day prior)</u>
□	Schedule a new test to wake up at least 1 hour prior to desired test time
□	**<u>Bottle Rack</u>**
□	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
	<u>PEMS</u>
□	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
	<u>PEMS Setup</u>
□	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
	<u>Start New Test</u>
□	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
	<u>PEMS Zero Span (Co-Pilot)</u>
□	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 #	
	<u>PEMS (day prior)</u>
□	Schedule a new test to wake up at least 1 hour prior to desired test time
	<u>PEMS (day of)</u>
□	Take PEMS unit outside at least 1 hour prior to start of test
	<u>Bottle Rack</u>
□	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
	<u>PEMS Setup</u>
□	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
	<u>Start New Test</u>
□	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
	<u>PEMS Zero Span</u>
□	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
	<u>After Test</u>:
□	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 G

SUPPLEMENTAL PLOTS AND TABLES FOR STATISTICAL ANALYSIS RESULTS

The full set of plots and tables used in the statistical analysis are given in this section by parameter. Each section includes the raw data plot in original units, the raw data plot in transformed units, the least squares mean plot from the drift analysis, the set-to-set variability tests, the PEMS bias tables, and a plot of the parameter vs. Fuel PMI and Fuel RVP. The statistical section of this report describes methodologies, models, assumptions, and other details relating to these plots and tables.

G.1 Particulate Matter (PM)

Raw Data Plots by Method and Vehicle, Colored by Fuel

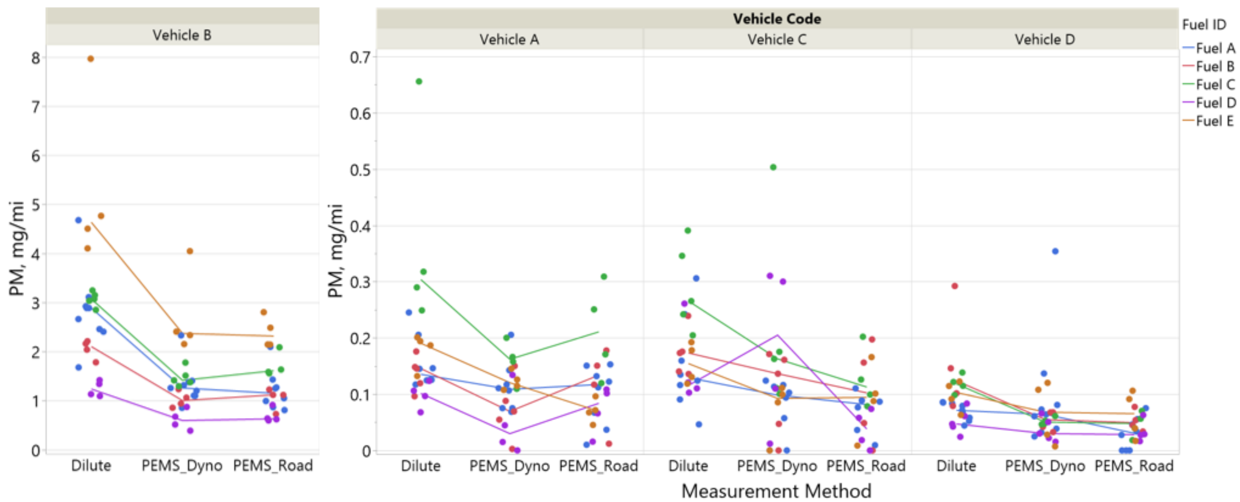


FIGURE 88. RAW DATA PLOT OF PM (MG/MI) BY METHOD AND VEHICLE, COLORED BY FUEL

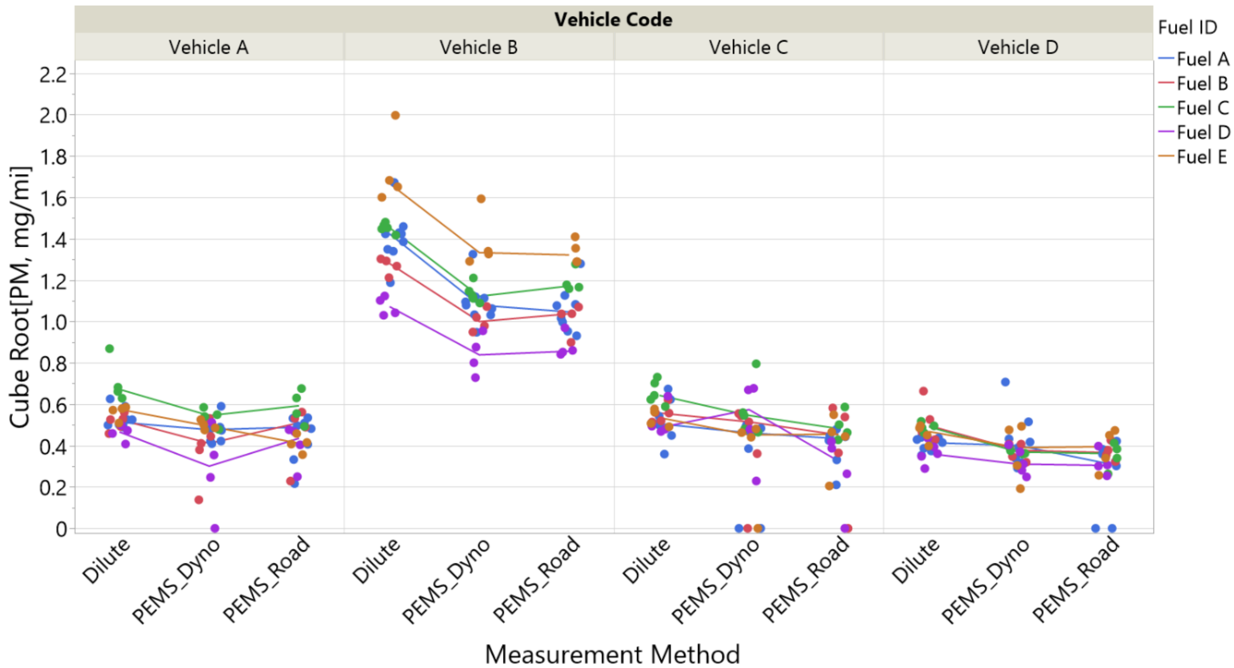


FIGURE 89. RAW DATA PLOT OF CUBE ROOT (PM) BY METHOD AND VEHICLE, COLORED BY FUEL

Drift Check

Some significantly different test sets observed, but no major concern with test drift for PM.

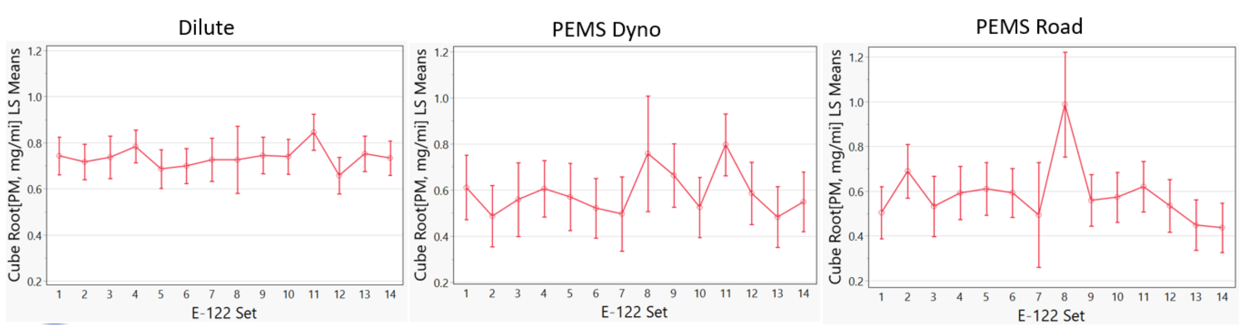


FIGURE 90. PM TEST SET LEAST SQUARES (LS) MEANS FOR DRIFT CHECK

Set-to-Set Variability Test

TABLE 37. PM SET-TO-SET VARIANCE COMPONENT TEST BY METHOD

Dilute

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.010547	-5.466e-5	-0.001685	0.0015761	0.9476	0.000
Residual		0.0051826	0.0036251	0.0080186		100.000
Total		0.0051826	0.0036251	0.0080186		100.000

PEMS Dyno

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.077322	-0.001172	-0.006029	0.0036854	0.6363	0.000
Residual		0.0151547	0.0104635	0.0239102		100.000
Total		0.0151547	0.0104635	0.0239102		100.000

Set 11 excluded

PEMS Road

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.7586683	0.0061819	0.0003581	0.0120057	0.0375*	43.139
Residual		0.0081484	0.0056058	0.0129265		56.861
Total		0.0143303	0.0099139	0.0225419		100.000

PEMS Accuracy (Bias) Tables

TABLE 38. PEMS BIAS ESTIMATES FOR PM

Median Bias,

$\sqrt[3]{PM}\ Delta,$
$PEMS_{Dyno} - Dilute$

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	-0.100	-0.125	-0.068
Vehicle B	-0.307	-0.332	-0.278
Vehicle C	-0.092	-0.169	-0.026
Vehicle D	-0.056	-0.103	-0.014

Bias back-transformed to PM, mg/mi

Vehicle	Median Dilute PM, mg/mi	PEMS Bias Estimate, mg/mi	Lower 95%	Upper 95%
Vehicle A	0.146	-0.068	-0.081	-0.049
Vehicle B	2.867	-1.486	-1.577	-1.375
Vehicle C	0.166	-0.070	-0.111	-0.022
Vehicle D	0.083	-0.028	-0.046	-0.008

Median Bias Relative to Median PM

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	-46.9%	-55.7%	-34.0%
Vehicle B	-51.8%	-55.0%	-48.0%
Vehicle C	-42.3%	-66.8%	-13.5%
Vehicle D	-33.7%	-55.4%	-9.3%

Plots of the Quantiles of the Empirical Distribution of Delta and % Delta for all Pairwise Differences, PEMS_Road-Dilute and Dilute-Dilute

