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PEMS PHASE 3- ALTITUDE, TEMPERATURE AND GRADE EFFECTS

Final Report

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COORDINATING RESEARCH COUNCIL, INC.
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CRC E-134 Final Report

Light Duty PEMS Phase 3: PEMS Performance at Altitude, Grade and Low Temperature Test Program

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List of Acronyms

Acronym	Definition
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CFV	Critical Flow Venturi
CH4	Methane
CI	Confidence Interval
CO	Carbon Monoxide
CO2	Carbon Dioxide
CRC	Coordinating Research Council
CVS	Constant Volume Sampling
DTC	Diagnostic Trouble Code
EFM	Exhaust Flow Meter
EPA	Environmental Protection Agency
ESS	Engine Stop-Start
FID	Flame Ionization Detector
FTP	Federal Test Procedure
GPS	Global Positioning System
HFEDS	Highway Fuel Economy Driving Schedule
HVAC	Heating, Ventilation, and Air Conditioning
LS	Least Squares
MSS	Micro Soot Sensor
NDUV	Non-dispersive Ultraviolet
NMHC	Nonmethane hydrocarbons
NMOG	Non-Methane Organic Gas
NO	Nitric Oxide
NO2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
OBD	On-Board Diagnostic
OEM	original equipment manufacturer
PEMS	Portable Emissions Measurement System
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
PMI	Particulate Matter Index
PTFE	polytetrafluoroethylene
RMSE	Root Mean Square Error
RWC	Real-World Cycle
SCS	Sample Conditioning System
SOC	State of Charge
SwRI	Southwest Research Institute
THC	Total Hydrocarbons
UDDS	Urban Dynamometer Driving Schedule

1 Executive Summary

Coordinating Research Council (CRC) project E-134 focused on the assessment of Portable Emissions Measurement System (PEMS) performance relative to conventional Constant Volume Sampling (CVS) system performance. The unique aspect of the project was to perform this assessment under more severe environmental conditions, namely: steep grades, high altitude, and wintertime ambient temperatures. Two market winter fuels, a low- and high- Particulate Matter Index (PMI) fuel, 0.53 and 1.76 respectively, were used throughout the program on four different test vehicles, Vehicle A, C, D, and E, with varying engine technologies. The program was conducted by 44 Energy in collaboration with Southwest Research Institute (SwRI) and TRP Laboratories. The testing was conducted in Aurora Colorado during Winter and early-Spring months. Emissions measurements included carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x), total hydrocarbons (THC), and particulate matter (PM).

An on-road test route was developed to include city, highway, and rural driving conditions with road grades up to 5%. The test route was one way (point A-to-B) with a total test time of approximately 44 minutes. The route was designed to limit the number of left turns and yields in order to prevent excessive road-testing variability; total route idle time was approximately 7%. Speed and grade profiles were defined to be representative of the on-road test route and were used to complete the chassis dynamometer emissions testing. A total of 130 official emissions tests were completed for the program: four vehicles, two test fuels, road and dyno test environment, and eight tests per combination.[1]

Key topics of analysis were PEMS repeatability, accuracy, and sensitivity to fuel changes, all relative to similar assessments for the CVS system. Three of the four test vehicles, Vehicle A, C and D, were also used in the predecessor CRC E-122-2 program which focused on the same key analysis topics with tests conducted under more “normal” environmental conditions. Thus, comparisons were made to the E-122-2 project where it is possible to help assess the impact of the more severe conditions in E-134.

Test variability for both the CVS and PEMS systems was assessed on the chassis dynamometer; in addition, PEMS variability was assessed for road conditions. Both CO_2 and fuel economy results were observed to be more variable during road testing, unsurprisingly; similar observations were made in E-122-2. NO_x variability was generally consistent across all test conditions except for Vehicle A which produced much more variable NO_x results during road testing relative to testing on the chassis dynamometer. The source of the on-road variability for Vehicle A was attributed to the NO_x emissions during high speed/load driving conditions. Similar NO_x road-testing variability for this vehicle was observed in the E-122-2 program.

PM variability was observed to be significantly higher in E-134 than E-122-2, particularly during road-testing. For CO results, the three common vehicles across programs demonstrated a large decrease in PEMS road variability relative to both PEMS chassis dynamometer results in E-134 and PEMS road results in E-122-2. The difference was most notable for Vehicle A. This unique variability-related result triggered an investigation which revealed a moderate correlation between CO emissions and driver behavior. Smoother accelerations and decelerations for E-134 road-testing likely contributed to this observed difference in CO emissions.

[1] Two additional tests were completed and included in all relevant analysis. These two tests were intended “make-up” tests. The corresponding original tests intended for replacement ended up being validated after the “make-ups” were completed.

The PEMS accuracy assessment was broken into two components. First was an assessment of PEMS instrument bias which was conducted by comparing measurements taken simultaneously with the PEMS unit and the CVS for chassis dynamometer tests. The CVS result is taken to be the gold standard "true" value, and any difference in results seen on the PEMS for an identical test is taken to be a "PEMS Instrument Bias." The second assessment focused on additional road bias, attributed to factors such as environmental differences, traffic, or additional test weight, by comparing the PEMS average emissions measurements taken on the road to the PEMS average emissions measurements for the chassis dynamometer. Because the same PEMS instrument is used for both road testing and chassis dynamometer testing, this "Road Factor Bias" estimate is completely independent of the previous instrument bias estimate. The two independent bias estimates are summarized for each vehicle and emissions parameter below in Table 1-1 for E-134. For comparison, estimates based on the stated bias in E-122-2 are given in Table 1-2. An example baseline value is given in both tables because the biases are dependent on the level of emissions. This baseline value is the median CVS dyno value observed in E-134 and is therefore a representative level to use for comparison. The percentage bias values shown are only applicable at the median emissions level shown and are independent of the other adjacent bias estimate. Therefore, the biases in the table are not meant to be applied consecutively, though for log-transformed parameters, this would be an acceptable application. Negative biases are highlighted in red, indicating the PEMS would measure a smaller value, while positive biases are highlighted in blue, indicating the PEMS would measure a larger value.

Table 1-1: PEMS Bias for E-134

	Vehicle A			Vehicle C			Vehicle D			Vehicle E		
	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias
PM (mg/mi)	0.461	-32%	-72%	0.131	-	-49%	0.355	-49%	-49%	0.823	-15%	-23%
THC (g/mi)	0.0529	+18%	-9%	0.0142	-	-	0.0241	+20%	+4%	0.0337	+8%	+7%
CO (g/mi)	0.715	-6%	-38%	0.278	-	-28%	0.142	-11%	-10%	0.212	-	-13%
CO2 (g/mi)	339	+2.2%	+5.9%	338	-	-2.3%	100	-1.5%	+12.7%	253	+1.8%	+8.3%
NOx (g/mi)	0.0097	+20%	+86%	0.0054	+20%	-51%	0.0021	+11%	-37%	0.0095	+10%	-

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

Table 1-2: PEMS Bias for E-122-2

	Vehicle A			Vehicle C			Vehicle D		
	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias
PM (mg/mi)	0.461	-34%	-	0.131	-45%	-21%	0.355	-22%	-18%
THC (g/mi)	0.0529	-20%	-13%	0.0142	-27%	-33%	0.0241	-29%	-
CO (g/mi)	0.715	+8%	-23%	0.278	+11%	-40%	0.142	+7%	-15%
CO2 (g/mi)	339	+8.7%	+5.6%	338	+10.5%	+1.2%	100	+9.4%	+15.7%
NOx (g/mi)	0.0097	+30%	-17%	0.0054	+24%	-8%	0.0021	+11%	-41%

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

The tables indicate that the PEMS instrument bias, based on chassis dynamometer data, did not stay consistent between programs. However, the PEMS instrument bias tended to be consistent across vehicles in both programs. Therefore, the bias differences across programs may simply be attributable to the multiple years between each program being conducted.

Road factor bias was observed in almost all cases. Interestingly, this road bias tended to be much more similar across projects with a few particularly consistent road tests biases. This includes a negative PM and CO bias for all vehicles except PM for Vehicle A in E-122-2. There is also a consistent positive CO_2 bias, which is seen by all vehicles in both programs, with the exception of Vehicle C in E-134. It was also observed that the road biases tended to be larger in magnitude for E-134, particularly for PM.

Finally, PEMS sensitivity to fuel and fuel property changes was assessed. First it is noted that both CVS and PEMS results for all four test vehicles demonstrated higher PM emissions with the higher PMI fuel relative to the lower PMI fuel. The magnitude of difference in PM varied from vehicle to vehicle, but was consistent across measurement methods, with the only exception being Vehicle A PEMS road tests, which showed a much smaller difference between fuels than what was observed with CVS dyno or PEMS dyno testing. The difference in PM emissions also appeared to be greater in this program relative to E-122-2 which used a similar variety of low- and high-PMI fuels.

The conclusion for the fuel property sensitivity analysis was that the PEMS responds very similarly to changes in test fuel compared to the CVS system. Other relevant observations noted during the fuel sensitivity study for gaseous emissions included:

THC

- There were observed discrepancies in the correlation between THC and higher PMI fuels across programs. For example, the correlation between THC emissions and PMI for Vehicle C was inversely proportional in E-134 for but directionally proportional in E-122-2. This indicates that PMI is likely not a key factor in THC emissions.

CO

- Vehicles A and C both produced lower CO emissions with higher PMI fuels in both programs, but Vehicle D saw an increase in CO with higher PMI fuels which was not consistent with E-122-2 observations. No change in CO was observed with Vehicle E when switching fuels.

CO_2

- All vehicles saw directionally higher CO_2 at a marginal significance level (some models slightly yes, some slightly no) with the higher PMI fuel. Vehicle A saw the largest difference, with an estimated 13 g/mi to 26 g/mi difference between fuels, while the other three vehicles were estimated to produce only up to 10 g/mi more CO_2 with the higher PMI fuel.

NO_x

- No differences observed between fuels for any vehicles. This aligns with E-122-2.

Overall, results tended to be consistent across the E-134 and E-122-2 programs which suggests that steep grades, high altitude, and winter-time ambient temperatures may not impact the PEMS or CVS measurement variability, accuracy, or sensitivity to fuel property differences. However, it is worthwhile to consider that the individual impacts of each test condition are indistinguishable in the results. Furthermore, it is notable that PM measurements were more variable with both the CVS and the PEMS in E-134. This variability assessment is irrespective of PM emissions levels and the test fuels that were used. Therefore, this unique result may be related to the difference in environmental conditions across programs.

Key lessons learned throughout the project are discussed below:

- Development of a one-way test route introduced a few calibration issues during the start of on-road testing. It is recommended that future programs involving on-road PEMS testing employ routes that start and end at the same location. Or, if this is not possible/feasible, it is recommended that the test protocol be designed to allow PEMS start and end calibrations to be performed with the same set of gas cylinders.

- Wintertime test conditions naturally involved ambient temperatures near or below freezing with road conditions that were wet, slushy, and snowy: an unavoidable source of variability. The combination of these conditions results in “kick up” which would wet the equipment mounted on the rear of the vehicle. The wet equipment was then prone to freezing over. Although most of the equipment is sheltered from this effect, some components such as the ambient weather probe were exposed. Precautions should be taken in the future to protect all equipment either by sheltering it or adjusting the location of the equipment such as moving the equipment inside of the vehicle if possible/feasible.

- Variability in driver behavior was identified to impact emissions test results on the chassis dynamometer. This could potentially have been avoided by using the same driver for both chassis dynamometer and road tests. Another method to avoid this additional variability is to identify a drive metric to quantify driver behavior and apply it during the test validation process: the average of accelerator pedal position cubed was analyzed in E-134 to identify outlying behavior.

2 Introduction

Since the European Union has adopted the use of PEMS for their regulatory assessment of light-duty real-world emissions compliance, there has been a growing interest in PEMS among the US regulatory agencies. The Environmental Protection Agency (EPA) and California Air Resources Board (CARB) are conducting PEMS studies with light-duty vehicles to assess the viability of incorporating PEMS into the current regulatory test procedures. Other organizations have conducted correlative testing between PEMS and CVS, which has been adopted worldwide as the measurement methodology for chassis dynamometer regulatory emissions testing. However, these correlative studies are mostly limited to test conditions representative of vehicle operation at zero grade, sea level, and moderate ambient temperatures. This project seeks to evaluate the performance of PEMS vis-a-vis chassis dynamometer-based tests for measuring emissions from light-duty vehicles representative of a range of gasoline engine technologies, using a matrix of fuels representative of a range of properties, and operating under severe test conditions including high altitude, steep grades, and low temperatures.

PEMS was used to assess the emissions performance of four selected project vehicles over a unique on-road drive cycle incorporating urban, rural, and highway driving at altitude over steep grades and under wintertime ambient temperatures. The vehicles were also driven over the same drive cycle on a chassis dynamometer where emissions measurements were made using both PEMS and CVS systems. Emissions measurements included CO_2, CO, NO_x, THC, and PM. Two different market winter fuels, a low and high PMI, were tested in both on-road and chassis dynamometer conditions.

Project objectives included:

- Determine and compare the repeatability of the CVS system and PEMS during chassis roll testing.
- Determine repeatability and accuracy of PEMS unit under real on-road driving conditions.
- Determine if PEMS unit can detect differences in PMI of fuel as measured by gaseous and PM emissions.
- Determine how exhaust flow measurement from the individual PEMS system correlates with the direct vehicle exhaust flow meter from the test cell and with the CVS bags based on CO2.

A virtual project kickoff meeting was held on October 19th, 2023. Official testing began in January of 2024 and was completed in July of 2024.

3 Testing Methodology

3.1 Vehicles

Four vehicles were selected for this project: three which were carried over from the predecessor CRC E-122 Phase 2 project and one which was recently purchased and provided by CRC. The vehicles span a variety of common engine technologies which are shown below in Table 3-1. Because there may be reason to compare results between the two projects, the naming conventions have been maintained (Vehicle B from the predecessor project was not carried over and Vehicle E was added instead). Vehicle D was the only plug-in hybrid electric vehicle (PHEV). Vehicle E was a newer model year and was received with relatively lower mileage. Vehicle E was also the only test car with direct fuel injection and a turbo charger.

Table 3-1: Test Vehicle Specifications

Vehicle Identifier	A	C	D	E
Model year	2019	2019	2019	2021
Engine Type	PFI NA	PFI NA	PFI NA	DI Turbo
EPA Certification Standard	Tier 3 Bin 125	Tier 3 Bin 30	Tier 3 Bin 30	Tier 3 Bin 70
Exhaust Control Systems[2]	2TWC (2), 2WR-HO2S, 2HO2S, SFI	2HO2S (2), SFI, 2TWC, EGR, EGRC	SFI, EGR, EGRC, WR-HO2S, TWC (2), HO2S	DFI, WR-B02S, BO2S, WU-TWC, TWC, TC, CAC, EGR, EGRC
Engine Stop Start (ESS)	No	Yes	No	No
Fuel Tank Capacity (gal.)	19	19	11.4	14.8
ETW (lbs)	4750	4750	3625	3625
Target A (lbs)	26.79	38.24	18.816	26.961
Target B (lbs/mph)	0.6021	0.2803	0.38689	0.27033
Target C (lbs/mph^2)	0.0166	0.02328	0.012501	0.017815
Set A (lbs)	3.34	25.87	7.62	8.77
Set B (lbs/mph)	0.5355	0.03124	0.03608	0.2284
Set C (lbs/mph^2)	0.01519	0.02419	0.01627	0.01702
Received Mileage (mi)	9353.7	11468	9508	4940

3.1.1 Vehicle Check-in and Modifications

Vehicles A, C, and E were delivered to TRP Laboratories on 10/31/2023 while Vehicle D was delivered to TRP Laboratories on 11/20/2023 to allow a previous study to finish defining an appropriate state of charge (SOC) procedure. The SOC procedure was developed to balance the engine on/off time in Vehicle D. In a previous project it was observed that there was high variability in emissions results for Vehicle D and it was theorized that this was due to the engine on time being a small fraction of the emissions tests. By having a more appropriate balance of engine on/off time, this project seeks to reduce the variability in emissions results for Vehicle D.

Upon arrival, each vehicle received an On-Board Diagnostic (OBD) scan, oil and filter change, road-load derivation, and mileage accumulation. The OBD scan for Vehicle C reported an implausible wheel speed sensor diagnostic trouble code (DTC) and a physical inspection of the wheel speed sensor showed that a previous project attempted to splice into the wire harness to allow the vehicle to operate on a chassis dynamometer. For Vehicle C, a proprietary original equipment manufacturer (OEM) software tool was used to enable and verify that a 'rolls mode' was active so that the vehicle would operate on the chassis dynamometer. As demonstrated in the following section, Vehicle C was able to be run on a chassis dynamometer and the wire harness splicing did not adversely impact the emissions performance of the

[2] TWC: Three Way Catalyst, WR: Wide-range, HO2S: Heated Oxygen Sensor, SFI: Sequential Fuel Injection, EGR: Exhaust Gas Recirculation, EGRC: Exhaust Gas Recirculation Cooler, DFI: Direct Fuel Injection, BO2S: Before Oxygen Sensor, WU: Warm-up, TC: Turbocharger, CAC: Charge Air Cooler.

vehicle, so no other adjustments were made. No issues were observed from the OBD scans for Vehicles A, D, and E.

A later investigation, during the course of testing, revealed that engine stop-start (ESS) was not active for Vehicle C due to a missing auxiliary battery. ESS was restored by cleaning up the wire harness splicing and replacing the auxiliary battery to clear existing DTCs. A single chassis dynamometer test was run with ESS active, but no significant impact to tailpipe emissions was observed relative to previously run tests with ESS inactive. Additional details can be found in APPENDIX A: Emissions Impact of Engine Stop Start Feature of Vehicle C. The CRC technical panel ultimately requested that the ESS functionality continue to be disabled for all remaining testing so that the same performance could be evaluated for the whole program. This is a deviation from the E-122-2 program where ESS was operational for Vehicle C.

Vehicles A, C, and D were previously modified with hitch receivers as part of the E-122-2 program and the PEMS equipment was fully compatible for installation. Vehicle E was a new vehicle to the PEMS testing program and was modified with a hitch receiver and exhaust tubing to connect the vehicle tailpipe to the PEMS measurement device.

3.1.2 Emissions Verification

The emission controls system of each vehicle was verified before any program testing began. A full Federal Test Procedure (FTP) was performed for each vehicle following the current Code of Federal Regulations (CFR) described in 40 CFR Part 1066. The regulated emissions CO, NOx, Non-methane Organics (NMOG), and PM were measured and compared to the appropriate certification standard so that the CRC technical panel could provide approval for program testing. Three vehicles produced emissions well below their certification standard. One vehicle, Vehicle E, initially produced elevated levels of PM above the PM emissions standard. After additional mileage accumulation it was demonstrated that the PM emissions stabilized to just below the emissions standard. However, CRC requested that TRP remove the fuel injectors, sonically clean them, and repeat the Federal Test Procedure. After the injectors were cleaned from Vehicle E, two more certification tests confirmed that the PM emissions were significantly reduced and congruent with CRC’s expectation.

After the entire testing program was completed, the certification FTP cycles were repeated on all vehicles to verify that the emissions performance had not drifted over the course of the project. The results are shown in Table 3-2 and demonstrate that the emissions performance of all four test vehicles remained consistent across the span of the project.

Table 3-2: FTP-75 Verification 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 Check-in Results	0.613	0.049	0.4
	FTP-75 Checkout Results	0.754	0.062	0.6
	FTP-75 Check-in E-122-2 Comparison	0.26	0.029	0.7
Vehicle C	EPA Tier 3 Bin 30 Certification Standard	1.0	0.03	3
	FTP-75 Check-in Results	0.324	0.015	0.3
	FTP-75 Checkout Results	0.451	0.009	0.1
	FTP-75 Check-in E-122-2 Comparison	0.334	0.005	0.6
Vehicle D	EPA Tier 3 Bin 30 Certification Standard	1.0	0.03	3
	FTP-75 Check-in Results	0.144	0.021	0.3
	FTP-75 Checkout Results	0.162	0.015	0.2
	FTP-75 Check-in E-122-2 Comparison	0.12	0.017	0.6
Vehicle E	EPA Tier 3 Bin 70 Certification Standard	1.7	0.07	3
	FTP-75 Check-in Results	0.077	0.022	2.7
	FTP-75 Results After Injector Cleaning	0.161	0.026	1.0
	FTP-75 Repeat Results After Injector Cleaning	0.185	0.027	0.9
	FTP-75 Checkout Results	0.180	0.031	0.6

3.2 Fuels

Two market winter fuels, a low- and high- PMI, were chosen for this project. Eight fuel drums of each fuel were delivered to TRP laboratories. Both fuels were stored indoors in controlled, cool conditions throughout the project. Certification fuel was also purchased for this project as used for verification procedures described in Section 3.1.2. Fuel A arrived at TRP Laboratories on 10/31/2023 and Fuel B arrived 1/8/2024.

3.2.1 Fuel Specs

All contractors were blinded to fuel specifications throughout the project's testing phase except for fuel properties required to process and calculate emissions results. Fuels analyses were conducted by CRC panel members and provided to TRP and 44 Energy for emissions calculations. These required fuel properties are shown in Table 3-3 alongside PMI which was later disclosed after testing was completed. Additional fuel properties are available in APPENDIX B: Additional Test Fuel Characteristics.

Table 3-3: Fuel Properties

Fuel ID	Relative PMI	Ethanol vol %	Carbon wt %	Hydrogen wt %	Oxygen wt %	Specific Gravity	Net Heat of Combustion BTU/lb	Sulfur ppm	PMI
Fuel A	High	10.19	82.4	13.79	3.81	0.7362	17968	5.1	1.76
Fuel B	Low	10.13	81.93	14.259	3.815	0.7316	17918	6.9	0.53

3.2.2 Fuel Swap Procedure

A fuel swap procedure was accompanied with a preconditioning sequence which prevented any carryover artifacts from contaminating the emission measurements or performance influence from fuels effects. The full fuel swap and preconditioning sequence took three days and involved multiple fuel changes, overnight soaks, catalyst cleanouts, coast downs, and transient driving on the dynamometer using the same route developed for the chassis emissions tests. The step-by-step details are listed below. Vehicle coastdown times are listed in APPENDIX C: Vehicle Coastdown Data.

- Conduct a fuel drain/fill using test fuel
- Conduct a sulfur purge on the dynamometer
- Conduct vehicle coast downs
- Conduct a 2nd and 3rd drain/fill using test fuel
- Soak vehicle overnight
- Conduct preconditioning cycles: Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Driving Schedule (HFEDS), and US06
- Soak vehicle overnight
- Conduct a cold-start LA92 2 phase preconditioning cycle
- Soak vehicle overnight
- Conduct a real-world cycle preconditioning cycle (Section 3.3)
- Soak vehicle overnight at 50°F (10°C)

3.3 Route Development

Objectives of the on-road drive route were to incorporate 1/3 urban, 1/3 rural, and 1/3 highway drive styles, 45-minute total drive time, steep grades, and operation at high altitude during winter-like climate conditions. The test route was developed in Aurora, Colorado (near Denver, Colorado) and planned to start from TRP Laboratories, the location of the chassis dynamometer lab used for this project. The time of year chosen to perform testing in this location covers the high altitude and winter-like conditions required for the drive route. Google Earth Pro and Google Maps were used as tools to draft a drive route meeting the other route requirements. Because of logistical constraints, the only steep (4+%) grades available within the boundaries of the route objectives resulted in a draft test route that ended at a different location than the start. The impacts of this design are discussed in APPENDIX D: PEMS Route End Location. The draft route is shown in Figure 3-1 with orange, red, and yellow color coding for rural, highway, and urban driving respectively.[3] Careful consideration was given to the frequency of traffic stops and there was an effort to minimize the number of left turns as there was concern regarding how these may impact the test-to-test variability of the on-road speed profile.

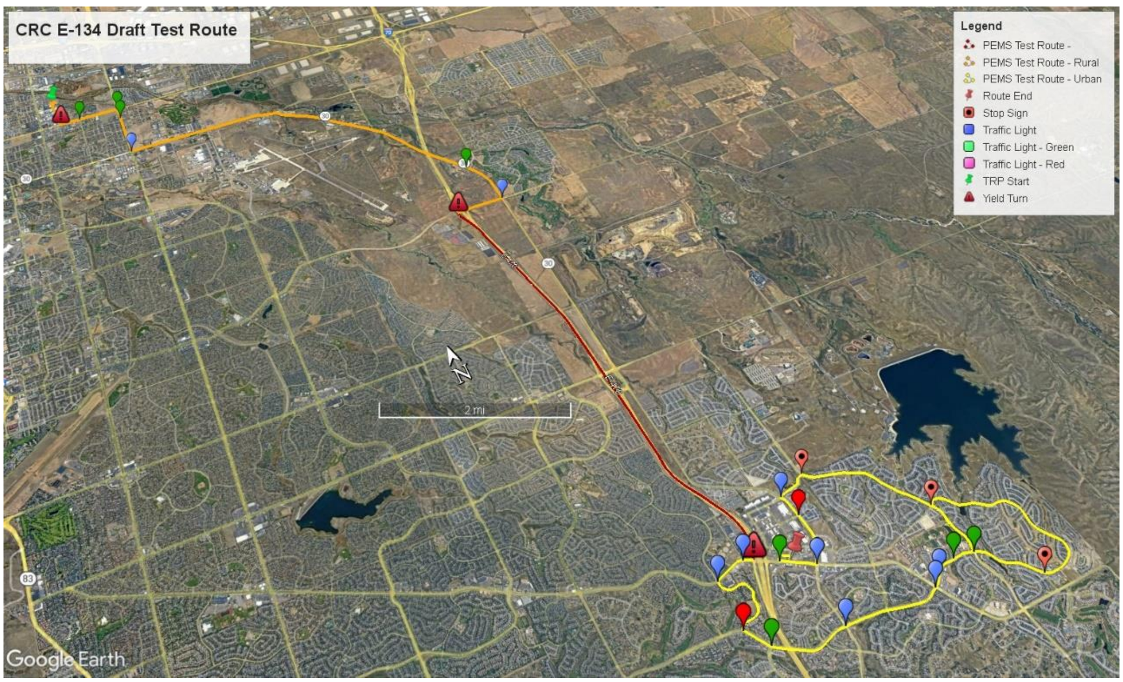

Figure 3-1: Draft Test Route

A speed and elevation profile were acquired by driving the draft route using a VBOX Racelogic global positioning system (GPS). Because of delays obtaining the test vehicles, the vehicle used for this data acquisition was a non-test vehicle. The impacts of this decision are analyzed and discussed in APPENDIX E: Chassis vs. On-road Speed Profile and Driving Behavior. After completing three runs of the draft route, it was determined that there was a consistent GPS dropout during a portion of the urban section (visualized in yellow). Figure 3-2 below expands on the extent of the GPS dropout.

[3] Note the occurrence of the figure eight urban section.

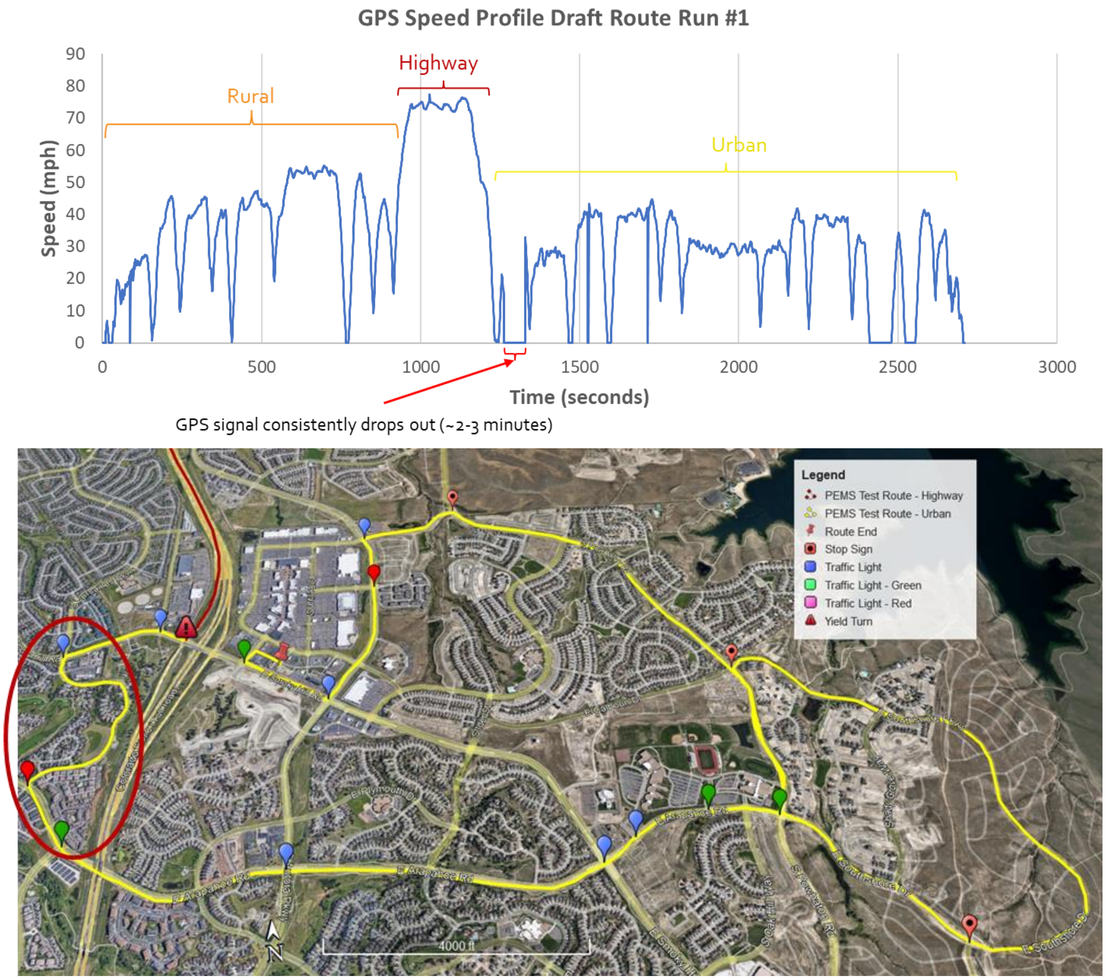

Figure 3-2: GPS Dropout During Draft Route Runs

To remedy this issue and prevent potential PEMS GPS dropouts during testing, multiple alternative routes were considered and tested. The final modification included an extension of the highway route and only a slight adjustment to the start of the urban route. This modification is shown in Figure 3-3. The final speed and grade profiles, jointly referred to as the real-world cycle (RWC), used for chassis dynamometer testing are shown in Figure 3-4. Route statistics for the three runs of the draft route and the final route are shown in Table 3-4. Additional details on data smoothing and concatenation can be found in APPENDIX F: Route Development Data Smoothing and Concatenation.

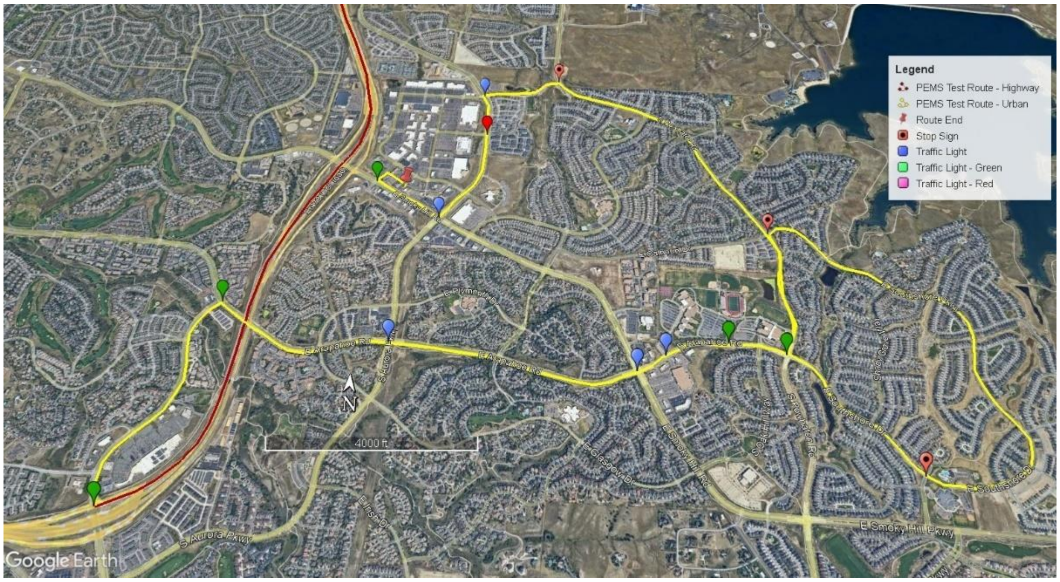

Figure 3-3: Final Test Route

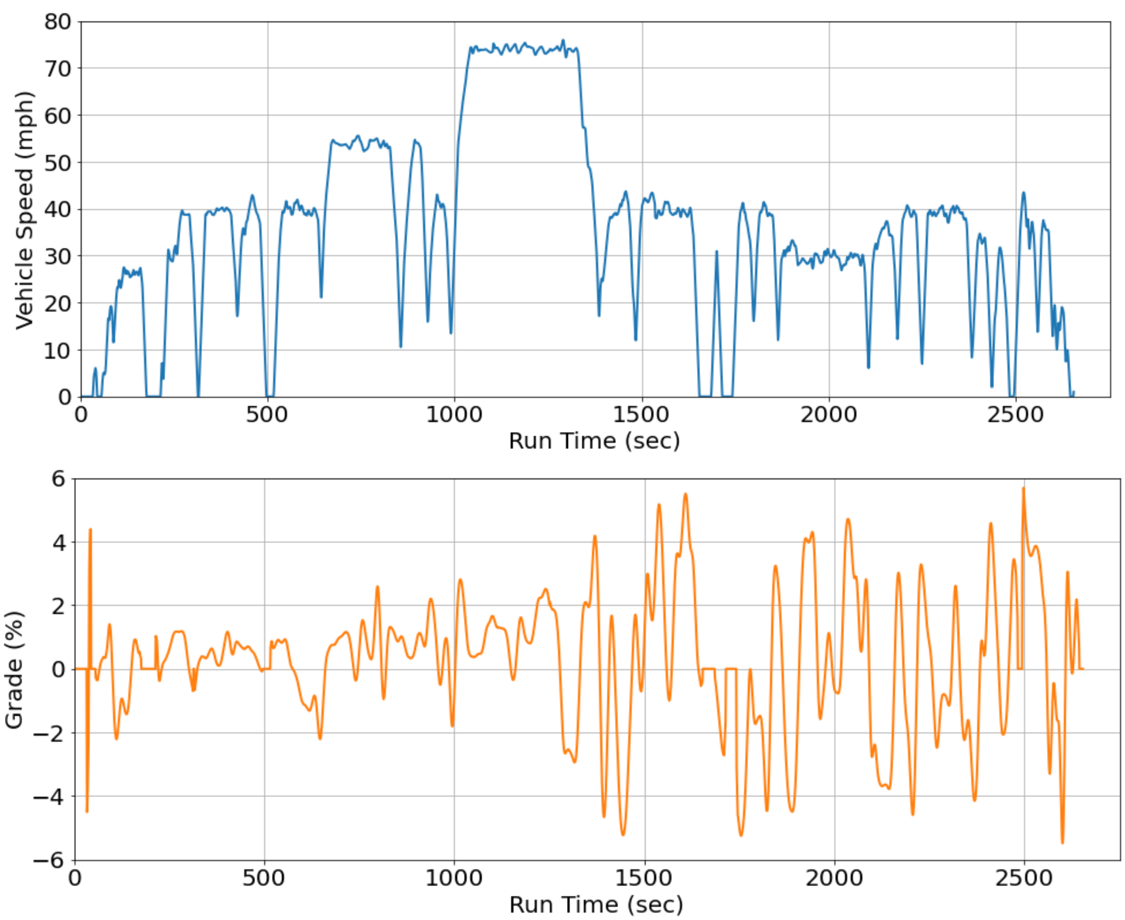

Figure 3-4: Final Speed and Grade Profiles

Table 3-4: Route Statistics[4]

	1st Run	2nd Run	3rd Run	Average	Dyno Profile
Start Time	9:33 am	9:20 am	11:24 am		
Test Duration (min/sec)	46 / 2733	46 / 2784	46 / 2781	46 / 2746	44 / 2653
Average Speed (mph)	33.7	32.4	33.5	33.2	35.5
Relative Positive Acceleration (RPA)	0.108	0.100	0.105	0.104	0.117
VAPOS (95th %)	10.6	11.9	12.3	11.6	9.3
# of Stops	9	9	9	9	7
% Idle	7.4%	11.1%	8.2%	8.9%	7.1%
Notes		Extended idle mid-test to adjust GPS			Route mod with more highway time and reduced # of stops.

All on-road PEMS tests followed the specified route with one exception. During this exception a tipped box truck caused a temporary road closure which necessitated a temporary modification to the route. The driver was able to navigate around the closure by driving down one block to the next available road which reconnected with the specified route. This temporary modification, shown in Figure 3-5, added roughly 0.5 miles to the total test distance. An analysis of this test, Vehicle A R-A-2, demonstrated that there was no significant impact on the distance weighted emissions results. During the second test of the day the box truck was removed, and the road was open.

[4] Run 1-3 statistics are calculated from raw GPS data with varying impacts from GPS connection issues. For example, because of missing data, the duration of the test and average speed suggest different total route distances. Final dyno profile statistics are not impacted by such an issue.

Figure 3-5: Box Truck Route Modification

3.4 PEMS Operation

3.4.1 PEMS Setup

The Sensors Inc. PEMS equipment used for this project was provided by CRC and was also used in the preceding phase 2 program. Major equipment items include a sample conditioning system (SCS), gas analyzer, flame ionization detector (FID), PM2 measurement system with both gravimetric filter media for cumulative measurements and Pegasor for continuous real-time measurements, exhaust flow meter (EFM), GPS, and weather probe. The system is capable of measuring and recording the following data: CO2, CO, nitric oxide (NO), nitrogen dioxide (NO2), THC, and PM concentrations, exhaust mass flow rate, ambient temperature, ambient humidity, GPS, and OBDII.

The PEMS setup includes all listed equipment mounted on a carrier rack which is then attached to a tow hitch on any of the test vehicles; this setup was adopted from the previous project as it allows the full setup to be quickly transferred between test vehicles. The setup was transported between vehicles using a portable hydraulic jack. An example of the full setup is picture below in Figure 3-6.

Figure 3-6: PEMS Setup of Hydraulic Jack

Figure 3-7: PEMS Setup Mounted on Test Vehicle

3.4.2 PEMS Maintenance and Linearity Verification

Prior to the start of testing, several PEMS issues were identified as the equipment operation was being assessed:

1. Non-dispersive ultraviolet light (NDUV) analyzer "service needed soon" warning via Sensors Inc. PEMS user interface.

2. PM2 module "loose faceplate" warning via Sensors Inc. PEMS user interface.

3. EFM 6-month 1065 calibration was expired

4. SCS 1-year 1065 calibration was expired

A new NDUV was purchased from Sensors Inc. and installed in-house in order to prevent decaying analyzer accuracy throughout the course of the project. The PM2 module was sent to Sensors Inc. and received its annual 1065 compliance certification while also having several internal pressure regulators adjusted to resolve the loose faceplate warning. The EFM and SCS were also sent to Sensors Inc. to receive 1065 compliance certifications.

The gas analyzer and FID system required 35-day linearity verification as per 40 CFR part 1065.307 which were completed in-house. Several linearity verifications checks were completed throughout the course of the project to maintain 1065 compliance.[5]

3.4.3 PEMS Issues

3.4.3.1 GPS Connectivity

As discussed later, all on-road PEMS tests begin from the same location from within the laboratory building. Tests were started from within the building rather than outside to prevent several small logistical issues. An unforeseen, but unsurprising, consequence of this decision was that the PEMS GPS commonly had connectivity issues during the start of on-road testing. Figure 3-8 demonstrates how the GPS does not connect until about a minute after the first acceleration of the drive cycle. Figure 3-9 demonstrates that while sometimes the GPS may be connected while still inside the building, there may be significant noise within the positioning data that leads to erroneous speed data; in other words, the GPS is reporting movement while the vehicle is stationary.

[5] A total of two emissions tests were performed using the gas analyzer and FID outside of their 35-day linearity periods. The equipment passed all linearity criteria directly following these tests and had passed all criteria during the previous linearity period. The data from these two tests also passed all other quality control verification checks; therefore, these data were determined to be valid.

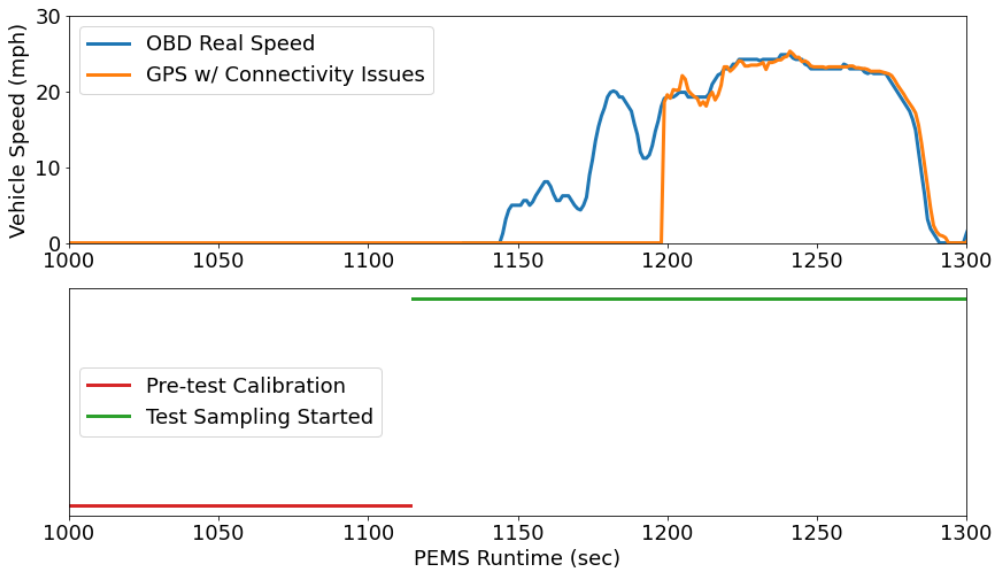

Figure 3-8: GPS Connectivity Example: Missing Data

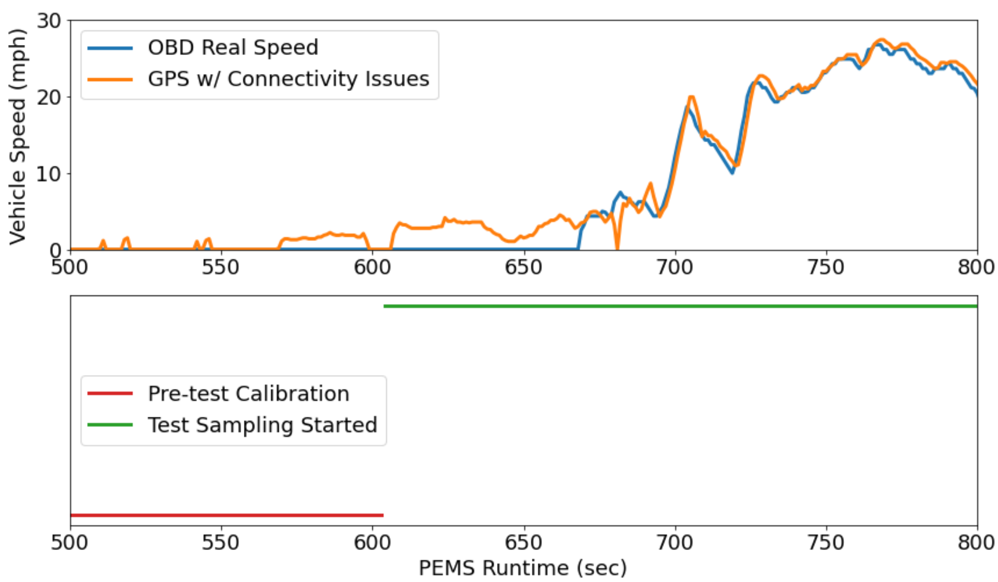

Figure 3-9: GPS Connectivity Example: Erroneous Data

The PEMS GPS system is generally regarded as more accurate than speed data broadcast from the vehicle's OBD system and is therefore preferably used for the calculation of distance weighted emissions. However, due to the above-mentioned GPS connectivity issues, there is higher uncertainty in the accuracy of these calculations. A brief confirmation analysis was performed, and it was verified that the OBD vehicle speed data yielded more precise results than the GPS speed data. All final distance weighted emissions results were therefore calculated based on OBD vehicle speed.

3.4.3.2 Iced Weather Probe

A unique aspect of this project was the operation of PEMS during wintertime climate conditions which periodically includes snow. PEMS tests were not run during heavy snow conditions but were sometimes run during light snow or after snowstorms. During a few tests, the accumulated snow/slush on the ground would get kicked up by the vehicles' rear wheels and hit the PEMS, Figure 3-10. The PEMS fairing and fairing cover successfully prevented any impact to the operation of the PEMS equipment. However, the sun-cover of the weather probe was not sufficient for preventing snow/slush from wetting the sensor tip.

Figure 3-10: Frozen PEMS Fairing (center) and Weather Probe (Bottom Right)

Once the tip is wetted, the sensor reading is significantly impacted and will output a value of -38°C. This weather probe issue was detected in five on-road PEMS tests and required a unique data processing solution which is discussed further in Section 3.6.4.1. Another simple solution, although not attempted in this project, would be to mount the weather probe in another location where it cannot be wetted by snow/slush/water kicked up by the vehicle.

3.4.3.3 FID Scrubber

The low ambient temperature is another significant factor of on-road PEMS testing in winter climate conditions. Ambient temperatures ranged from about 25°F to 72°F during on-road tests. PEMS operation down to freezing temperatures was robust throughout the project; however, during a few tests the PEMS operator observed a "Temperature Error" message on the PEMS user interface. Analysis of the data and a discussion with Sensors Inc. confirmed that the error was due to the FID scrubber internal temperature falling below the minimum threshold, Figure 3-11. Maintaining a high enough temperature is necessary for the FID scrubber to successfully remove any ambient hydrocarbon from the air flow used to maintain the FID flame. If any ambient hydrocarbon is not removed the sample can become contaminated and result in inaccurately high measurements of total hydrocarbon. Further analysis and discussion with Sensors Inc, led to the conclusion that the measurement accuracy of the FID was unaffected. All tests experiencing the FID "Temperature Error" were validated.

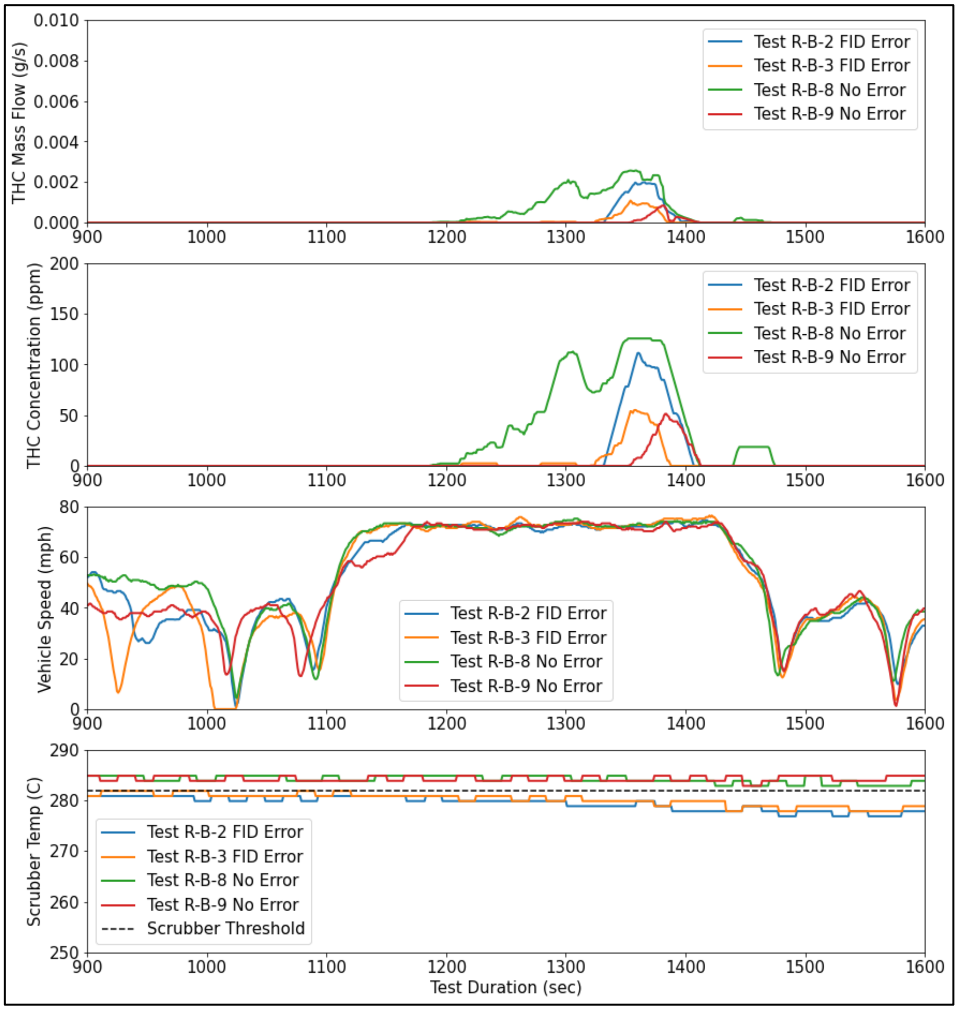

Figure 3-11: FID Scrubber Temperature Below Threshold

Sensors Inc. commented that the error was due to cold ambient air ventilating through the unit and passing over the surface of the scrubber system. To resolve the issue, the ventilation inlet was partially covered to limit the flow of cold ambient air across the scrubber. With this solution in place, no temperature errors were observed or detected for any other on-road tests.

3.4.3.4 Battery Power Supply

Operation of the PEMS on the road requires a portable power source. The two most reasonable options for power supply are batteries or a generator. To use a generator, the generator must be placed outside of the vehicle (on a basket for a car or in the bed of a truck). For this project none of the vehicles had room outside the vehicle as the PEMS took up the available space off the tow hitch. Two lead acid deep cycle batteries were sourced for the project (~150 amp hours each). Both batteries proved to be able to power a full 45 minutes PEMS test if started at full charge. This approach largely worked but required efficient coordination to ensure the batteries were always fully charged prior to testing.[6] During some tests it was observed that the batteries' voltage dropped over the course of the test. This resulted in the PEMS throwing a power supply warning which indicates the risk of equipment shutting down if not enough power is consistently supplied.[7] While this did not affect any of the data during the project, it is recommended for future projects with similar length PEMS tests to utilize lithium-ion batteries rather than lead acid. Lithium-ion batteries maintain a constant voltage throughout most of discharge and allows the full capacity of the batteries to be used without risking equipment shutdown during testing.

3.4.3.5 Impact of Elevation

The PEMS is largely robust to elevation and elevation change but there are a few limitations on the system. Sensors Inc. has indicated that the FID is sensitive to elevation in two ways. First, there is reduced stability of the FID flame; this may be related to reduced levels of oxygen and reduced FID fuel flow to feed the flame, both of which are caused by decreased atmospheric pressure. If the flame is unable to light, or if the flame goes out during sample collection, a valid test is not possible. Second, the accuracy of the FID may also decrease at high elevation. Sensors Inc. calibrates the FID such that it can comply with linearity requirements across a wider range of elevations, as opposed to being calibrated to be highly linear within a smaller range of elevation. However, at a high enough elevation, the FID will no longer be able to maintain sufficient linearity which will compromise the measurement accuracy. Figure 3-12 contains test data from Sensors Inc. which exemplifies the drop off in analyzer accuracy beginning around 2500 meters (8200 ft). Throughout the course of testing, there were no observed issues with FID flame stability and the FID analyzer passed all linearization checks. The maximum elevation of the on-road test route was 6145 feet.

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[6] One test was invalidated because a partially charge battery was used and the battery died ~30 minutes into a 45 minute test

[7] Warning is triggered if the power supply drops below ~11V. The warning will remain on the PEMS user interface even if the voltage increases above the threshold again.

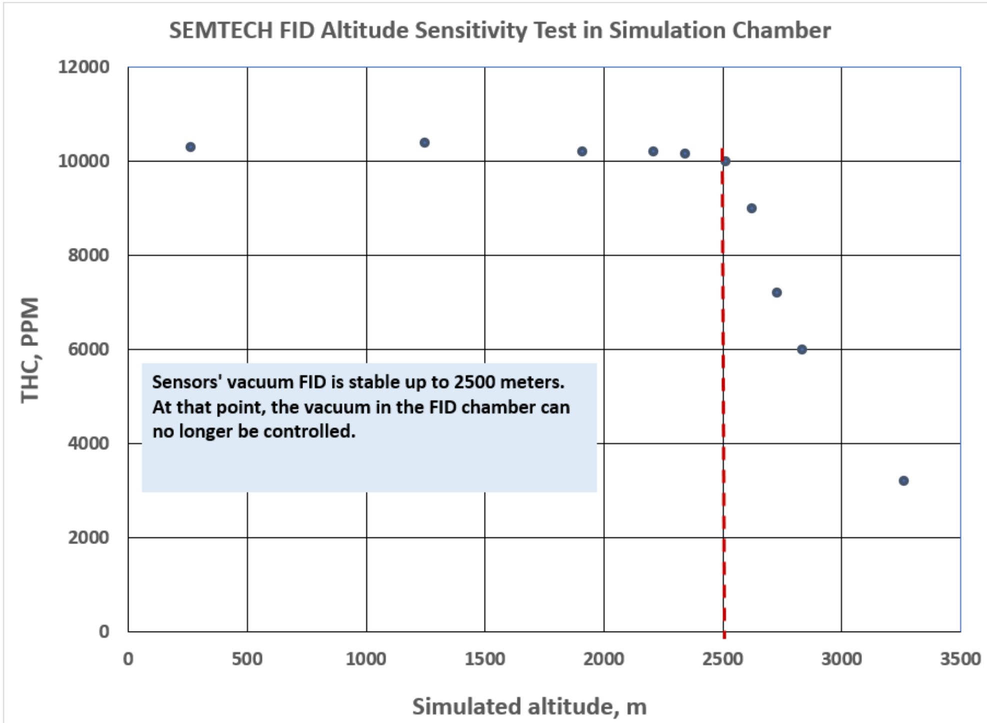


Figure 3-12: FID Sensitivity to Elevation

An interesting phenomenon was also observed with the PM2 system. During PEMS on-road testing, the vehicles are driven up to a maximum absolute elevation change of about 700 feet. Over the course of this elevation change the average sample flow to the PM2 system trends lower.[8] During chassis testing, performed at a constant elevation, the PM sample flow rate appears more constant. It is possible that the reduced sampling rate is related to the decreasing barometric pressure at higher elevation which would only be experienced with on-road testing. PM sample flow rate is also sensitive to other factors such as exhaust flow rate. The correlation between elevation, exhaust flow rate, and PM sample flow rate is exemplified in Figure 3-13 and Figure 3-14 for Vehicle A. Interestingly, this phenomenon was much more noticeable for Vehicles A and E and less so for Vehicles C and D.

Although the PEMS accounts for the reduced sample flow relative to the total exhaust mass flow, the measurement uncertainty of the Pegasor and/or gravimetric filter could increase because of this phenomenon. When asked about the effect on measurement uncertainty, Sensors Inc. suggested an average of 0.5 SLPM as a tolerance threshold. In other words, any less than 0.5 SLPM of sample flow and the measurement uncertainty of the Pegasor and gravimetric filter could be too high. No tests were invalidated because of a reduced PM sample flow rate. Furthermore, it is not believed that this phenomenon significantly impacted PEMS on-road PM variability or bias. This is primarily because the vast majority of PM emissions are produced before the reduction in PM sample flow occurs in the latter half of the on-road tests. Although it is concluded that this phenomenon did not significantly impact results for E-134, future high elevation PEMS PM sampling programs should consider this potential impact during development of any on-road testing protocols.

[8] See Figure G-2 in APPENDIX G: PM Measurement Methods for details on PM2 flow path.

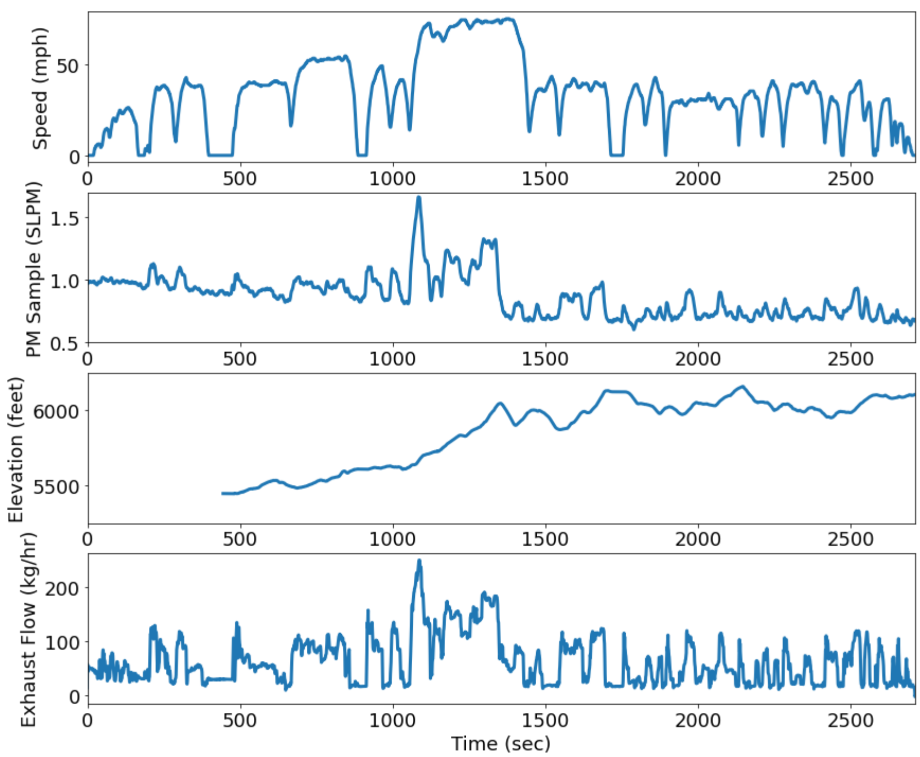


Figure 3-13: On-Road PEMS PM Sample Flow Related to Elevation and Exhaust Flow (Vehicle A)

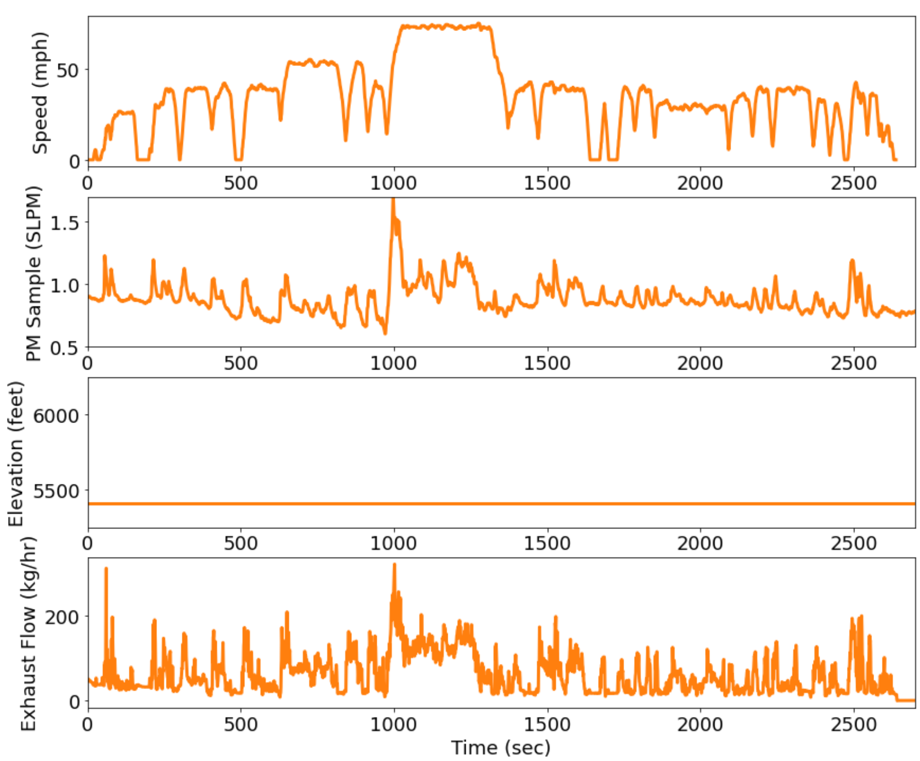


Figure 3-14: Chassis PEMS PM Sample Flow at Constant Elevation (Vehicle A)

3.5 Chassis Dynamometer and CVS

3.5.1 Chassis Dynamometer

All chassis emissions were collected using the same test cell and Burke Porter 48-inch electric roller. Road-load force models were simulated for each vehicle using the target coefficients sourced from the EPA database. For Vehicles A, C, and D the target coefficients were also verified against the previous E-122-2 program. Table 3-1, previously shown, describes the target and set coefficients derived from the road-load force model. The simulated road-load force model uses the road-grade data collected during the route development stage to adjust the real-time resistance of the chassis roller. For all emission sampling on Fuel A and Fuel B, the test cell environmental conditions were controlled to 50°F (10°C). Prior to emission testing, both the vehicle and PEMS equipment were stored in the same environmental conditions of 50°F (10°C) overnight.

The same driver was used for all chassis dynamometer emissions tests when possible. The primary technician drove 59 of the 64 chassis dynamometer emissions tests. The remaining 5 tests were driven by one of three other backup technicians because the primary technician was unavailable. The chassis emission tests that were not driven by the primary technician are shown in Table 3-5. The backup technicians are referenced as technicians B, C, and D. No single backup technician drove more than one test per vehicle/fuel combination.

Table 3-5 Chassis Emission Tests Driven by Backup Technicians

Vehicle	Test Identifier	Backup Technician
A	D-B-1	B
C	D-B-3, D-B-5, and D-A-7	C, D, and D
D	D-B-7	D
E	N/A	N/A

3.5.2 Laboratory Emissions Sampling System

Tailpipe exhaust emissions were determined using CVS by collecting dilute emissions into Kynar bags. Gaseous analyzers compatible with the required specifications described in 40 CFR Part 1066 were used to determine the concentrations of CO, CO_2, THC, methane (CH_4), and oxides of nitrogen (NO_x and N_2O). THC and CH_4 were used to determine nonmethane hydrocarbons (NHMC) and NMOG using equations defined in 40 CFR Part 1066.635. PM were collected onto a 47mm polytetrafluoroethylene (PTFE) membrane filter by drawing a proportional amount of dilute exhaust at a temperature of 47°C. The same PTFE membrane filters were used for PEMS PM sampling. All PTFE filters were weighed onsite in a clean room compliant to the required specifications described in CFR 40 Part 1065.

Continuous tailpipe emissions (CO, CO_2, THC, NO_x) were collected at 1Hz from the raw exhaust near the sample extraction of the PEMS equipment. The modal tailpipe emissions were used to supplement the PEMS modal emissions in case of emission spikes that might either go undetected or overrepresented.

Exhaust flow was calculated in the CVS using the CO_2 method whereby a sample from the dilute exhaust is simultaneously analyzed for CO_2 concentration and a pseudo-dilution factor can be determined. The exhaust flow determined from the CVS using the CO_2 method can then be compared to the exhaust flow measured from the PEMS unit that uses a Pitot tube.

Real-time soot measurement was also collected at the same location of the PEMS equipment using an AVL Micro Soot Sensor (MSS). The MSS data were also used to verify the PM emissions collected from the CVS system. Because the MSS emissions were collected near the PEMS equipment, they can be directly compared to the soot emissions collected with the PEMS equipment for time-based resolution or aggregate results.

The CVS tunnel flow rates were selected for each vehicle to allow for acceptable concentrations of dilute constituents and to target a dilution factor between 7:1 and 20:1 using a combination of up to three separate critical flow venturis (CFV). Typical values for CVS tunnel flow and time-weighted dilution factors for the RWC used for emission testing are shown in Table 3-6. Vehicle D is a PHEV and is not required to meet the dilution factor requirements. Vehicle E used 2 different CVS tunnel flow rates that met the dilution factor criteria for PM sampling. No difference in PM emissions were observed using one CVS flow rate versus the other for Vehicle E and there was no specific reason for switching the target flow rate other than a built-in software tool recommends which selections to use that meet the criteria. The 2 different CVS flow rates for Vehicle E were split across the 16 chassis tests (9 tests at 193 scf/min and 7 tests at 282 scf/min). The 9 tests using 193 scf/min were made up of 4 tests of Fuel B and 5 tests of Fuel A. The 7 tests using 282 scf/min were made up of 4 tests of Fuel B and 3 tests of Fuel A. Figure 3-15 shows the layout of the test cell and the relative sample locations for each major measurement method.

Table 3-6 CVS Flows

Vehicle	CVS flow (scf/min)	Time-weighted Dilution Factor
A	282	9.56
C	282	9.77
D	193	22.9
E	193, 282	9.20, 13.1

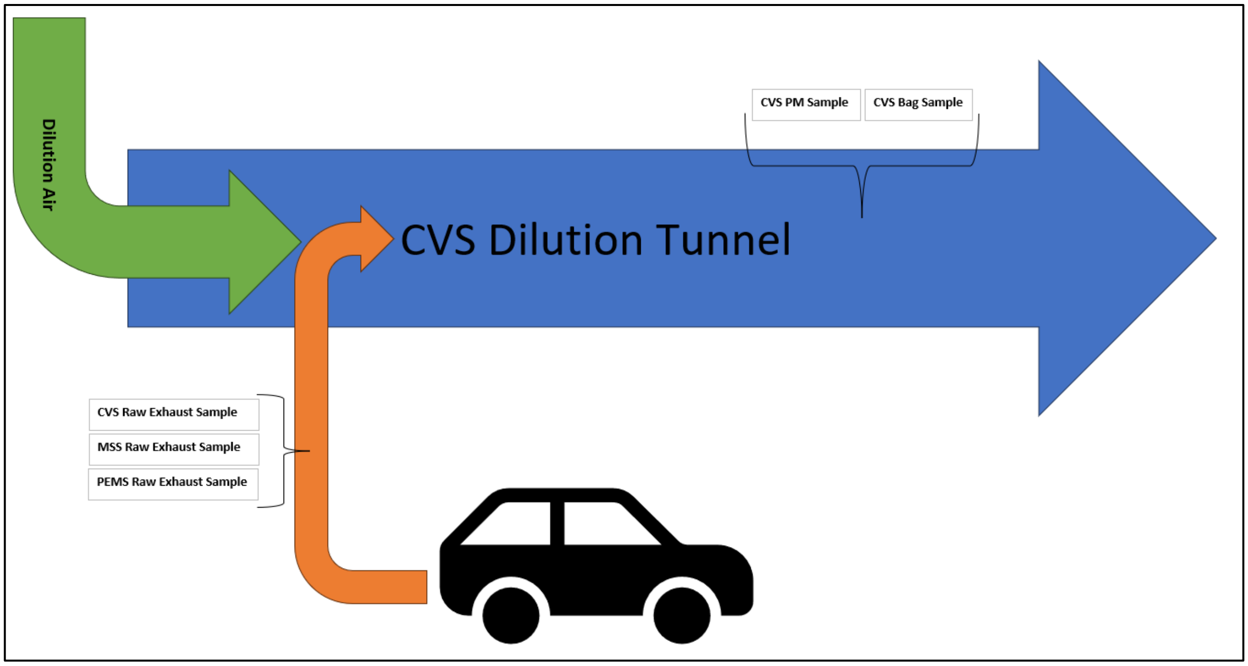


Figure 3-15: Test Cell Layout

3.6 Test Procedure

3.6.1 Preconditioning and Test Preparation

A chassis dynamometer preparatory cycle was created with the intent of matching the full drive route of the on-road test, including the return route. A return cycle was created using a similar procedure described in Section 3.3 and the prep cycle was defined to be the direct combination of the RWC and the return cycle. For this project, a valid preconditioning procedure required the vehicle to be driven over the prep cycle on the dyno or to be driven over the full test route the day before official testing. This preconditioning procedure allows each vehicle to receive the same treatment prior to testing, on-road variability aside. A hypothetical test schedule demonstrates how a vehicle is preconditioned for each test:

- Monday: Prep cycle on chassis dynamometer (serves as preconditioning for Tuesday)
- Tuesday: On-road test + drive back to lab (serves as preconditioning for Wednesday)
- Wednesday: Chassis RWC test + return cycle (serves as preconditioning for Thursday)
- Thursday: On-road test + drive back to lab (serves as preconditioning for Friday)
- Friday: Chassis RWC test (no preconditioning for Saturday)

In addition to the preconditioning drive, the vehicles were soaked overnight in a cold room at 50°F prior to each official test, both on-road and chassis tests. The length of the soak period ranged from about 16-24 hours which is compliant with the 8-hour minimum soak requirement requested for this project. The importance of properly following this soak procedure and ensuring consistent vehicle start conditions is showcased in APPENDIX H: Emissions Impact of Engine Start Temperature.

A unique SOC preconditioning procedure was used to address the hybrid electric Vehicle D. Prior to either the prep cycle or an official test, the battery would be fully charged to 100% and then drained down to exactly 50% by turning on seat warmers and placing the heating, ventilation, and air conditioning (HVAC) system on high heat.[9]

3.6.2 Emissions Test

The following test procedure assumes that the proper preconditioning/soak procedure described in the previous section has already been completed. The on-road test starts from within the laboratory building; gates/doors leading out to the roadway are opened before the start of testing to allow a fluid and consistent drive profile. Very similar procedures are followed for both on-road and chassis testing; notes are made regarding differences in chassis testing. Additional details are included in APPENDIX I: PEMS Testing Checklists.

1. PEMS setup and pre-test calibrations completed
2. PEMS emissions sampling started, and vehicle engine started
3. Idle in Park for 15 seconds
4. Within this 15 second period of time, engage front and rear defrosters
5. Idle in Drive for 5 seconds
6. Start drive route[10]
7. Turn off defrosters at designated location (intersection of Jasper Street and E Colfax Avenue). Location indicated on speed profile interface for chassis test operator.
8. Vehicle off and PEMS emissions sampling stopped at route end location
9. PEMS end-test calibrations completed
10. Drive back on designated return route if on-road testing or perform return cycle if chassis testing and preconditioning is needed.

[9] CRC SMC-E-18_E-142 Appendix C Section 4.2 (https://crcao.org/wp-content/uploads/2024/07/CRC-Project-SME18_E142-Final-Report-July-2024.pdf)

[10] Chassis testing RWC includes 14 additional seconds idling in Drive. The first acceleration of the on-road PEMS testing route begins here after the preceding 5 seconds of idle in Drive.

3.6.3 Test Sequence

A total of 128 emissions tests were required to complete the project objectives: 4 vehicles, 2 fuels, dyno and road conditions, 8 tests per combination. Due to resource limitations, it was only feasible to complete 2 tests per day (8 total tests per week because of the need to precondition the test vehicles, see Section 3.6.1). The test sequence was therefore planned to be completed over a 16-week period as shown below in Table 3-7. CRC directed which 2 vehicles would start on Fuel A and which vehicles would start on Fuel B based on data from the previous E-122-2 project. Vehicle A and Vehicle B started on Fuel A. Vehicle C and Vehicle E started on Fuel B.

Table 3-7: Planned Test Sequence

	Vehicle A			Vehicle B			Vehicle C			Vehicle E		
Week	Road/Dyno	Fuel	Test Number	Road/Dyno	Fuel	Test Number	Road/Dyno	Fuel	Test Number	Road/Dyno	Fuel	Test Number
1	Road	A	1-4	Road	A	1-4						
2	Dyno	A	1-4	Dyno	A	1-4						
3							Dyno	B	1-4	Dyno	B	1-4
4	Road	A	5-8				Road	B	1-4			
5				Road	A	5-8				Road	B	1-4
6	Fuel Swap			Fuel Swap			Road	B	5-8	Road	B	5-8
7	Road	B	1-4	Road	B	1-4	Fuel Swap			Fuel Swap		
8							Road	A	1-4	Road	A	1-4
9	Road	B	5-8				Road	A	5-8			
10				Road	B	5-8				Road	A	5-8
11	Dyno	B	1-4	Dyno	B	1-4						
12							Dyno	A	1-4	Dyno	A	1-4
13	Dyno	B	5-8	Dyno	B	5-8						
14	Fuel Swap			Fuel Swap			Dyno	A	5-8	Dyno	A	5-8
15	Dyno	A	5-8	Dyno	A	5-8	Fuel Swap			Fuel Swap		
16							Dyno	B	5-8	Dyno	B	5-8

Because of several logistical issues and delays, testing started during late January. In an effort to complete as much of the on-road testing as possible during winter months, the test sequence was designed to include an additional fuel swap procedure for each vehicle which allowed most of the dyno tests to be completed during the end of the sequence. This sequence also allowed for an assessment of the impact of performing the fuel swamp. As can be observed in the portrayed data throughout Section 4, there was no significant impact on emissions results from the fuel swap procedure. Final cumulative, distance weighted emissions results are tabulated in APPENDIX J: Tabulated Test Data.