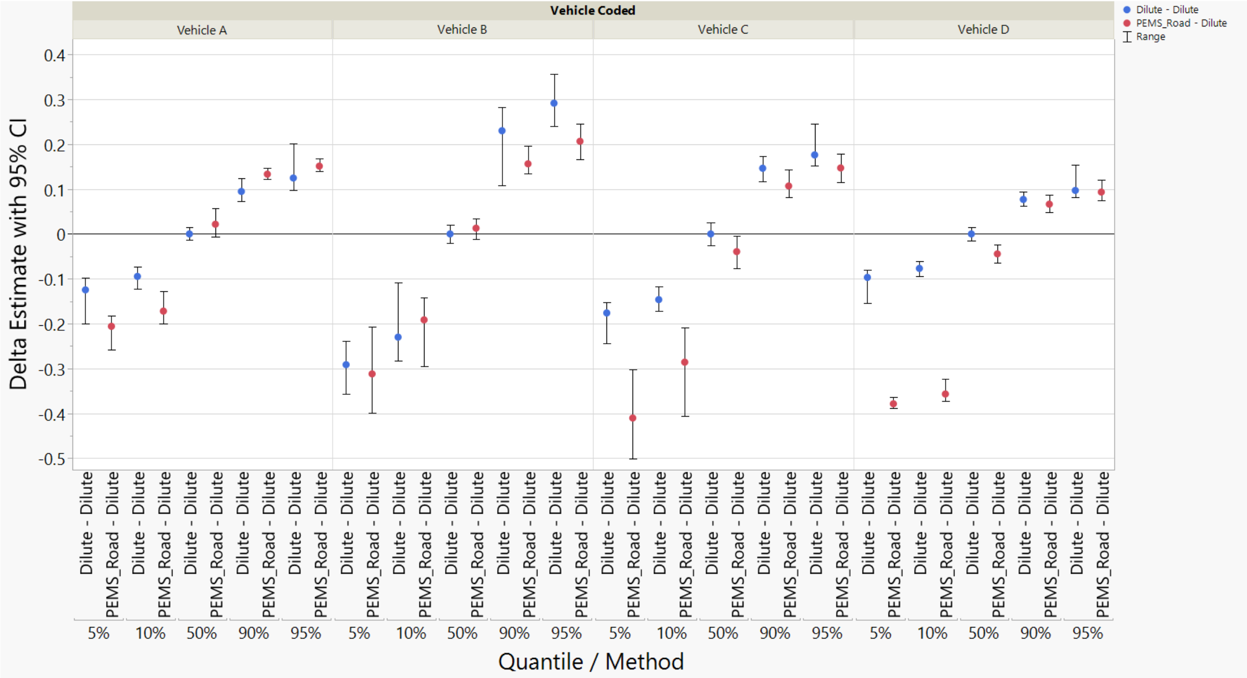


FIGURE 91. QUANTILES OF DELTA PM WITH 95% CONFIDENCE INTERVALS

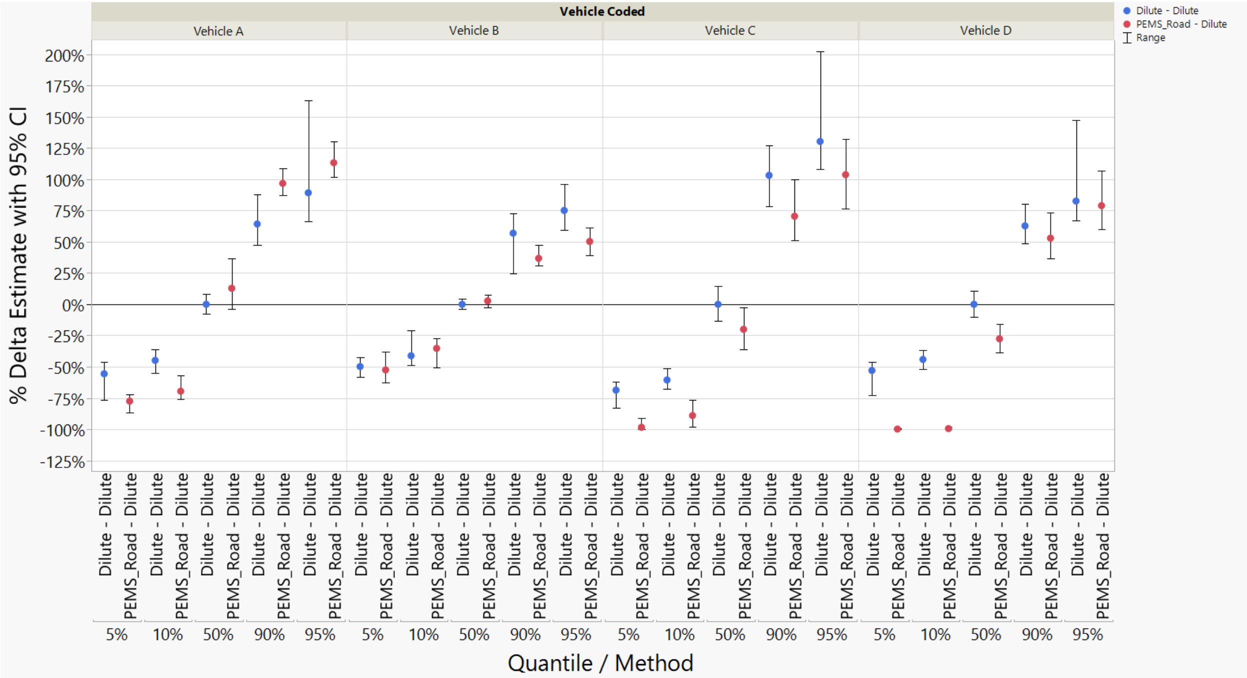


FIGURE 92. QUANTILES OF % DELTA PM WITH 95% CONFIDENCE INTERVALS

Plot Vs. Fuel PMI and Fuel RVP

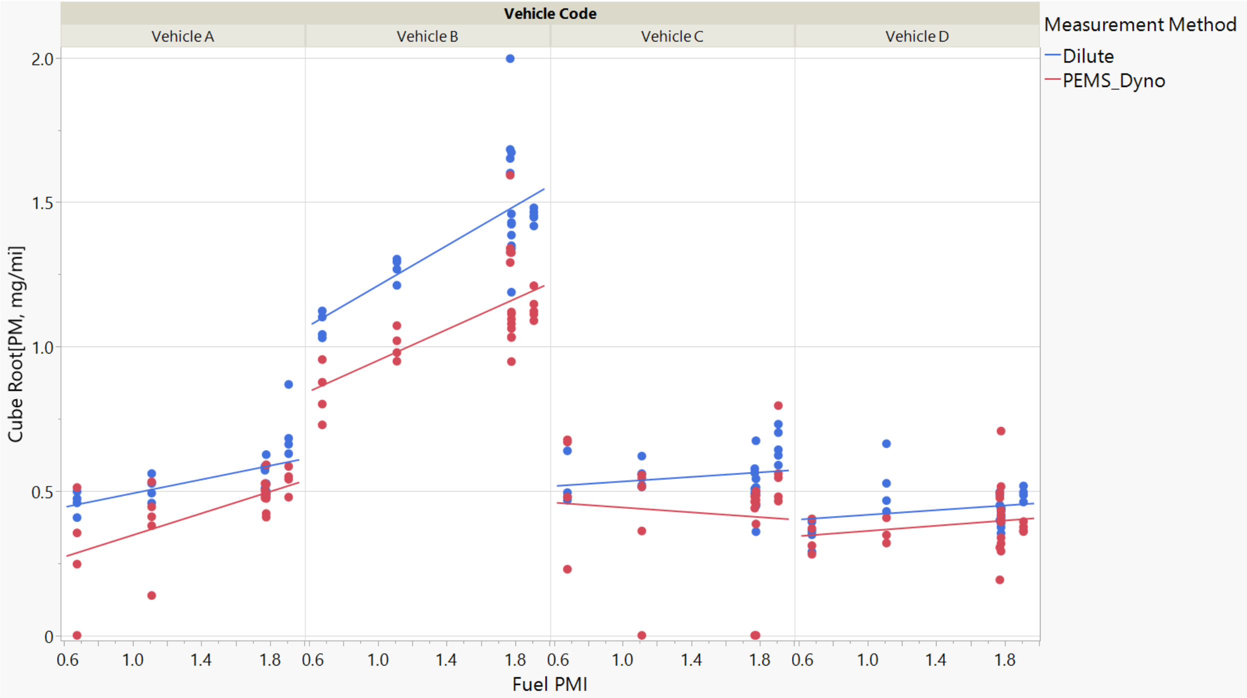


FIGURE 93. CUBE ROOT (PM) VS. FUEL PMI, COLORED BY METHOD

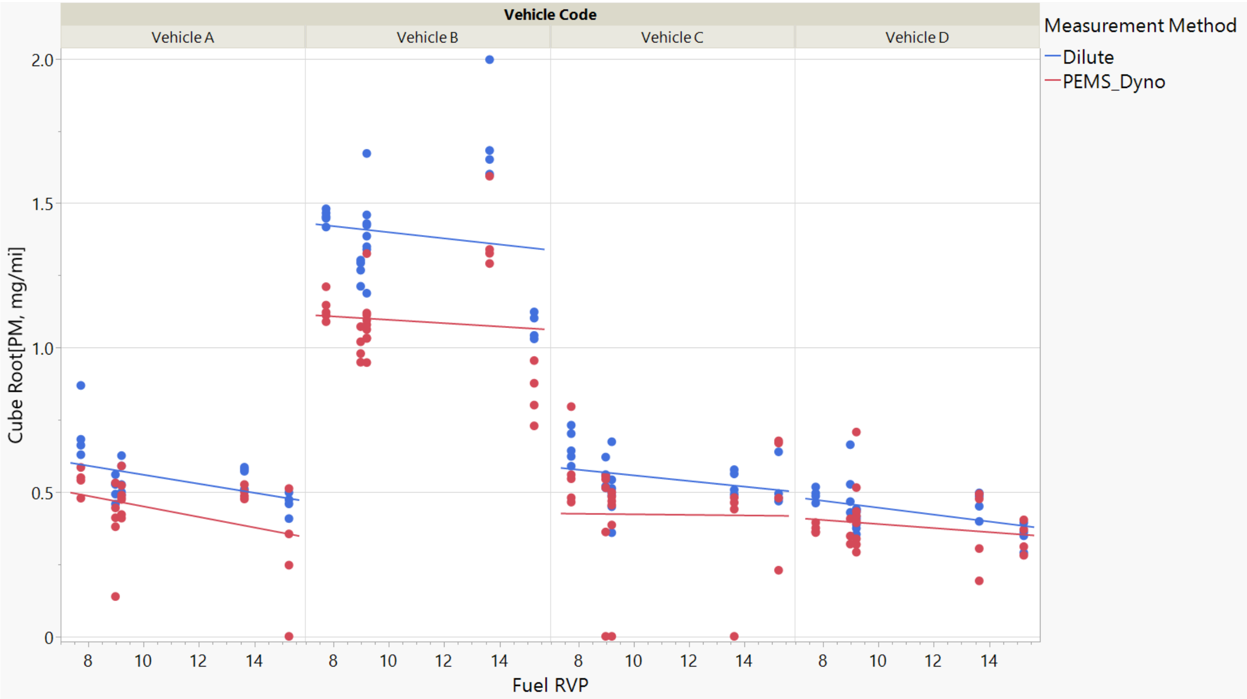


FIGURE 94. CUBE ROOT (PM) VS. FUEL RVP, COLORED BY METHOD

G.2 NO_x

Raw Data Plots by Method and Vehicle, Colored by Fuel

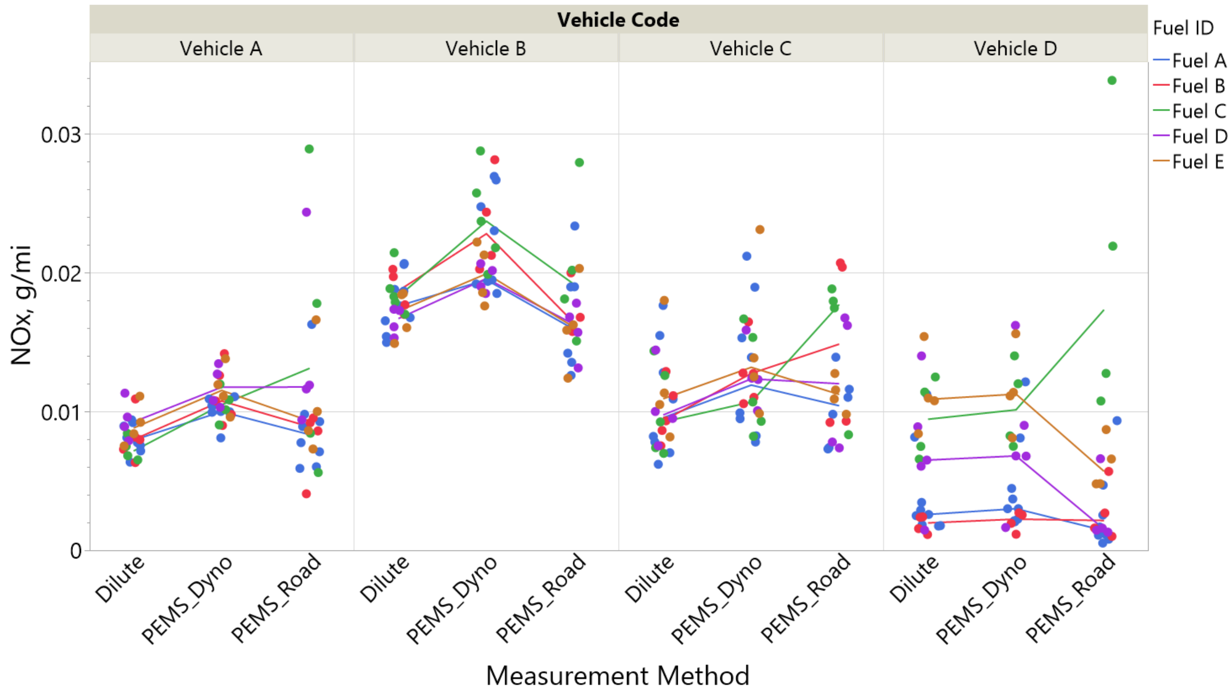


FIGURE 95. RAW DATA PLOT OF NO_X (G/MI) BY METHOD AND VEHICLE, COLORED BY FUEL

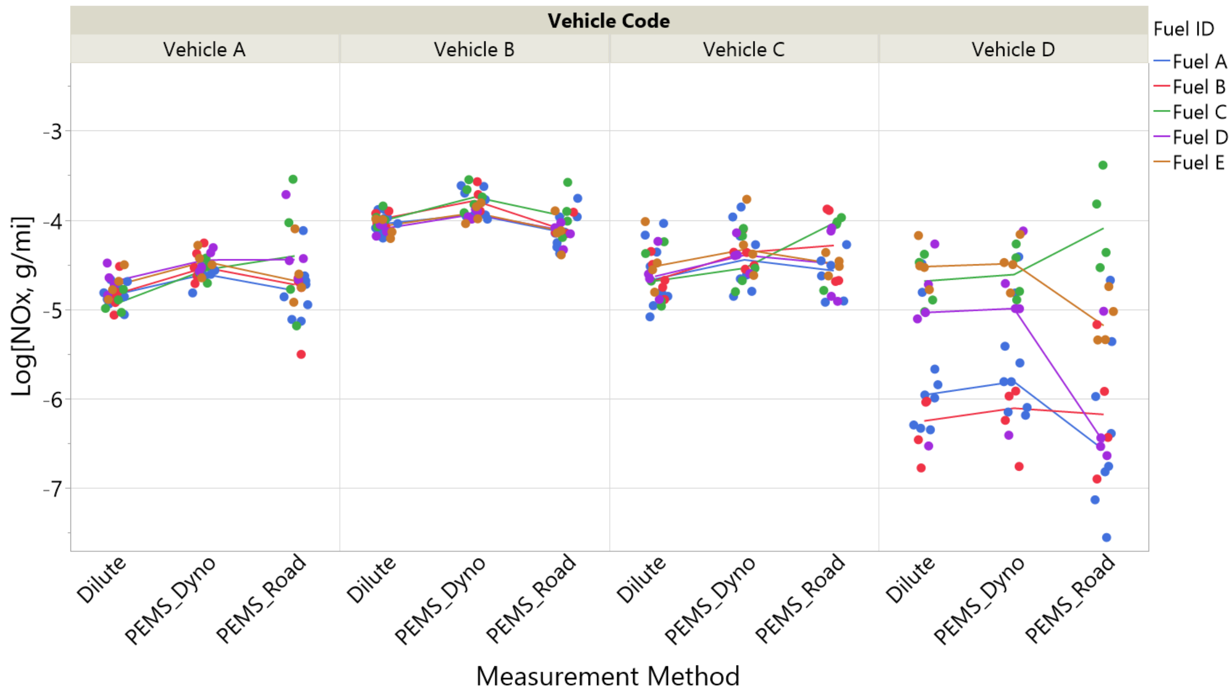


FIGURE 96. RAW DATA PLOT OF LN (NO_X) BY METHOD AND VEHICLE, COLORED BY FUEL

<u>Drift Check</u>

There was some higher variability on PEMS_Road test sets but no drift observed for NO_X.

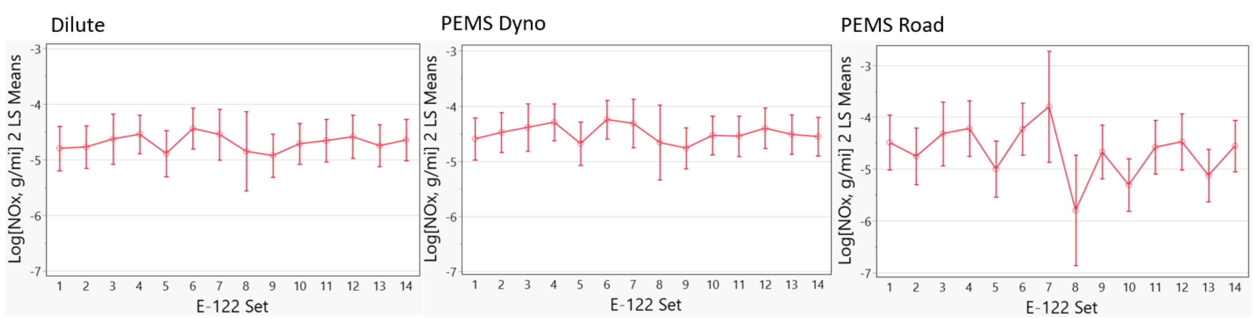


FIGURE 97. NO_X TEST SET LEAST SQUARES (LS) MEANS FOR DRIFT CHECK

Set-to-Set Variability Test

TABLE 39. NO_X SET-TO-SET VARIANCE COMPONENT TEST BY METHOD AND VEHICLE

Vehicle A

Dilute

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.7771716	0.0117951	-0.008787	0.0323768	0.2613	43.731
Residual		0.015177	0.008002	0.0391153		56.269
Total		0.0269721	0.0141343	0.0704528		100.000

PEMS Dyno

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.4874884	0.0064334	-0.0073	0.0201672	0.3586	32.773
Residual		0.013197	0.0069965	0.033608		67.227
Total		0.0196304	0.0106334	0.0477512		100.000

PEMS Road

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	1.4525288	0.1386156	-0.060292	0.3375228	0.1720	59.226
Residual		0.0954305	0.0490716	0.2600412		40.774
Total		0.2340461	0.1163295	0.6902054		100.000

Vehicle B

Dilute

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.017397	-0.000172	-0.005912	0.005569	0.9533	0.000
Residual		0.0098702	0.0052896	0.0245589		100.000
Total		0.0098702	0.0052896	0.0245589		100.000

PEMS Dyno

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	1.0175425	0.0105363	-0.005786	0.0268586	0.2058	50.435
Residual		0.0103546	0.0055636	0.025622		49.565
Total		0.0208909	0.0108081	0.0561478		100.000

PEMS Road

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.1157884	0.0039747	-0.022083	0.0300328	0.7650	10.377
Residual		0.0343271	0.0176514	0.0935389		89.623
Total		0.0383018	0.0214406	0.0870963		100.000

Vehicle C

Dilute

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.4456032	0.0403763	-0.069718	0.1504705	0.4723	30.825
Residual		0.0906105	0.0462012	0.2517103		69.175
Total		0.1309868	0.0656656	0.3785105		100.000

PEMS Dyno

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.5829999	0.0476502	-0.066244	0.1615442	0.4122	36.829
Residual		0.0817327	0.0416295	0.2276125		63.171
Total		0.1293828	0.0633719	0.3953023		100.000

PEMS Road

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.192606	-0.022678	-0.093189	0.0478319	0.5284	0.000
Residual		0.1177449	0.0557072	0.3924265		100.000
Total		0.1177449	0.0557072	0.3924265		100.000

Vehicle D

Dilute

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.057994	0.0194202	-0.184205	0.2230453	0.8517	5.482
Residual		0.3348659	0.1811326	0.8169899		94.518
Total		0.3542861	0.2051474	0.754045		100.000

PEMS Dyno

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.0506098	0.0157929	-0.17373	0.2053161	0.8703	4.817
Residual		0.3120513	0.1685833	0.7633133		95.183
Total		0.3278442	0.1899246	0.697149		100.000

PEMS Road

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.257072	-0.180735	-0.514097	0.1526274	0.2880	0.000
Residual		0.7030518	0.3615179	1.9157645		100.000
Total		0.7030518	0.3615179	1.9157645		100.000

PEMS Accuracy (Bias) Tables

TABLE 40. PEMS BIAS ESTIMATES FOR NO_X

Median Bias,

$Ln(NOx)\ Delta,$
$PEMS_{Dyno}\ -Dilute$

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	0.2660	0.2382	0.2866
Vehicle B	0.1851	0.1687	0.2262
Vehicle C	0.2113	0.1783	0.2377
Vehicle D	0.1003	0.0656	0.1361

Bias back-transformed to NOx, g/mi

Vehicle	Median Dilute NOx, g/mi	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	0.0081	0.0025	0.0022	0.0027
Vehicle B	0.0177	0.0036	0.0033	0.0045
Vehicle C	0.0099	0.0023	0.0019	0.0027
Vehicle D	0.0056	0.0006	0.0004	0.0008

Median Bias Relative to Median NOx

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	30.47%	26.90%	33.19%
Vehicle B	20.33%	18.38%	25.38%
Vehicle C	23.53%	19.52%	26.83%
Vehicle D	10.55%	6.78%	14.58%

Plots of the Quantiles of the Empirical Distribution of Delta and % Delta for all Pairwise Differences, PEMS_Road-Dilute and Dilute-Dilute