3.6.4 PEMS Data Processing and Quality Control

Following completion of PEMS emissions testing, a data processing and quality control check procedure is conducted to validate the collected data, and to determine if any action is needed (e.g. redo test, manual correction to emissions results, etc.). The data processing procedure includes a strict set of steps required to produce a modal data file and a summary of emissions results over the full cycle. The procedure for the quality control check is more loosely defined as flexibility is needed to address a wide variety of possible issues. However, the procedure generally includes drive procedure verification, drift verification, and an assessment of emissions results including a comparison to CVS data if applicable. Information specific to drift verification can be found in APPENDIX K: Drift Verification.

Raw emissions data output from the PEMS SCS is run through a Sensors Inc. specific “basic post processor” application.[11] The application uses the Kh calculation methodology from 40 CFR 1065.670 and

[11] Version 7.02

requires specific gravity and molar ratio fuel properties for the relevant fuel. The PEMS PM filter weight is also included in this processing step.[12]

Sets of summary emissions data were qualitatively reviewed to assess the existence of potential outlier tests. Evidence of potential outliers would trigger an investigation into the cause of the outlying test result. Tests of this nature were only invalidated if the cause was determined to be anything other than reasonable test procedure variability. For example, total CO emissions may be higher in an iteration of a chassis dynamometer emissions test where a notably more aggressive cold start acceleration rate occurs; however, if the acceleration rate and vehicle speed are within the acceptable boundaries relative to the target speed profile, the test would still be validated.

Drive/test notes were also reviewed as documented by the PEMS operator during testing. Some analyses were performed to address drive procedure deviations including extended idle in park, minor route modifications due to road construction, and defogger status. Generally, if any evidence existed to suggest that the emissions performance of the vehicle was impacted by a procedural deviation, the emissions test was invalidated and rerun.

3.6.4.1 Substituting for Weather Probe Data

As discussed in Section 3.4.3.2, during a few tests the weather probe data profile would deviate as a result of the sensor tip becoming wet. Because the weather probe data is no longer accurate, this deviation then impacts the calculation of kNOx (NOx corrected for intake air humidity).[13] To allow the correct computation of kNOx, constant values of ambient temperature and relative humidity were substituted into the PEMS post processing software. These constant values were determined on a case-by-case basis by analyzing the weather probe data prior to the deviations. An example of a corrected data file is shown in Figure 3-16.[14]

[12] For measured filter weight values <=0 a value of 0.0001 mg was used for processing.

[13] 40CFR§1066.615 NOX intake-air humidity correction.

[14] Correction for relative humidity was often chosen to be around 75-80% although there is evidence in the data that the real relative humidity during these wintertime conditions may be closer to 100%. The impact on the kNOx calculation between these RH settings is negligible.

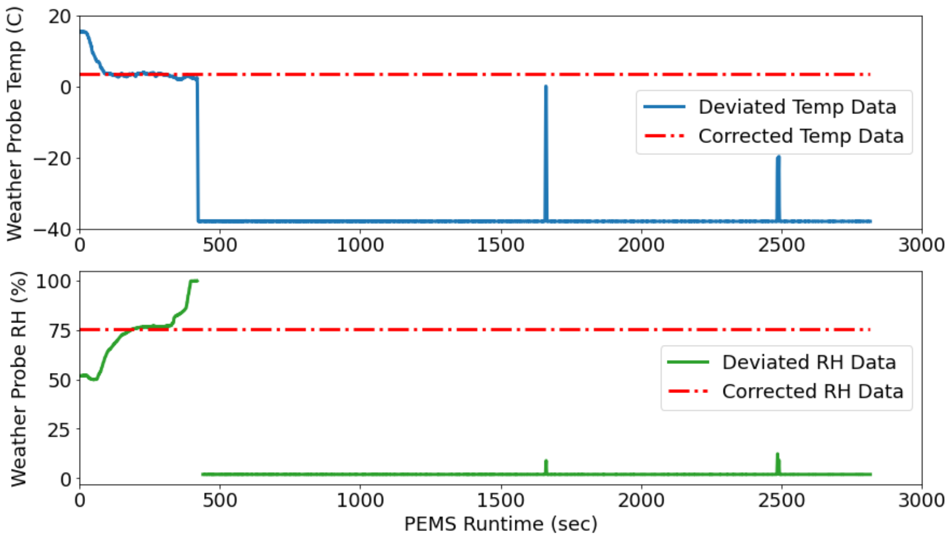


Figure 3-16: Corrected Weather Probe Data

3.6.4.2 Vehicle Speed Sensor Fault

As noted in Section 3.1.1, a vehicle speed sensor fault was discovered on Vehicle C during the check-in and verification process. Using OEM specific software, the vehicle was able to be placed in dyno mode and successfully run on a 4-wheel dyno without issue. However, after performing the first set of four chassis dynamometer tests, it was discovered that the wheel speed sensor fault prevented the collection of OBD vehicle speed data which is required for distance weighted emissions calculations. Wheel speed data from the chassis speed rollers was used as a substitute to calculate distance weighted emissions.

The four tests requiring this substitute calculation were all iterations of Vehicle C, Fuel B chassis tests. To be consistent, distance weighted emissions for all other Vehicle C, Fuel B chassis tests were also calculated using wheel speed data. However, distance weighted emissions for all other Vehicle C tests, namely Fuel A chassis tests, were calculated using OBD vehicle speed data (after wire harness splicing was corrected). For Vehicle C, total chassis test distance is roughly 1% less when calculated using chassis wheel speed data relative to when calculated using OBD vehicle speed data. This translates to distance weighted emissions results that are roughly 1% greater in magnitude for the eight Vehicle C Fuel B tests calculated using chassis wheel speed data.

3.6.4.3 PEMS Phase Segmentation

The CRC E-134 project was originally scoped to achieve project goals by analyzing emissions results weighted over the full distance of the on-road and chassis emissions tests. However, the CRC emissions committee requested an extension of this analysis to include emissions results weighted over smaller phases of the test cycle; this more precise analysis could offer additional insight into how unique characteristics of each phase impact emissions. The process of calculating phase level emissions from the PEMS data is referred to as PEMS phase segmentation.

The CVS system naturally requires the chassis emissions test data to be split into phases. This is because, due to the length of the RWC and total volume of dilute exhaust, multiple bags are required for emissions analysis. Each bag represents a phase of the RWC. To ensure that the calculated PEMS phase level data is comparable to the CVS phase level data, the PEMS phase end points were designed to be the same as those used for the CVS bags. The phase end points, shown overlayed on the RWC chassis cycle in Figure 3-17, are defined at the following elapsed test time points: 507 seconds, 1163 seconds, and 2654 seconds. OBD vehicle speed was used to calculate distance weighted emissions for all PEMS chassis testing phases. A similar procedure discussed in preceding Section 3.6.4.2 was used to calculate phase level data for Vehicle C Fuel B tests impacted by the vehicle speed sensor fault.

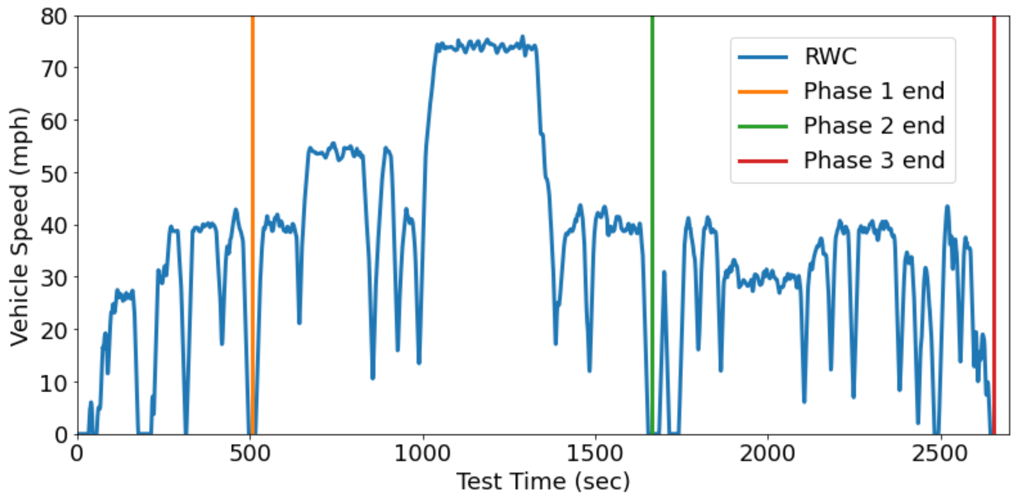


Figure 3-17: PEMS and CVS Phase End Points on RWC

PEMS phase segmentation for on-road test data has no CVS phase level data counterpart, but an effort was made to define on-road test phases that were as similar as possible to the chassis test phases. Defining phases using elapsed test time points is inappropriate because each on-road test has a unique speed profile and unique total test duration. Instead, phase end points were defined using GPS coordinates and PEMS GPS data from each on-road test was used to locate each phase end point.[15] The chosen coordinates are representative of the chassis test phase end points.[16] As with the PEMS chassis testing phases, OBD vehicle speed was used to calculate distance weighted emissions for PEMS on-road chassis testing phases as well.

3.7 Exhaust Flow Measurement

Below is a comparison of the two different measurement methods for exhaust flow. The CVS system uses a CO_2 tracer method that measures a dilute concentration in the tailpipe exhaust and calculates a dilution factor following the carbon balance method of the combustion equation. The CO_2 tracer method is only needed to determine the mass values of the raw tailpipe exhaust for any direct comparison with the PEMS sample. The PEMS equipment uses pitot tube technology to measure real-time air flow in the

[15] GPS coordinates were only used to define phase 1 and 2 end points. The phase 3 end point was simplified to be the end of the PEMS test. This is appropriate because some idling is included in the PEMS test at the final destination of the test.

[16] Note the phase end points of the RWC are during idle periods. These idle periods occurring during stops at known road intersections. The on-road test phase end points are therefore the GPS coordinates of these road intersections.

exhaust using temperature and pressure sensors. The PEMS emissions results are dependent on accurate exhaust flow measurement.

Below are plots for the first 200 seconds of test D-A-8 for Vehicle A. The first 200 seconds were chosen since most of the pollutant tailpipe emissions are produced during this time frame.

A parity plot between the PEMS exhaust flow and CVS exhaust flow is shown below in Figure 3-18 for these first 200 seconds. Two observations stand out in this comparison: (1) The PEMS exhaust flow measurement records flow almost immediately once the engine is started (see Figure 3-19), and (2) the PEMS exhaust flow measurement is noisier and more sensitive to dynamic behavior, exemplified here with the OBD accelerator pedal position, see Figure 3-19 and Figure 3-20.

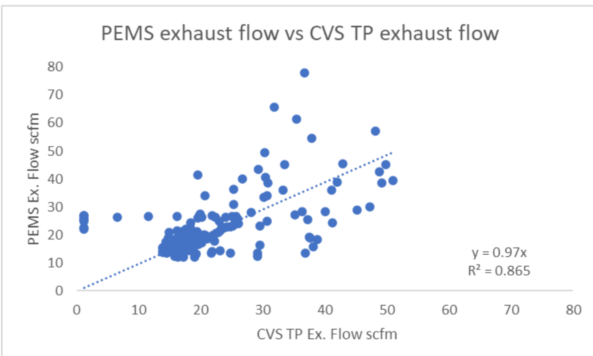


Figure 3-18: Exhaust Flow Correlation Vehicle A

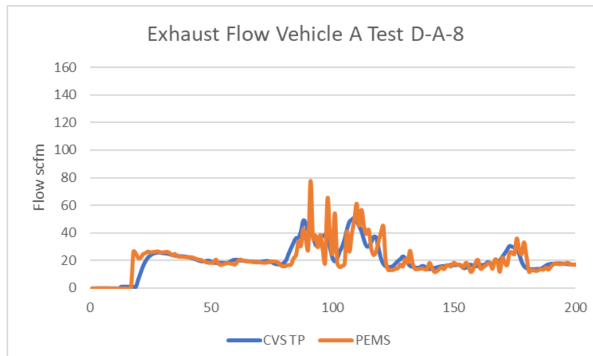


Figure 3-19: Exhaust Flow Profile Vehicle A

For comparison, Figure 3-20 and Figure 3-21 show the pedal position and exhaust flow profile for Vehicle A during a road test and dyno test. The engine start and initial acceleration procedure were the same for the road tests and the dyno tests and is illustrated in the exhaust flow and speed plots, Figure 3-21 and Figure 3-22. Even though there is a slightly different speed profile at the start of the test, the max vehicle speeds within the first 200 seconds are the same, but the pedal position behavior/exhaust flow rate for the dyno test are not as smooth as the road test.[17]

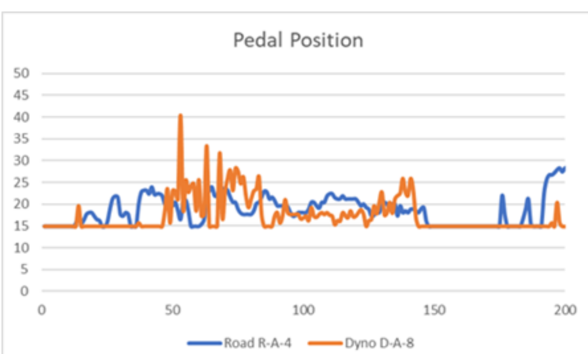


Figure 3-20: Pedal Position Road vs Dyno Vehicle A

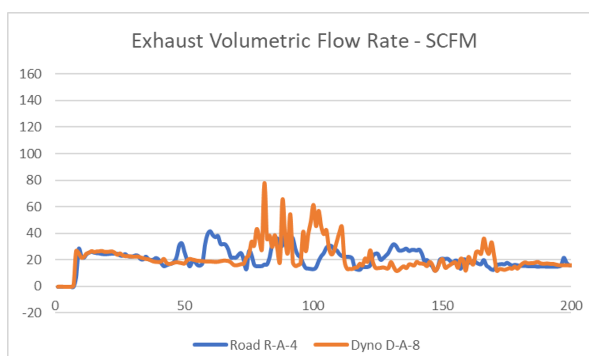


Figure 3-21: Exhaust Flow Profile Road vs Dyno Vehicle A

[17] See APPENDIX E: Chassis vs. On-road Speed Profile and Driving Behavior for more details.

Figure 3-22 shows the speed profile for a road test and dyno test for Vehicle A. Every single road test will be slightly different while the dyno testing is a consistent representation of the test route.

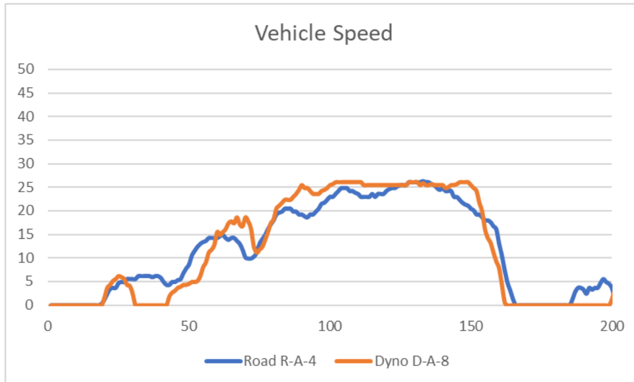
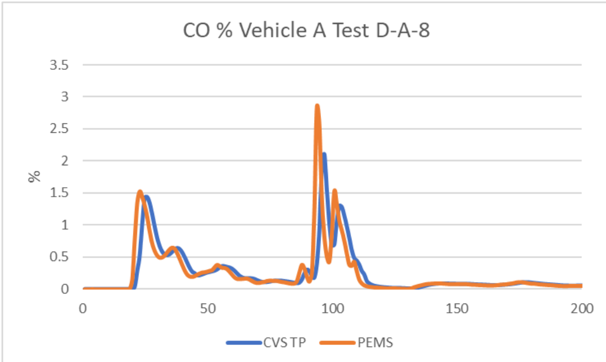


Figure 3-22: Speed Profile Road vs Dyno Vehicle A

The real-time exhaust flow measurement from the PEMS equipment is an important factor when interpreting when the raw tailpipe emissions occur during a test. As previously shown in Figure 3-19, the PEMS exhaust flow measurement device immediately records the exhaust flow whereas the CO_2 tracer method in the CVS records a slower ramp up in exhaust flow as it requires the concentration of CO_2 in the raw exhaust to be measured through a NDIR analyzer rather than a near instantaneous pressure and temperature measurement. Even though the two exhaust flow measurement methods trend very close together during the transient events, larger spikes and valleys are consistently observed from the PEMS pitot tube. The turbulent nature of the tailpipe exhaust fluid dynamics coupled with pedal inputs demanding immediate engine power will have an influence on the real-time exhaust flow measurements in the PEMS equipment. See Figure 3-23 and Figure 3-24. The real-time concentration measurements are nearly identical between the CVS TP and PEMS, but when the two different exhaust flow methods are applied to determine the mass to results, larger separation in cold-start CO emissions are observed including the more erratic pedal position influence on the PEMS exhaust flow that either adds, removes, or emphasizes the concentration profile. Figure 3-25 shows the cumulative CO mass emissions for test D-A-8. The impact of pedal position is discussed further in Section 4.1.2.2 and APPENDIX E: Chassis vs. On-road Speed Profile and Driving Behavior.



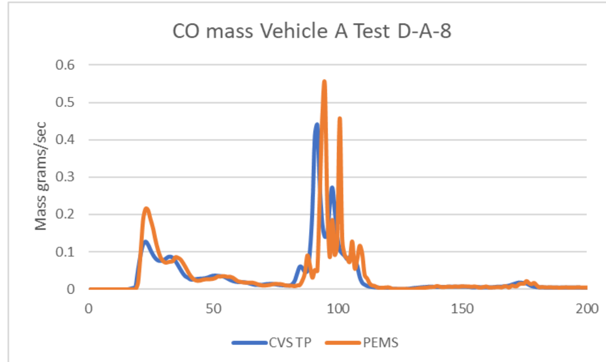


Figure 3-23: CO Concentration CVS TP vs PEMS Vehicle A

Figure 3-24: CO Mass CVS TP vs PEMS Vehicle A

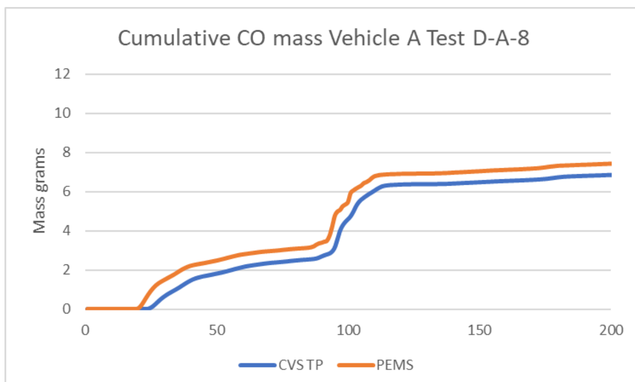


Figure 3-25: Cumulative CO vs TP vs PEMS Vehicle A

A complete comparison of PEMS and CVS exhaust flow measurement methods is shown below. A comparison is made for each vehicle and each chassis dynamometer test phase, as defined in Section 3.6.4.3. Each comparison is plotted along with a linear regression line and a parity line.

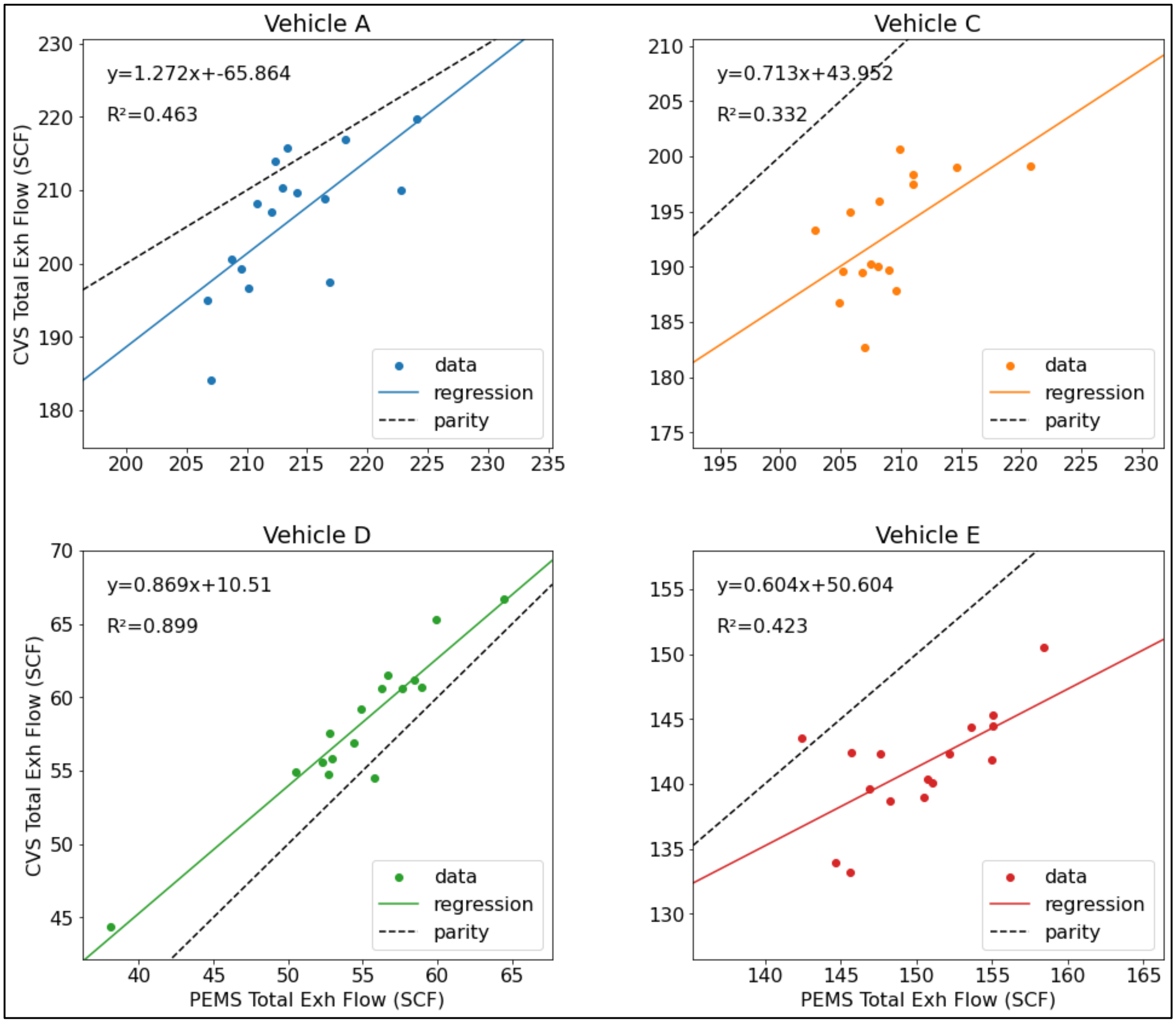


Figure 3-26: PEMS vs. CVS Total Exhaust Flow Phase 1

The above plot demonstrates a relatively poor correlation between PEMS and CVS exhaust flow measurements for Vehicles A, C, and E. This likely stems from the PEMS sensitivity to transient perturbations which clouds the steady state similarities in exhaust flow, as shown before in Figure 3-19. Additionally, the PEMS tends to measure increased total exhaust flow during Phase 1 of the test for the same three vehicles. Interestingly, Vehicle D produces a much tighter correlation than the other three vehicles and the PEMS is observed to measure less total exhaust flow. These differences may be related to Vehicle D's hybrid engine technology.

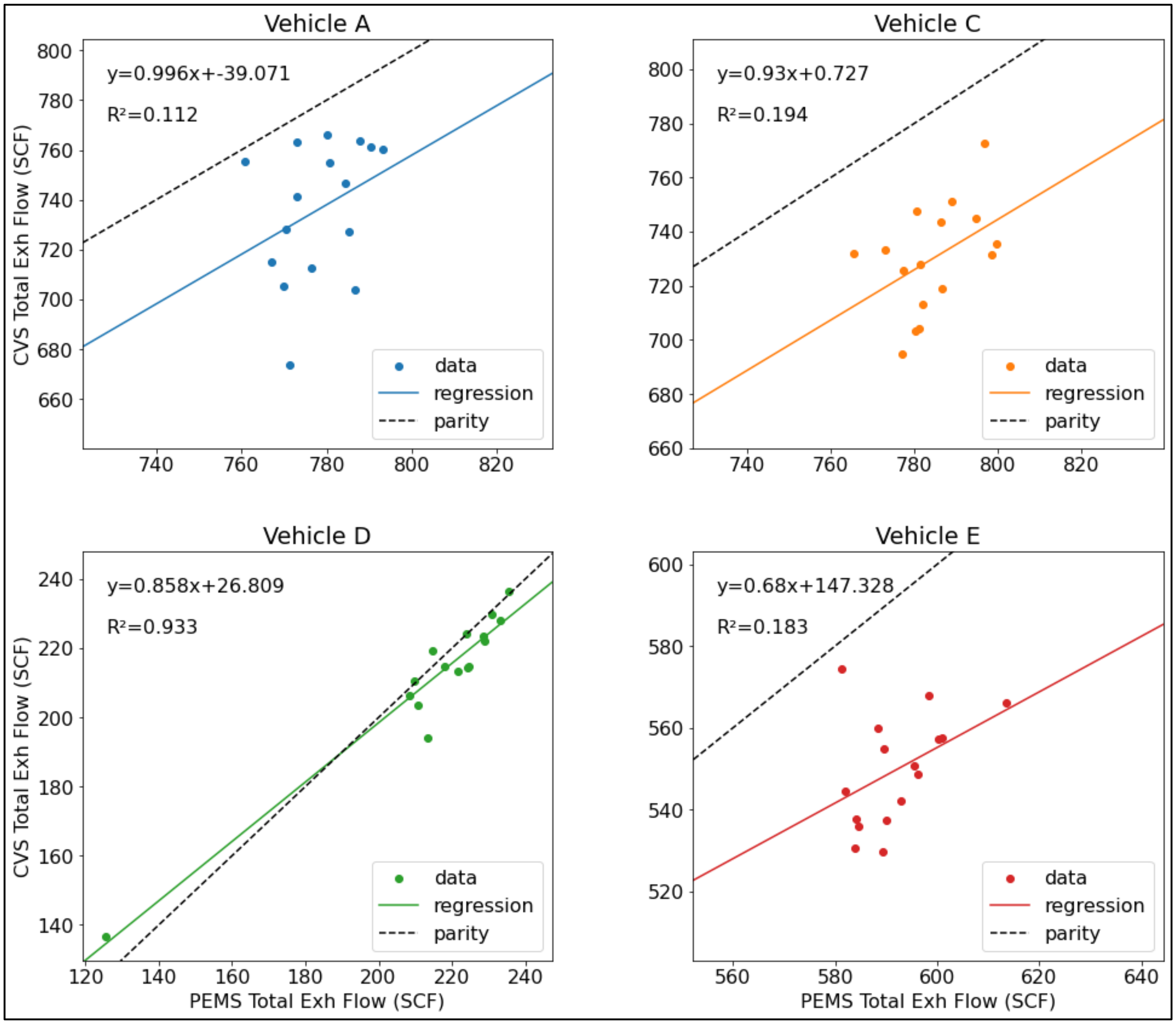


Figure 3-27: PEMS vs. CVS Total Exhaust Flow Phase 2

Observations for Phase 2 of emissions testing are very similar to Phase 1. The only noticeable difference is that the PEMS may be measuring increased total exhaust flow during Phase 2 for Vehicle D whereas the PEMS seemed to be measuring less during Phase 1.

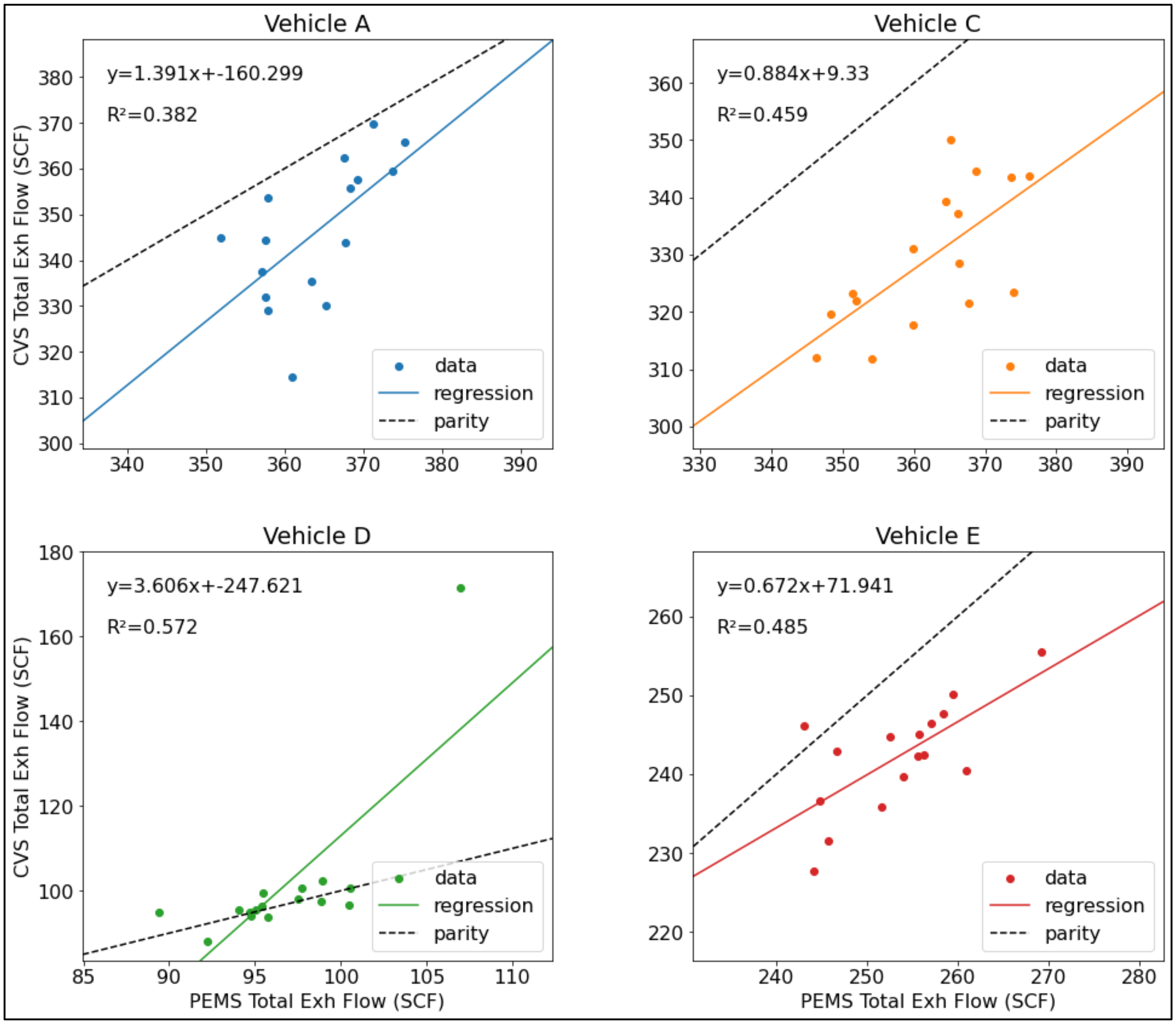


Figure 3-28: PEMS vs. CVS Total Exhaust Flow Phase 3

Lastly in Phase 3 of the emissions test, observations for Vehicle A, C, and E remain consistent. The data in Phase 3 for Vehicle D appears to suggest similar measurements between the PEMS and CVS whereas data from Phase 1 and 2 suggested lower and higher PEMS exhaust flow measurements respectively. During one test on Vehicle D, an outlier CVS data point heavily skews the correlation; the strength of the correlation is expected to be much better, as in Phase 1 and 2 data, if the outlier was removed. The root cause of the outlier was not investigated.

The biases demonstrated in several of these correlation plots cannot be accurately used to predict biases in emissions results. This is because the impact on emissions is directly influenced by the combination of exhaust flow and component concentration. A deeper analysis of PEMS vs. CVS measurement sensitivity to transient driving behavior would better clarify how the PEMS exhaust flow measurement may bias emissions results; this additional analysis is out of scope of the project.

4 Statistical Analysis and Results

Statistical analysis was conducted to assess PEMS variability, accuracy, and sensitivity to fuel property changes. A similar analysis was performed in CRC project E-122-2 under "mild" driving conditions. Therefore, with the PEMS exposure to more severe conditions in this project, including high altitude, steep grade, and low temperatures, it was of interest to determine if these conditions had an impact on any of these previously analyzed PEMS performance metrics. As in E-122-2, three emissions measurement methods are considered in the statistical analysis, PEMS results from the road tests, PEMS results from chassis dyno tests, and CVS results from dilute exhaust on the dyno. These are referred to as "PEMS Road," "PEMS Dyno," and "CVS Dyno," respectively.

Prior to conducting any statistical analysis, an outlier analysis was performed, along with an assessment of required data transformations necessary to meet required assumptions of the statistical models and methods, primarily that the data follow a Gaussian (Normal) distribution. This analysis is provided in Section 4.1. Following the outlier analysis and data transformation assessment, Section 4.2 is dedicated to analyzing variability and repeatability of the PEMS, followed by Section 4.3, which discusses accuracy and bias of the PEMS. Finally, Section 4.4 discusses PEMS sensitivity to fuel property changes, and overall conclusions are provided as Section 4.5.

4.1 Data Transformations and Outlier Analysis

4.1.1 Data Transformations

To properly compare variability between measurement methods and 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, many common statistical hypothesis tests, such as the t-test, assume the data to be from a Gaussian (Normal) distribution. To determine that appropriate transformation, a regression model was run separately for each emissions parameter, with the sole predicted variable Vehicle-Fuel-Method as a concatenated categorical variable with 24 levels (4 vehicles, 2 fuels, 3 measurement methods). A Box-Cox transformation analysis was done for each of these models. 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 graph is shown below in Figure 4-1. Values below the red line in the plot are within a 95% confidence interval (CI) 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 $\lambda = 0.292$.

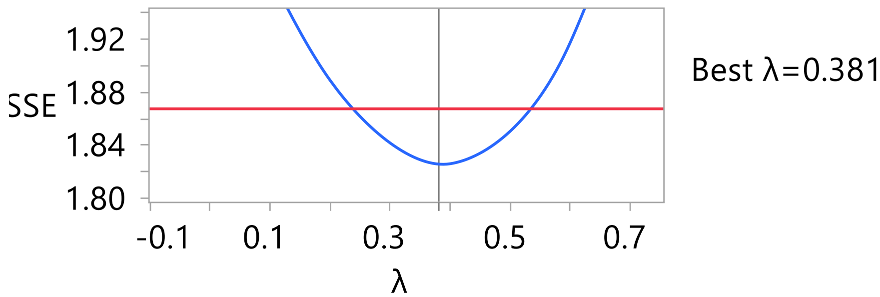


Figure 4-1: Box-Cox Analysis for Particulate Matter

The list of transformations used for all emissions parameters is shown below in Table 4-1, along with comparisons to the transformation chosen in E-122-2. For PM, the addition of a small constant of 0.1 was necessary for the transformation to work properly due to the number of zero PM results, which do not change when taking the cubed root. Though this was not necessary in E-122-2, when comparisons are made later in Section 4.2.1 this same transformation including the constant is applied to E-122-2 data. The natural log transformation was appropriate for THC, CO, CO_2, fuel economy, and NO_x data in both projects.

Table 4-1: Transformation Summary

Parameter	E-134 Transformation	E-122-2 Transformation
PM	$\sqrt[3]{PM + 0.1}$	$\sqrt[3]{PM}$
CO	Ln(CO)	Ln(CO)
CO_2	Ln(CO_2)	Ln(CO_2)
Fuel Economy	Ln(Fuel Economy)	Ln(Fuel Economy)
NO_x	Ln(NO_x)	Ln(NO_x)
THC	Ln(THC)	Ln(THC)

4.1.2 Outliers and Abnormal Data

The data was inspected for outliers using both visual inspection of the data and considering studentized residuals from the model described in Section 4.1.1. Since variability estimates are a key project goal, it was important not to remove any data which may be considered a part of normal variability, and to only eliminate data which was clearly unrepresentative or for which a cause could be identified to indicate that removal was justified.

In total, twelve points were identified as potential outliers for further review, eight of which were for PM, two for CO, one for THC, and two for fuel economy. Of the eight PM outliers, four were from Vehicle C. The full list is shown below in Table 4-2.

Table 4-2: List of Potential Outlier Results

Parameter	Vehicle	Vehicle Test ID's
PM	Vehicle A	R-A-5, D-A-4
PM	Vehicle C	D-A-1, D-A-2, D-A-4, D-B-5
PM	Vehicle D	D-B-1, R-B-2
CO, THC	Vehicle A	D-A-4
CO	Vehicle A	D-A-5
CO_2, Fuel Economy	Vehicle D	D-B-4, D-B-8

These results were inspected carefully by 44 Energy and reviewed individually with the CRC project panel. PM data from the PEMS Pegasor and soot data from the MSS were used to help better understand the potential PM outliers.[18] The PEMS Pegasor PM data showed a good correlation to MSS PM results, but the slope of the correlation appeared to be vehicle dependent, with little to no correlation at PM levels below 0.5 mg/mi. The Vehicle C data was almost entirely at this low level and showed the poorest correlation while Vehicle E showed a strong correlation with some PM results near 1.5 mg/mi. The correlation also appeared to be worse on road tests as compared to chassis dyno tests, as seen below in Figure 4-2.