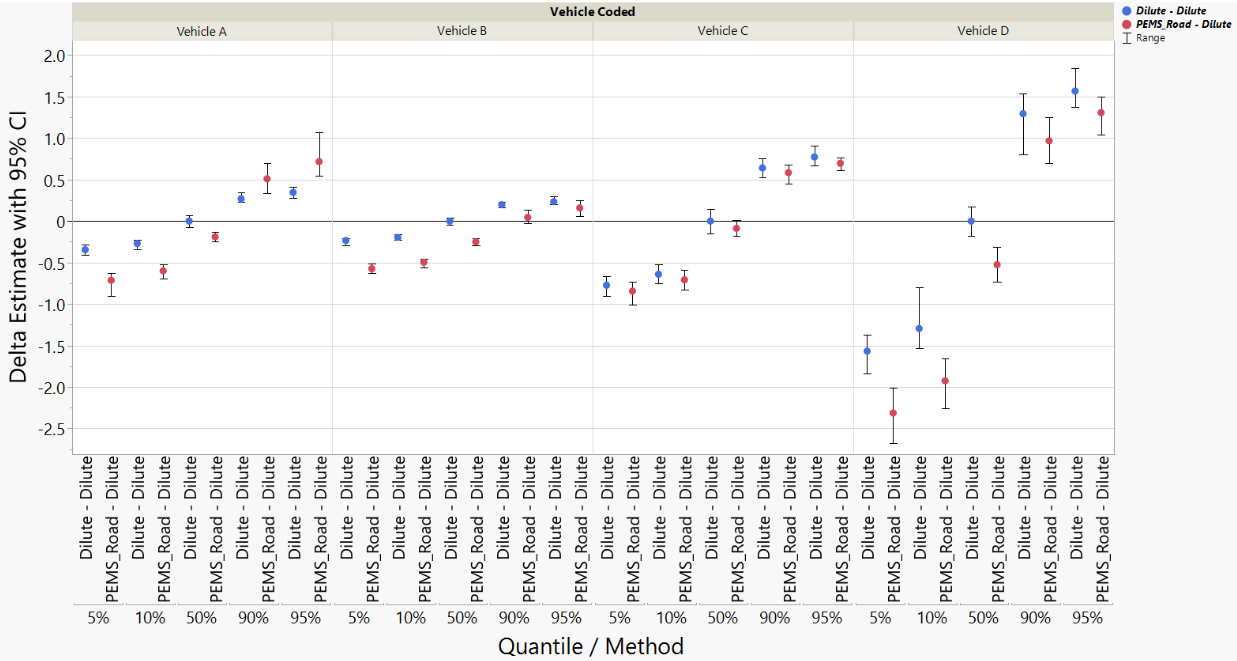


FIGURE 98. QUANTILES OF DELTA NO_X WITH 95% CONFIDENCE INTERVALS

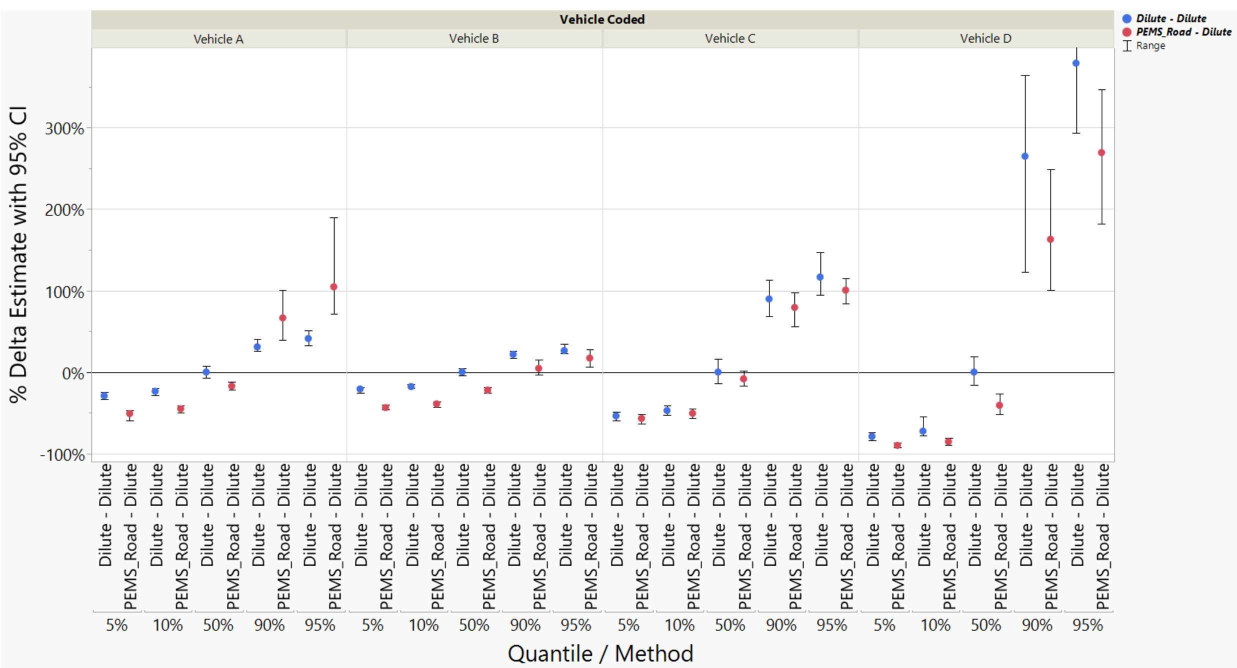


FIGURE 99. QUANTILES OF % DELTA NO_X WITH 95% CONFIDENCE INTERVALS

Plot Vs. Fuel PMI and Fuel RVP

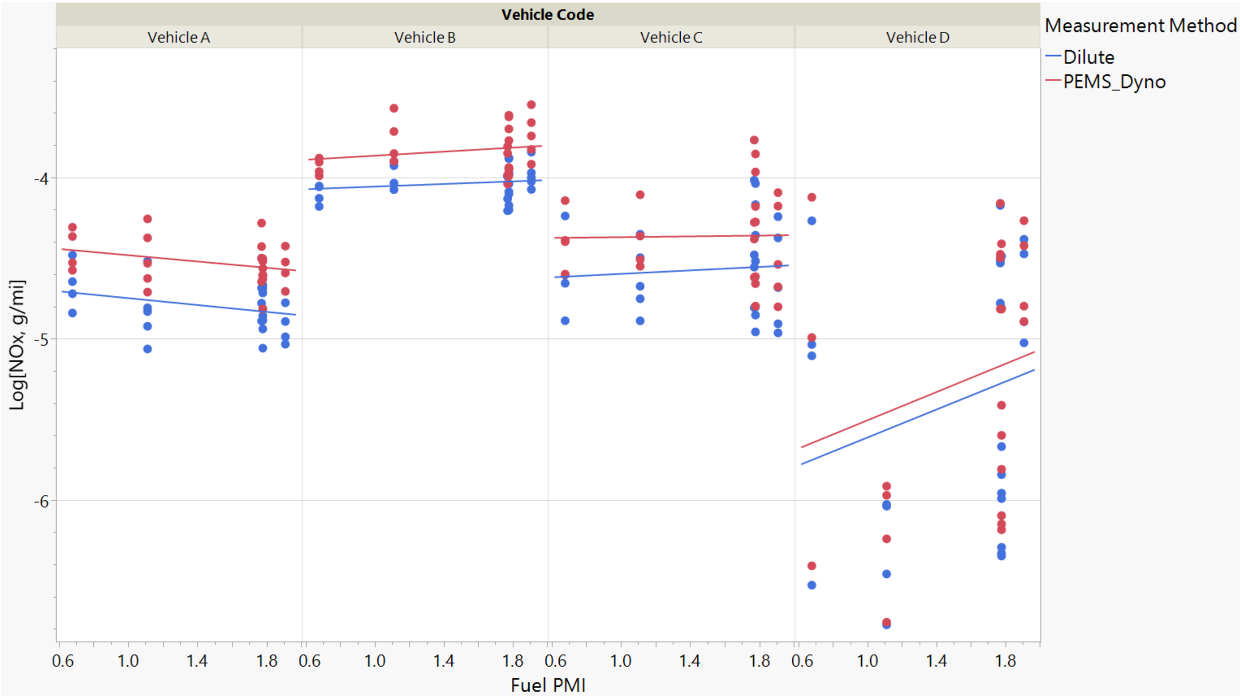


FIGURE 100. LN (NO_X) VS. FUEL PMI, COLORED BY METHOD

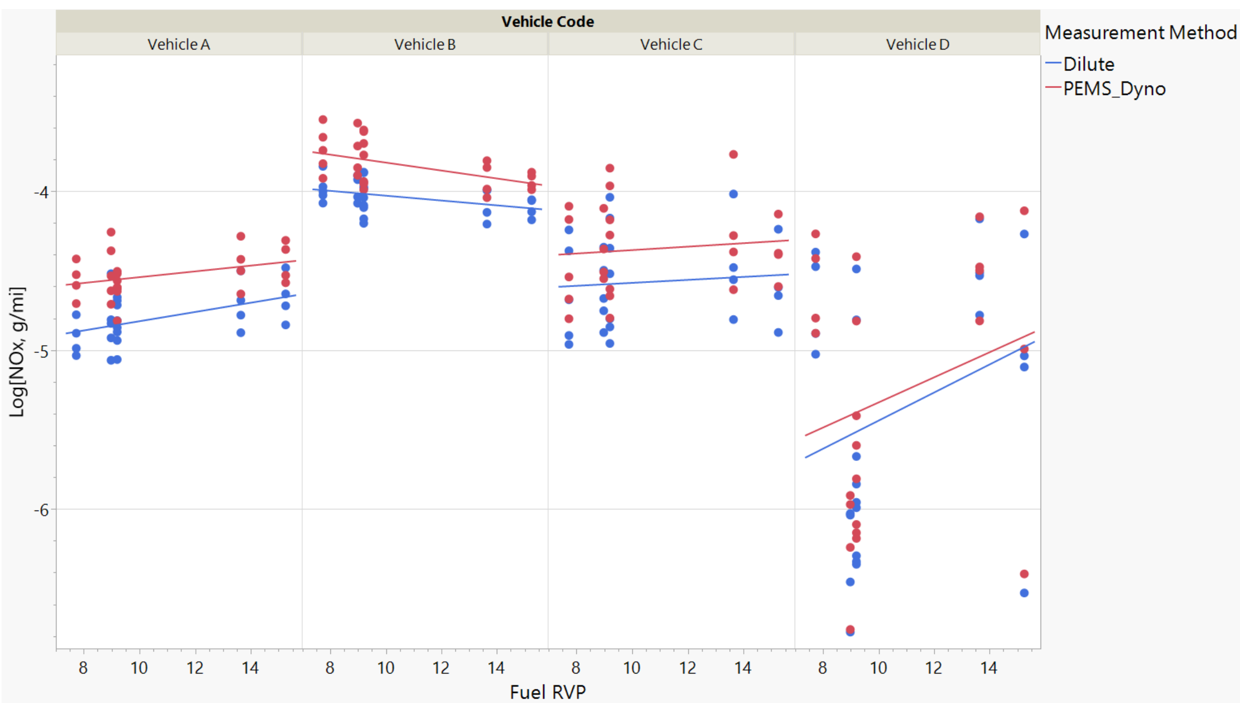


FIGURE 101. LN (NO_X) VS. FUEL RVP, COLORED BY METHOD

G.3 CO_2

Raw Data Plots by Method and Vehicle, Colored by Fuel

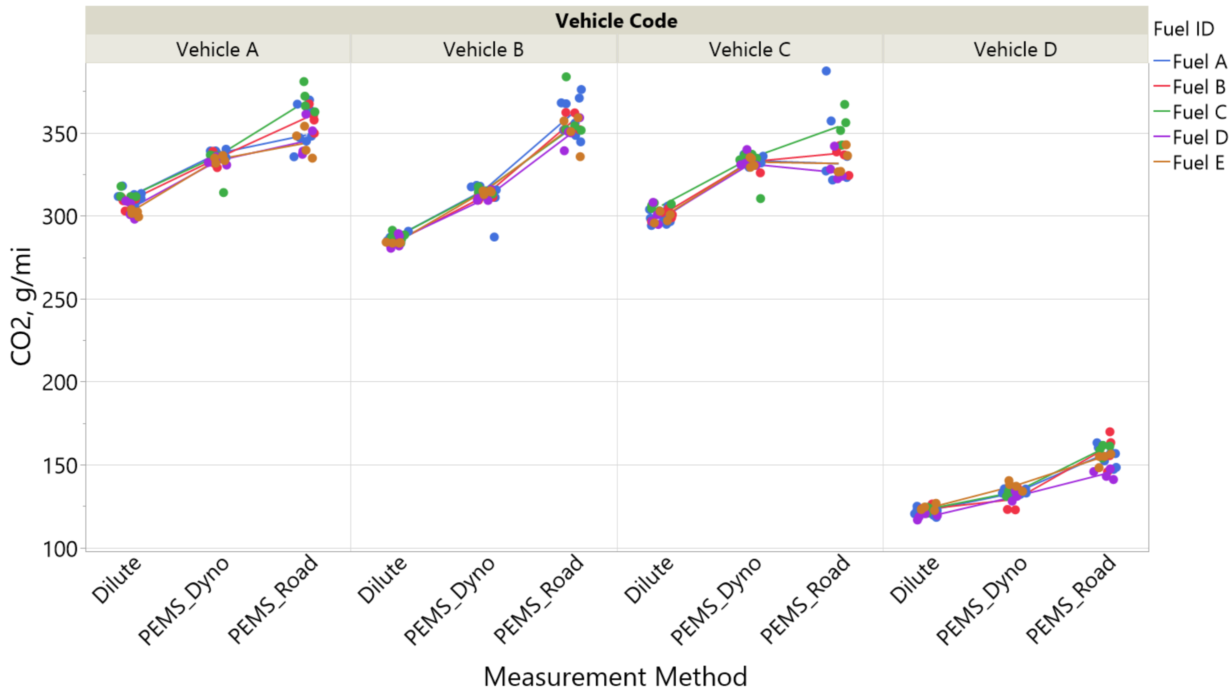


FIGURE 102. RAW DATA PLOT OF CO_2 (G/MI) BY METHOD AND VEHICLE, COLORED BY FUEL

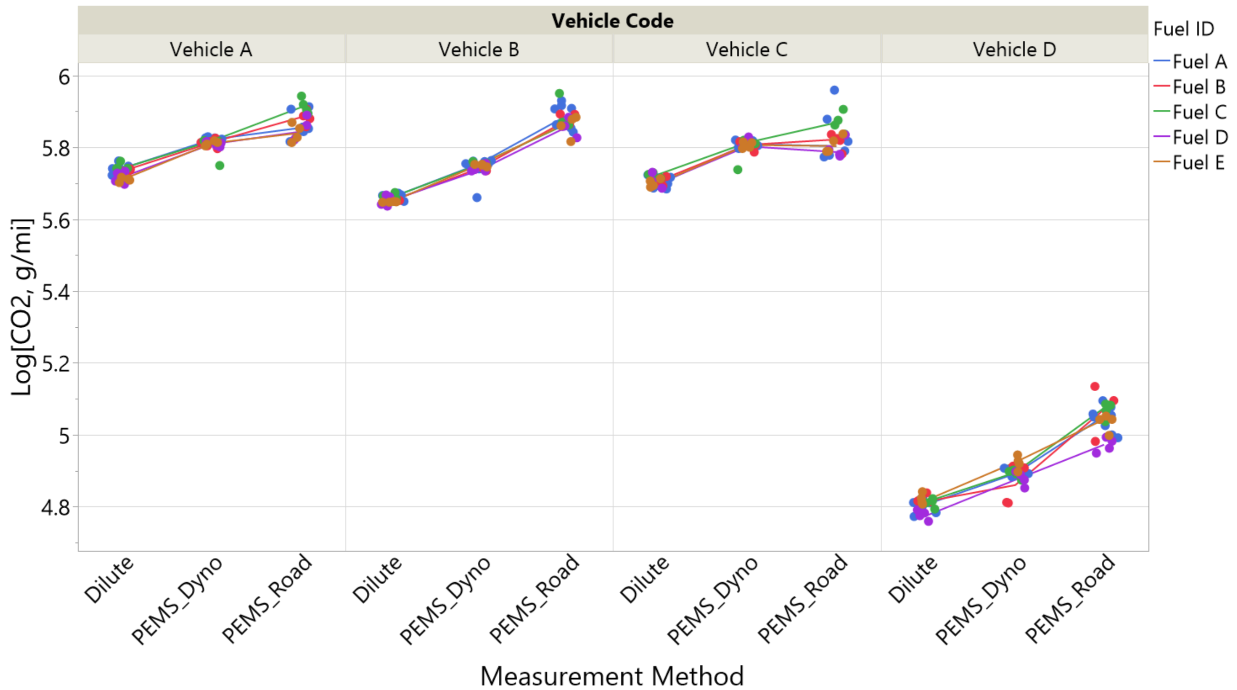


FIGURE 103. RAW DATA PLOT OF LN (CO_2) BY METHOD AND VEHICLE, COLORED BY FUEL

Drift Check

There was a shift in PEMS road test values corresponding with the beginning of the Winter Fuels Matrix.

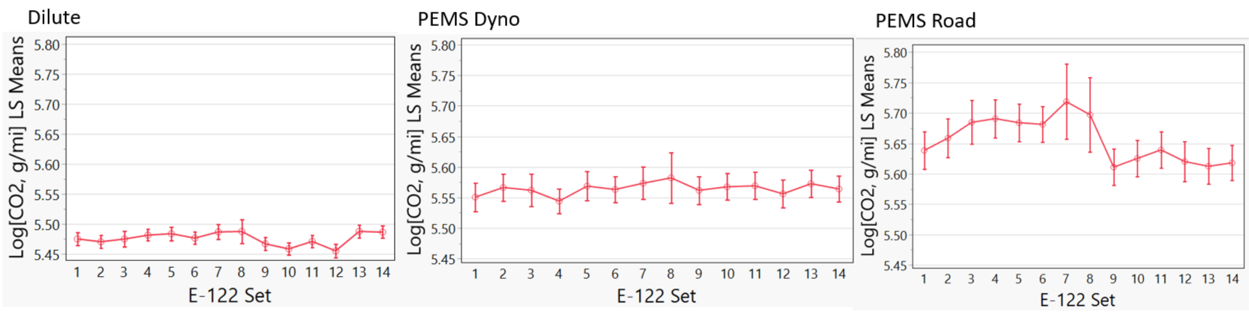


FIGURE 104. CO_2 TEST SET LEAST SQUARES (LS) MEANS FOR DRIFT CHECK

Set-to-Set Variability Test

TABLE 41. CO_2 SET-TO-SET VARIANCE COMPONENT TEST BY METHOD

Dilute

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.8377576	8.195e-5	1.3118e-5	0.0001508	0.0196*	45.586
Residual		9.7821e-5	6.9327e-5	0.0001484		54.414
Total		0.0001798	0.0001264	0.000276		100.000

PEMS Dyno

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.016335	-6.717e-6	-0.000121	0.0001081	0.9087	0.000
Residual		0.0004112	0.0002939	0.0006164		100.000
Total		0.0004112	0.0002939	0.0006164		100.000

PEMS Road

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.3199492	0.0003333	-0.000169	0.0008353	0.1931	24.240
Residual		0.0010418	0.000722	0.0016346		75.760
Total		0.0013752	0.0009846	0.0020561		100.000

PEMS Accuracy (Bias) Tables

TABLE 42. PEMS BIAS ESTIMATES FOR CO_2

Median Bias,

$Ln(CO_2)$ Delta, $PEMS_{Dyno} - Dilute$

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	0.0832	0.0789	0.0894
Vehicle B	0.0930	0.0891	0.0988
Vehicle C	0.0996	0.0970	0.1043
Vehicle D	0.0899	0.0841	0.0975

Bias back-transformed to CO2, g/mi

Vehicle	Median Dilute CO2, g/mi	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	309.3	26.8	25.4	28.9
Vehicle B	285.6	27.8	26.6	29.7
Vehicle C	300.9	31.5	30.6	33.1
Vehicle D	122.5	11.5	10.7	12.5

Median Bias Relative to Median CO2

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	8.68%	8.21%	9.35%
Vehicle B	9.75%	9.32%	10.38%
Vehicle C	10.47%	10.19%	10.99%
Vehicle D	9.41%	8.77%	10.24%

Plots of the Quantiles of the Empirical Distribution of Delta and % Delta for all Pairwise Differences, PEMS_Road-Dilute and Dilute-Dilute