[18] See APPENDIX G: PM Measurement Methods for additional information on PEMS Pegasor and MSS.

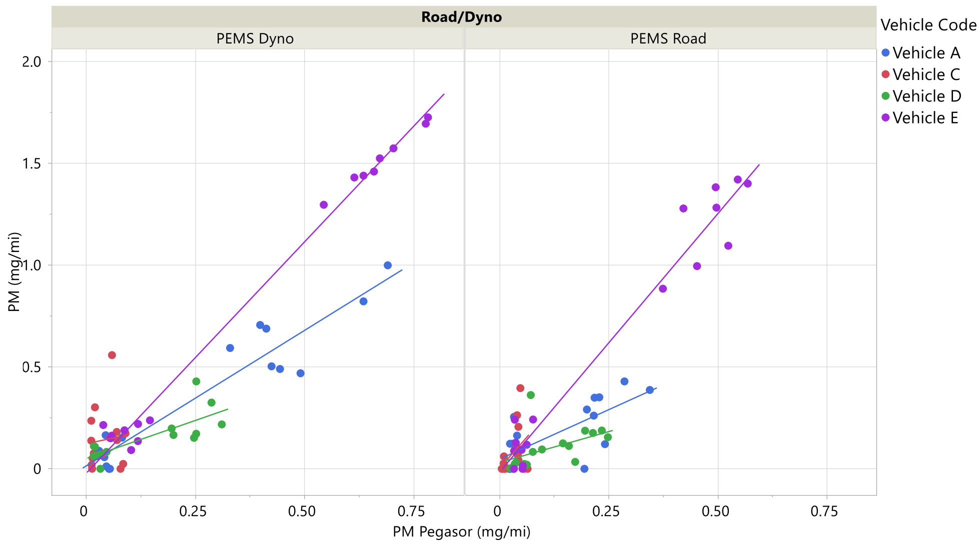


Figure 4-2: PEMS PM vs Pegasor PM

After review by the CRC project panel, it was determined that all of the PM potential outliers should be retained for statistical analysis purposes. For the CO and THC tests on Vehicle A, these tests were considered valid and were retained, though driver behavior is expected to have played a role in the increased emissions levels. More information on these two tests is provided in APPENDIX E: Chassis vs. On-road Speed Profile and Driving Behavior. For fuel economy, the project team decided to remove them from analysis of fuel economy and CO_2 only. The highest fuel economy result was determined to have had a usually low amount of engine on time, and though the other outlier result had no root cause discovered, it was also removed from CO_2 and fuel economy analysis in keeping with treatment of a very similar outlier which was removed in E-122-2. The two points, shown below in Figure 4-3, were still retained in the analysis of other emissions results.

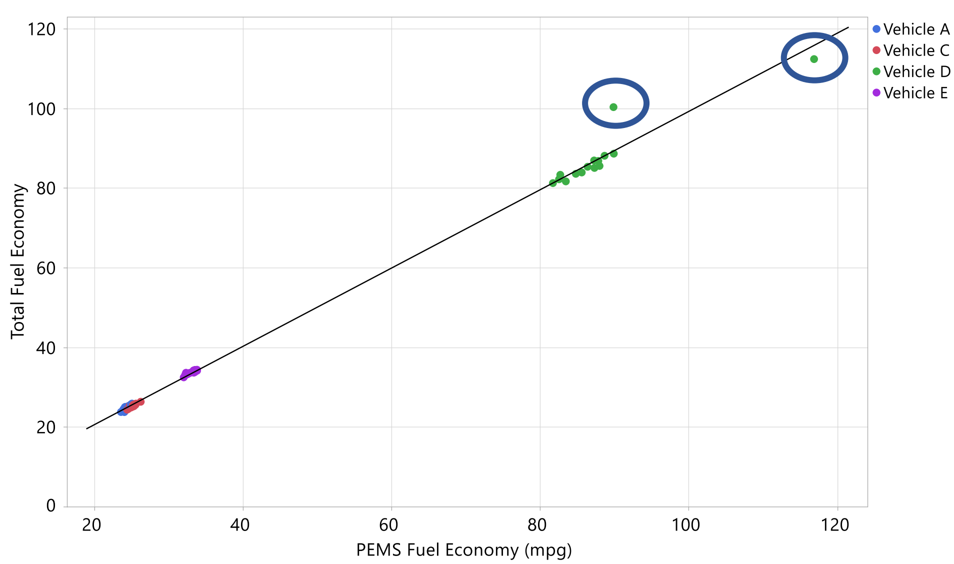


Figure 4-3: Fuel Economy Outliers

More detailed information about this outlier review is provided in APPENDIX L: Outlier Analysis.

4.1.2.1 Vehicle C CO and THC Test Set Differences

During the end of test data review, it was noticed that the first set of four Vehicle C chassis dyno tests with Fuel B had very different CO and THC than the second set of four tests on the same fuel which were run several months later. The differences are shown in Figure 4-4.

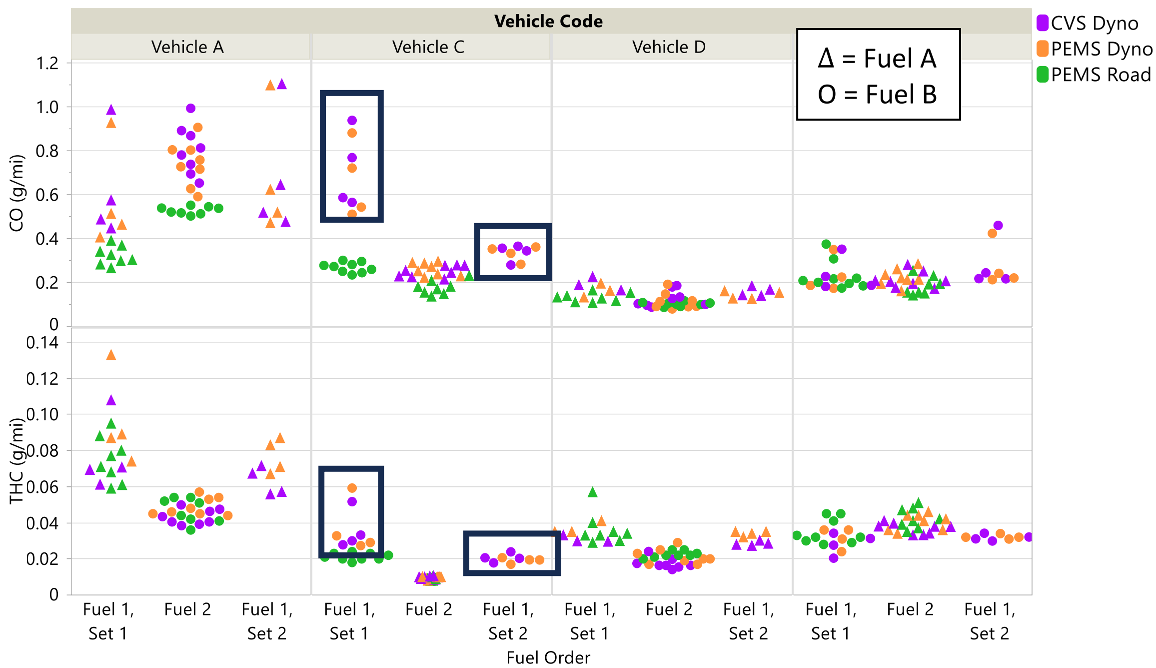


Figure 4-4: Vehicle C CO and THC Set Differences

Further review and discussion of these tests indicated that the first set of four tests had several differences as noted in Section 3.1.1 and Section 3.6.4.2, most notably an active check engine light related to a vehicle speed sensor fault during the first set of tests on the dyno. The known differences in the vehicle status between dyno test sets coupled with the observation of clear CO and THC emissions differences ultimately led the committee to determine that only the second set should be included in the analysis of CO and THC variability. Fuel economy and all other emissions component data from both sets were used in the variability analysis because no differences were observed between set 1 and 2 in Vehicle C for these data types.

4.1.2.2 Vehicle A CO Dyno vs. Road Variability

During the early data review, it was also noted that both Vehicle A and Vehicle C exhibited much less variability in CO for road testing as compared with chassis dyno testing.

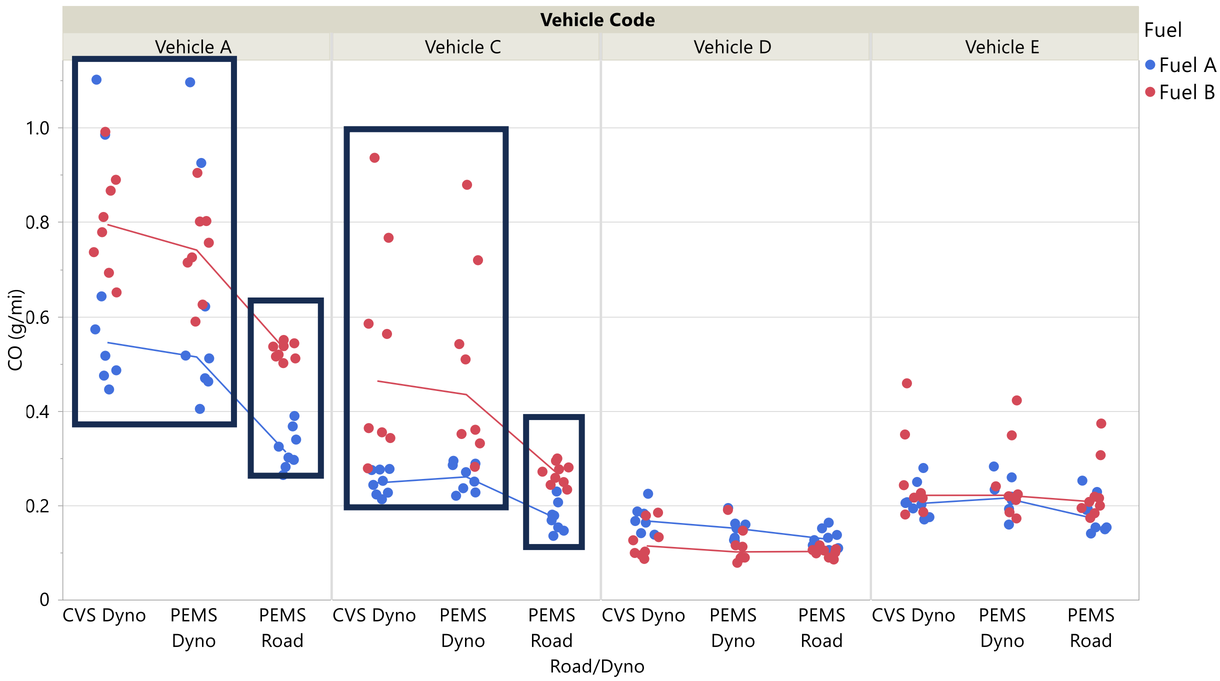


Figure 4-5: CO (g/mi) by Vehicle and Measurement Method

Note that the Vehicle C four highest CO data points on the dyno are the same four tests determined to be appropriate for removal as discussed in Section 4.1.2.1. For Vehicle A data, review of the highest two data points indicated differences in vehicle operation by the driver. To quantify the observed differences, a drive metric was derived using the OBDII accelerator pedal position: discussed further in APPENDIX E: Chassis vs. On-road Speed Profile and Driving Behavior. The plot of the CO data for Vehicle A showed a good correlation to this drive metric, shown in Figure 4-6, and the highest CO data point appeared to fall very near to the best fit line.[19] The drive metric value for the Fuel A CO data point just below 1 g/mi had a value near 2000 (not shown on the plots below) indicating that, though not falling on the correlation line with other data points, the driving style for this test was different from the other Vehicle A tests. It would also appear by looking at Figure 4-7 that this drive metric can help explain some of the increased variability on dyno testing when compared to road testing.

[19] Drive metric calculated here using values of N to represent the end of Phase 1 of the drive cycle. See Section 3.6.4.3

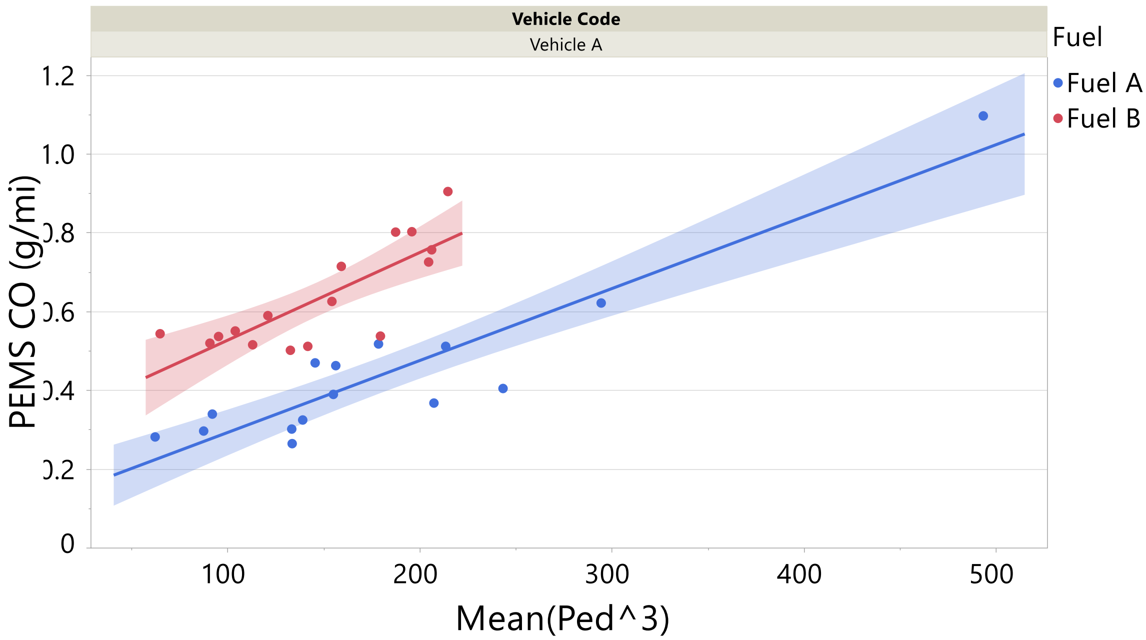


Figure 4-6: CO (g/mi) vs. Driver Pedal Statistic

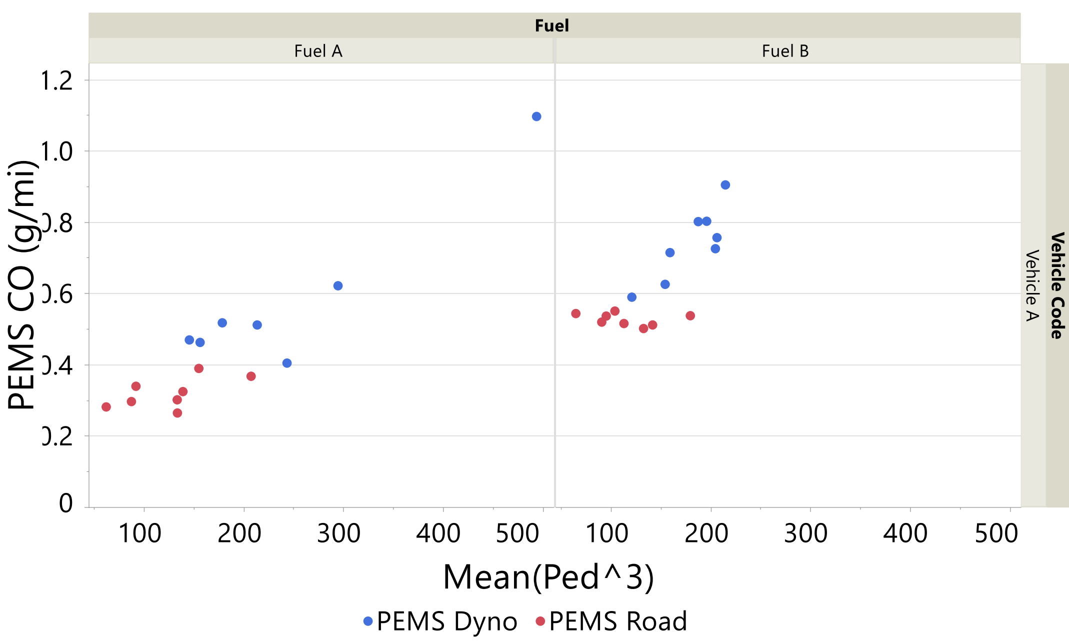


Figure 4-7: CO (g/mi) vs. Driver Pedal Statistic, Road vs. Dyno

4.2 PEMS Variability

In this section, PEMS variability and repeatability are discussed. For each emissions parameter, several variability comparisons are made. As a best estimate of variability differences which may be attributable to the severe cycle conditions of the E-134 cycle, comparisons are made back to results from the E-122-2 program, limiting to only the common Vehicles A, C, and D. While the data transformations discussed in Section 4.1.1 can remove some variability differences due to emissions level, it should be noted that these transformations do not always work optimally for all variable levels in a multi-factor study, and, in this case, across test programs conducted by different labs and cycles. In addition, there may be vehicle driver differences across projects which could confound the comparison further and that should be considered when drawing conclusions.

Next, variability is compared between emissions results from the CVS on the dyno to PEMS results on the dyno to determine differences attributable to the PEMS itself. Finally, variability comparisons are made to compare chassis dyno results, both from the CVS and the PEMS, to road results from the PEMS. Again, it should be noted that different vehicle drivers are used on chassis dyno and road tests, so these driver differences are a confounding factor for this comparison.

4.2.1 Variability of Particulate Matter (PM, mg/mi)

A plot of the PM data for E-134 is given below in Figure 4-8, with the same data from E-122-2 following in Figure 4-9. The variance-stabilizing transformation to remove variability due to level was $\sqrt[3]{PM + 0.1}$. The graph of the transformed data for E-134 is given in Figure 4-10.

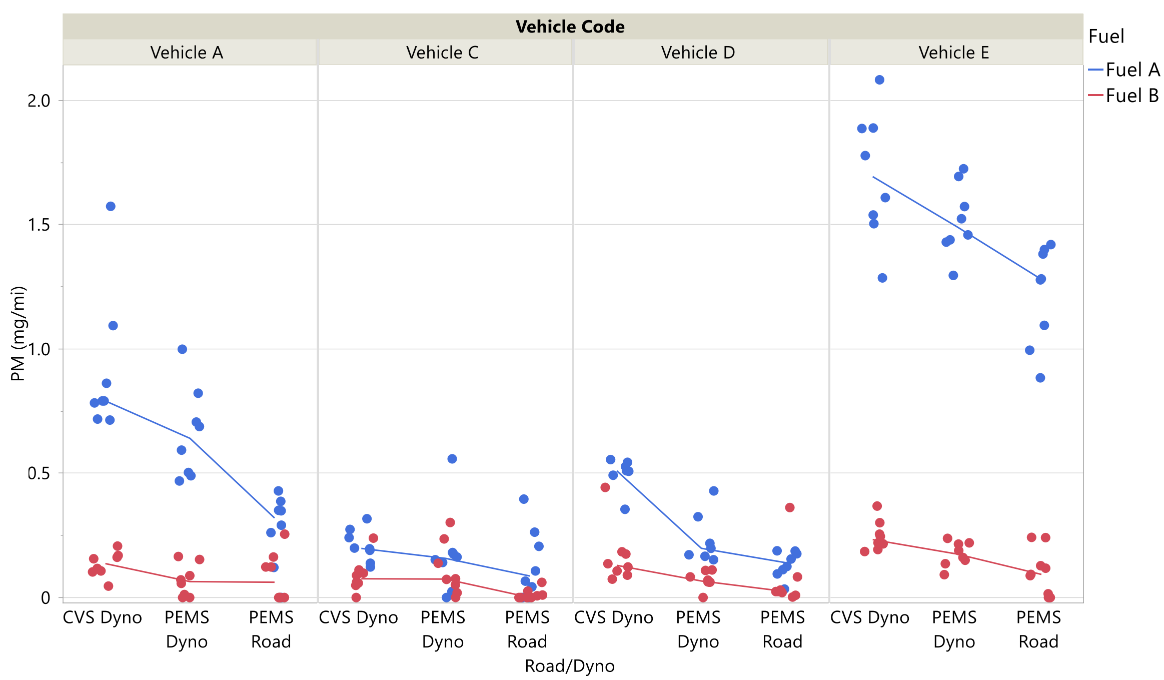


Figure 4-8: E-134 PM (mg/mi) by Vehicle and Measurement Method

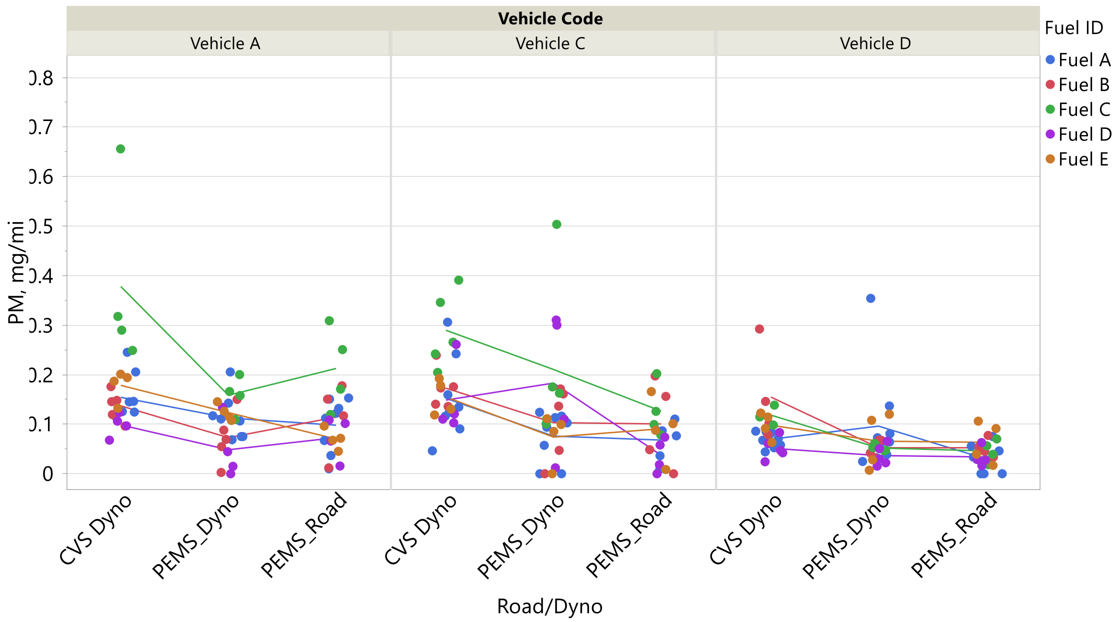


Figure 4-9: E-122-2 PM (mg/mi) by Vehicle and Measurement Method

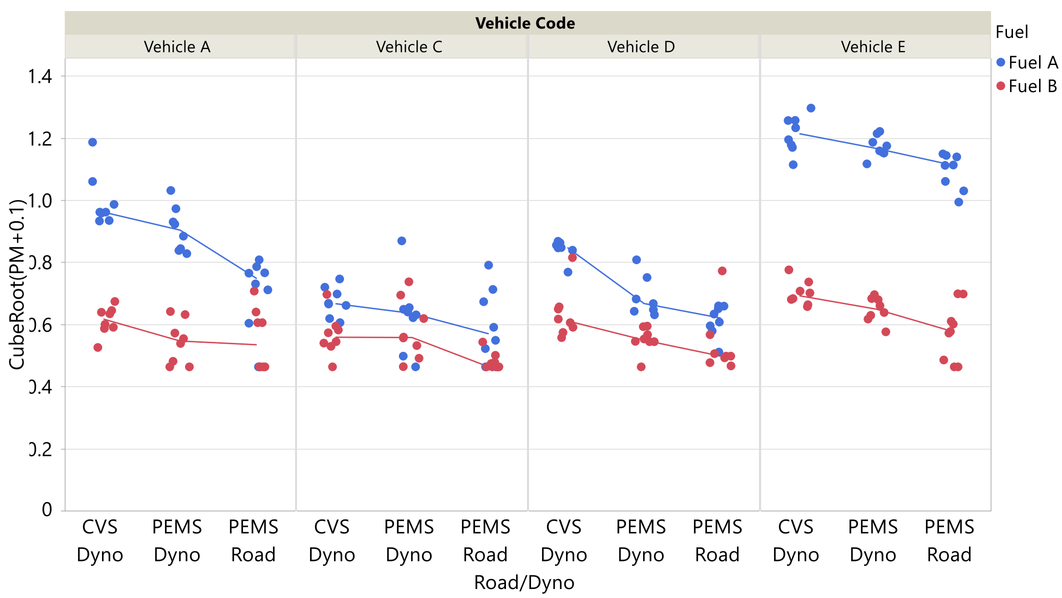


Figure 4-10: E-134 CubedRoot(PM+0.1) by Vehicle and Measurement Method

In the previous E-122-2 project, the small constant value of 0.1 was not a part of the transformation formula. Therefore, to make the comparison across programs more appropriate, this transformation using the constant value was applied to the E-122-2 data. For the three common vehicles from both test programs, the E-122-2 transformed data is shown in Figure 4-11. It should be noted in the figure that there were five test fuels in E-122-2, and that “Fuel A” and “Fuel B” in the figure are not the same as the fuels with the same name in the current E-134 project.

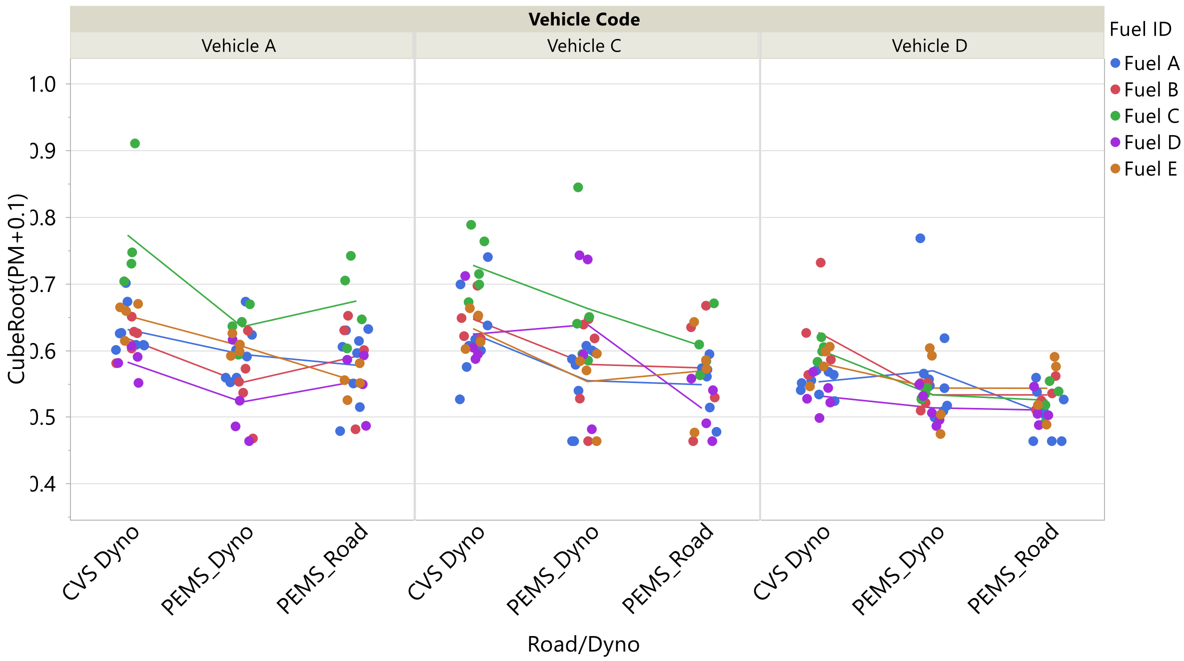


Figure 4-11: E-122-2 CubedRoot(PM+0.1) by Vehicle and Measurement Method

A regression model was run of the form:

$$\sqrt[3]{PM + 0.1} \sim Vehicle + Fuel + Vehicle * Fuel.$$

From the model, root mean square error (RMSE) values were obtained. These values represent the model estimated standard deviations for repeated data on the same vehicle and fuel combination. Squaring the RMSE therefore provides a variance estimate. The well-known F-test is performed by taking the ratio of two variances and comparing the value to distributional cut-off based on the degrees of freedom from each variance estimate. A two-sided F-test was performed on the data to compare the variability from E-134 to variability observed in E-122-2, using only the common vehicles from both projects. The results of the testing is given in the fourth column of Table 4-3, with a highlighted “Yes” if the E-134 variability was statistically different from E-122-2 variability, based on a 5% significance level for the test. Additionally, an F-test was run to compare PEMS data (dyno and road) to CVS dyno data within the same program. Highlighted and starred PEMS standard deviations in the second and third column of Table 4-3 indicate that this value is statistically greater than the CVS dyno standard deviation in the same column. Also included for comparison only are the E-134 standard deviation estimates with Vehicle E included.

Finally, another model was run individually by vehicle and measurement method, with fuel as the only model factor. This data is shown in Table 4-4. Highlighting is again provided to show statistically significance differences, following the same format as in Table 4-3.

Table 4-3: CubedRoot(PM+0.1) Pooled Standard Deviation Estimates

Measurement Method	E-122-2 Std. Dev. (Veh's A,C,D)	E-134 Std. Dev. (Veh's A,C,D)	Program Variances Statistically Different?	E-134 Std. Dev. (w/ Veh. E)
CVS Dyno	0.0448	0.0637	Yes	0.0606
PEMS Dyno	0.0653*	0.0814	No	0.0733
PEMS Road	0.0516	0.0913*	Yes	0.0877

Starred and highlighted results in the second and third column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

Table 4-4: CubedRoot(PM+0.1) Individual Vehicle Standard Deviation Estimates

Measurement Method	Vehicle	Std. Dev. (E-122-2)	Std. Dev. (E-134)	Program Variances Statistically Different?
CVS Dyno	Vehicle A	0.0458	0.0691	No
	Vehicle C	0.0526	0.0580	No
	Vehicle D	0.0341	0.0636	Yes
	Vehicle E	N/A	0.0502	N/A
PEMS Dyno	Vehicle A	0.0460	0.0712	No
	Vehicle C	0.0854*	0.1093*	No
	Vehicle D	0.0582*	0.0537	No
	Vehicle E	N/A	0.0375	N/A
PEMS Road	Vehicle A	0.0561	0.1078	Yes
	Vehicle C	0.0606	0.0841	No
	Vehicle D	0.0340	0.0796	Yes
	Vehicle E	N/A	0.0769	N/A

Starred and highlighted results in the third and fourth column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column for that vehicle. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

From the tables, one can conclude the following:

- Variability due to cycle differences:
  - The E-134 cycle had higher variability than the E-122-2 cycle for CVS dyno results and for PEMS road results. Vehicles A and D saw the biggest changes, while Vehicle C showed the least change and was the only vehicle of the three from E-122-2 to not be significantly greater for any statistical comparison utilizing only that vehicle's data. Some of the difference in variability may be attributable to some degree to higher PM emissions in E-134 for Vehicles A and D. In the previous E-122-2 program, both of these vehicles had

PEMS road results very near zero and may have limited the full distribution of result. Vehicle C, which showed no statistical change, was very near the same PM levels in both programs.

- Variability of PEMS vs. CVS Dyno
    - Of all four vehicles, only Vehicle C showed a statistically significant increase in variability of PEMS results (PEMS dyno) when compared to CVS dyno results. However, PEMS road PM variability was directionally higher on all four vehicles, and therefore when grouping all vehicles together to test if the PEMS road PM variability is higher for the entire group when compared to the CVS dyno results, there is enough statistical power to claim a significant increase.

4.2.1.1 Variability of PM (mg/mi) by Phase

PM results were also looked at by Phase. Only a single filter was used to determine composite PM, so in an attempt to gain more insight into the phase-by-phase PM accumulation, PM data calculated from the PEMS Pegasor was inspected and compared to final PM filter data from the PEMS unit. These are plotted by Vehicle in Figure 4-12 to Figure 4-15 for Vehicles, A, C, D, and E, respectively. In the plots, the phase level data from the Pegasor is in the first three columns, followed by cumulative PM from the Pegasor in the fourth column, and finally PM from the PEMS filter in the final column.