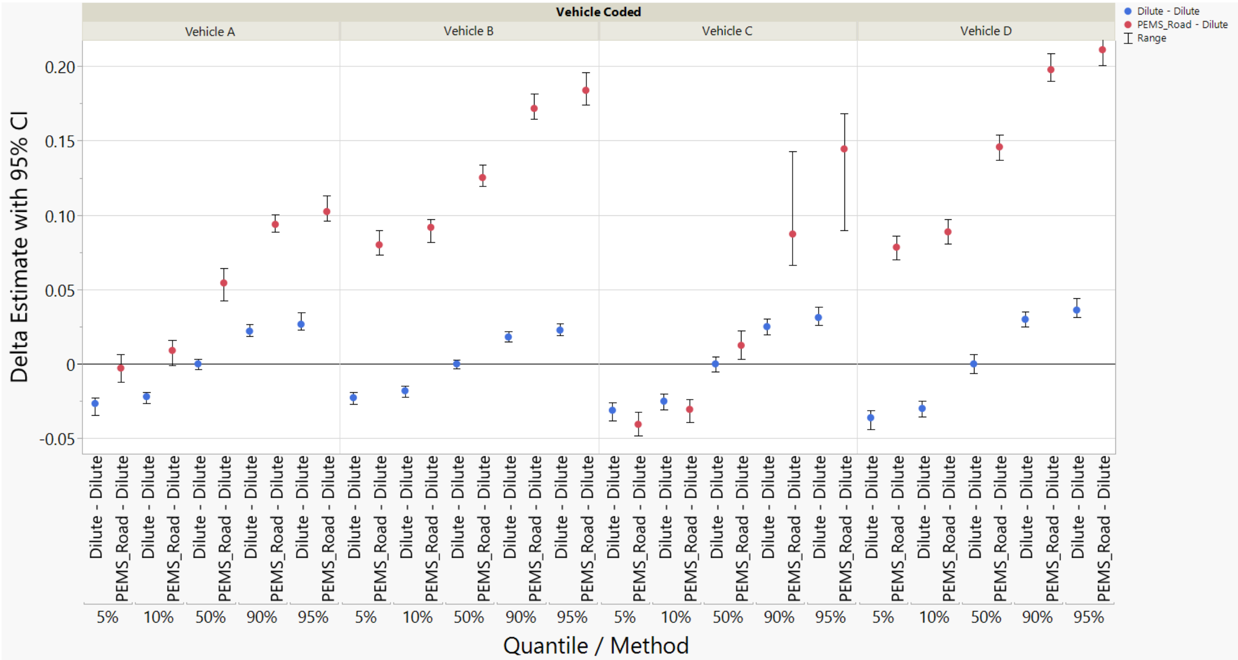


FIGURE 105. QUANTILES OF DELTA CO_2 WITH 95% CONFIDENCE INTERVALS

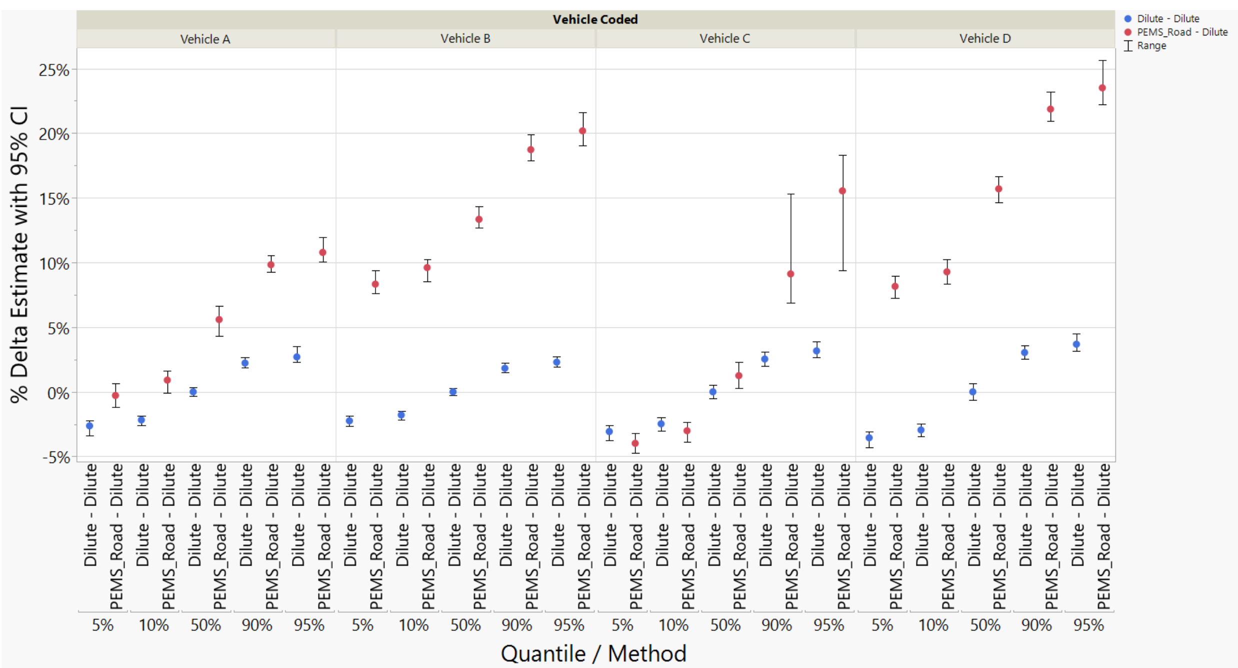


FIGURE 106. QUANTILES OF % DELTA CO_2 WITH 95% CONFIDENCE INTERVALS

Plot Vs. Fuel PMI and Fuel RVP

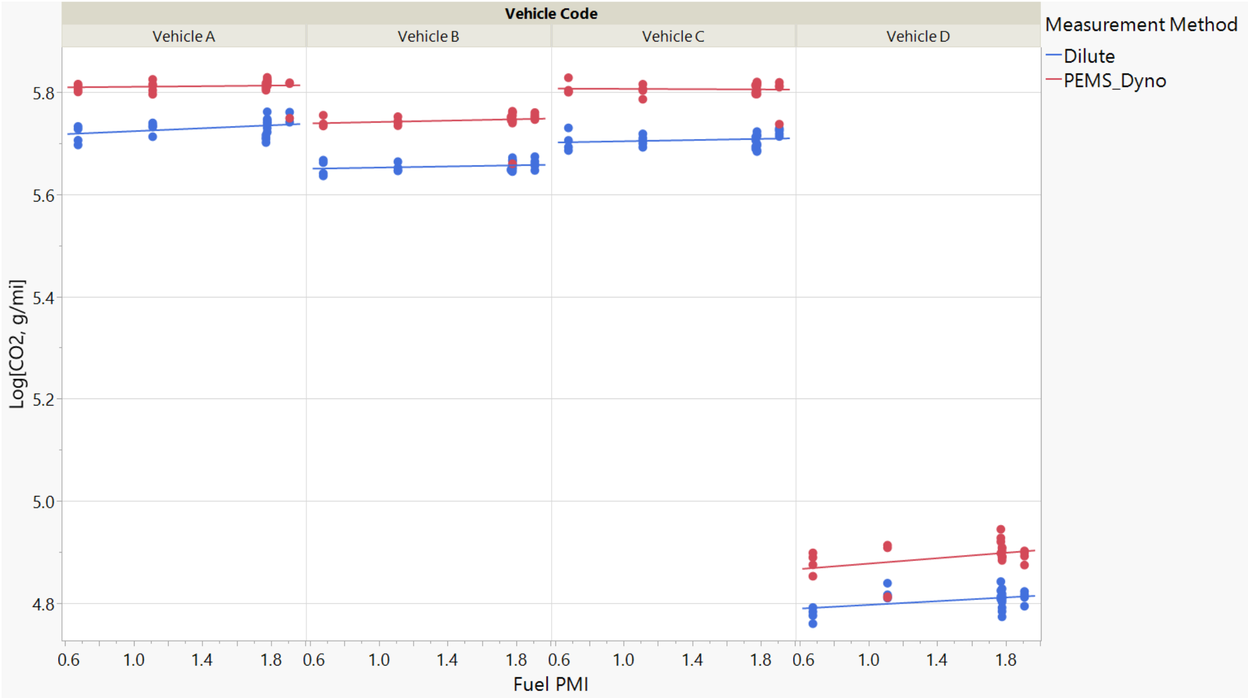


FIGURE 107. LN (CO_2) VS. FUEL PMI, COLORED BY METHOD

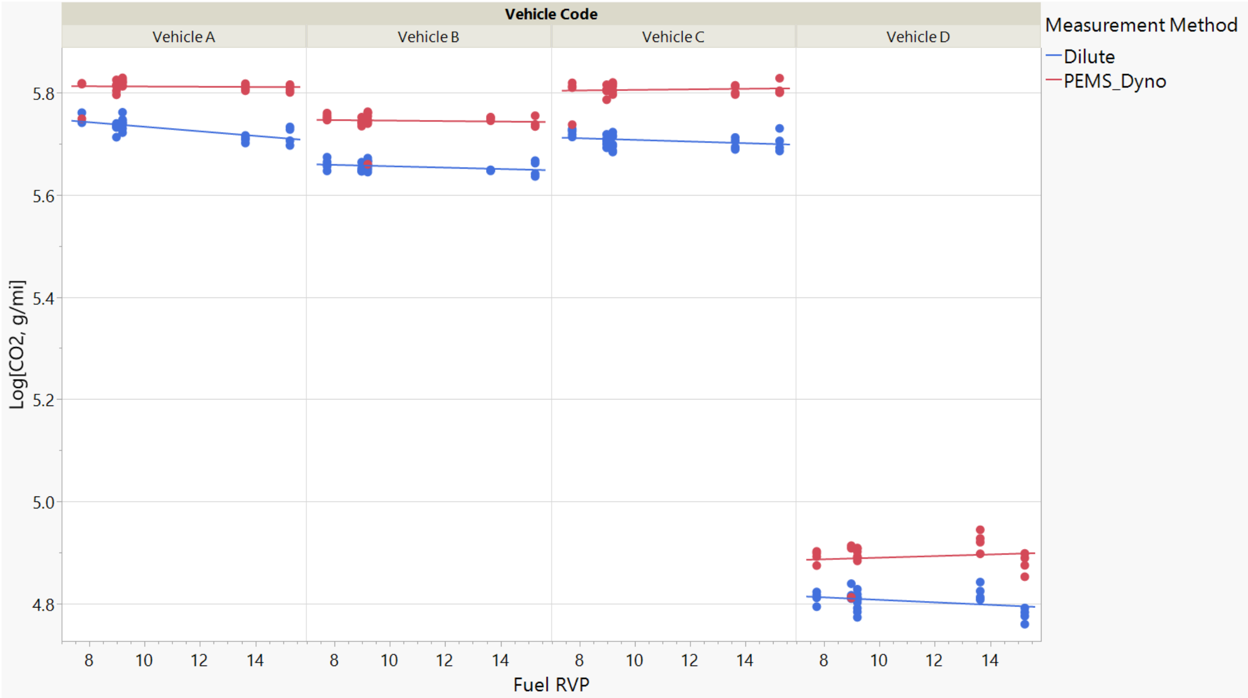


FIGURE 108. LN (CO_2) VS. FUEL RVP, COLORED BY METHOD

G.4 Fuel Economy

Raw Data Plots by Method and Vehicle, Colored by Fuel

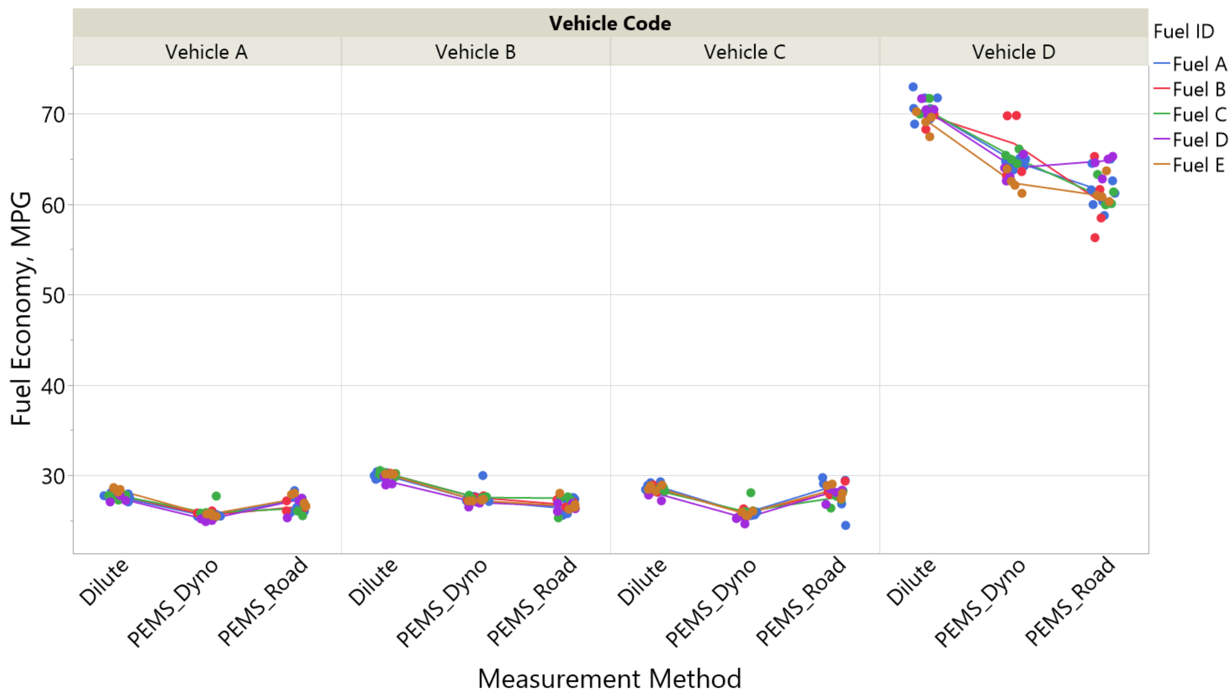


FIGURE 109. RAW DATA PLOT OF FUEL ECONOMY (MPG) BY METHOD AND VEHICLE, COLORED BY FUEL

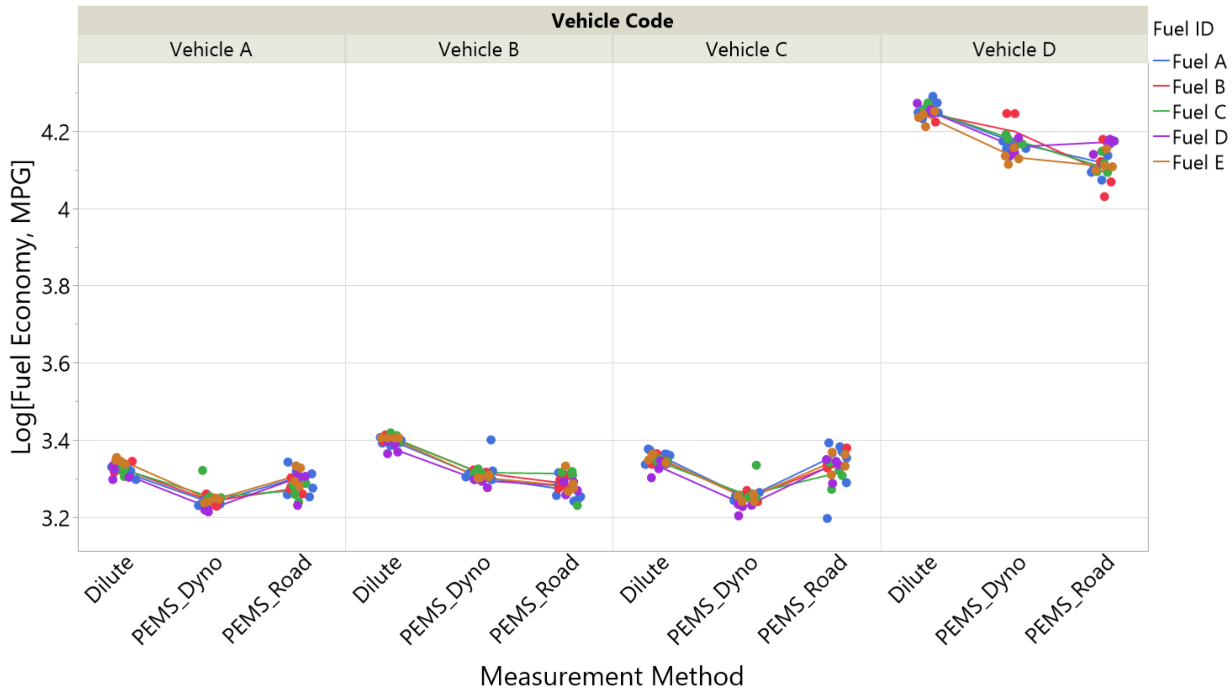


FIGURE 110. RAW DATA PLOT OF LN (FUEL ECONOMY) BY METHOD AND VEHICLE, COLORED BY FUEL

<u>Drift Check</u>

There was a shift in PEMS road test values corresponding with the beginning of the Winter Fuels Matrix.

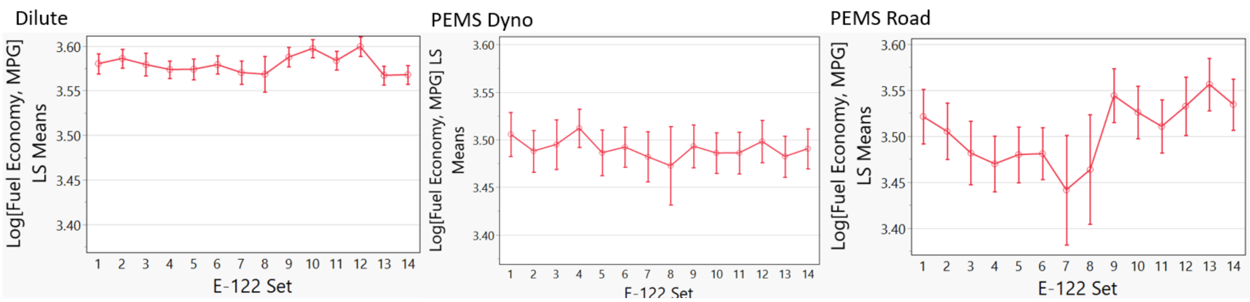


FIGURE 111. FUEL ECONOMY TEST SET LEAST SQUARES (LS) MEANS FOR DRIFT CHECK

Set-to-Set Variability Test

TABLE 43. FUEL ECONOMY SET-TO-SET VARIANCE COMPONENT TEST BY METHOD

Dilute

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.8268157	8.1683e-5	1.2448e-5	0.0001509	0.0208*	45.260
Residual		0.0000988	6.9985e-5	0.00015		54.740
Total		0.0001805	0.0001269	0.0002771		100.000

PEMS Dyno

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.011963	-4.864e-6	-0.000119	0.0001094	0.9335	0.000
Residual		0.0004066	0.0002905	0.0006096		100.000
Total		0.0004066	0.0002905	0.0006096		100.000

PEMS Road

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.2109099	0.0002322	-0.000241	0.0007053	0.3361	17.417
Residual		0.0011009	0.0007629	0.0017272		82.583
Total		0.0013331	0.0009626	0.0019688		100.000

PEMS Accuracy (Bias) Tables

TABLE 44. PEMS BIAS ESTIMATES FOR FUEL ECONOMY

Median Bias,

$Ln(FE)$ $Delta,$ $PEMS_{Dyno} - Dilute$

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	-0.0855	-0.0915	-0.0790
Vehicle B	-0.0934	-0.0984	-0.0894
Vehicle C	-0.0995	-0.1040	-0.0964
Vehicle D	-0.0881	-0.0965	-0.0827

Bias back-transformed to FE, mpg

Vehicle	Median Dilute FE, mpg	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	27.79	-2.28	-2.43	-2.11
Vehicle B	30.07	-2.68	-2.82	-2.57
Vehicle C	28.49	-2.70	-2.81	-2.62
Vehicle D	70.18	-5.92	-6.46	-5.57

Median Bias Relative to Median Fuel Economy

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	-8.19%	-8.74%	-7.60%
Vehicle B	-8.92%	-9.37%	-8.55%
Vehicle C	-9.47%	-9.88%	-9.19%
Vehicle D	-8.43%	-9.20%	-7.94%

Plots of the Quantiles of the Empirical Distribution of Delta and % Delta for all Pairwise Differences, PEMS_Road-Dilute and Dilute-Dilute