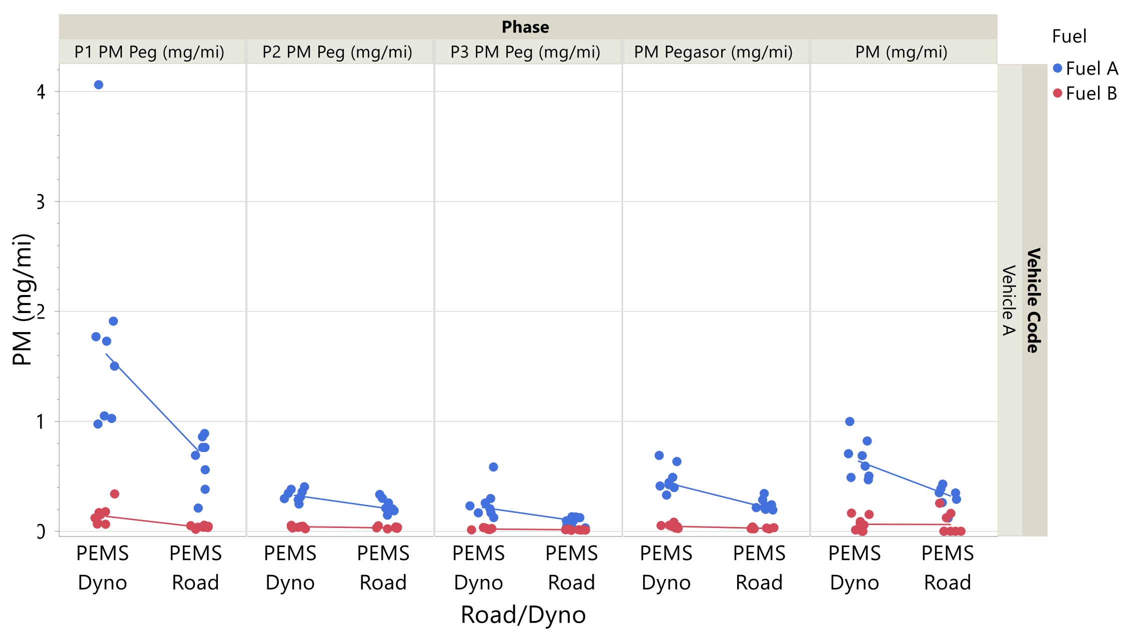


Figure 4-12: Vehicle A PM (mg/mi) by Phase

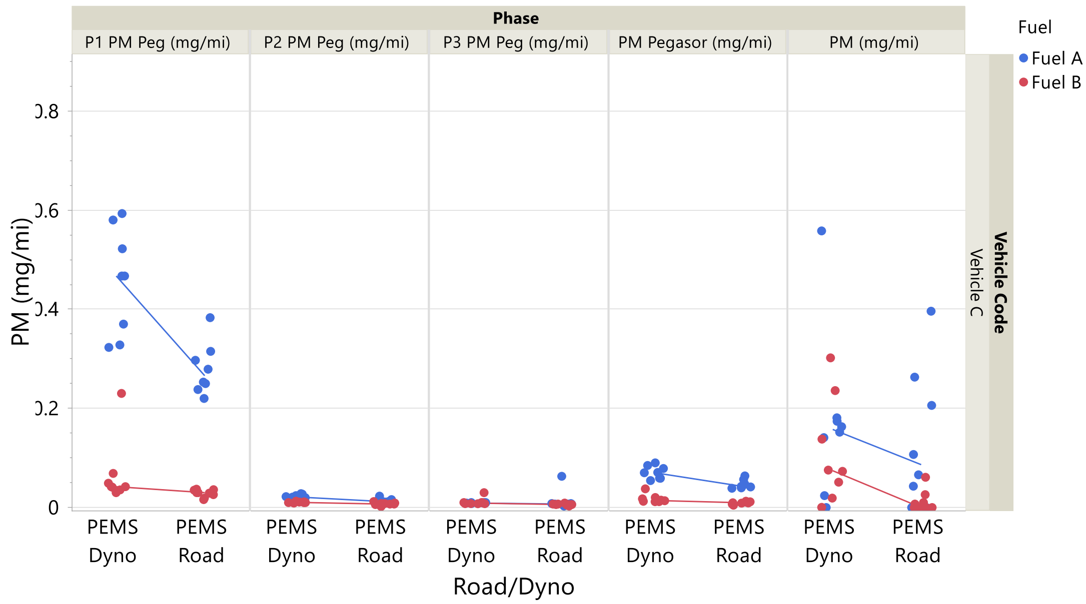


Figure 4-13: Vehicle C PM (mg/mi) by Phase

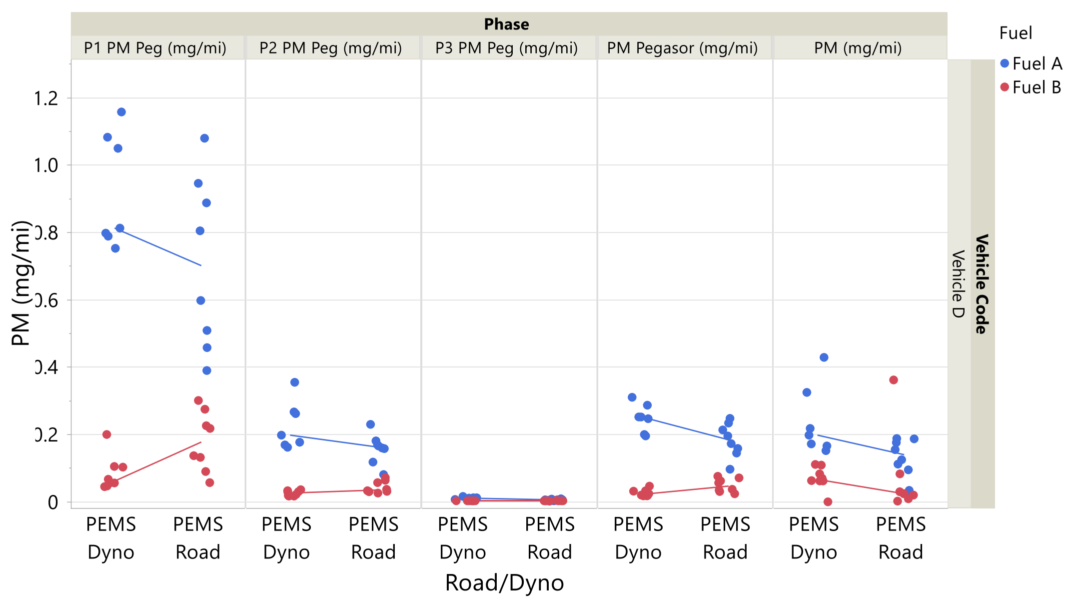


Figure 4-14: Vehicle D PM (mg/mi) by Phase

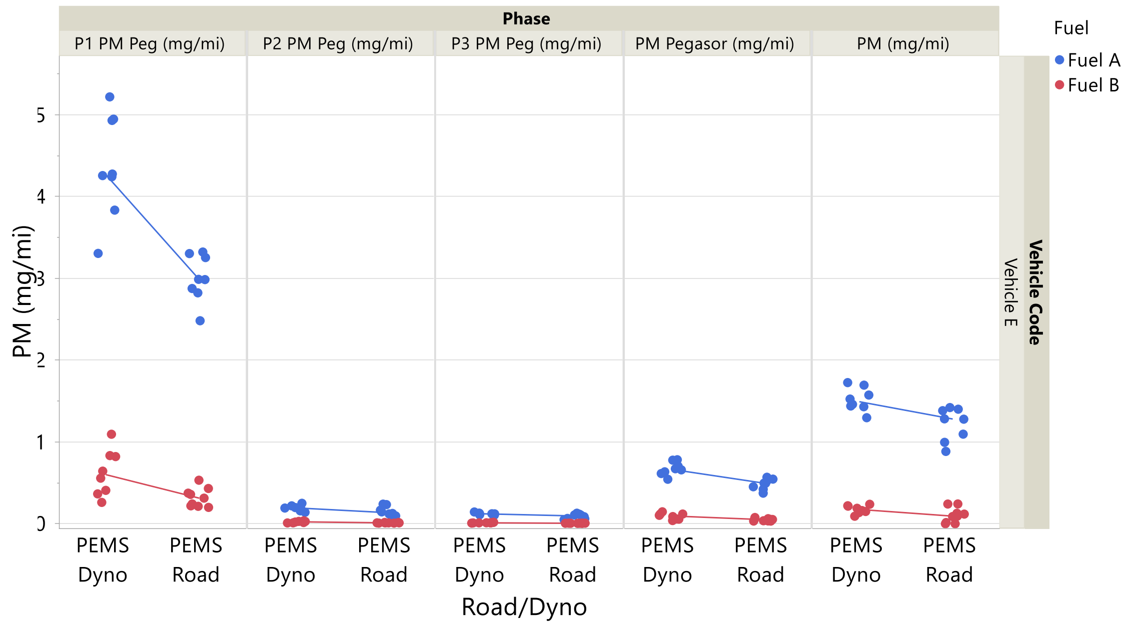


Figure 4-15: Vehicle E PM (mg/mi) by Phase

From the plots, Vehicle A and Vehicle E appear to have the best correlation of Pegasor PM to PEMS filter PM. As discussed previously, this appears to be closely related to PM levels. Vehicle C and Vehicle D have a poorer correlation, but these vehicles have PM filter levels consistently below 0.5 mg/mi, and below this level the correlation is very weak. This is further supported by Figure 4-16, which shows PEMS filter PM plotted against Phase 1 PM Pegasor data in red, and vs. composite PM Pegasor data in blue. Though the Phase 1 PM level is higher, the composite PM data shows a slightly better correlation to composite PM filter data.

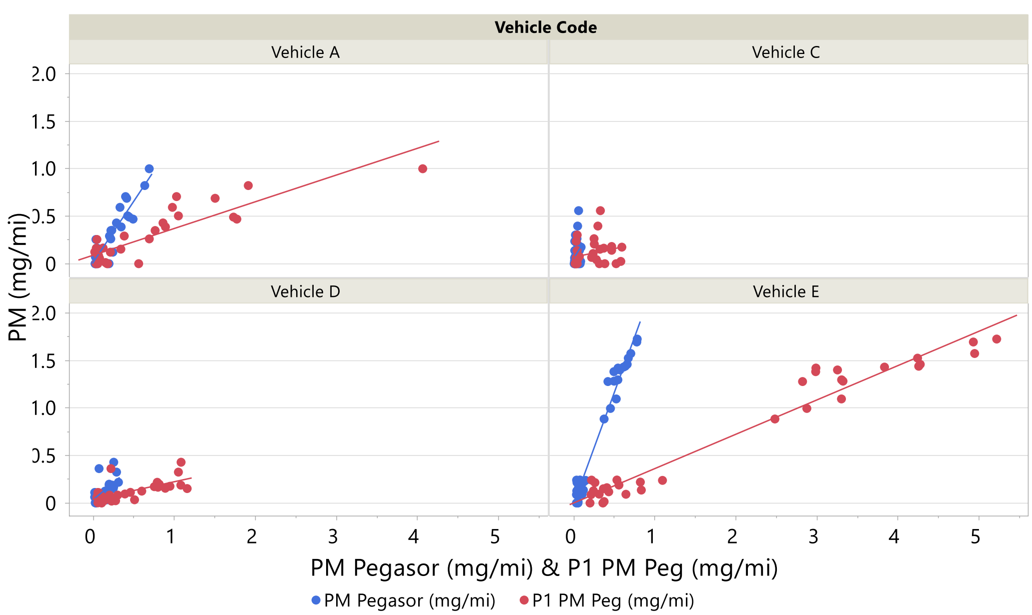


Figure 4-16: PEMS PM Filter vs. PM from Pegasor and Phase 1 PM from Pegasor

4.2.2 Variability Gaseous Emissions and Fuel Economy

For gaseous emissions (THC, CO, CO_2, NO_x) and fuel economy, the same methodology is followed as detailed in Section 4.2.1. Each section includes a plot of the emissions parameter in original units and transformed units (where applicable), along with a plot of E-122-2 data for comparison. Tables summarizing the RMSE's from the model along with statistically significant differences are provided, first for the aggregate data, and then by individual vehicle. Plots of E-134 phase-level data are included at the end of each section.

4.2.2.1 Variability of Total Hydrocarbons (THC, g/mi)

A plot of the untransformed THC data is shown below in Figure 4-17 for E-134 and in Figure 4-18 for E-122-2, with the natural log transformed data for both projects following in Figure 4-19 and Figure 4-20.

Comparing the E-134 data to the E-122-2 data in the plots, there were higher levels of THC in E-134 for both Vehicle A and Vehicle D, and for Vehicle C Fuel B data.

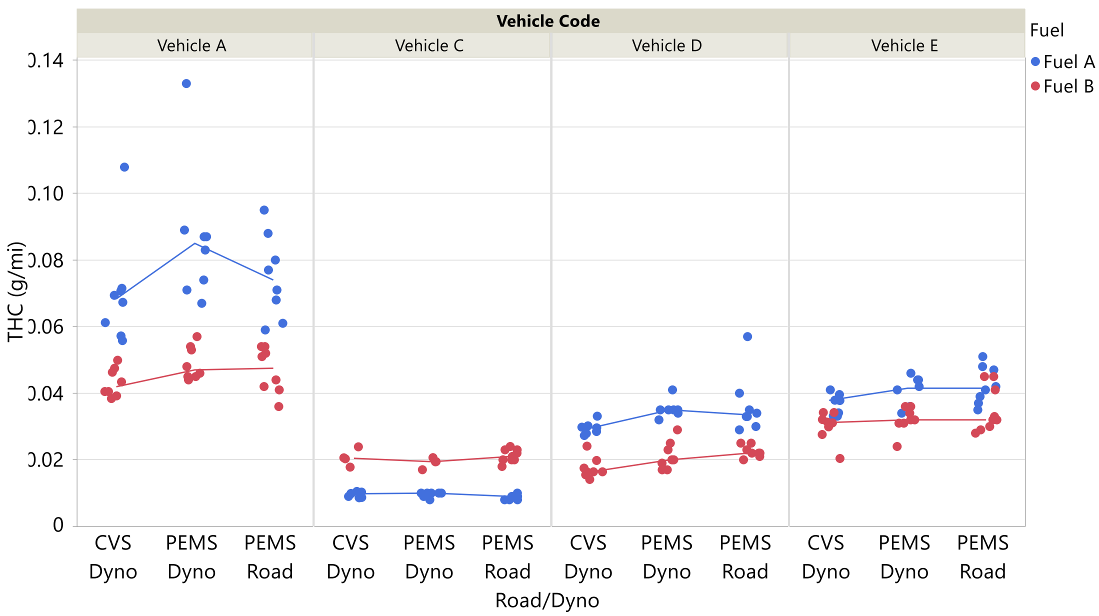


Figure 4-17: E-134 THC (g/mi) by Vehicle and Measurement Method

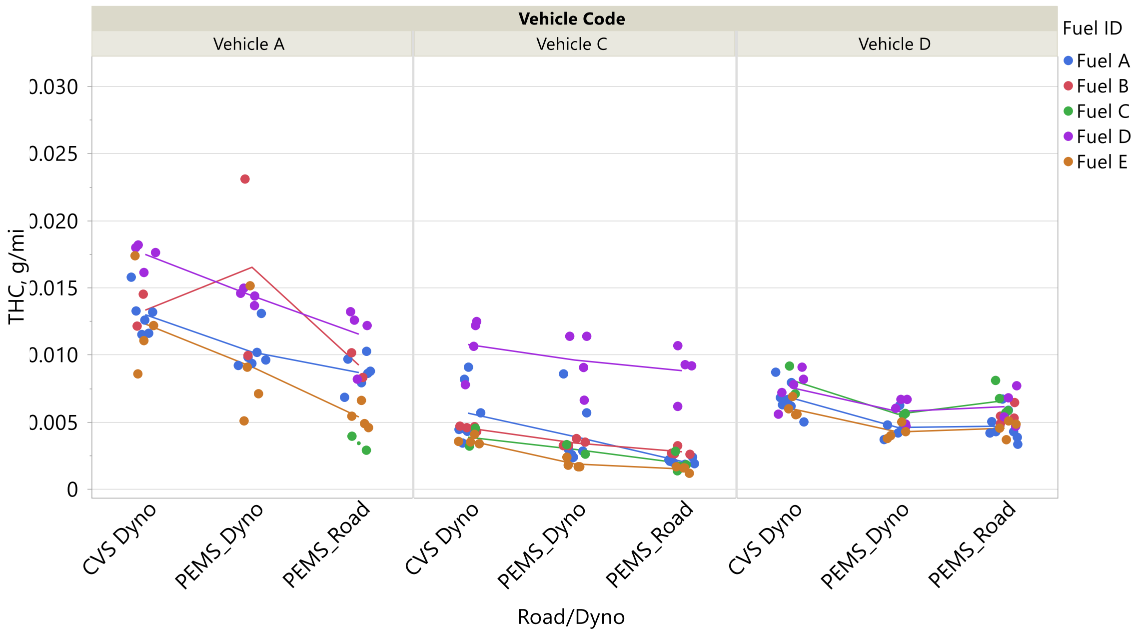


Figure 4-18: E-122-2 THC (g/mi) by Vehicle and Measurement Method

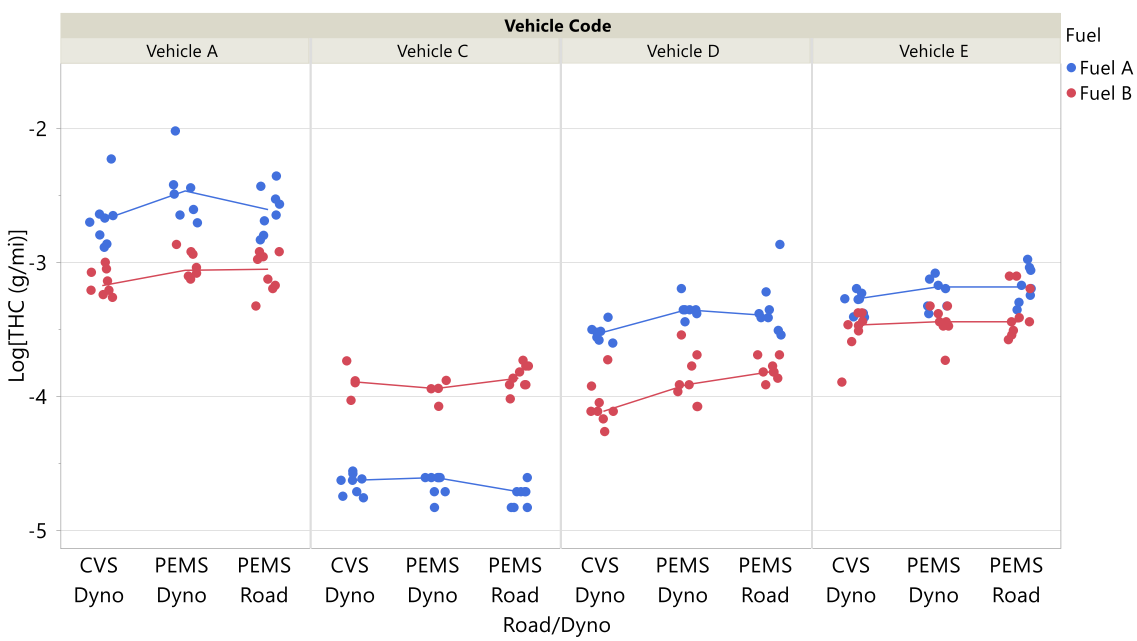


Figure 4-19: E-134 Ln(THC (g/mi)) by Vehicle and Measurement Method

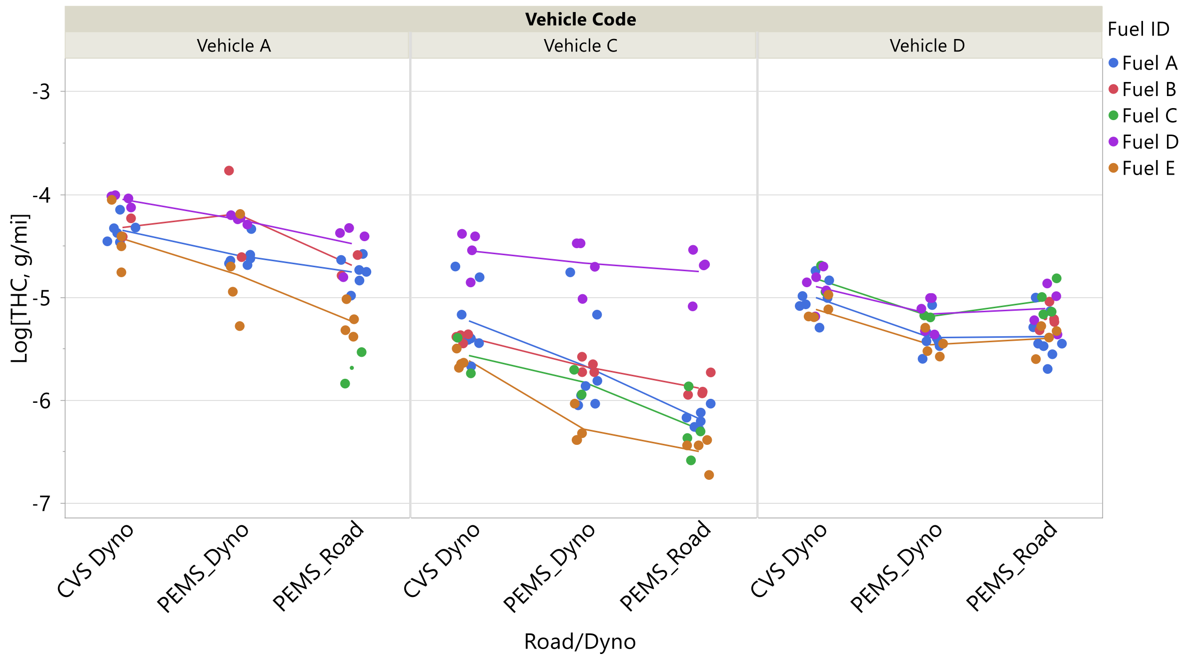


Figure 4-20: E-122-2 Ln(THC (g/mi)) by Vehicle and Measurement Method

The pooled standard deviation estimates for both programs are given in Table 4-5 and the individual vehicles estimates are given in Table 4-6. E-134 variability was significantly lower, but this is mainly driven by the estimates for Vehicle C. While the variability in THC is statistically much larger in E-122-2 for Vehicle C, the difference is not of much practical meaning because the magnitude of THC emissions in both projects is very low for this vehicle.

Table 4-5: Ln(THC) Pooled Standard Deviation Estimates

Measurement Method	E-122-2 Std. Dev. (Veh's A,C,D)	E-134 Std. Dev. (Veh's A,C,D)	Program Variances Statistically Different?	E-134 Std. Dev. (w/ Veh. E)
CVS Dyno	0.2030	0.1338	Yes	0.1333
PEMS Dyno	0.2766*	0.1405	Yes	0.1354
PEMS Road	0.1844	0.1392	No	0.1459

Starred and highlighted results in the second and third column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

Table 4-6: Ln(THC) Individual Vehicle Standard Deviation Estimates

Measurement Method	Vehicle	Std. Dev. (E-122-2)	Std. Dev. (E-134)	Program Variances Statistically Different?
CVS Dyno	Vehicle A	0.1699	0.1610	No
	Vehicle C	0.2493	0.0917	Yes
	Vehicle D	0.1668	0.1286	No
	Vehicle E	N/A	0.1321	N/A
PEMS Dyno	Vehicle A	0.2991*	0.1650	Yes
	Vehicle C	0.3376	0.0827	Yes
	Vehicle D	0.1504	0.1469	No
	Vehicle E	N/A	0.1210	N/A
PEMS Road	Vehicle A	0.1738	0.1599	No
	Vehicle C	0.1856	0.0864	Yes
	Vehicle D	0.1903	0.1611	No
	Vehicle E	N/A	0.1635	N/A

Starred and highlighted results in the third and fourth column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column for that vehicle. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

4.2.2.1.1 Variability of Total Hydrocarbons (THC, g/mi) by Phase

The E-134 THC phase level data is provided below in Figure 4-21 to Figure 4-24 by vehicle for Vehicles A, C, D, and E, respectively. As can be seen from the plots, almost all the hydrocarbons come from Phase 1, which is expected. Figure 4-25 further shows the strength of correlation between Phase 1 and final THC, with an R^2 value of 0.976 for the regression line fit of the two parameters. There is not much else that appears noteworthy in the plots by phase.

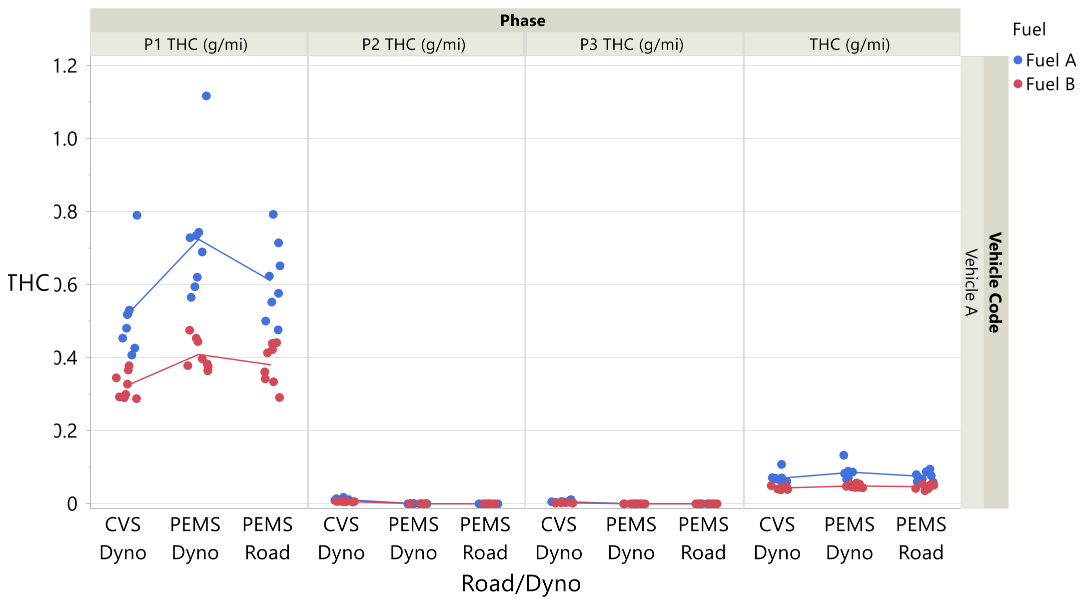


Figure 4-21: Vehicle A THC (g/mi) by Phase

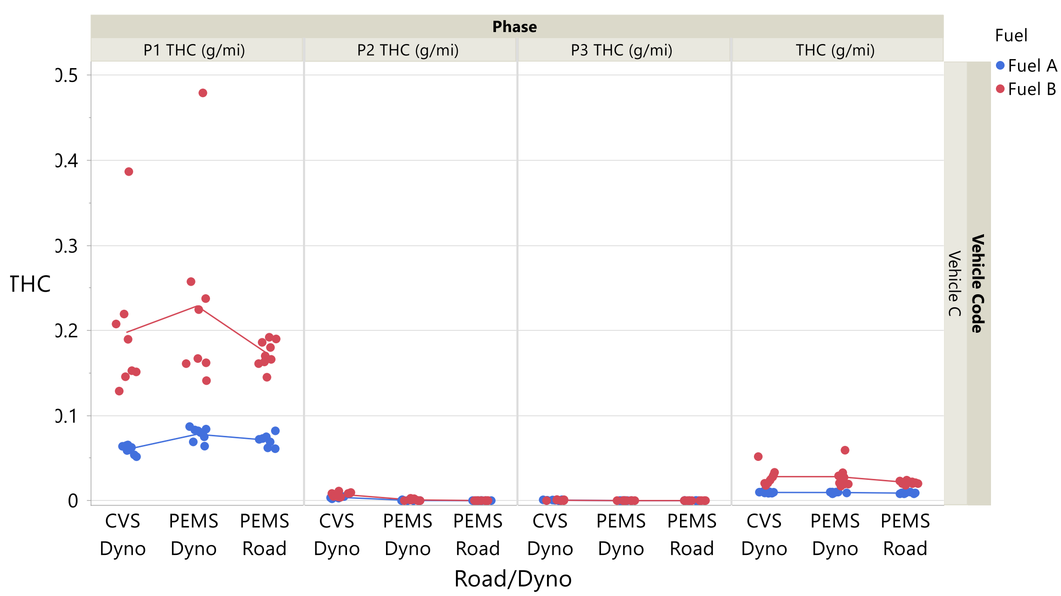


Figure 4-22: Vehicle C THC (g/mi) by Phase

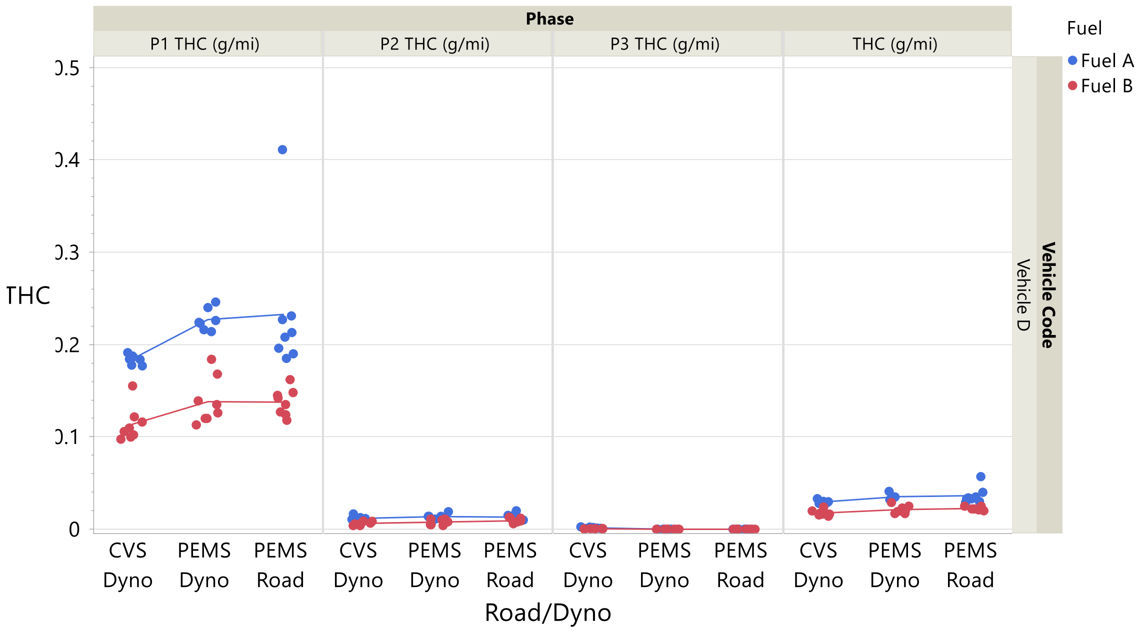


Figure 4-23: Vehicle D THC (g/mi) by Phase

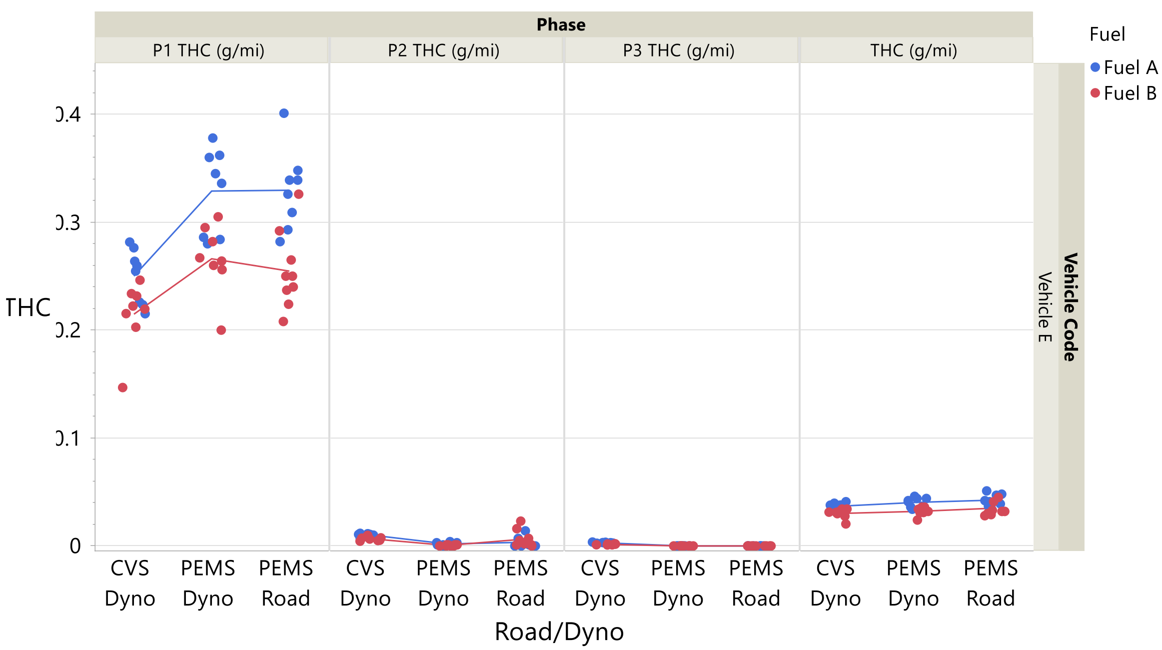


Figure 4-24: Vehicle E THC (g/mi) by Phase

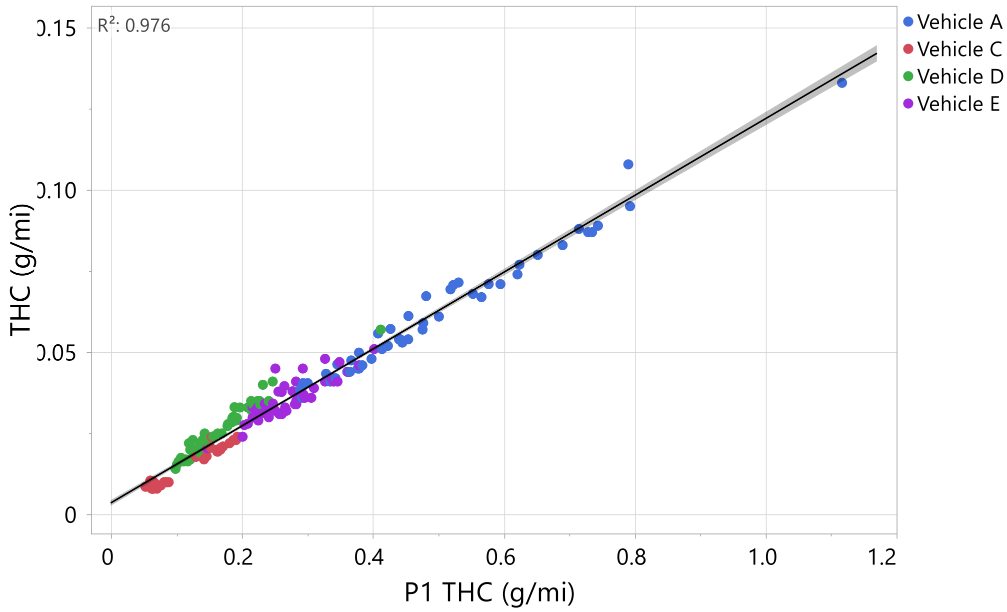


Figure 4-25: THC (g/mi) vs. Phase 1 THC (g/mi)

4.2.2.2 Variability of Carbon Monoxide (CO, g/mi)

A plot of the untransformed CO data is shown below in Figure 4-26 for E-134 and in Figure 4-27 for E-122-2, with the natural log transformed data for both projects following in Figure 4-28 and Figure 4-29.

Comparing the E-134 data to the E-122-2 data in the plots, it is worth noting that the range of CO values is very similar in both projects for the three common vehicles, so the choice of transformation is not as important to hold similarly across the two projects to make variance comparisons.

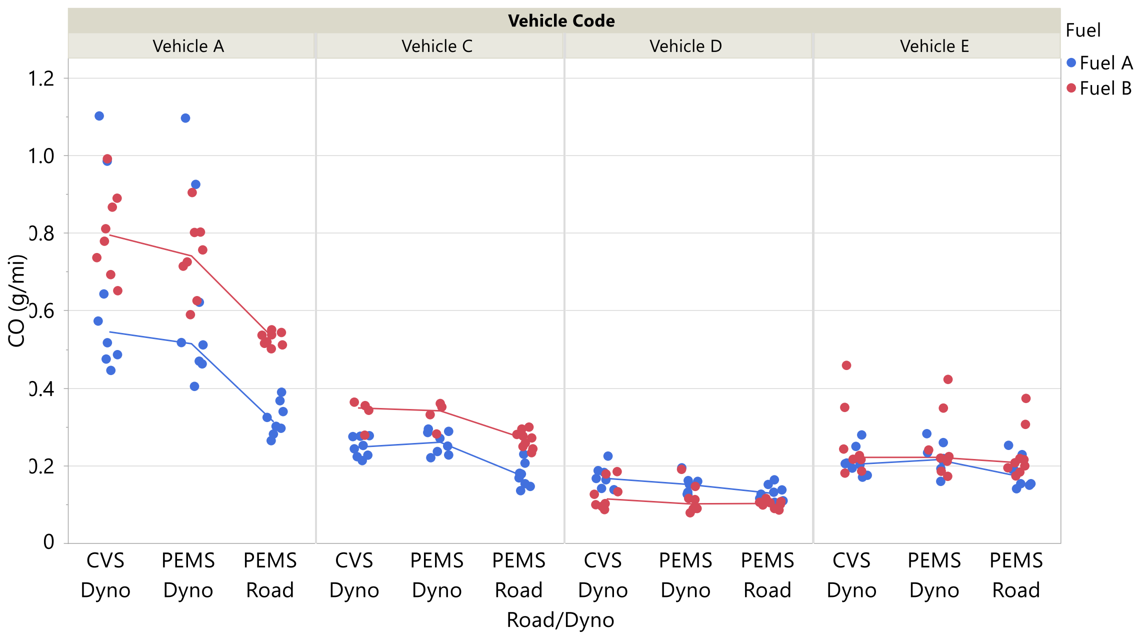


Figure 4-26: E-134 CO (g/mi) by Vehicle and Measurement Method

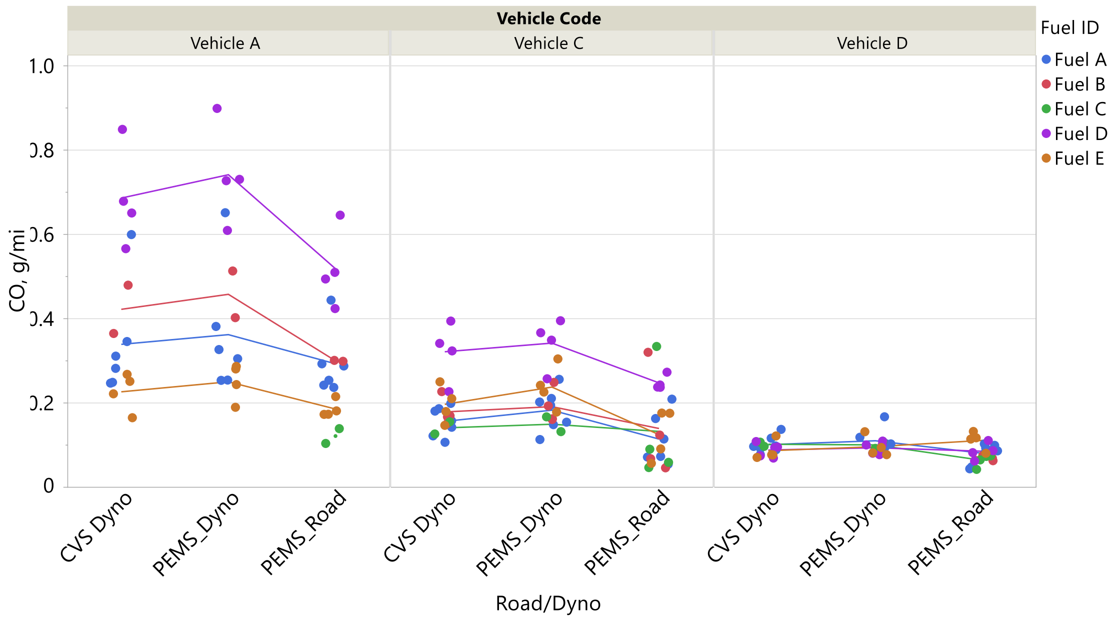


Figure 4-27: E-122-2 CO (g/mi) by Vehicle and Measurement Method

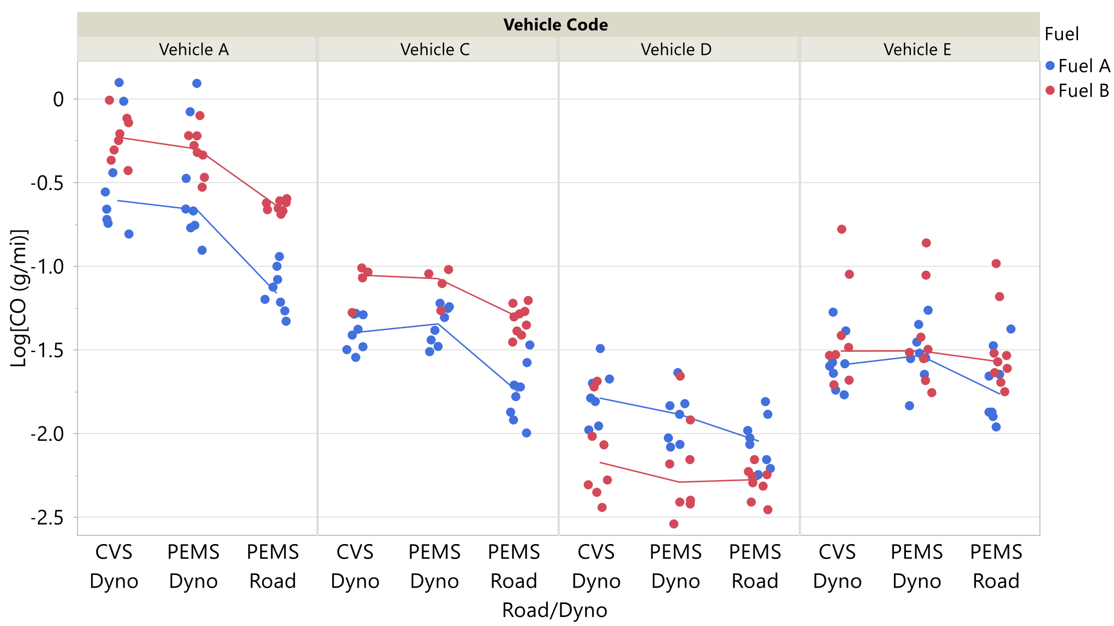


Figure 4-28: E-134 Ln(CO (g/mi)) by Vehicle and Measurement Method

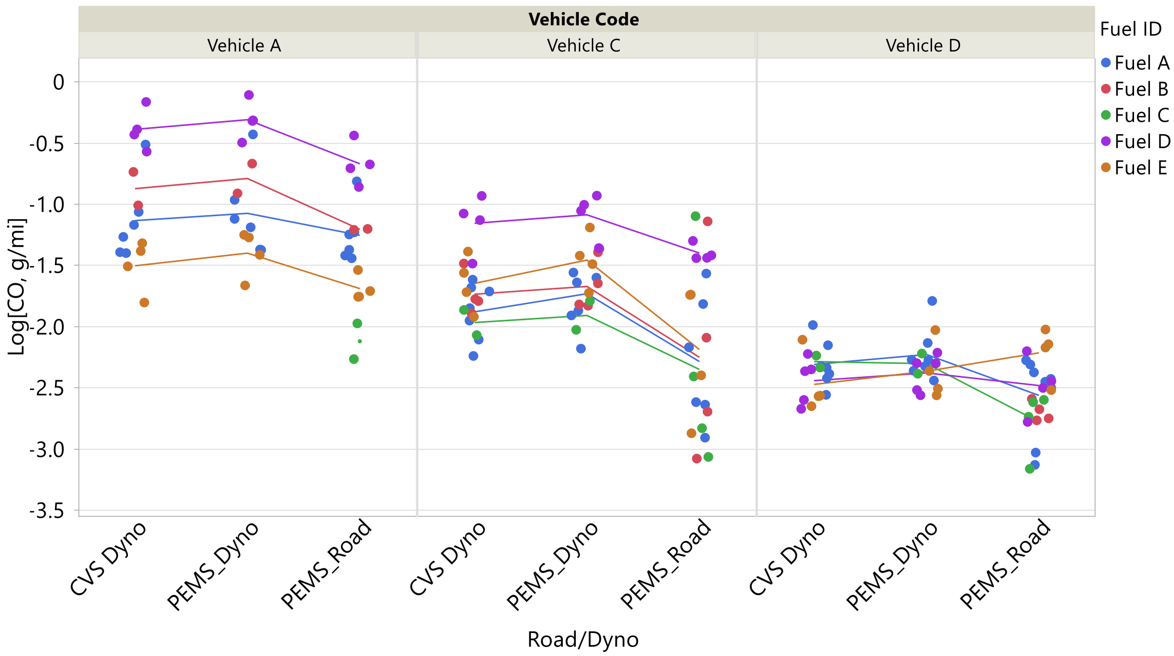


Figure 4-29: E-122-2 Ln(CO (g/mi)) by Vehicle and Measurement Method

The pooled standard deviation estimates for both programs are given in Table 4-7 and the individual vehicle estimates are given in Table 4-8. From the tables one can see that the dyno variability, PEMS and CVS, was very similar between the two programs, but the PEMS Road variability is very different between the two programs.