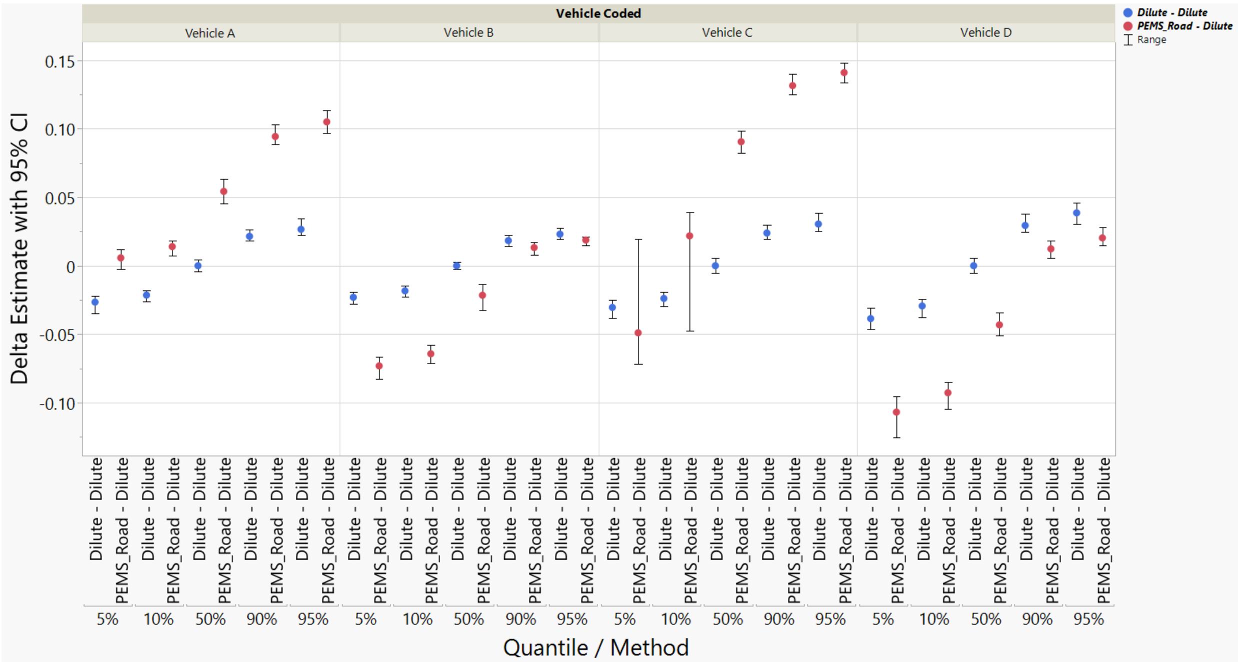


FIGURE 112. QUANTILES OF DELTA FUEL ECONOMY WITH 95% CONFIDENCE INTERVALS

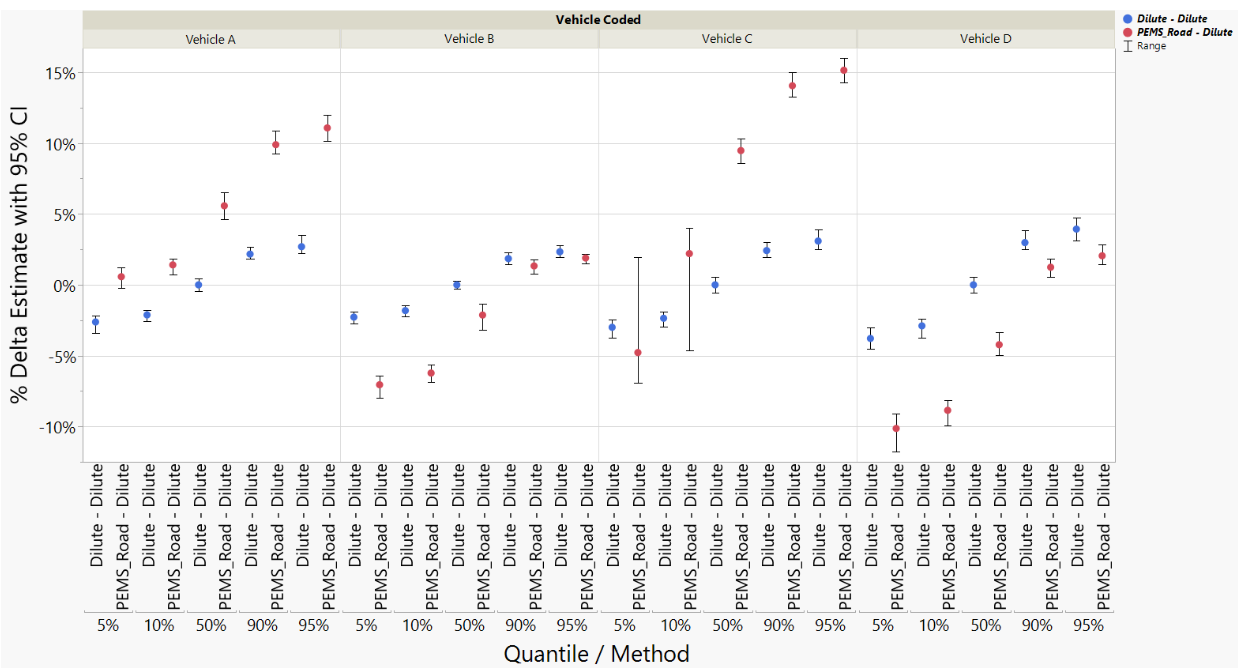


FIGURE 113. QUANTILES OF % DELTA FUEL ECONOMY WITH 95% CONFIDENCE INTERVALS

Plot Vs. Fuel PMI and Fuel RVP

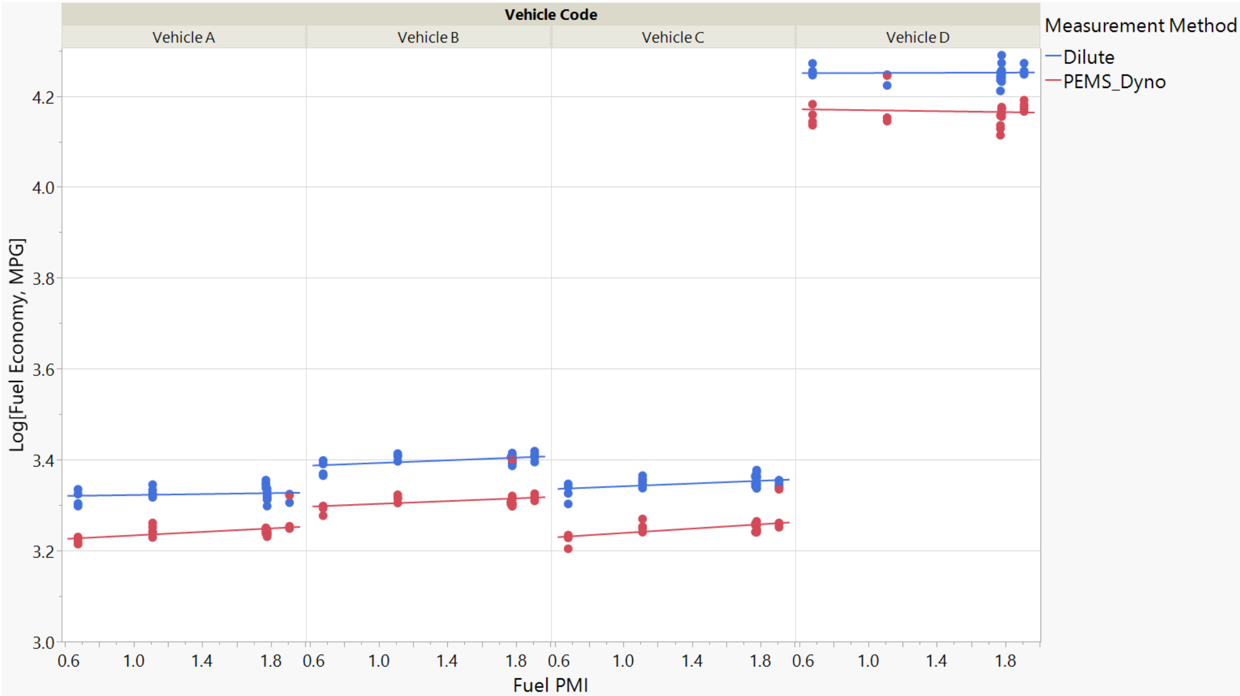


FIGURE 114. LN (FUEL ECONOMY) VS. FUEL PMI, COLORED BY METHOD

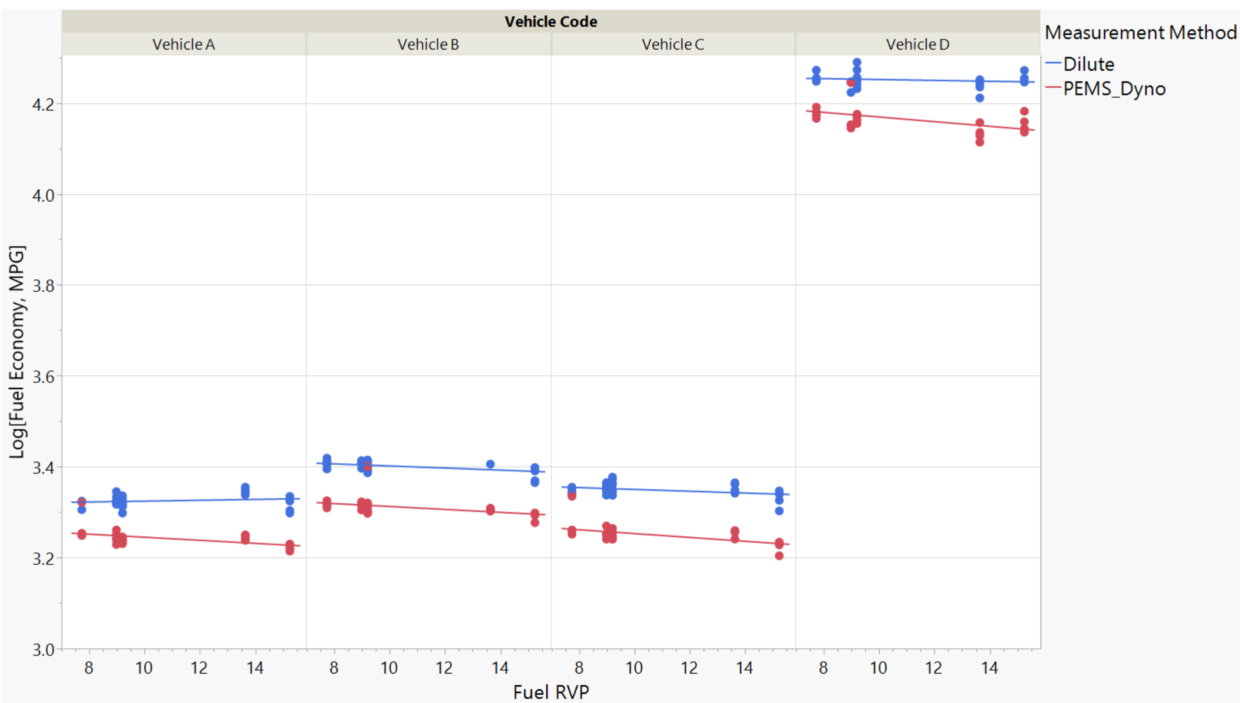


FIGURE 115. LN (FUEL ECONOMY) VS. FUEL RVP, COLORED BY METHOD

G.5 THC

Raw Data Plots by Method and Vehicle, Colored by Fuel

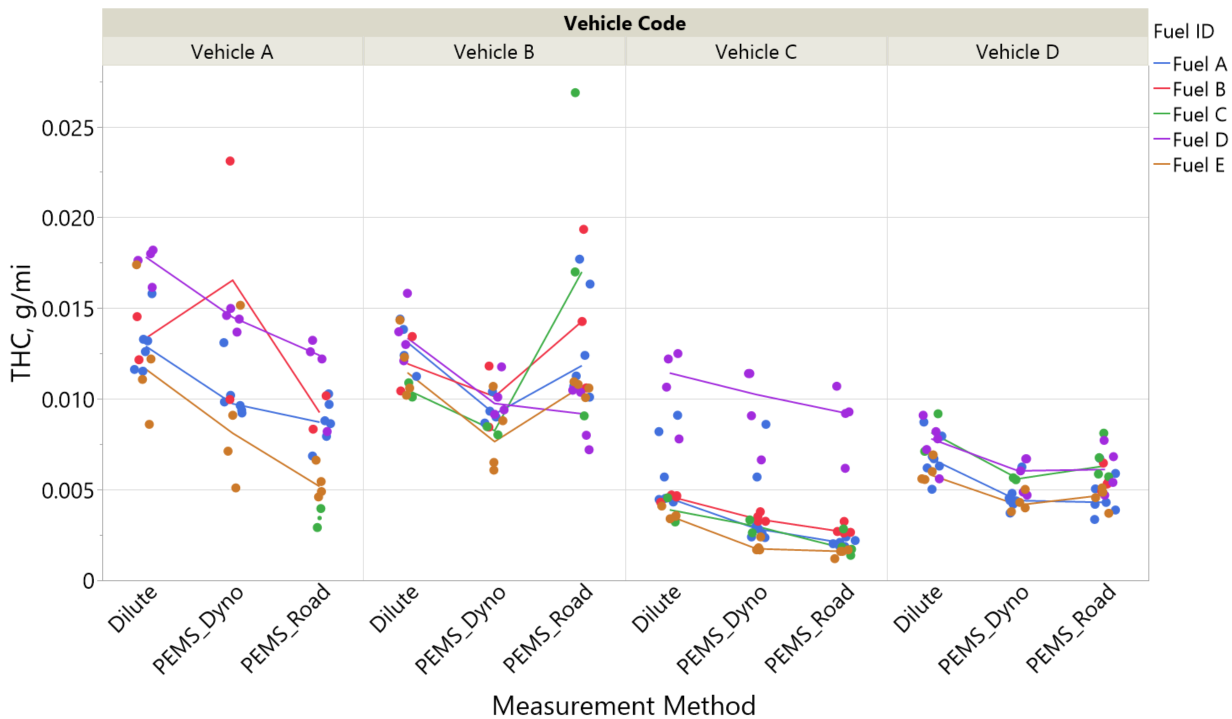


FIGURE 116. RAW DATA PLOT OF THC (G/MI) BY METHOD AND VEHICLE, COLORED BY FUEL

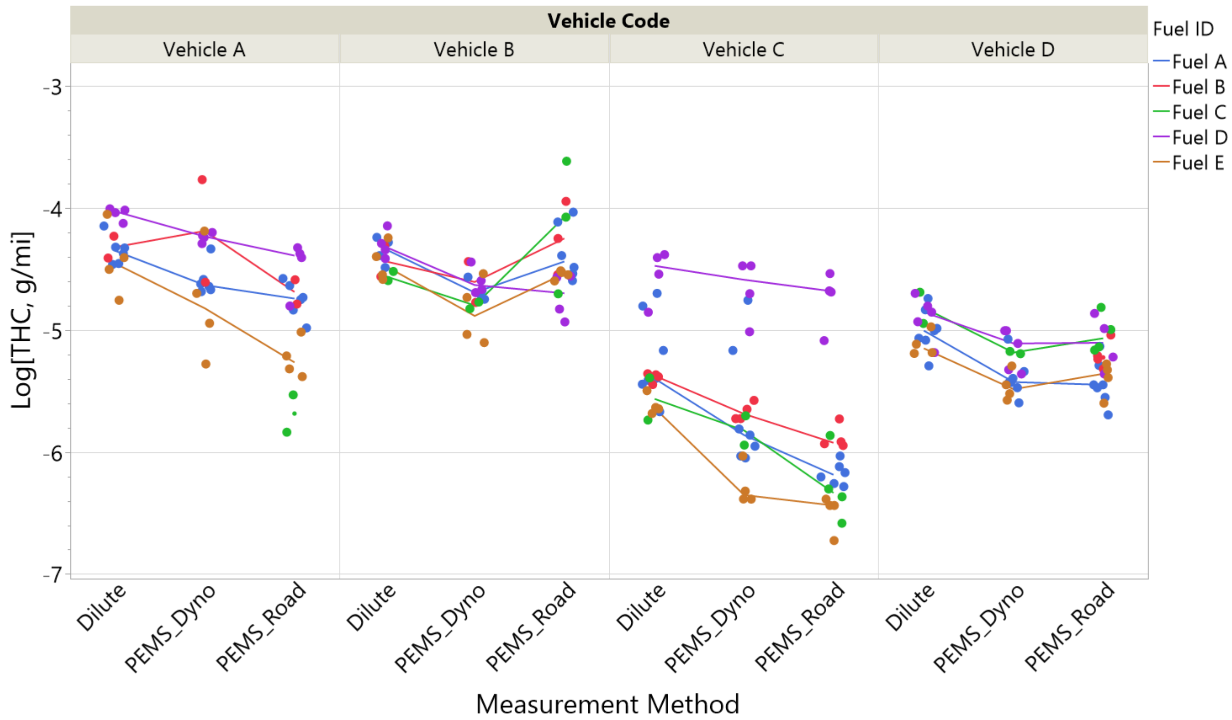


FIGURE 117. RAW DATA PLOT OF LN (THC) BY METHOD AND VEHICLE, COLORED BY FUEL

Drift Check

There was high set-to-set variation, but no drift observed for THC.

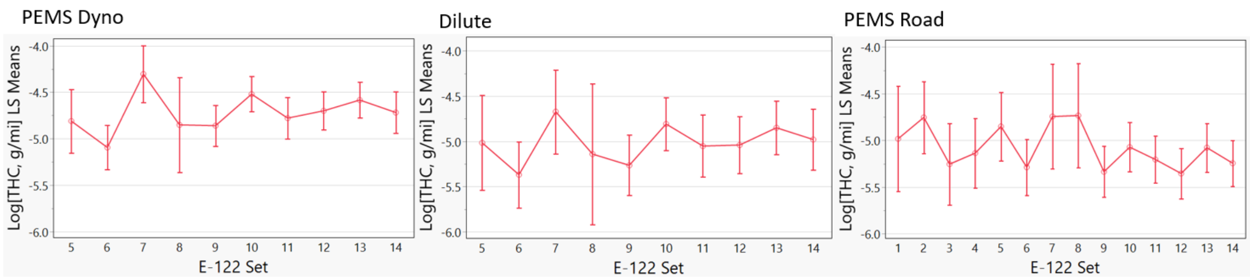


FIGURE 118. THC TEST SET LEAST SQUARES (LS) MEANS FOR DRIFT CHECK

Set-to-Set Variability Test

TABLE 45. THC SET-TO-SET VARIANCE COMPONENT TEST BY METHOD AND VEHICLE

Vehicle A

Dilute — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.2290725	0.0057384	-0.022392	0.0338692	0.6893	18.638
Residual		0.0250505	0.0114291	0.0919398		81.362
Total		0.0307889	0.0146654	0.1008549		100.000

PEMS Dyno — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.228875	-0.024156	-0.089327	0.0410144	0.4675	0.000
Residual		0.1055426	0.048153	0.3873603		100.000
Total		0.1055426	0.048153	0.3873603		100.000

PEMS Road — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.357294	0.0083172	-0.0216	0.0382346	0.5858	26.324
Residual		0.0232784	0.0106206	0.0854359		73.676
Total		0.0315956	0.0147263	0.1094988		100.000

Vehicle B

Dilute — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.427653	-0.00928	-0.020206	0.0016455	0.0960	0.000
Residual		0.0217004	0.0099006	0.0796442		100.000
Total		0.0217004	0.0099006	0.0796442		100.000

PEMS Dyno — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.44252	-0.017166	-0.036506	0.0021735	0.0819	0.000
Residual		0.0387924	0.0176987	0.1423749		100.000
Total		0.0387924	0.0176987	0.1423749		100.000

PEMS Road — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.4574851	0.0180429	-0.045403	0.0814891	0.5773	31.389
Residual		0.0394393	0.0179939	0.1447493		68.611
Total		0.0574822	0.0242748	0.2643041		100.000

Vehicle C

Dilute — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	2.0827014	0.0624296	-0.04158	0.1664389	0.2394	67.561
Residual		0.0299753	0.0142711	0.0983086		32.439
Total		0.092405	0.0382413	0.4529596		100.000

PEMS Dyno — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.5959096	0.0582615	-0.082186	0.1987089	0.4162	37.340
Residual		0.097769	0.0468822	0.3148655		62.660
Total		0.1560305	0.0726445	0.5423021		100.000

PEMS Road — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.04671	-0.001517	-0.027391	0.0243575	0.9085	0.000
Residual		0.0324766	0.0148172	0.119195		100.000
Total		0.0324766	0.0148172	0.119195		100.000

Vehicle D

Dilute — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.2199357	0.005359	-0.02772	0.0384379	0.7508	18.028
Residual		0.0243661	0.0107727	0.0976728		81.972
Total		0.029725	0.0142461	0.0958589		100.000

PEMS Dyno — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.20479	-0.005425	-0.022823	0.0119719	0.5411	0.000
Residual		0.0264927	0.0122822	0.0931211		100.000
Total		0.0264927	0.0122822	0.0931211		100.000

PEMS Road — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	3.0370677	0.0457962	-0.02849	0.1200829	0.2269	75.230
Residual		0.0150791	0.0068797	0.055343		24.770
Total		0.0608753	0.0239855	0.3519745		100.000

PEMS Accuracy (Bias) Tables

TABLE 46. PEMS BIAS ESTIMATES FOR THC

Median Bias,

Ln(THC) Delta, $PEMS_{Dyno} - Dilute$

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	-0.2194	-0.2796	-0.1809
Vehicle B	-0.2937	-0.3493	-0.2565
Vehicle C	-0.3203	-0.4673	-0.2151
Vehicle D	-0.3388	-0.3799	-0.2973

Bias back-transformed to THC, g/mi

Vehicle	Median Dilute THC, g/mi	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	0.0136	-0.0027	-0.0033	-0.0023
Vehicle B	0.0124	-0.0031	-0.0036	-0.0028
Vehicle C	0.0048	-0.0013	-0.0018	-0.0009
Vehicle D	0.0069	-0.0020	-0.0022	-0.0018

Median Bias Relative to Median THC

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	-19.70%	-24.39%	-16.55%
Vehicle B	-25.45%	-29.48%	-22.62%
Vehicle C	-27.41%	-37.33%	-19.35%
Vehicle D	-28.74%	-31.61%	-25.72%

<u>Plots of the Quantiles of the Empirical Distribution of Delta and % Delta for all Pairwise Differences, PEMS_Road-Dilute and Dilute-Dilute</u>

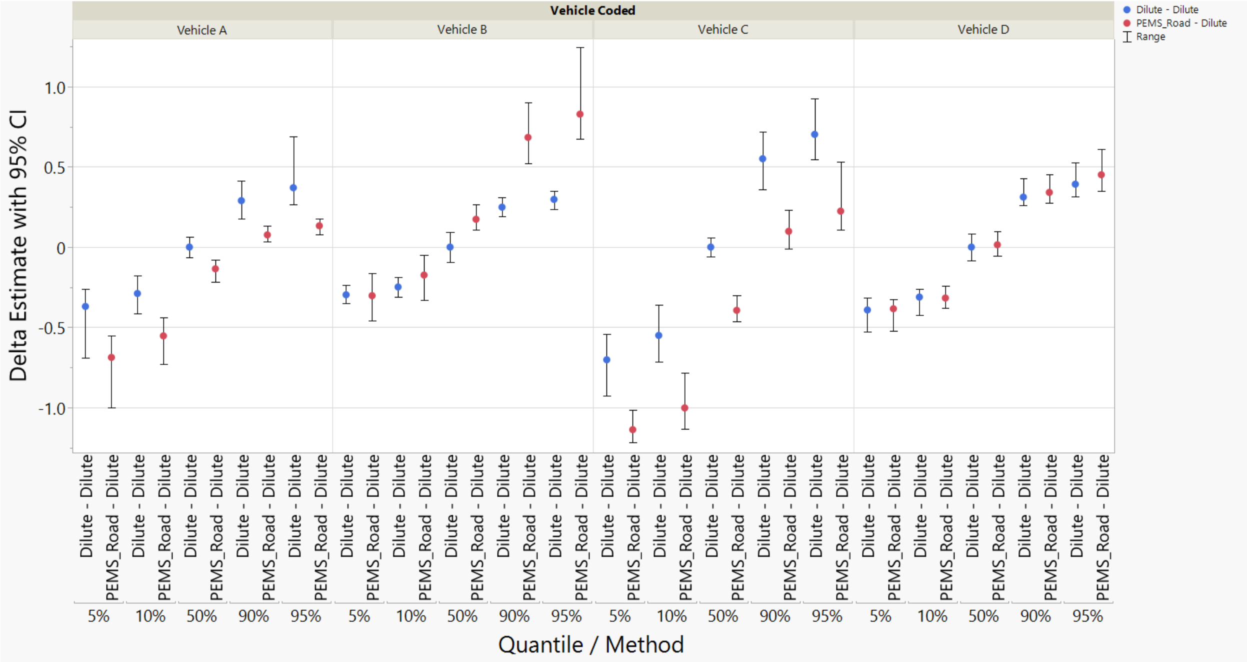


FIGURE 119. QUANTILES OF DELTA THC WITH 95% CONFIDENCE INTERVALS

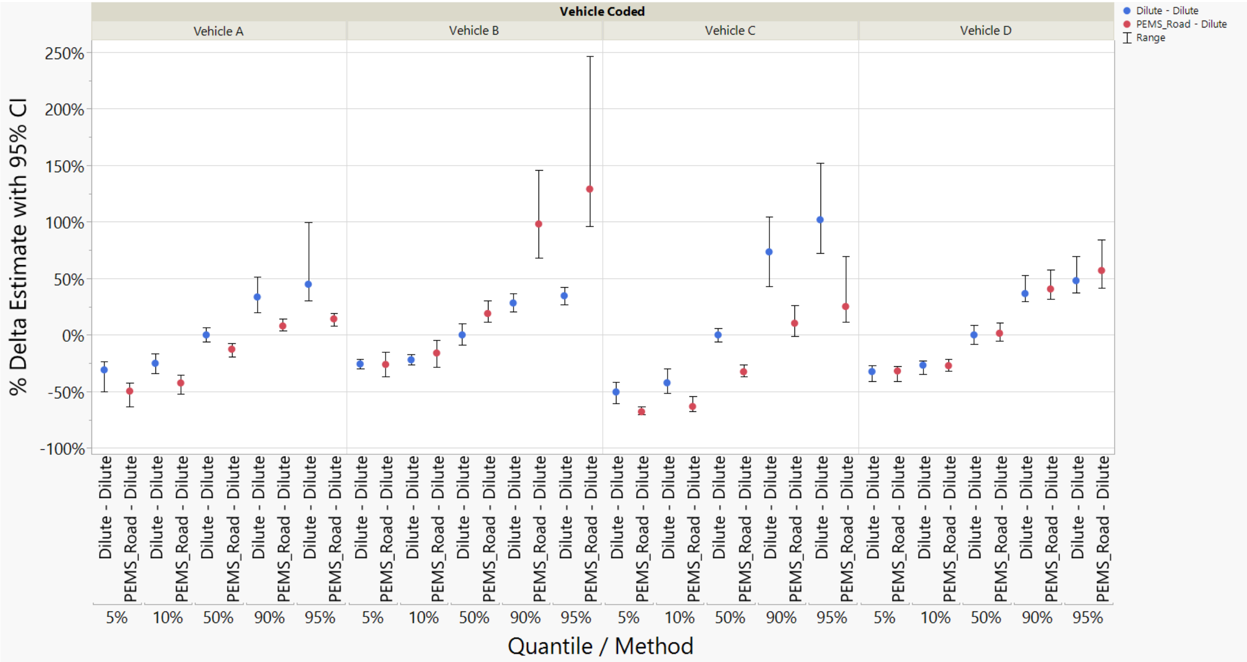


FIGURE 120. QUANTILES OF % DELTA THC WITH 95% CONFIDENCE INTERVALS

Plot Vs. Fuel PMI and Fuel RVP

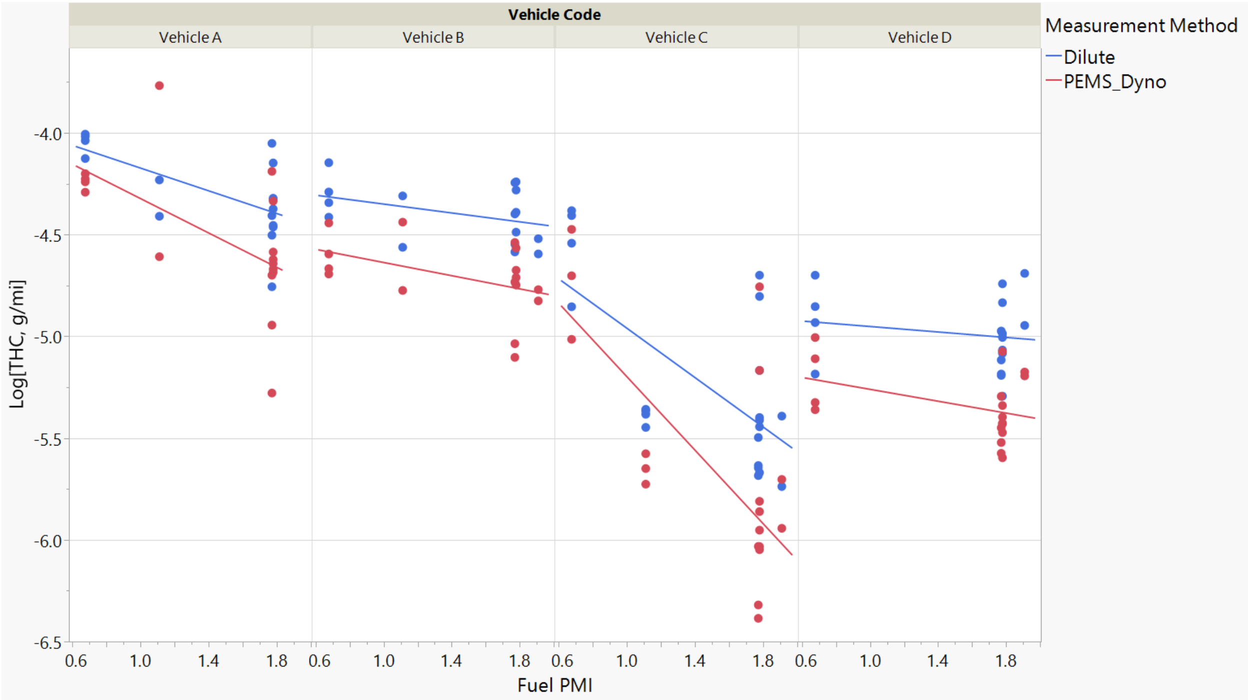


FIGURE 121. LN (THC) VS. FUEL PMI, COLORED BY METHOD

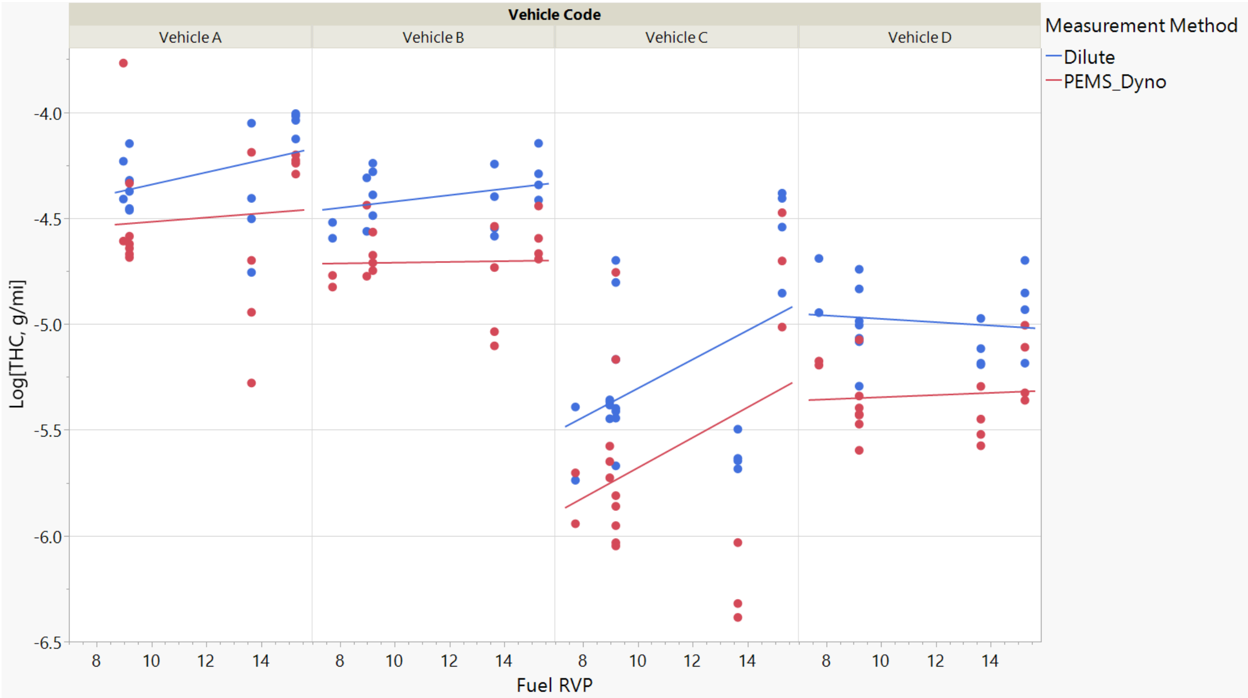


FIGURE 122. LN (THC) VS. FUEL RVP, COLORED BY METHOD

G.6 NMHC

Raw Data Plots by Method and Vehicle, Colored by Fuel

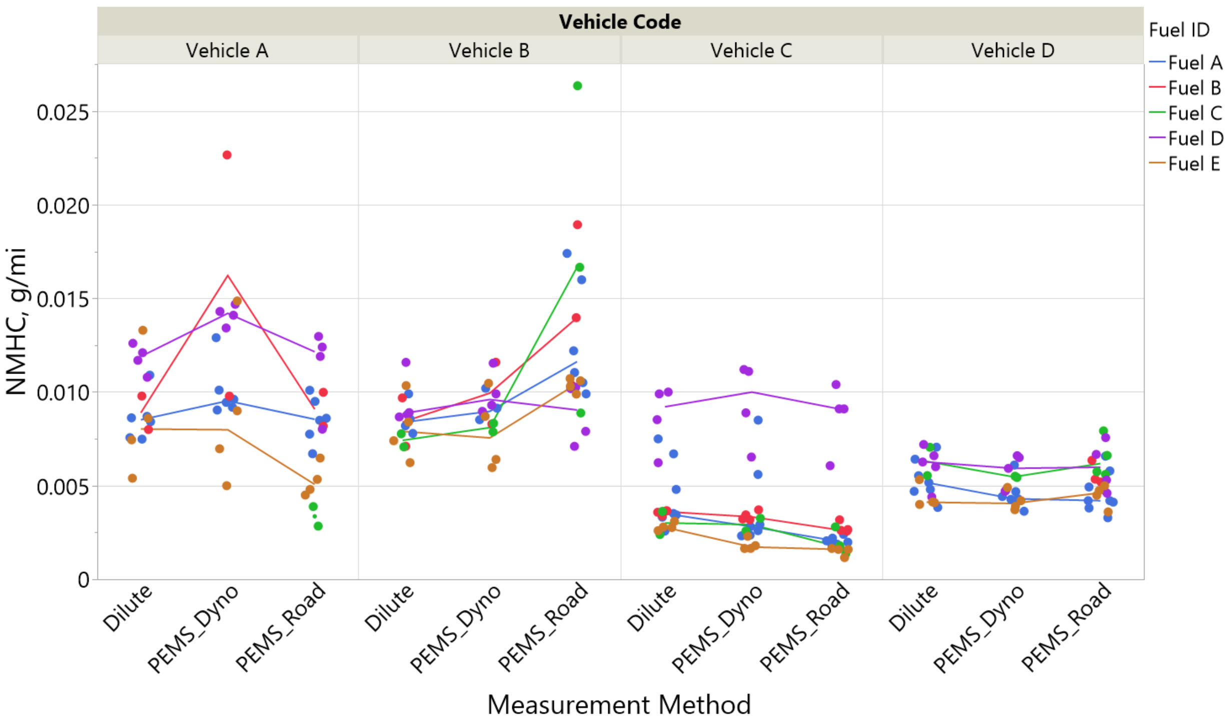


FIGURE 123. RAW DATA PLOT OF NMHC (G/MI) BY METHOD AND VEHICLE, COLORED BY FUEL

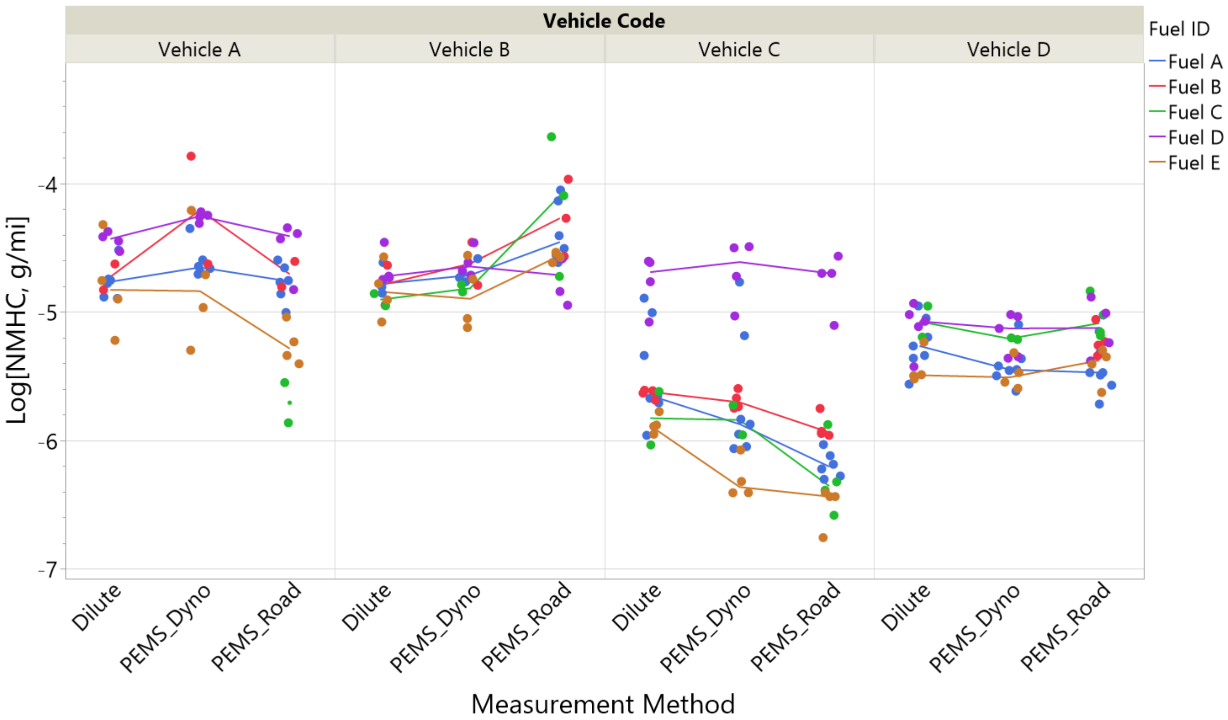


FIGURE 124. RAW DATA PLOT OF LN (NMHC) BY METHOD AND VEHICLE, COLORED BY FUEL

Drift Check

There was high set-to-set variation, but no drift observed for NMHC.