In E-122-2, an increase in CO variability was observed for road testing. From Table 4-8, this increase is shown to be primarily due to the increase in Vehicle C PEMS road variability. Based on the raw data, it appears this is somewhat caused by choice of transformation not being appropriate for this vehicle. The transformations are selected based on average behavior across all vehicles, and it appears this vehicle is not as repeatable as others at very low CO levels. Therefore, the data seems to indicate that the road variability between road tests and dyno tests for Vehicle C is in fact very similar in E-122-2 for road tests and dyno tests before transformation, but the lower absolute CO levels for road testing after a log-transformation become a statistically larger standard deviation.

For E-134 data, one can see that the decrease in PEMS road-testing variability when compared to the chassis dyno testing is driven by Vehicle A and Vehicle D. For Vehicle D, the difference appears to be driven by a pair of higher-than-normal results on the dyno (D-B-1 and D-B-8). At these very low levels, small deviations have a large impact in log-transformed units. Without these two data points, the difference in variability is not statistically significant. For Vehicle A, there were also two higher than normal results for chassis dyno tests, discussed previously in the outlier section, Section 4.1.2 (D-A-4 and D-A-5). Without these two previously discussed results, the variability difference is not statistically significant. However, there is still very likely a contribution of previously discussed driver pedal behavior differences that is contributing to the small road-test standard deviations in E-134.

Table 4-7: Ln(CO) Pooled Standard Deviation Estimates

Measurement Method	E-122-2 Std. Dev. (Veh's A,C,D)	E-134 Std. Dev. (Veh's A,C,D)	Program Variances Statistically Different?	E-134 Std. Dev. (w/ Veh. E)
CVS Dyno	0.2236	0.2220	No	0.2319
PEMS Dyno	0.2306	0.2278	No	0.2342
PEMS Road	0.4157*	0.1216*	Yes	0.1589

Starred and highlighted results in the second and third column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

Table 4-8: Ln(CO) Individual Vehicle Standard Deviation Estimates

Measurement Method	Vehicle	Std. Dev. (E-122-2)	Std. Dev. (E-134)	Program Variances Statistically Different?
CVS Dyno	Vehicle A	0.2594	0.2615	No
	Vehicle C	0.2174	0.1100	Yes
	Vehicle D	0.1957	0.2393	No
	Vehicle E	N/A	0.2563	N/A
PEMS Dyno	Vehicle A	0.2635	0.2692	No
	Vehicle C	0.2300	0.1129	Yes
	Vehicle D	0.1990	0.2447	No
	Vehicle E	N/A	0.2502	N/A
PEMS Road	Vehicle A	0.1832	0.0965*	Yes
	Vehicle C	0.6300*	0.1351	Yes
	Vehicle D	0.2602	0.1288*	Yes
	Vehicle E	N/A	0.2349	N/A

Starred and highlighted results in the third and fourth column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column for that vehicle. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

4.2.2.2.1 Variability of Carbon Monoxide (CO, g/mi) by Phase

The E-134 CO phase level data is provided below in Figure 4-30 to Figure 4-33 by vehicle for Vehicles A, C, D, and E, respectively.

For Vehicle A, the highest CO result from Phase 1 (D-A-4) is the second highest composite CO result for that fuel. The Phase 2 deviation near 1 g/mi on Fuel A (D-A-5) is the result which finished with the highest CO for that fuel. The unique source of additional CO during Phase 2 of this test was determined to occur during a hard acceleration up to highway speeds (~75 mph). The cause was determined to be an excessive pedal position of ~80% for a short period of time during the acceleration relative to the 30-50% pedal position typically required to achieve the target acceleration rate.

For Vehicle D, the two highest results on Fuel B (D-B-1 and D-B-8) appear to have both come from deviations in Phase 1 CO. No clear cause of the higher CO emissions was identified for these tests.

For Vehicle E, there are two dyno tests and two road tests which gave higher than normal results on Fuel B (dyno tests D-B-1 and D-B-5 and road tests R-B-4 and R-B-8). In all four cases, deviations in final composite values were driven by differences seen in Phase 2 and Phase 3. Like the cases in Vehicle A test D-A-5, the driver for high composite CO during the two Vehicle E dyno tests was determined to be excessive pedal position values during the acceleration to highway speeds. This was not the case for the two high CO results for the two Vehicle E road tests; high CO was observed throughout the high speed portion of the cycle. The cause is unknown for these road tests but may be related to the cold ambient temperatures the tests were performed at.[20]

Finally, Figure 4-34 shows the strength of correlation between Phase 1 and final composite CO, with and R^2 value of 0.893 for the regression line fit of the two parameters. The value is driven lower by the Phase 2 and Phase 3 deviations described above.

[20] Ambient temperatures for these two tests were around 35-38°F. One other test was performed at a similar temperature with no observed impact on CO emissions. All other Vehicle E Fuel B tests were performed at ambient temperatures above 44°F.

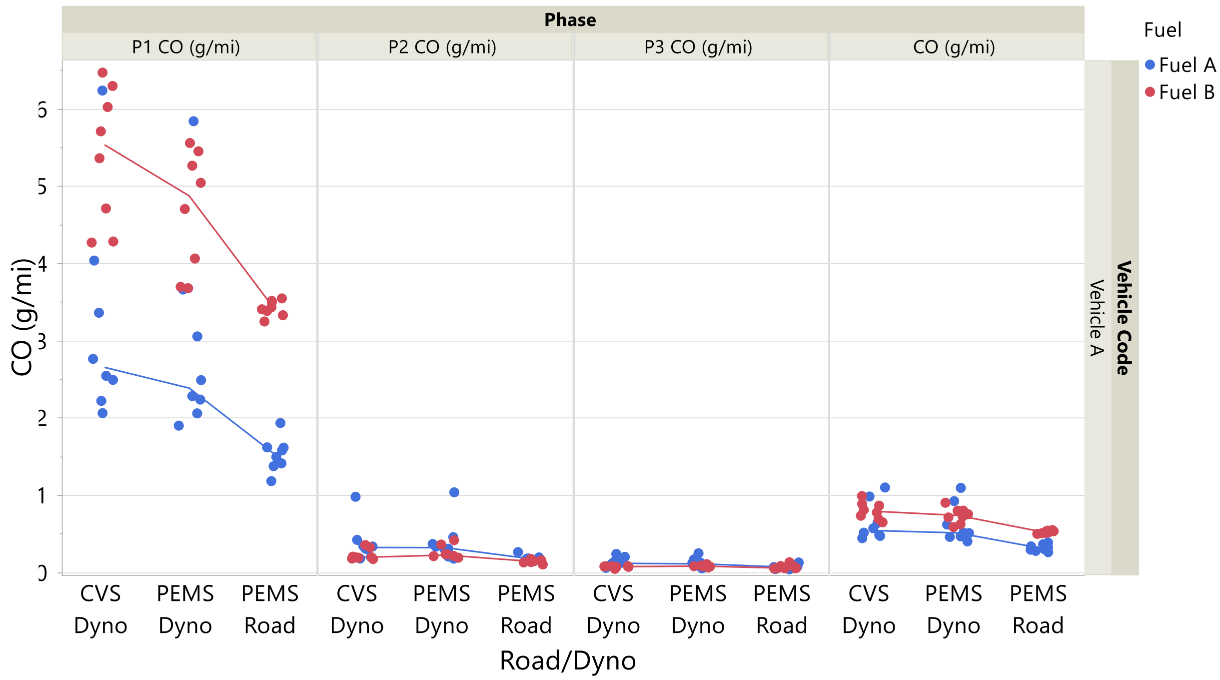


Figure 4-30: Vehicle A CO (g/mi) by Phase

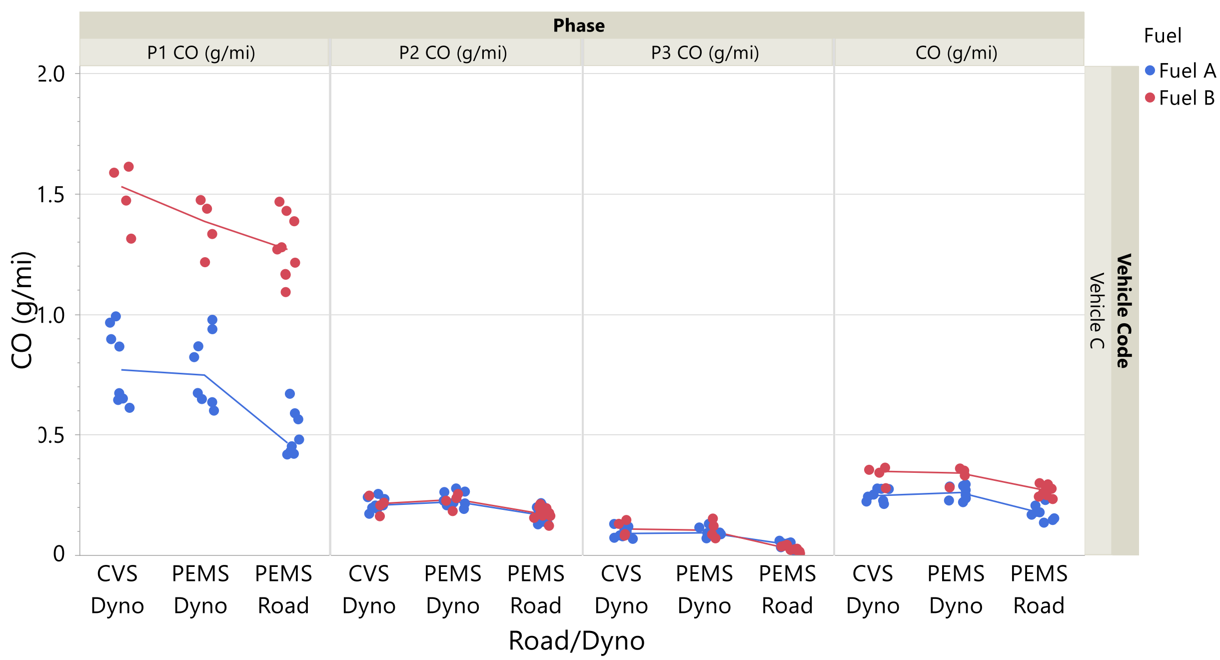


Figure 4-31: Vehicle C CO (g/mi) by Phase

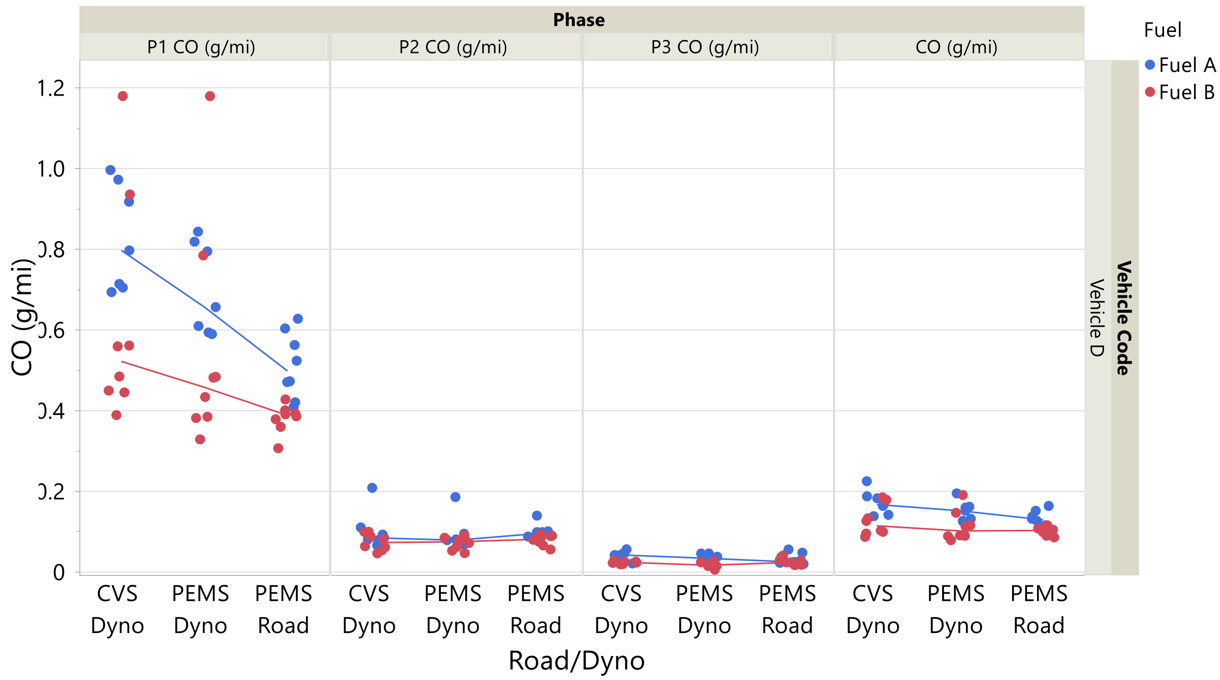


Figure 4-32: Vehicle D CO (g/mi) by Phase

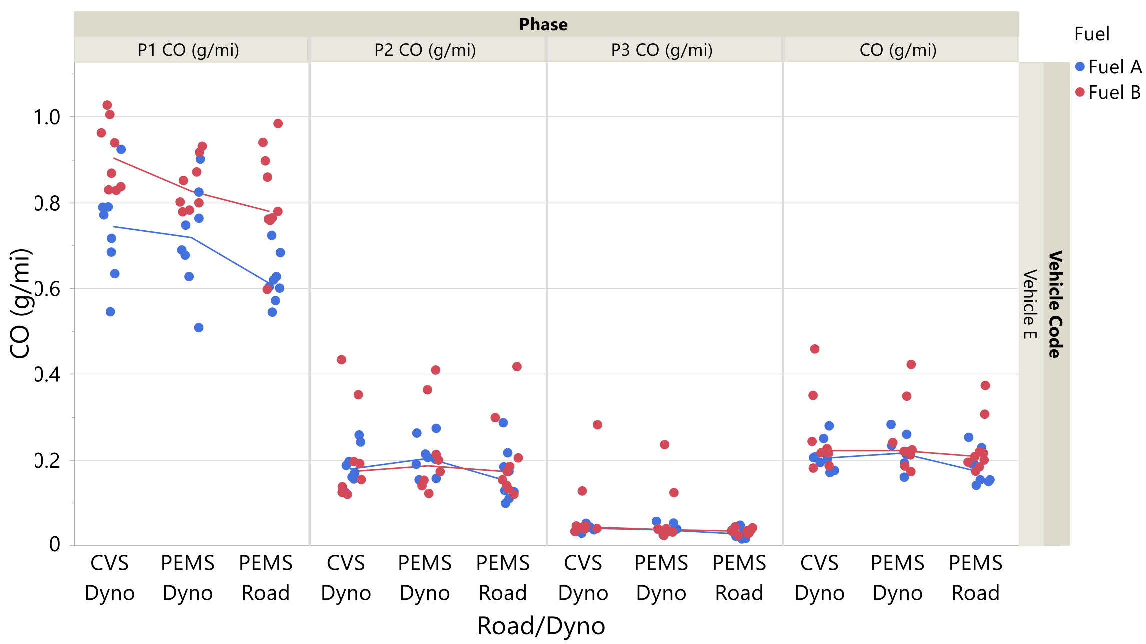


Figure 4-33: Vehicle E CO (g/mi) by Phase

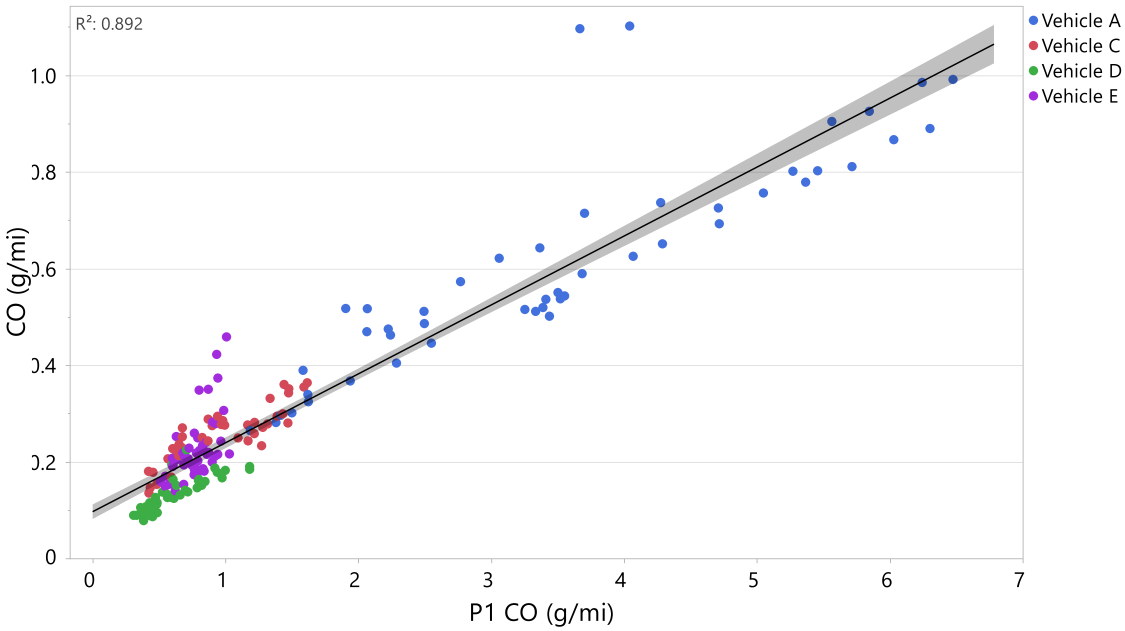


Figure 4-34: CO (g/mi) vs. Phase 1 CO (g/mi)

4.2.2.3 Variability of Carbon Dioxide (CO_2, g/mi)

A plot of the untransformed CO_2 data is shown below in Figure 4-35 for E-134 and in Figure 4-36 for E-122-2, with the natural log transformed data for both projects following in Figure 4-37 and Figure 4-38. Comparing the E-134 data to the E-122-2 data in the plots, it is visually clear that both projects appear to have more variability on road testing when compared with chassis-dyno testing, which is an expected result.

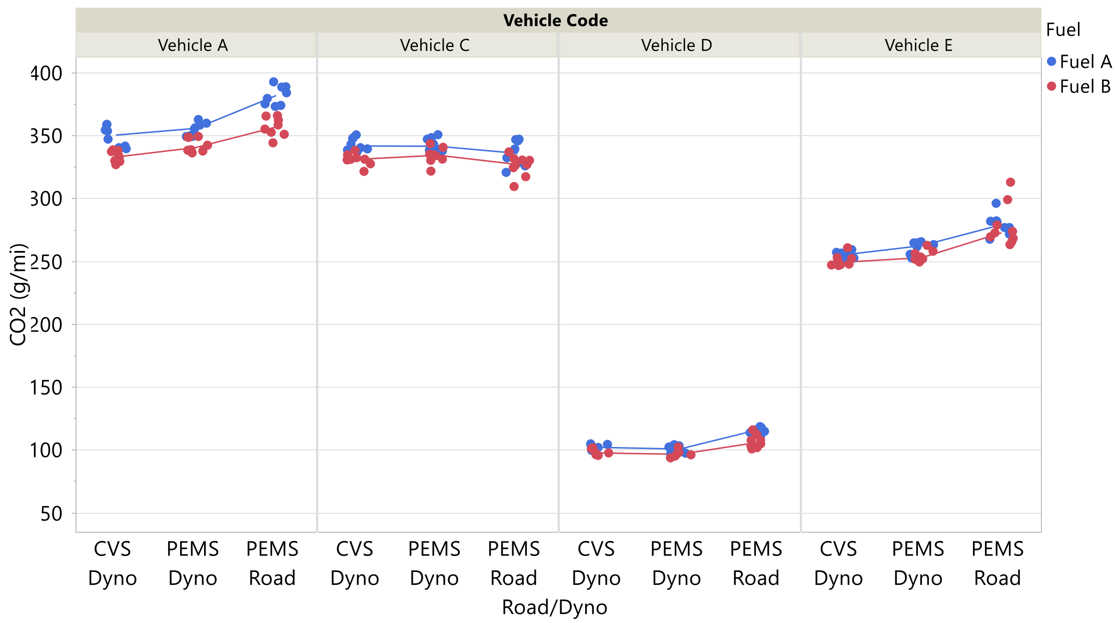


Figure 4-35: E-134 CO_2 (g/mi) by Vehicle and Measurement Method

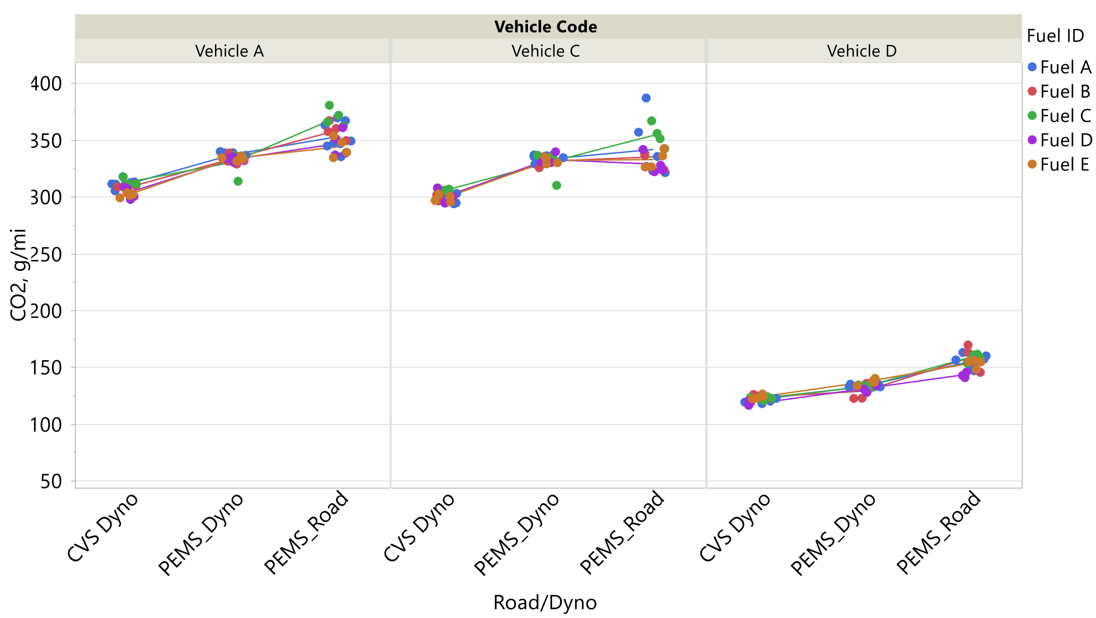


Figure 4-36: E-122-2 CO_2 (g/mi) by Vehicle and Measurement Method

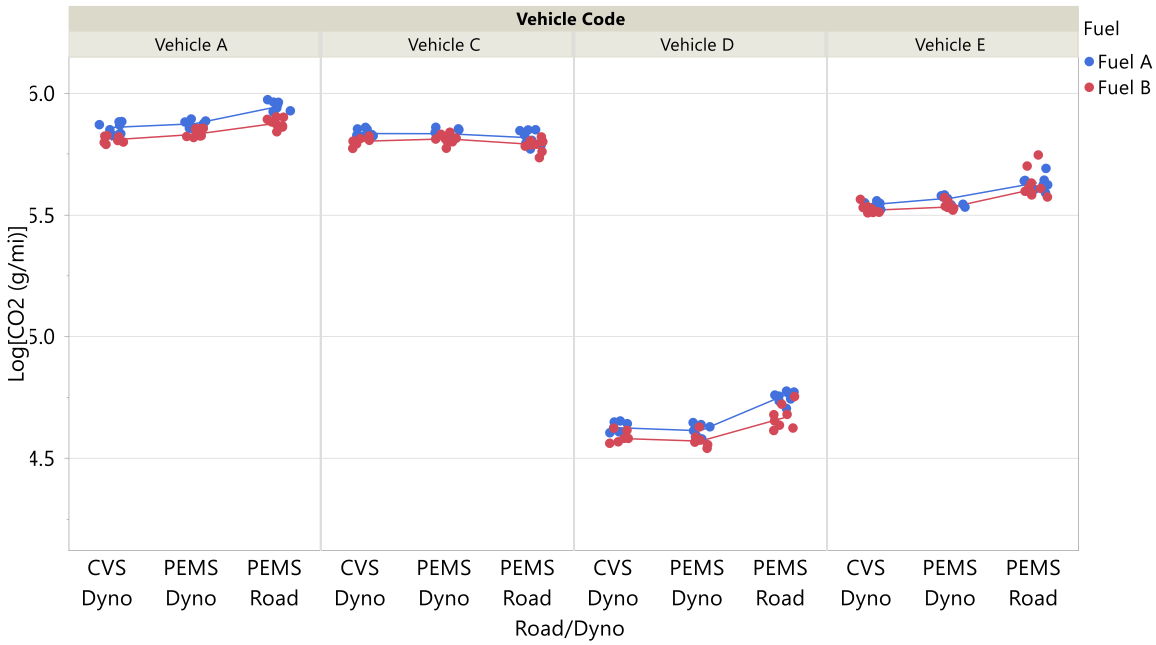


Figure 4-37: E-134 Ln(CO_2 (g/mi)) by Vehicle and Measurement Method

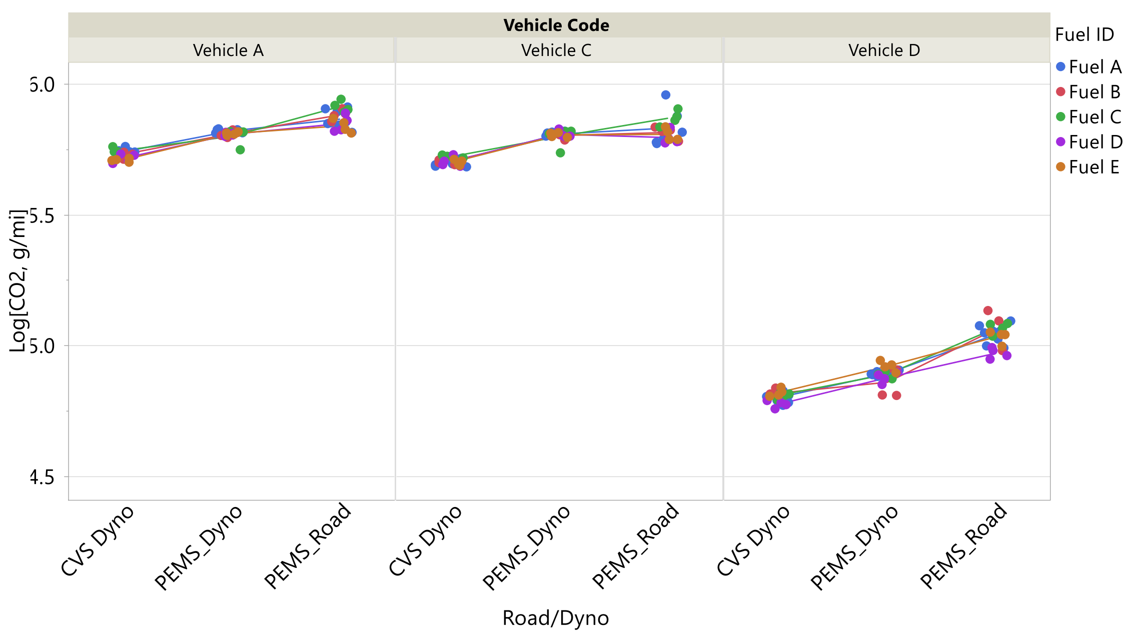


Figure 4-38: E-122-2 Ln(CO_2 (g/mi)) by Vehicle and Measurement Method

The pooled standard deviation estimates for both programs are given in Table 4-9 and the individual vehicle estimates are given in Table 4-10. From the tables, one can see that the CO_2 variability was higher for CVS results on the chassis-dyno for E-134 when compared with E-122-2. Based on results from Table 4-10, only Vehicle A was statistically more variable on the chassis-dyno across projects when tested at the individual vehicle level, though all three common vehicles had a directionally higher standard deviation. Aside from Vehicle A CVS results on the dyno, there were no individual vehicle variability comparisons across programs which were statistically different. Both programs showed clear increases in variability of road testing on all vehicles when compared to chassis-dyno testing.

Table 4-9: Ln(CO_2) Pooled Standard Deviation Estimates

Measurement Method	E-122-2 Std. Dev. (Veh's A,C,D)	E-134 Std. Dev. (Veh's A,C,D)	Program Variances Statistically Different?	E-134 Std. Dev. (w/ Veh. E)
CVS Dyno	0.0134	0.0190	Yes	0.0181
PEMS Dyno	0.0201	0.0210	No	0.0204
PEMS Road	0.0374	0.0299	No	0.0352

Starred and highlighted results in the second and third column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

Table 4-10: Ln(CO_2) Individual Vehicle Standard Deviation Estimates

Measurement Method	Vehicle	Std. Dev. (E-122-2)	Std. Dev. (E-134)	Program Variances Statistically Different?
CVS Dyno	Vehicle A	0.0117	0.0190	Yes
	Vehicle C	0.0130	0.0148	No
	Vehicle D	0.0153	0.0233	No
	Vehicle E	N/A	0.0155	No
PEMS Dyno	Vehicle A	0.0150	0.0154	No
	Vehicle C	0.0179	0.0175	No
	Vehicle D	0.0258*	0.0295	No
	Vehicle E	N/A	0.0184	No
PEMS Road	Vehicle A	0.0289*	0.0206	No
	Vehicle C	0.0451*	0.0282*	No
	Vehicle D	0.0373*	0.0383	No
	Vehicle E	N/A	0.0473*	No

Starred and highlighted results in the third and fourth column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column for that vehicle. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

4.2.2.3.1 Variability of CO_2 (g/mi) by Phase

The E-134 CO_2 phase level data is provided below in Figure 4-40 to Figure 4-43 by vehicle for Vehicles A, C, D, and E, respectively.

Vehicles A, C, and E appear to have the most variability in Phase 1 of the cycle, while Vehicle D tends to have the most variability in Phases 2 and 3. This may be related to the hybrid engine technology used for Vehicle D which was observed to be used as follows:

1. Engine-only for first couple minutes of test. After which battery SOC is at 50%.
2. All electric until acceleration to highway speeds during phase 2: high vehicle speed/load triggers engine on. After which battery SOC typically 18-23%.
3. Hybrid electric until battery is fully depleted around start of phase 3. After which battery SOC is at 0%
4. Hybrid electric until end of test. After which battery SOC is still 0%

SOC data was not collected throughout the course of testing; however, engine speed data was often referenced to determine whether or not the engine was being engaged. An example plot from Vehicle D test D-A-1 is shown below in Figure 4-39.

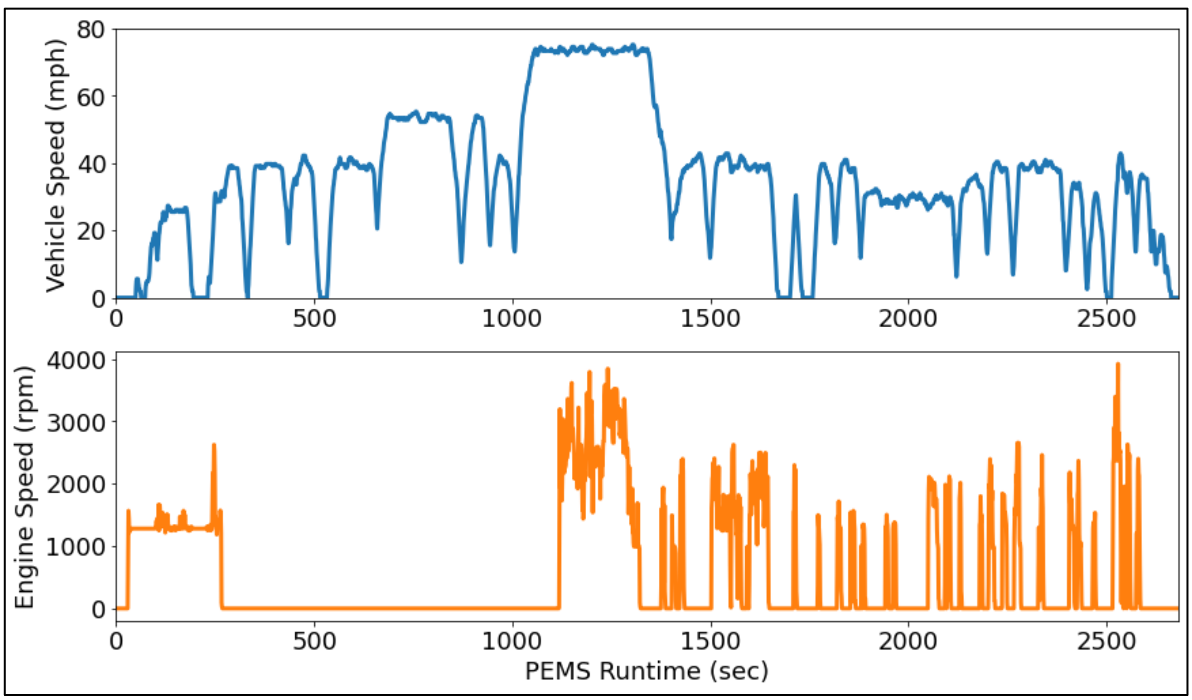


Figure 4-39: Vehicle D Engine-On Time

Finally, though difficult to see the trend lines due to the range of CO_2 values between vehicles, Figure 4-44 shows the R^2 values by vehicle and phase which indicates that, for all vehicles, Phase 2 CO_2 of this cycle is most highly correlated with final composite CO_2. This may be due to the large amount of CO_2 produced during the highspeed portion of Phase 2. For on-road tests, Phase 1 and Phase 3 may have been impacted by variance in traffic stops; see Figure 3-1 in Section 3.3 for a visualization of traffic stops. For Vehicles C and D, there is no correlation at all between Phase 1 CO_2 and final composite CO_2, whereas this is not the case for Vehicles A and E.