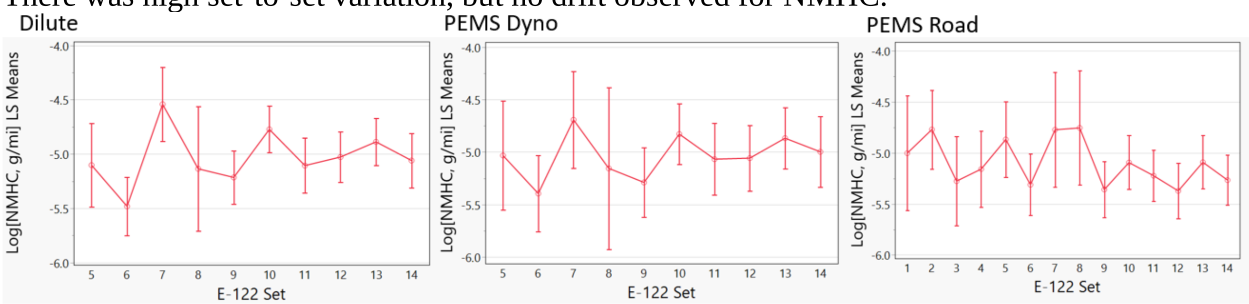


FIGURE 125. NMHC TEST SET LEAST SQUARES (LS) MEANS FOR DRIFT CHECK

Set-to-Set Variability Test

TABLE 47. NMHC SET-TO-SET VARIANCE COMPONENT TEST BY METHOD AND VEHICLE

Vehicle A

Dilute — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.1703853	0.0069528	-0.035909	0.049815	0.7505	14.558
Residual		0.0408063	0.0186176	0.1497665		85.442
Total		0.0477591	0.0229934	0.1522655		100.000

PEMS Dyno — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.230147	-0.024402	-0.08976	0.0409551	0.4643	0.000
Residual		0.1060292	0.048375	0.3891459		100.000
Total		0.1060292	0.048375	0.3891459		100.000

PEMS Road — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.2706685	0.0071077	-0.023451	0.0376664	0.6485	21.301
Residual		0.02626	0.012424	0.0875206		78.699
Total		0.0333677	0.0158712	0.1096975		100.000

Vehicle B

Dilute — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.365745	-0.01157	-0.028494	0.0053548	0.1803	0.000
Residual		0.0316331	0.0144323	0.116099		100.000
Total		0.0316331	0.0144323	0.116099		100.000

PEMS Dyno — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.449517	-0.017403	-0.03663	0.0018231	0.0760	0.000
Residual		0.0387154	0.0176636	0.1420925		100.000
Total		0.0387154	0.0176636	0.1420925		100.000

PEMS Road — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	1.1402274	0.0507981	-0.047066	0.1486621	0.3090	53.276
Residual		0.0445508	0.0205204	0.159341		46.724
Total		0.0953489	0.0438654	0.3421382		100.000

Vehicle C

Dilute — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	2.4426492	0.064305	-0.029031	0.1576409	0.1769	70.953
Residual		0.0263259	0.0133215	0.074429		29.047
Total		0.090631	0.0398064	0.3702962		100.000

PEMS Dyno — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.6753962	0.0517365	-0.054331	0.1578038	0.3391	40.313
Residual		0.0766016	0.0391114	0.2121326		59.687
Total		0.1283381	0.0629056	0.3914192		100.000

PEMS Road — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.405304	0.0109877	-0.019006	0.0409813	0.4728	28.841
Residual		0.0271098	0.0136043	0.0781519		71.159
Total		0.0380975	0.0197655	0.1017507		100.000

Vehicle D

Dilute — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.6031797	0.0148103	-0.027647	0.0572672	0.4942	37.624
Residual		0.0245537	0.0111932	0.0903202		62.376
Total		0.0393641	0.0179672	0.1443054		100.000

PEMS Dyno — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	-0.179813	-0.004516	-0.021549	0.0125177	0.6033	0.000
Residual		0.0251144	0.0116643	0.087853		100.000
Total		0.0251144	0.0116643	0.087853		100.000

PEMS Road — REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	2.013492	0.0294943	-0.009521	0.0685096	0.1384	66.816
Residual		0.0146483	0.0075324	0.0399156		33.184
Total		0.0441426	0.0214455	0.1375978		100.000

PEMS Accuracy (Bias) Tables

TABLE 48. PEMS BIAS ESTIMATES FOR NMHC

Median Bias,

$Ln(NMHC)\ Delta,$
$PEMS_{Dyno} - Dilute$

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	0.1525	0.0926	0.1937
Vehicle B	0.0537	0.0233	0.0865
Vehicle C	-0.0937	-0.2272	0.0035
Vehicle D	-0.0939	-0.1485	-0.0423

Bias back-transformed to NMHC, g/mi

Vehicle	Median Dilute NMHC, g/mi	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	0.0091	0.0015	0.0009	0.0020
Vehicle B	0.0084	0.0005	0.0002	0.0008
Vehicle C	0.0038	-0.0003	-0.0008	0.0000
Vehicle D	0.0054	-0.0005	-0.0007	-0.0002

Median Bias Relative to Median NMHC

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	16.47%	9.70%	21.37%
Vehicle B	5.52%	2.36%	9.04%
Vehicle C	-8.94%	-20.32%	0.35%
Vehicle D	-8.96%	-13.80%	-4.14%

Plots of the Quantiles of the Empirical Distribution of Delta and % Delta for all Pairwise Differences, PEMS_Road-Dilute and Dilute-Dilute