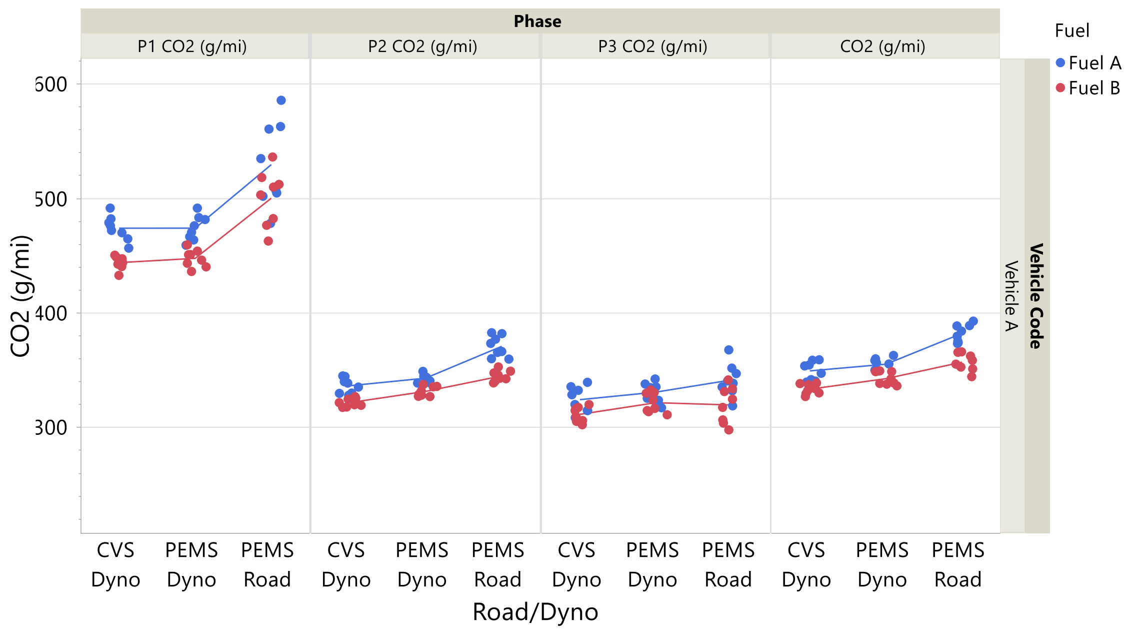


Figure 4-40: Vehicle A CO_2 (g/mi) by Phase

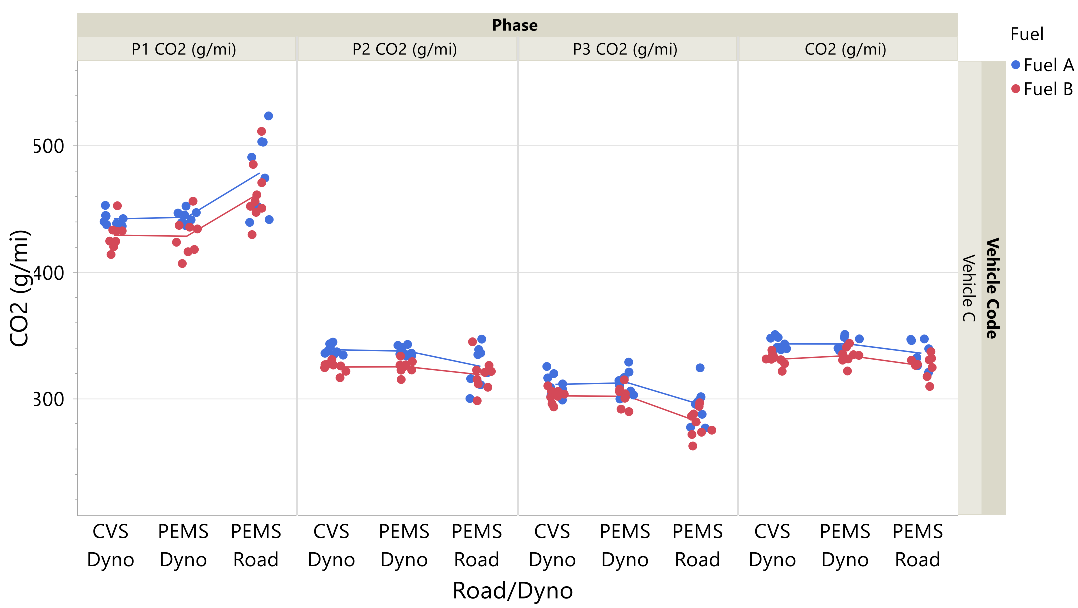


Figure 4-41: Vehicle C CO_2 (g/mi) by Phase

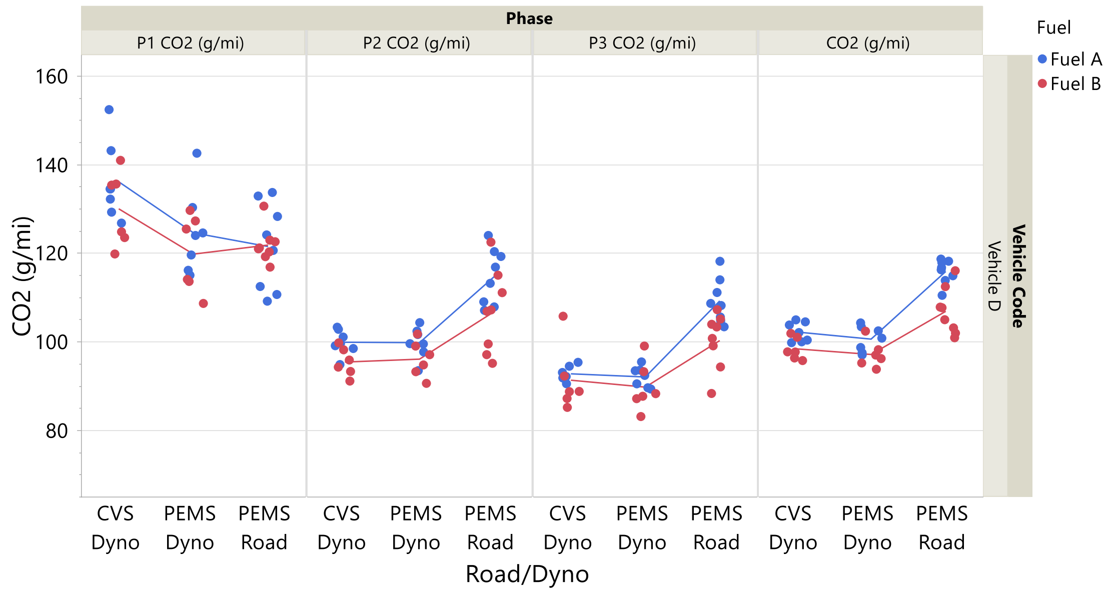


Figure 4-42: Vehicle D CO_2 (g/mi) by Phase

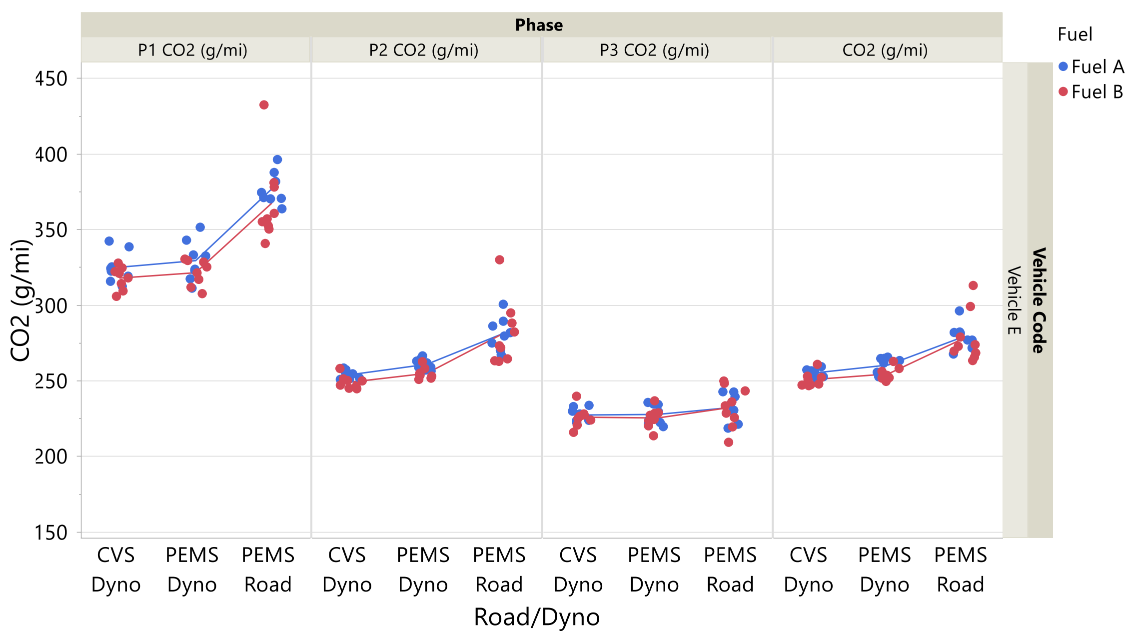


Figure 4-43: Vehicle E CO_2 (g/mi) by Phase

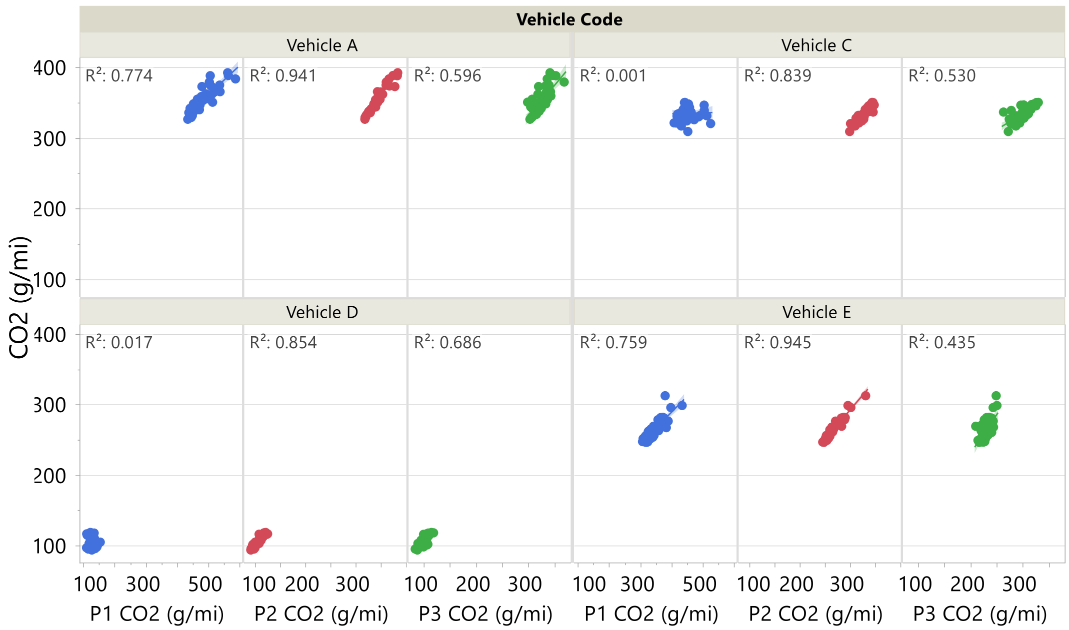


Figure 4-44: CO_2 (g/mi) vs. Phase 1-3 CO_2 (g/mi)

4.2.2.4 Variability of Fuel Economy (mpg)

A plot of the untransformed fuel economy data is shown below in Figure 4-45 for E-134 and in Figure 4-46 for E-122-2, with the natural log transformed data for both projects following in Figure 4-47 and Figure 4-48. The pooled standard deviation estimates for both programs are given in Table 4-11 and the individual vehicle estimates are given in Table 4-12. These plots and tables are provided for reference, but all conclusions regarding fuel economy are the same as with CO_2.

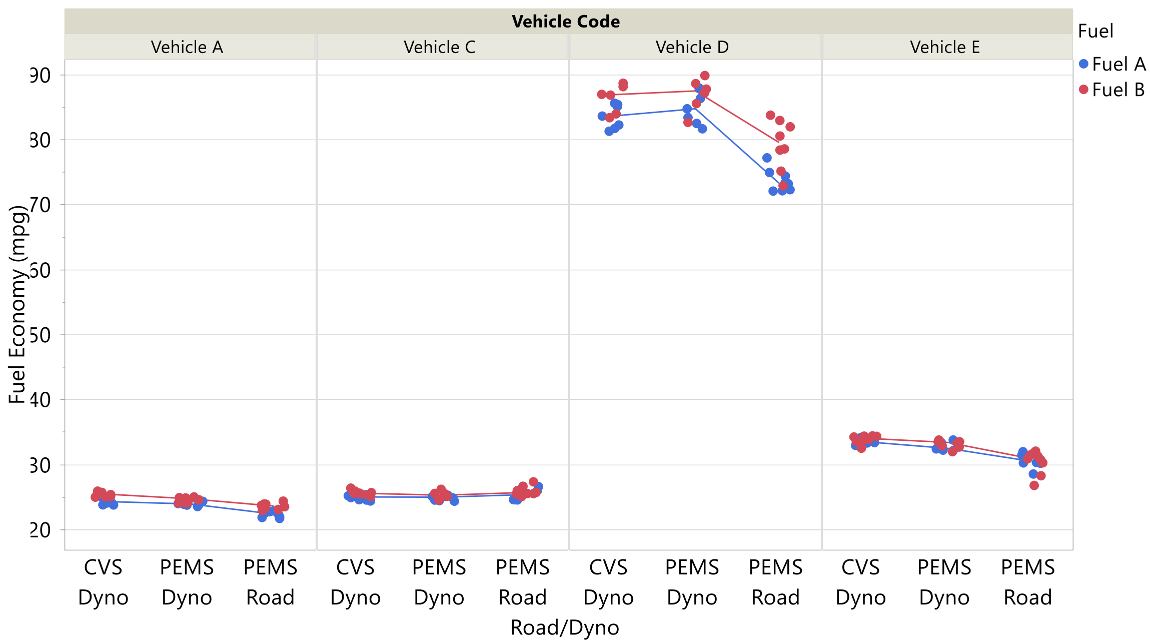


Figure 4-45: E-134 Fuel Economy (mpg) by Vehicle and Measurement Method

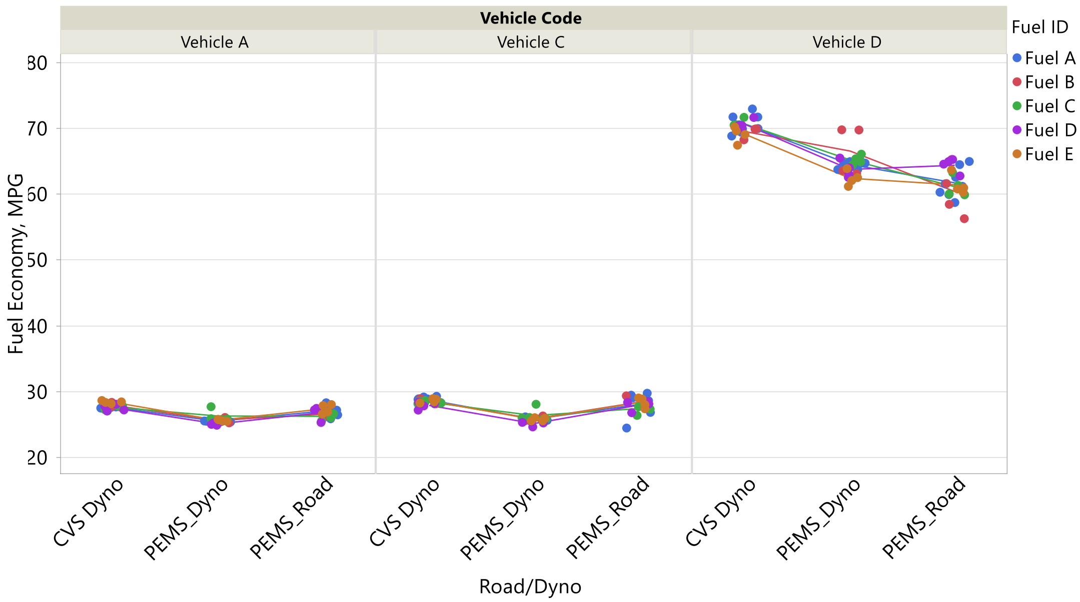


Figure 4-46: E-122-2 Fuel Economy (mpg) by Vehicle and Measurement Method

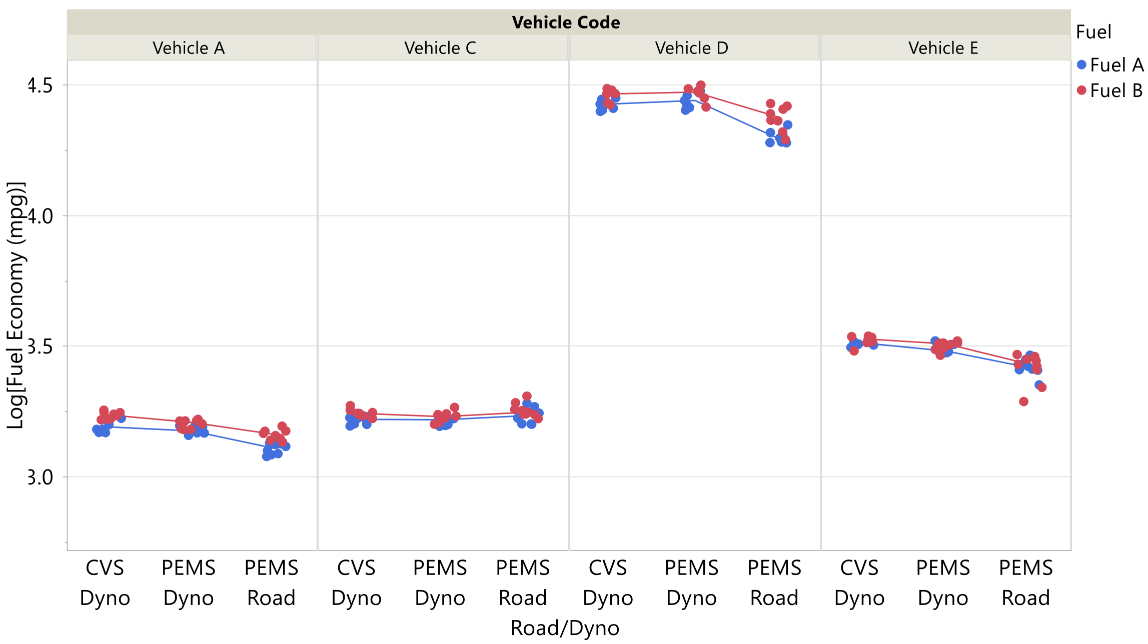


Figure 4-47: E-134 Ln(Fuel Economy (mpg)) by Vehicle and Measurement Method

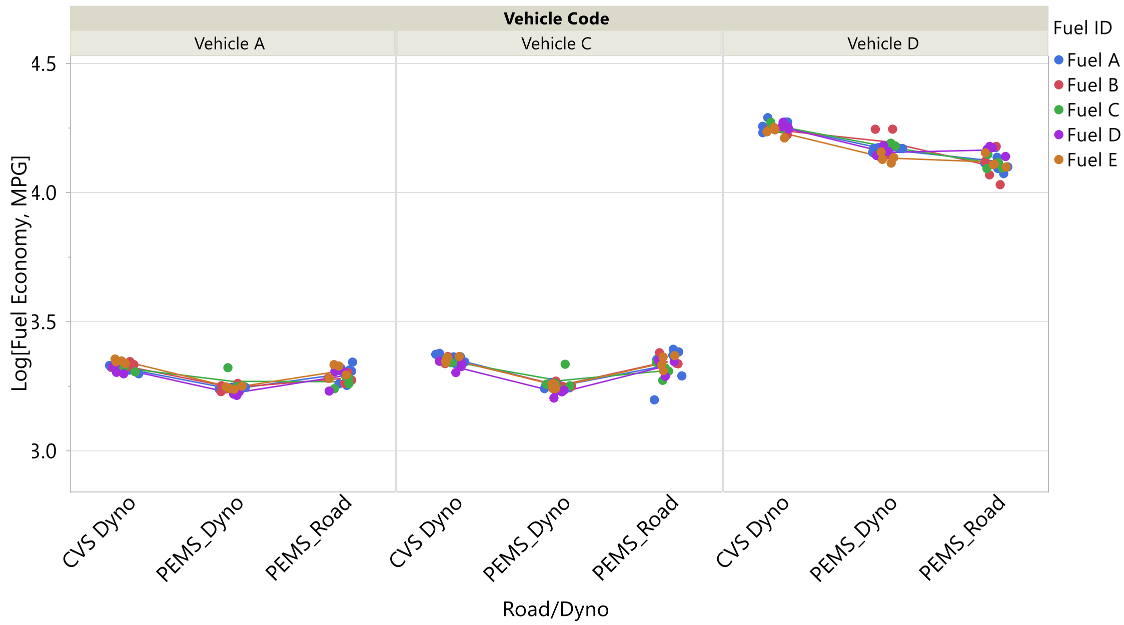


Figure 4-48: E-122-2 Ln(Fuel Economy (mpg)) by Vehicle and Measurement Method

Table 4-11: Ln(Fuel Economy) Pooled Standard Deviation Estimates

Measurement Method	E-122-2 Std. Dev. (Veh's A,C,D)	E-134 Std. Dev. (Veh's A,C,D)	Program Variances Statistically Different?	E-134 Std. Dev. (w/ Veh. E)
CVS Dyno	0.0134	0.0191	Yes	0.0183
PEMS Dyno	0.0198*	0.0208	No	0.0203
PEMS Road	0.0377*	0.0301*	No	0.0361

Starred and highlighted results in the second and third column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

Table 4-12: Ln(Fuel Economy) Individual Vehicle Standard Deviation Estimates

Measurement Method	Vehicle	Std. Dev. (E-122-2)	Std. Dev. (E-134)	Program Variances Statistically Different?
CVS Dyno	Vehicle A	0.0117	0.0191	Yes
	Vehicle C	0.0130	0.0147	No
	Vehicle D	0.0153	0.0236	No
	Vehicle E	N/A	0.0158	No
PEMS Dyno	Vehicle A	0.0155	0.0154	No
	Vehicle C	0.0181	0.0177	No
	Vehicle D	0.0249*	0.0290	No
	Vehicle E	N/A	0.0186	No
PEMS Road	Vehicle A	0.0287*	0.0206	No
	Vehicle C	0.0466*	0.0291*	No
	Vehicle D	0.0368*	0.0382	No
	Vehicle E	N/A	0.0492*	No

Starred and highlighted results in the third and fourth column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column for that vehicle. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

4.2.2.5 Variability of Nitrogen Oxides (NO_x, g/mi)

A plot of the untransformed NO_x data is shown below in Figure 4-49 for E-134 and in Figure 4-50 for E-122-2, with the natural log transformed data for both projects following in Figure 4-51 and Figure 4-52. The most significant result from the plots is the noticeably higher variability for Vehicle A NO_x on road testing as compared with chassis-dyno testing, and though this difference is larger in E-134, it is present in E-122-2 as well.

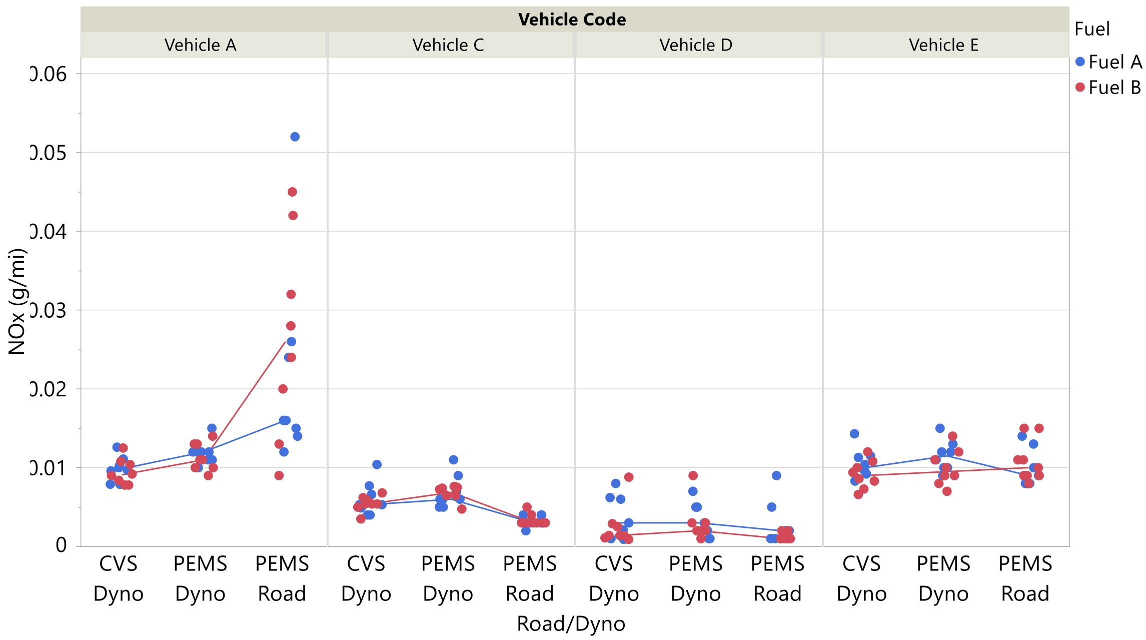


Figure 4-49: E-134 NO_x (g/mi) by Vehicle and Measurement Method

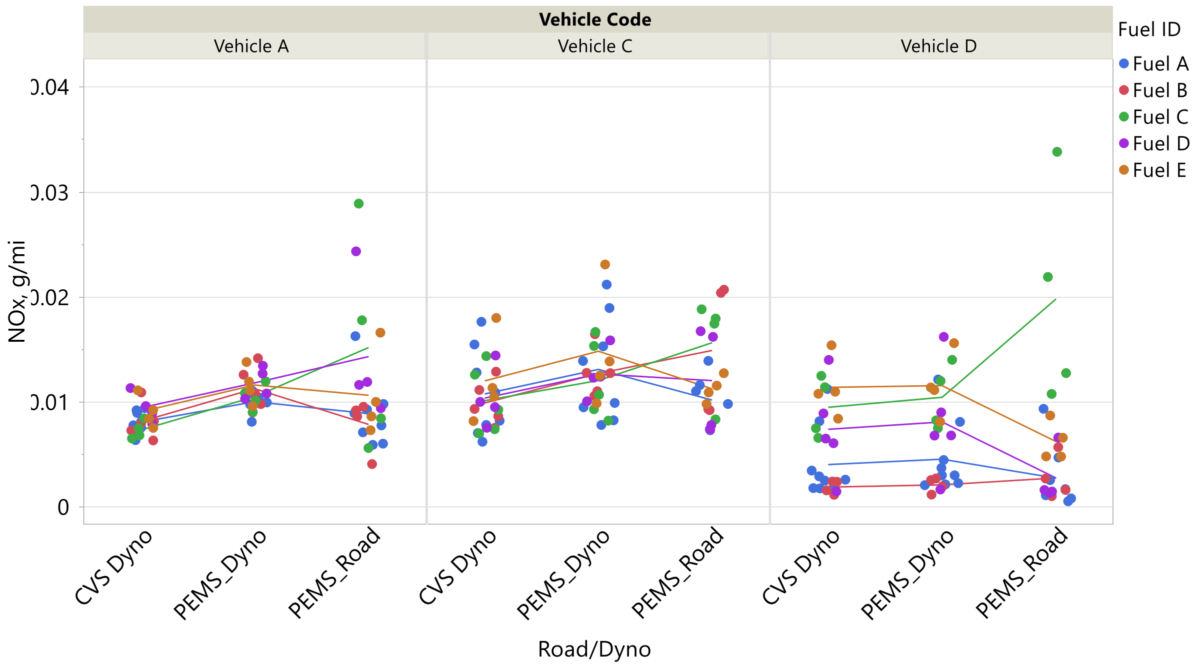


Figure 4-50: E-122-2 NO_x (g/mi) by Vehicle and Measurement Method

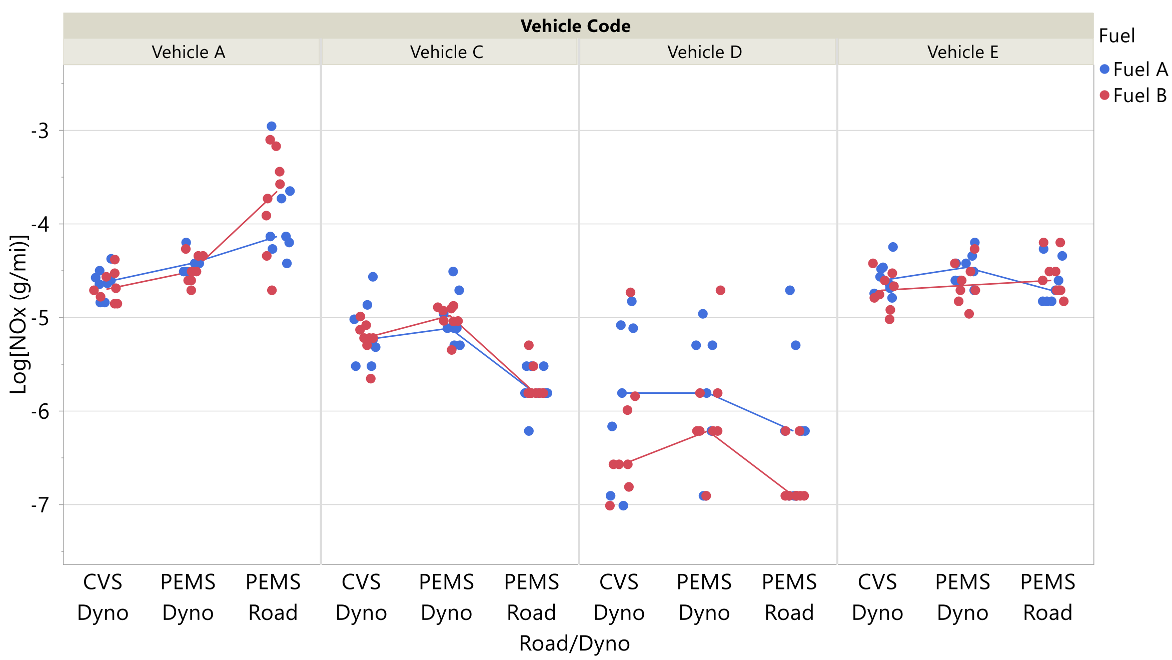


Figure 4-51: E-134 Ln(NO_x (g/mi)) by Vehicle and Measurement Method

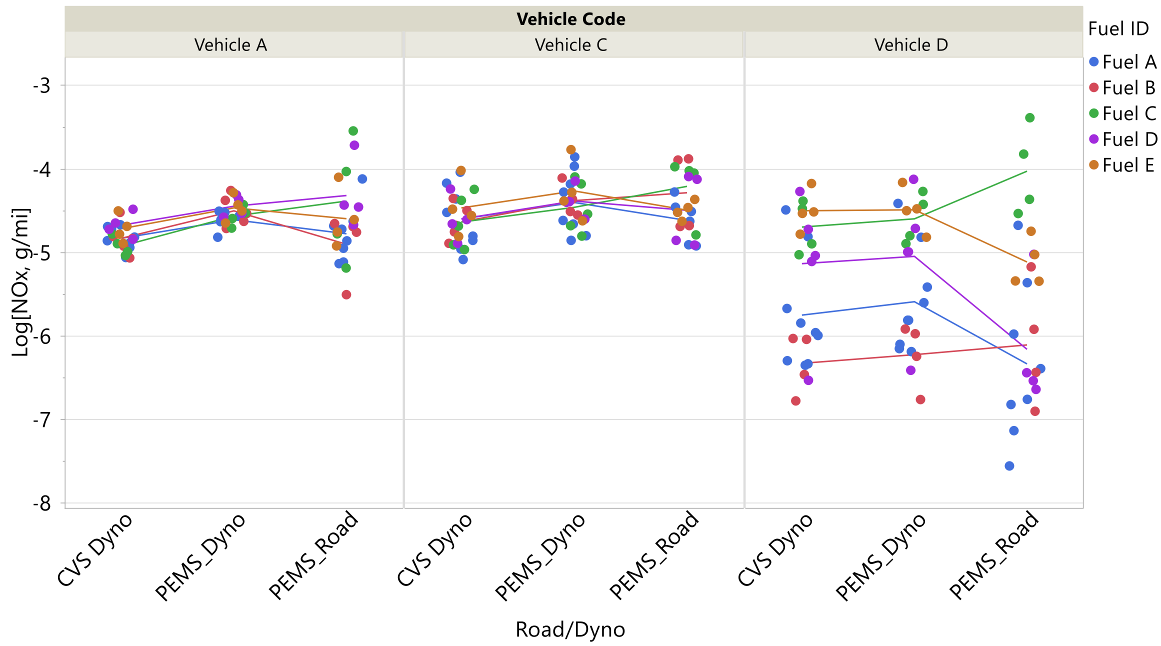


Figure 4-52: E-122-2 Ln(NO_x (g/mi)) by Vehicle and Measurement Method

The pooled standard deviation estimates for both programs are given in Table 4-13 and the individual vehicle estimates are given in Table 4-14. From the tables one can see that there were no statistically significant cross-program differences in terms of variability. Both E-122-2 and E-134 show statistically significant increases in Vehicle A NO_x on road-testing when compared to CVS results on the chassis-dyno.

Table 4-13: Ln(NO_x) Pooled Standard Deviation Estimates

Measurement Method	E-122-2 Std. Dev. (Veh's A,C,D)	E-134 Std. Dev. (Veh's A,C,D)	Program Variances Statistically Different?	E-134 Std. Dev. (w/ Veh. E)
CVS Dyno	0.4009	0.4910	No	0.4345
PEMS Dyno	0.3847	0.4265	No	0.3813
PEMS Road	0.5500*	0.4743	No	0.4239

Starred and highlighted results in the second and third column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

Table 4-14: Ln(NO_x) Individual Vehicle Standard Deviation Estimates

Measurement Method	Vehicle	Std. Dev. (E-122-2)	Std. Dev. (E-134)	Program Variances Statistically Different?
CVS Dyno	Vehicle A	0.1544	0.1626	No
	Vehicle C	0.3208	0.2714	No
	Vehicle D	0.5907	0.8079	No
	Vehicle E	N/A	0.1887	No
PEMS Dyno	Vehicle A	0.1341	0.1374	No
	Vehicle C	0.3104	0.2249	No
	Vehicle D	0.5687	0.7062	No
	Vehicle E	N/A	0.1964	No
PEMS Road	Vehicle A	0.4445*	0.5185*	No
	Vehicle C	0.3479	0.2097	No
	Vehicle D	0.7549	0.6123	No
	Vehicle E	N/A	0.2236	No

Starred and highlighted results in the third and fourth column indicate that the PEMS variability estimate is significantly greater than the CVS dyno estimate in the same column for that vehicle. A highlighted "Yes" in the fourth column indicates that the E-134 variability estimate is significantly different from the E-122-2 estimate in the same row.