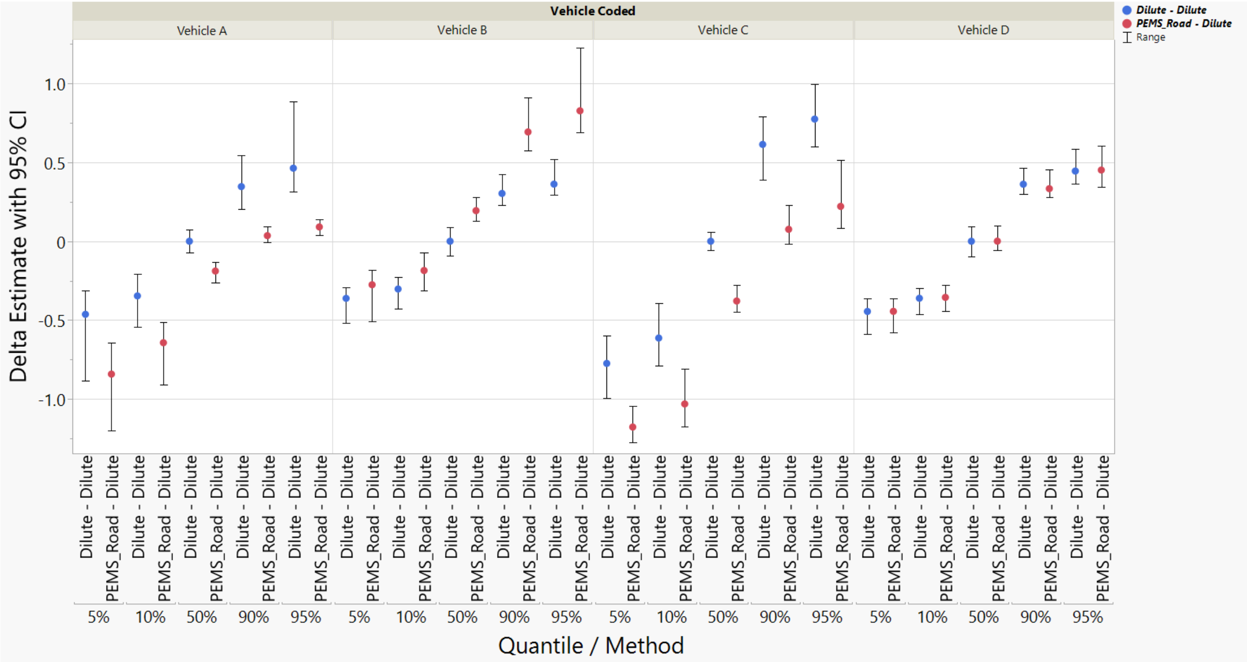


FIGURE 126. QUANTILES OF DELTA NMHC WITH 95% CONFIDENCE INTERVALS

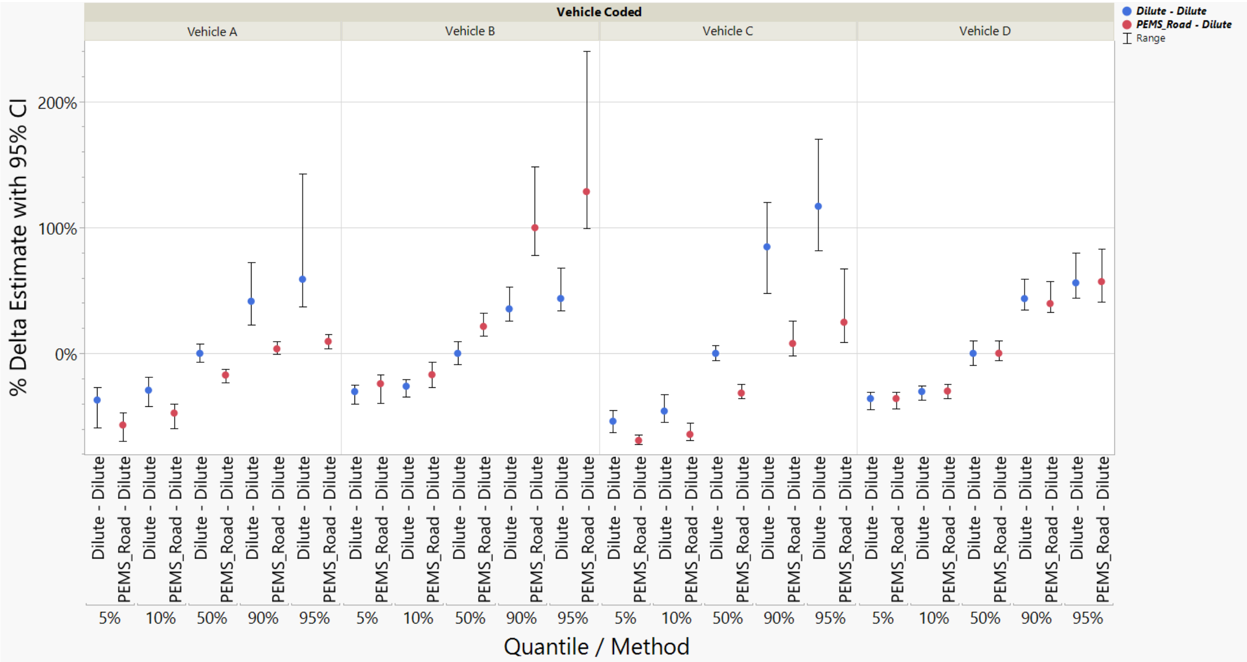


FIGURE 127. QUANTILES OF % DELTA NMHC WITH 95% CONFIDENCE INTERVALS

Plot Vs. Fuel PMI and Fuel RVP

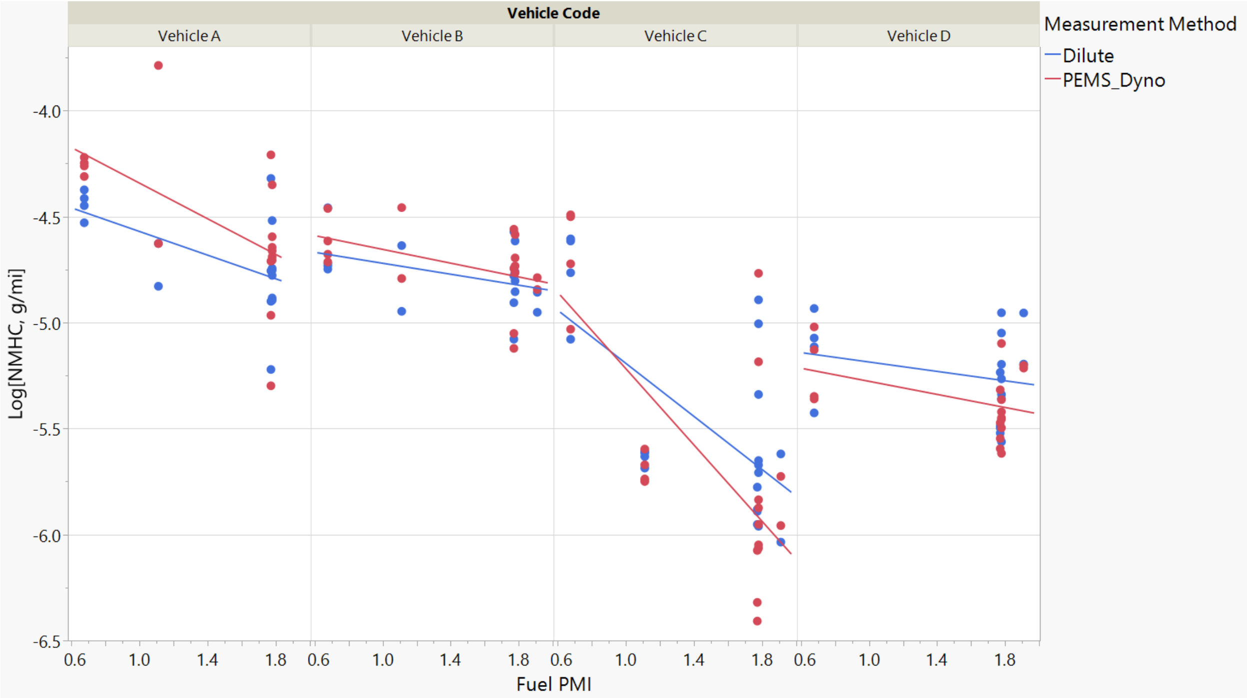


FIGURE 128. LN (NMHC) VS. FUEL PMI, COLORED BY METHOD

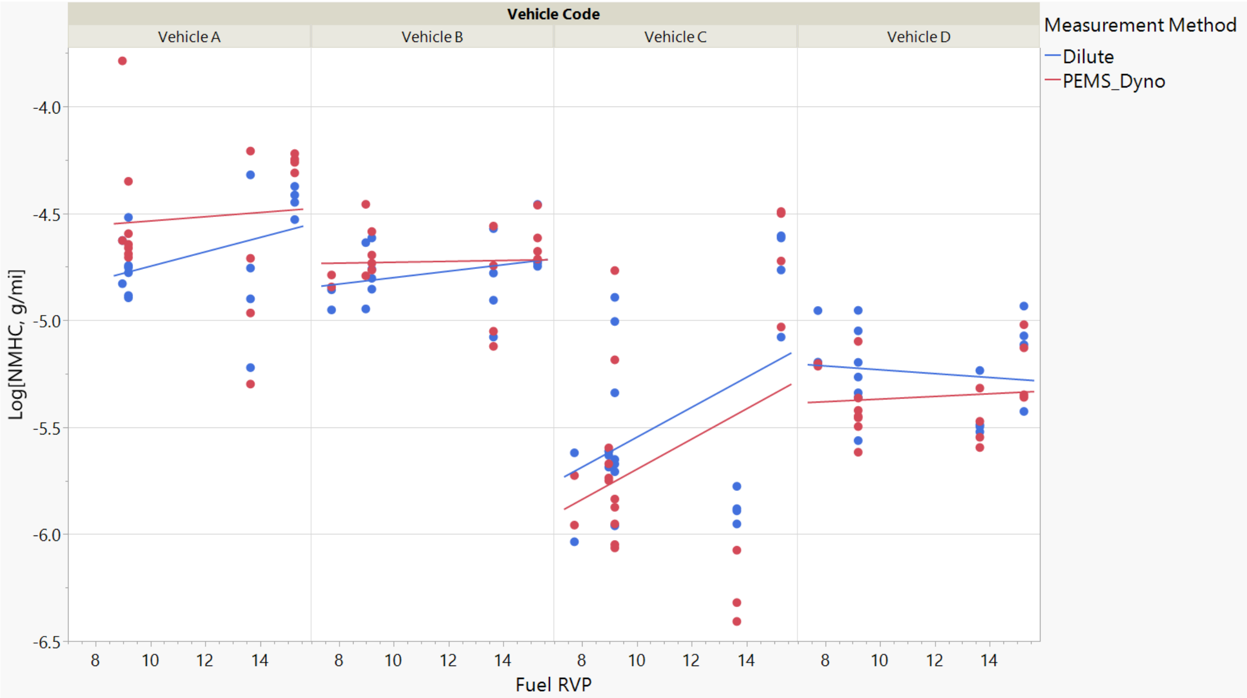


FIGURE 129. LN (NMHC) VS. FUEL RVP, COLORED BY METHOD

G.7 CO

Raw Data Plots by Method and Vehicle, Colored by Fuel

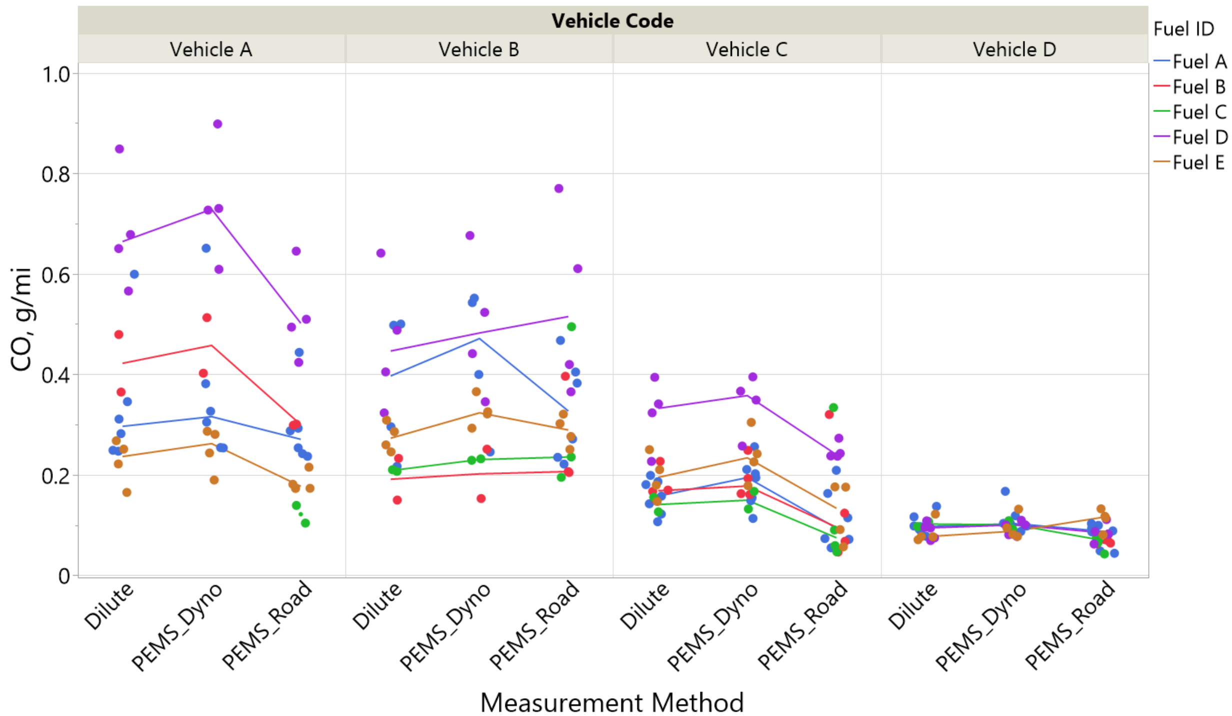


FIGURE 130. RAW DATA PLOT OF CO (G/MI) BY METHOD AND VEHICLE, COLORED BY FUEL

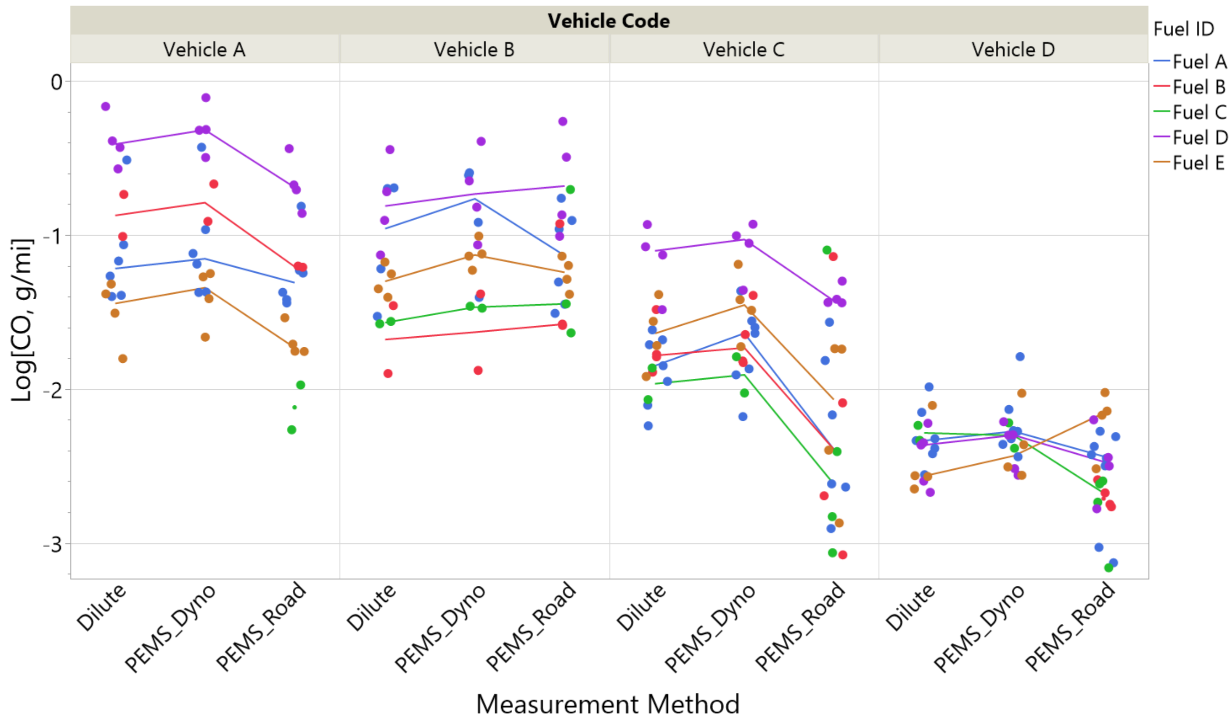


FIGURE 131. RAW DATA PLOT OF LN (CO) BY METHOD AND VEHICLE, COLORED BY FUEL

Drift Check

No drift observed with CO.

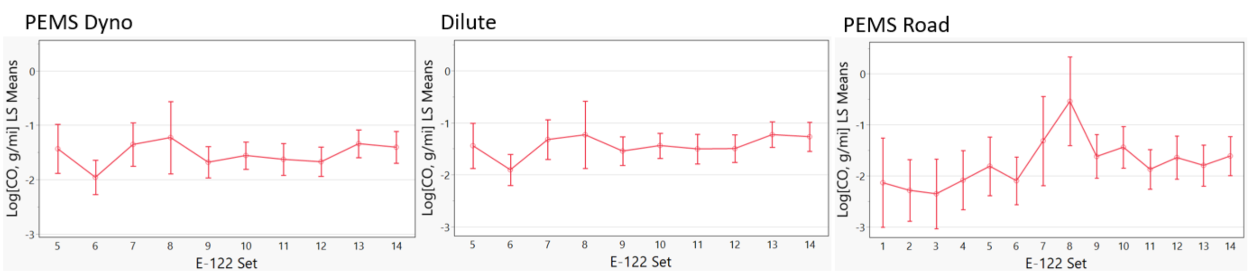


FIGURE 132. CO TEST SET LEAST SQUARES (LS) MEANS FOR DRIFT CHECK

Set-to-Set Variability Test

TABLE 49. CO SET-TO-SET VARIANCE COMPONENT TEST BY METHOD

Dilute

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.8108342	0.0199342	-0.002417	0.0422853	0.0805	44.777
Residual		0.0245848	0.0161634	0.0418733		55.223
Total		0.0445189	0.0283177	0.0800666		100.000

PEMS Dyno

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.1505068	0.009639	-0.018762	0.0380403	0.5059	13.082
Residual		0.0640439	0.0425506	0.1072616		86.918
Total		0.0736829	0.0499591	0.1195325		100.000

PEMS Road

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	95% Lower	95% Upper	Wald p-Value	Pct of Total
Vehicle-Fuel Set	0.6253043	0.0172386	-0.005968	0.0404455	0.1454	38.473
Residual		0.0275684	0.017829	0.0482313		61.527
Total		0.044807	0.028348	0.0813199		100.000

PEMS Accuracy (Bias) Tables

TABLE 50. PEMS BIAS ESTIMATES FOR CO

Median Bias,

$Ln(CO)\ Delta,$
$PEMS_{Dyno} - Dilute$

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	0.0789	0.0629	0.0956
Vehicle B	0.0994	0.0784	0.1402
Vehicle C	0.1075	0.0680	0.1623
Vehicle D	0.0631	0.0359	0.0979

Bias back-transformed to CO, g/mi

Vehicle	Median Dilute FE, mpg	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	0.3424	0.0281	0.0222	0.0344
Vehicle B	0.2914	0.0305	0.0238	0.0439
Vehicle C	0.1807	0.0205	0.0127	0.0318
Vehicle D	0.0929	0.0060	0.0034	0.0096

Median Bias Relative to Median CO

Vehicle	PEMS Bias Estimate	Lower 95%	Upper 95%
Vehicle A	8.21%	6.49%	10.03%
Vehicle B	10.45%	8.16%	15.05%
Vehicle C	11.35%	7.04%	17.62%
Vehicle D	6.51%	3.66%	10.29%

Plots of the Quantiles of the Empirical Distribution of Delta and % Delta for all Pairwise Differences, PEMS_Road-Dilute and Dilute-Dilute

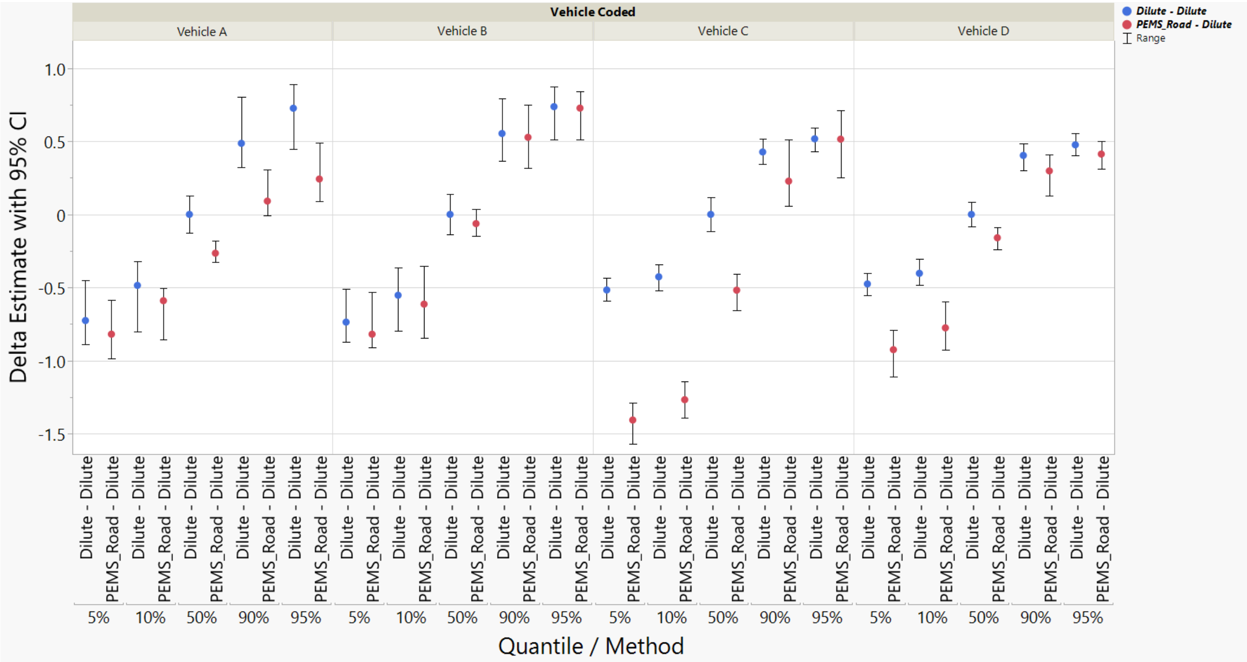


FIGURE 133. QUANTILES OF DELTA CO WITH 95% CONFIDENCE INTERVALS

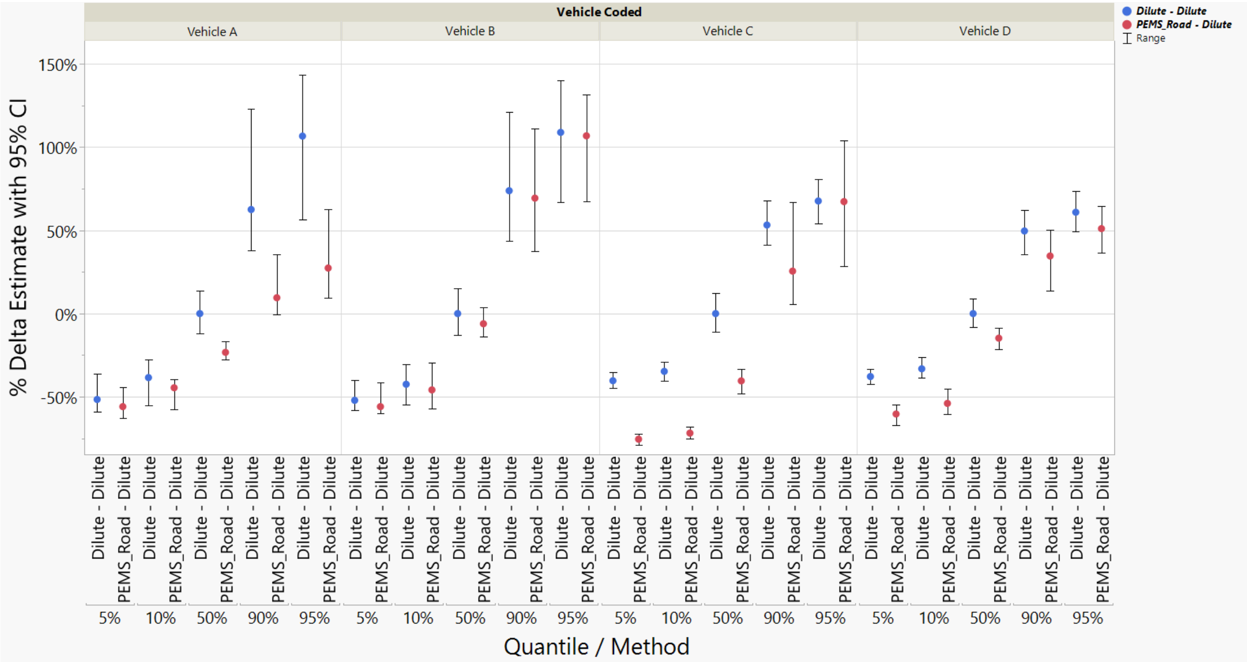


FIGURE 134. QUANTILES OF % DELTA CO WITH 95% CONFIDENCE INTERVALS

Plot Vs. Fuel PMI and Fuel RVP

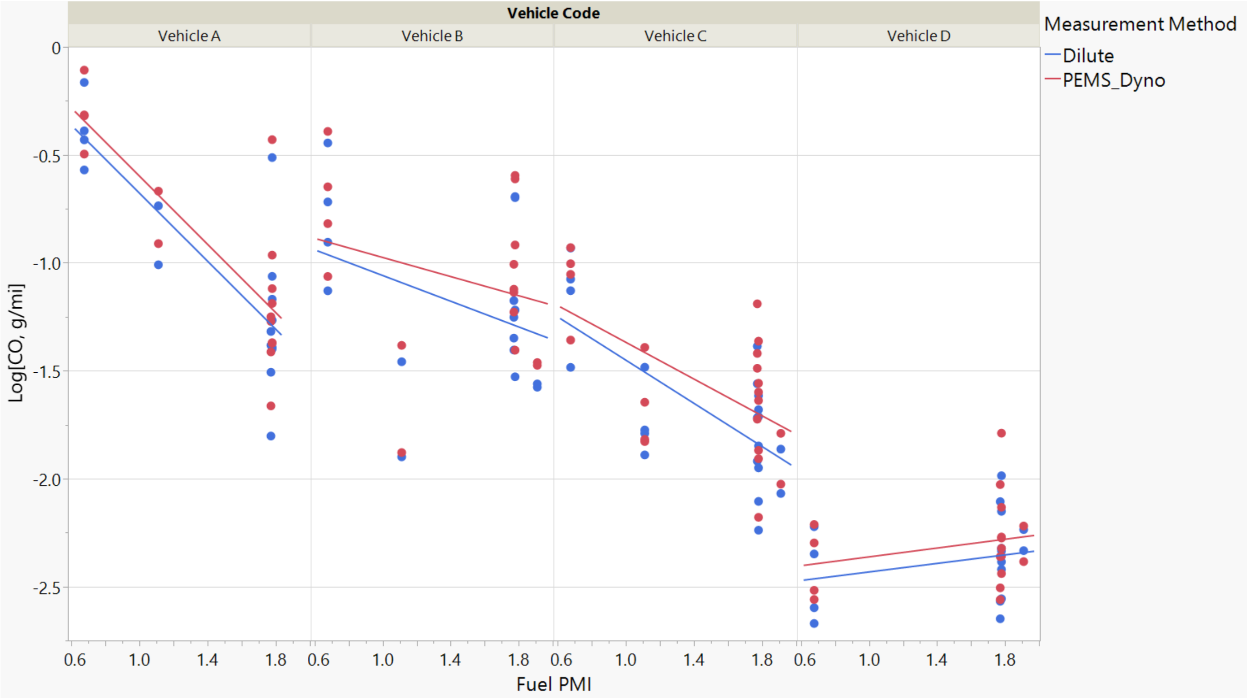


FIGURE 135. LN (CO) VS. FUEL PMI, COLORED BY METHOD

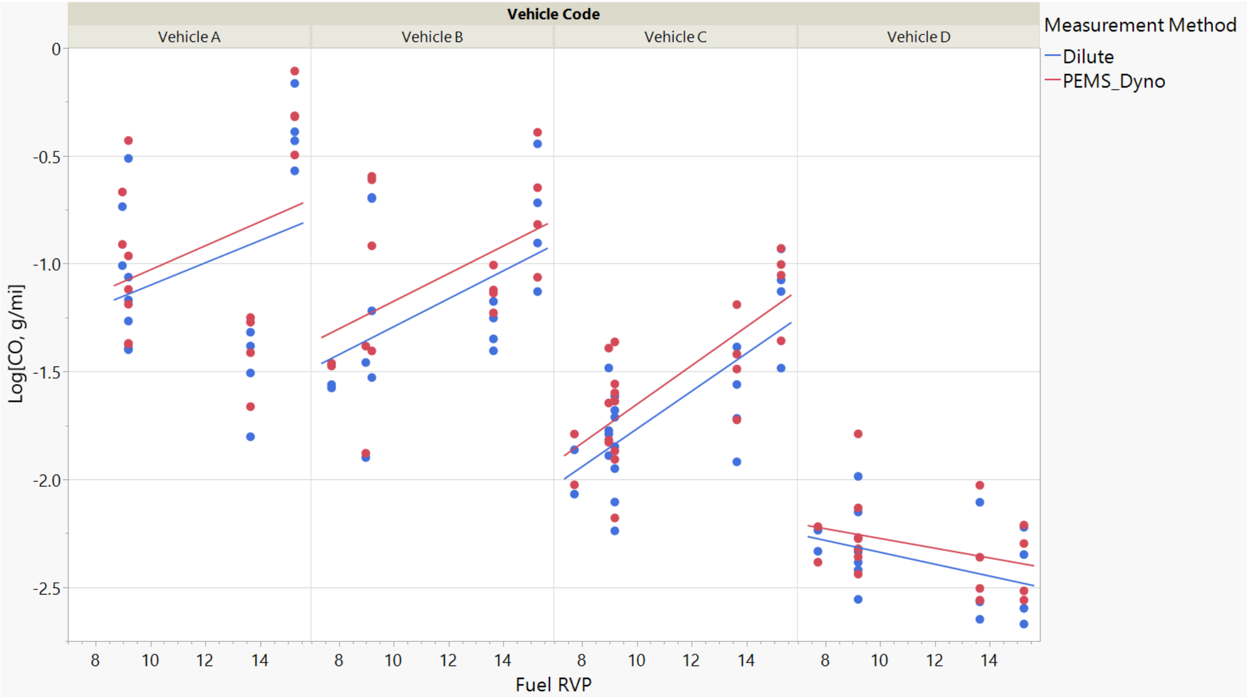


FIGURE 136. LN (CO) VS. FUEL RVP, COLORED BY METHOD