4.2.2.5.1 Variability of NO_x (g/mi) by Phase

The E-134 CO_2 phase level data is provided below in Figure 4-53 to Figure 4-56 by vehicle for Vehicles A, C, D, and E, respectively. It is clear from Figure 4-53 that the Vehicle A NO_x variability is driven by the Phase 2 result. The composite NO_x vs. phase-level NO_x is given in Figure 4-57, and one can see that the Phase 2 result is almost perfectly correlated with final composite NO_x for Vehicle A, while this vehicle has no correlation on Phase 1 or Phase 3 results to final results. The source of high NO_x in on-road Vehicle A tests is primarily from the steep highway grade which occurs during Phase 2. Phase 2 is the most strongly correlated phase on all vehicles, but to a lesser degree than seen with Vehicle A. The other three vehicles also show a weak but present correlation to Phase 3 results not seen with Vehicle A.

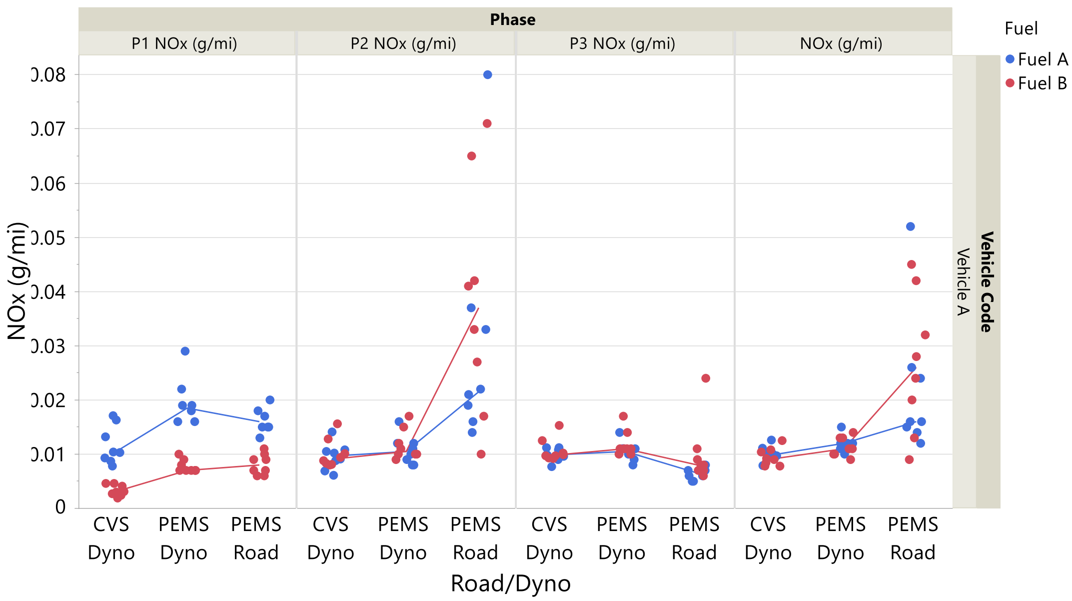


Figure 4-53: Vehicle A NO_x (g/mi) by Phase

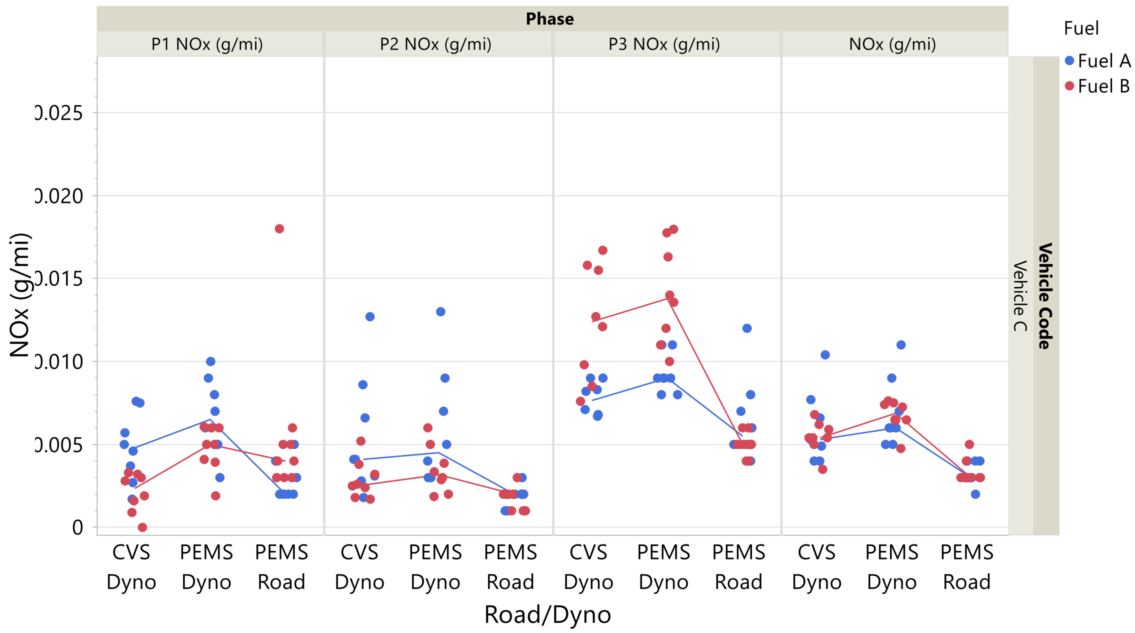


Figure 4-54: Vehicle C NO$_x$ (g/mi) by Phase

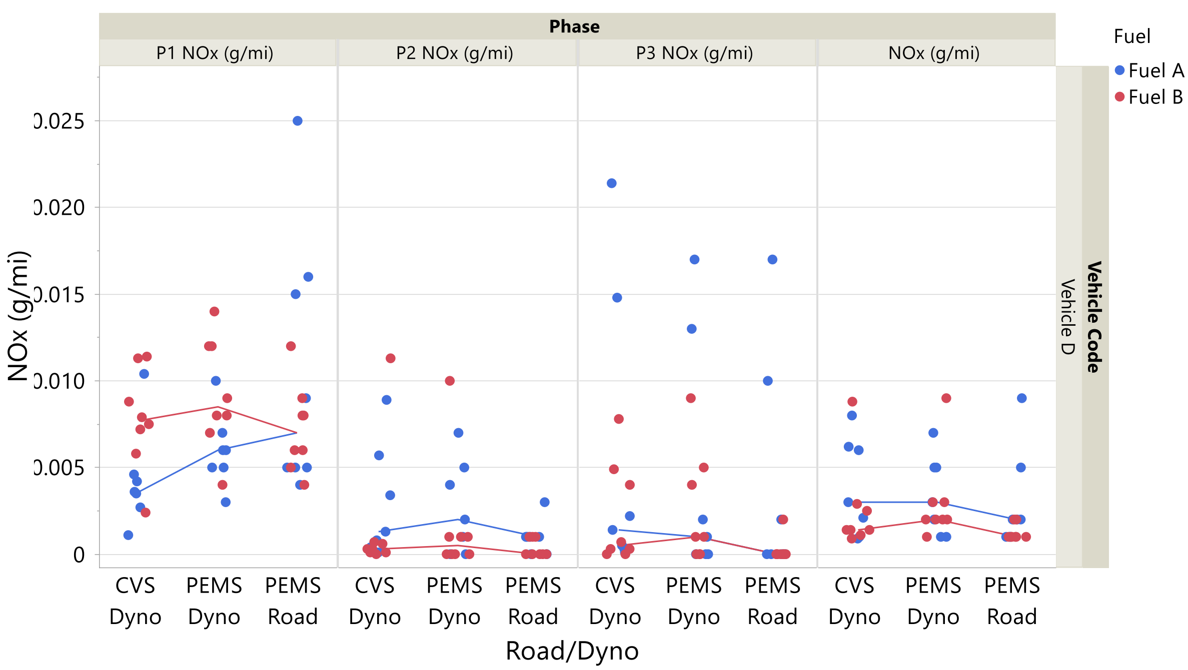


Figure 4-55: Vehicle D NO$_x$ (g/mi) by Phase

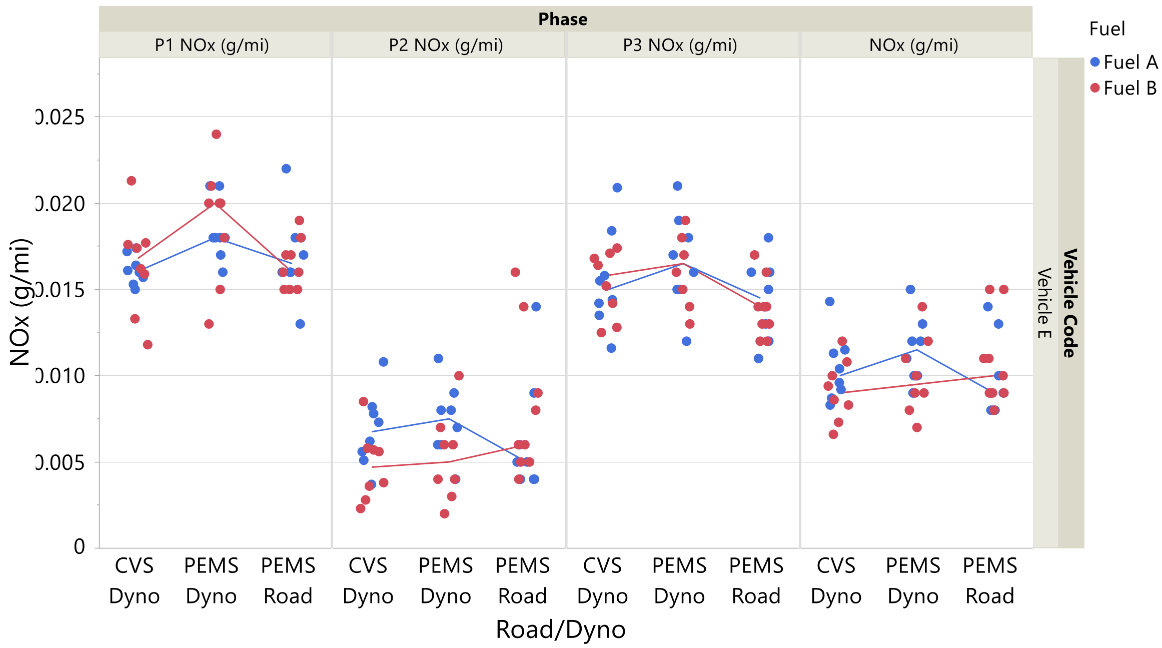


Figure 4-56: Vehicle E NO_x (g/mi) by Phase

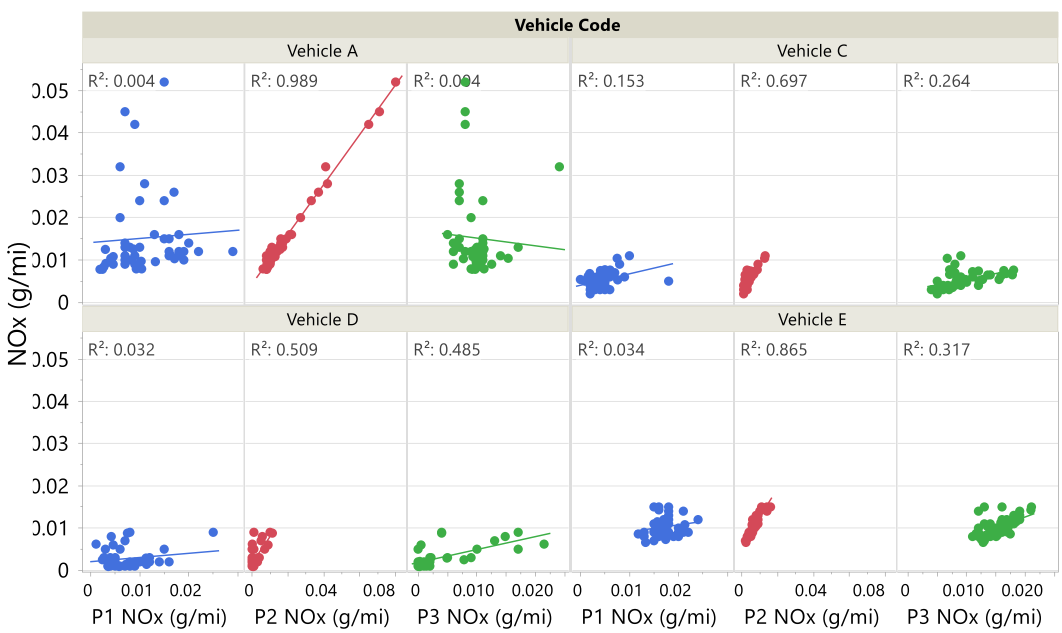


Figure 4-57: NO_x (g/mi) vs. Phase 1-3 NO_x (g/mi)

4.3 PEMS Accuracy and Bias

PEMS accuracy and bias in this section are broken into two components. The first is the instrument accuracy when compared with CVS dyno results. With results being measured side-by-side simultaneously using the CVS and the PEMS for each individual test on the chassis-dyno, one can estimate exactly what the bias is that can be attributed solely to the PEMS unit. The second component of accuracy is the additional bias added by non-PEMS factors that are present in road tests, including things such as traffic and temperature differences which may lead to offsets. It is noted again that for E-134 this also includes a driver difference, as different drivers were used for road testing and dyno testing, whereas the same driver was used for both types of testing in E-122-2.

4.3.1 PEMS Accuracy and Bias for Particulate Matter (mg/mi)

4.3.1.1 PEMS Instrument Bias for PM: Dyno Testing

Figure 4-58 is a plot of the PM data in untransformed units which show that PM results tend to be lower on the PEMS as PM results increase away from zero. Vehicle D demonstrates a potential fuel dependent bias because the bias observed is much greater than what is seen for other Vehicles at those lower PM levels.

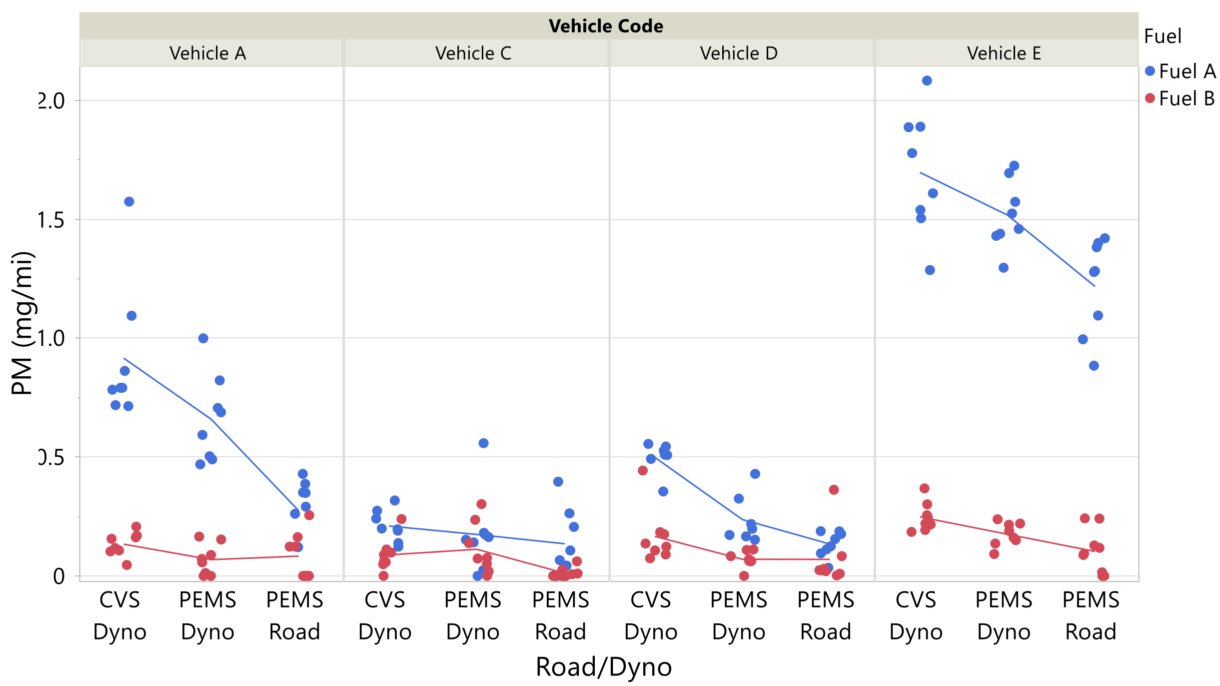


Figure 4-58: E-134 PM (mg/mi) by Vehicle and Measurement Method

Paired CVS and PEMS results were available because the data were collected simultaneously via both methods for each dyno test. For each result, the PM differences were calculated by first transforming using the cubed root transformation as described previously, and then subtracting the CVS result from the PEMS result (PEMS – CVS). Using this collection of differences, a model was run with vehicle, fuel, and the interaction of these terms as predictors of the transformed PM difference (T_PM_Diff). Both the interaction term and the fuel term were insignificant and were dropped from the model. From the final model, the least squares (LS) mean PM differences were calculated. A plot of the estimated PM differences by vehicle and a table of the values is given in Figure 4-59 and Table 4-15, respectively. The E-122-2 PM data is plotted for reference following the model results in Figure 4-60.

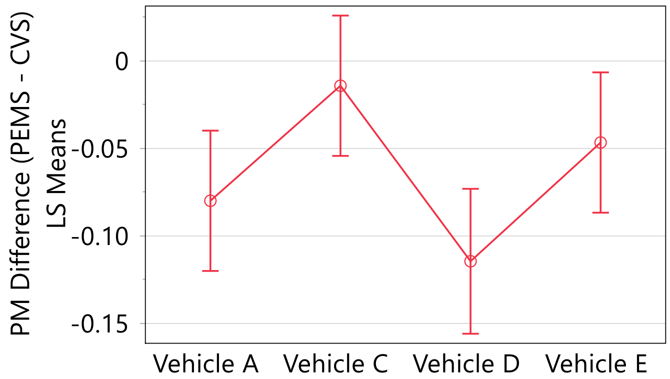


Figure 4-59: LS Mean CubedRoot(PM+0.1) Differences with 95% CI by Vehicle (PEMS – CVS)

Table 4-15: LS Mean CubedRoot(PM+0.1) Differences with 95% CI by Vehicle (PEMS – CVS)

Level				Least Sq Mean	Lower 95%	Upper 95%
Vehicle C	A			-0.014	-0.054	0.026
Vehicle E	A	B		-0.047	-0.087	-0.007
Vehicle A		B	C	-0.080	-0.120	-0.040
Vehicle D			C	-0.115	-0.156	-0.073

Levels not connected by same letter are significantly different.

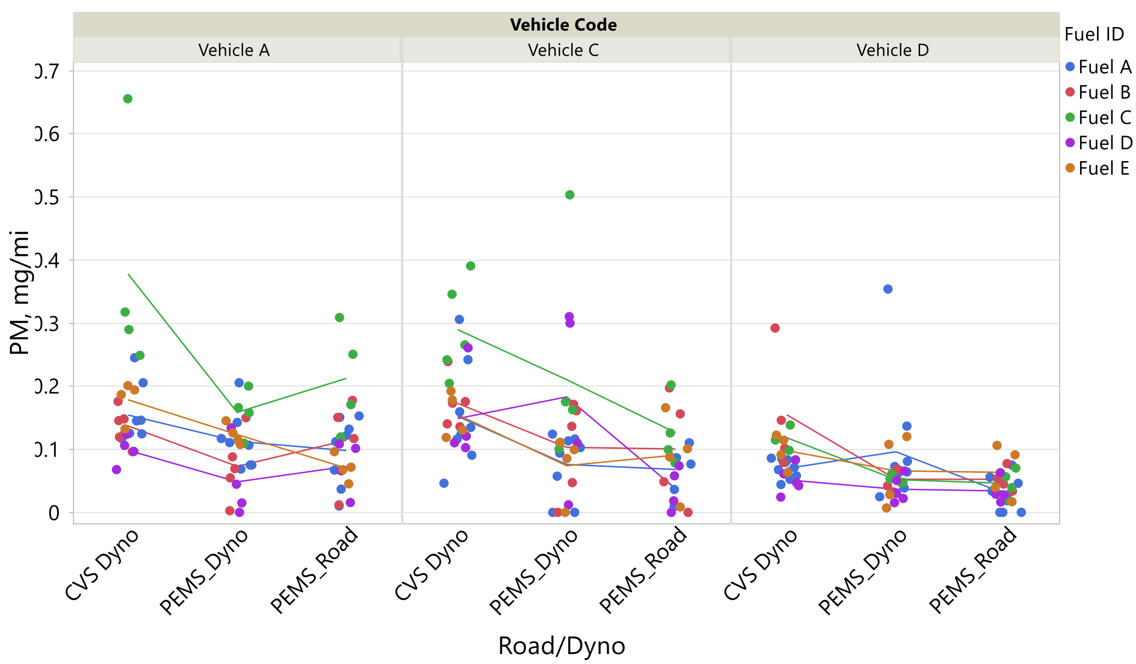


Figure 4-60: E-122-2 PM (mg/mi) for Chassis Dyno Testing

Since the model values above are given in transformed units and are level dependent for PM in mg/mi, Table 4-16 provides an example of the expected PM differences at the median E-134 PM result for each vehicle as measured by the CVS, along with a comparison to the observed instrument bias from E-122-2. Comparisons are difficult in this case because the bias is forced to change as results approach zero PM levels. Vehicle C was the only E-134 vehicle to not show a statistically significant negative bias. However, the CVS results from this vehicle are very close to zero for CVS measurements, in particular on Fuel B. Likewise, Vehicle D showed a much smaller bias in E-122-2 but was much closer to zero PM in that testing, so proximity of PM results to zero may be causing the bias differences observed.

Table 4-16: E-134 Expected PM Difference (PEMS – CVS) based on E-134 Median PM

Vehicle	Median PM (g/mi) E-134 CVS Dyno	Expected PM E-134 PEMS Dyno (%)	Expected PM E-122-2 PEMS Dyno (%)
Vehicle A	0.461	0.313(-32%)	0.304(-34%)
Vehicle C	0.131	0.116(-12%)*	0.072(-45%)
Vehicle D	0.355	0.180(-49%)	0.277(-22%)
Vehicle E	0.823	0.696(-15%)	N/A

*based on average bias, but the bias was not statistically significantly different from zero

4.3.1.2 PEMS Accuracy for PM: Road Testing

The bias estimated in the previous section is bias that can be attributed to the PEMS unit itself. These estimates were used to create a bias correction. Any remaining bias observed on road testing can be attributed to real-world-driving-induced bias and/or driver differences. Each PEMS Road result was corrected based on the average bias estimated from the chassis-dyno testing. Corrections were done in transformed units, and then back-transformed to original units and plotted in Figure 4-61.

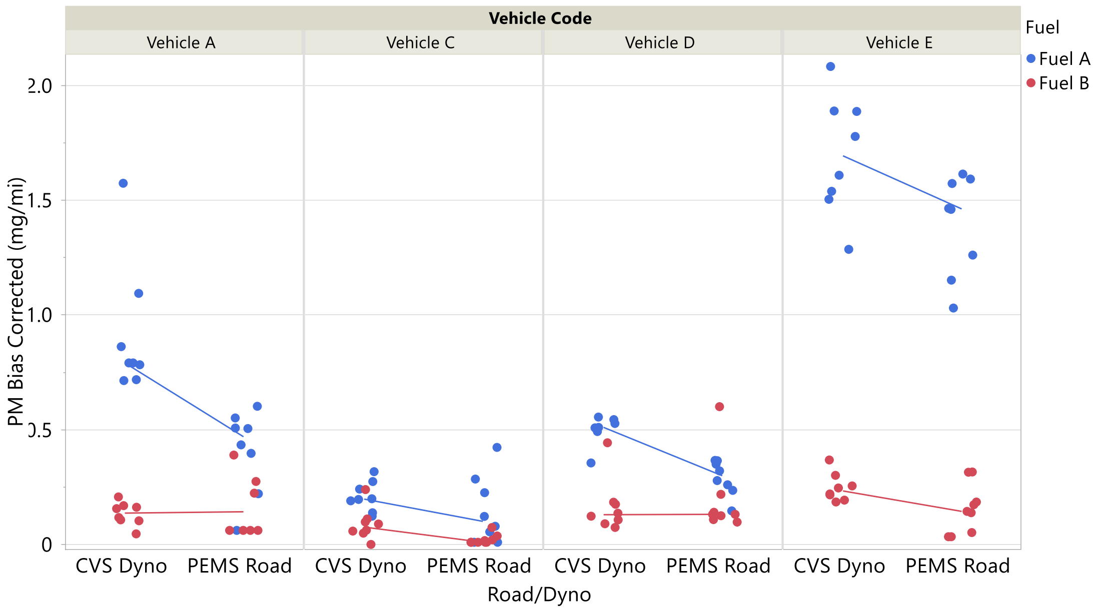


Figure 4-61: PM with Instrument Bias Correction Applied to PEMS Results

From the plot we see that it appears there is still an additional bias with road tests, and also that it appears inappropriate to include Fuel B results in the estimation of this additional bias, since these results were already so close to zero on the CVS dyno, any additional bias on road testing would likely be masked by the natural lower limit of zero.

Because there is not paired data for road tests vs. dyno tests, any CVS dyno point could be matched with any PEMS Road point on the same vehicle/fuel combination to represent a potential difference in outcome. Therefore, limiting to Fuel A data only, each possible pairwise difference was calculated, and these differences are plotted in Figure 4-62. The average value is shown in Table 4-17, along with the estimated bias from E-122-2. These values represent the expected amount of disagreement between a CVS dyno test and a PEMS road test for an unbiased (on the dyno) PEMS unit. Because the values are in transformed units and are again level dependent for PM in original units, an example application is given at the median E-134 PM level for each vehicle in Table 4-18, along with a comparison to E-122-2.

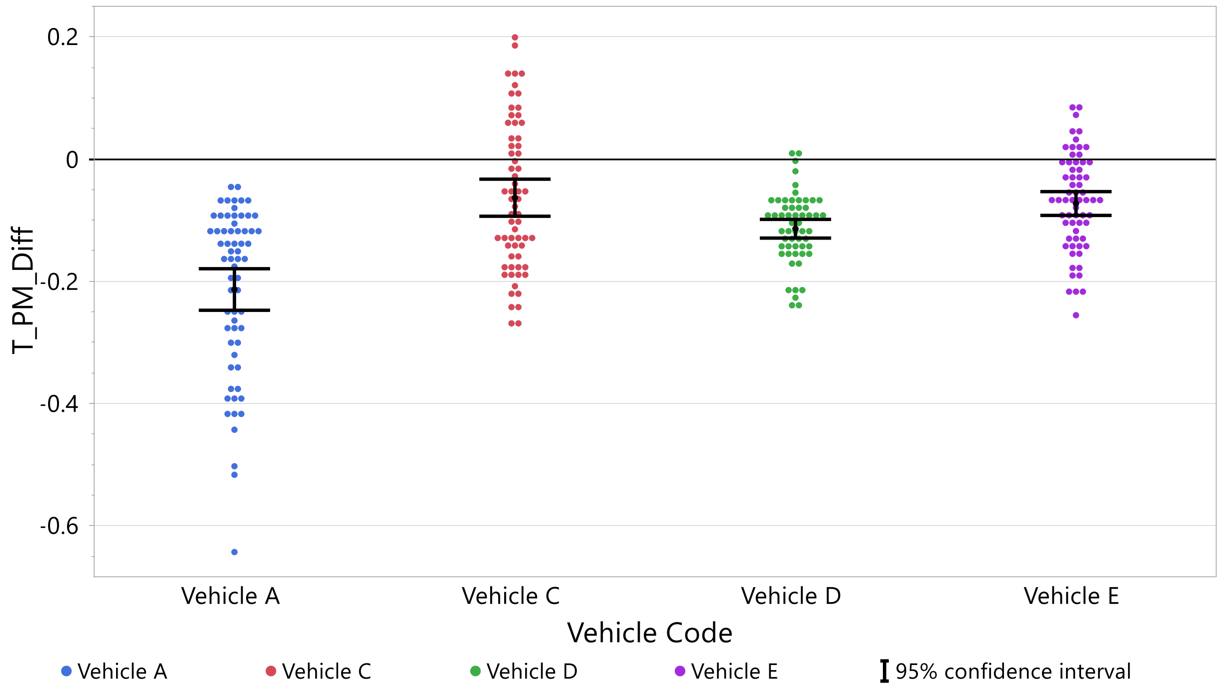


Figure 4-62: Simulated Transformed PM Differences (PEMS Road – CVS)

Table 4-17: T_PM Road Bias Estimates

Vehicle	E-134 PEMS Road Bias	E-122-2 PEMS Road Bias
Vehicle A	-0.214	0.022*
Vehicle C	-0.063	-0.039
Vehicle D	-0.114	-0.044
Vehicle E	-0.073	N/A

*bias was not statistically significantly different from zero

Table 4-18: E-134 Expected PM Difference (PEMS_Road – CVS) based on E-134 Median PM

Vehicle	Median PM (mg/mi) E-134 CVS Dyno	Expected PM E-134 PEMS Road (%)	Expected PM E-122-2 PEMS Road (%)
Vehicle A	0.461	0.128(-72%)	0.502(9%)*
Vehicle C	0.131	0.067(-49%)	0.103(-21%)
Vehicle D	0.355	0.181(-49%)	0.293(-18%)
Vehicle E	0.823	0.631(-23%)	N/A

*based on average bias, but the bias was not statistically significantly different from zero

All Vehicles showed an additional negative bias on the road testing in E-134. Vehicle A had the largest bias of about -0.214 in transformed units, while the other three vehicles ranged from -0.07 to -0.11. These differences are significantly larger than what was observed in E-122-2.

4.3.2 PEMS Accuracy and Bias for THC (g/mi)

4.3.2.1 PEMS Instrument Bias for THC: Dyno Testing

Figure 4-63 is a plot of the THC data in untransformed units which show that THC results appear slightly higher with the PEMS dyno results when compared to PEMS CVS results in all but Vehicle C. The same model was run as described in the previous section using the difference of PEMS and CVS paired results, and the LS mean differences were statistically significant for all vehicle except Vehicle C, as can be seen in Figure 4-64 and Table 4-19. A plot showing the data for E-122-2 is provided for reference following the model results.

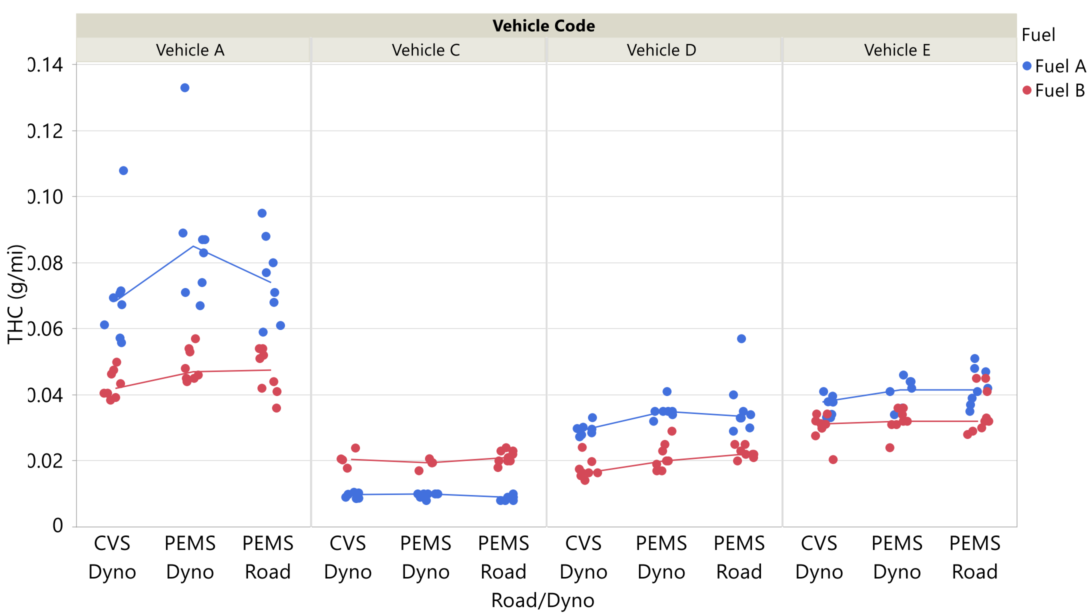


Figure 4-63: E-134 THC (g/mi) by Vehicle and Measurement Method

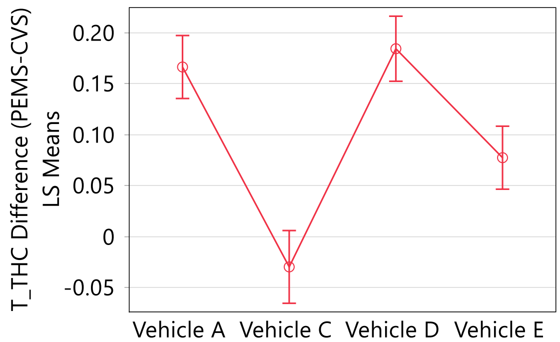


Figure 4-64: LS Mean Ln(THC) Differences with 95% CI by Vehicle (PEMS – CVS)

Table 4-19: LS Mean Ln(THC) Differences with 95% CI by Vehicle (PEMS – CVS)

Level				Least Sq Mean	Lower 95%	Upper 95%
Vehicle D	A			0.1845	0.1525	0.21643
Vehicle A	A			0.1665	0.1356	0.19746
Vehicle E		B		0.0774	0.0465	0.10836
Vehicle C			C	-0.0299	-0.0656	0.00584

Levels not connected by same letter are significantly different.

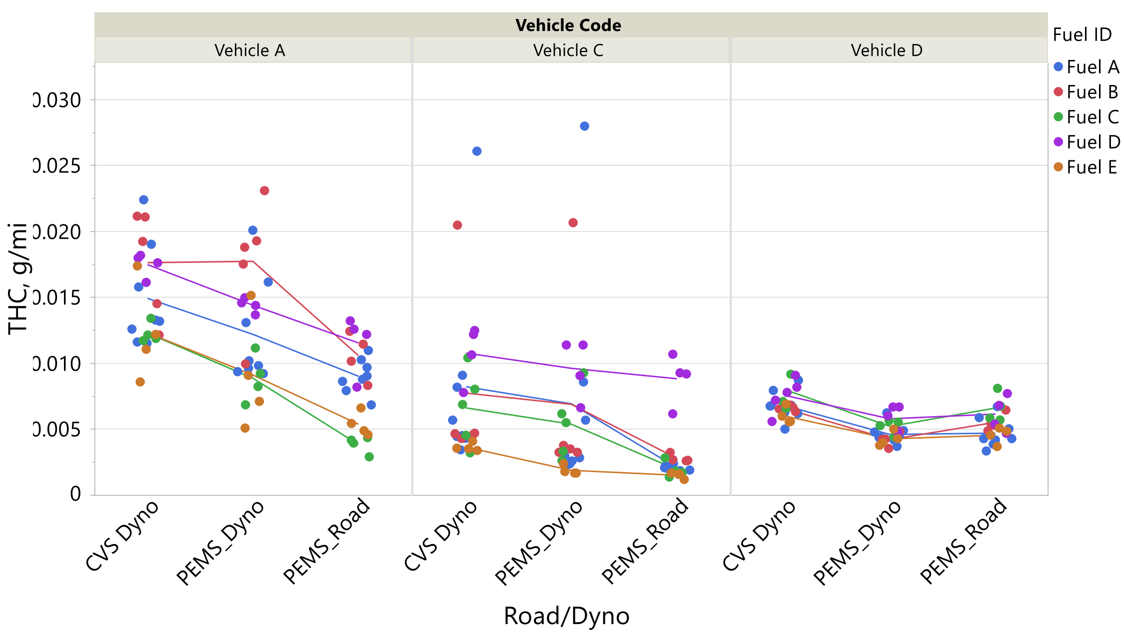


Figure 4-65: E-122-2 THC (g/mi) by Vehicle and Measurement Method

Because the model LS mean differences are given in transformed units and are level dependent for THC in g/mi, Table 4-20 provides an example of the expected THC differences at the median THC result measured by the CVS in E-134. Estimates are given for both projects, with asterisks given for differences which were not significantly different from zero. It is interesting to note that the bias observed for the PEMS was consistently negative in E-122-2 but is positive in E-134 for three of four vehicles.

Table 4-20: Expected THC Difference (PEMS – CVS) based on E-134 Median THC

Vehicle	Median THC (g/mi) E-134 CVS Dyno	Expected TCH E-134 PEMS Dyno (%)	Expected TCH E-122-2 PEMS Dyno (%)
Vehicle A	0.0529	0.0624(18%)	0.0424(-20%)
Vehicle C	0.0142	0.0137(-3%)*	0.0103(-27%)
Vehicle D	0.0241	0.0290(20%)	0.0172(-29%)
Vehicle E	0.0337	0.0364(8%)	N/A

*based on average bias, but the bias was not statistically significantly different from zero

4.3.2.2 PEMS Accuracy for THC: Road Testing

Each possible pairwise difference between a THC road test result and a CVS dyno result was simulated, and all simulated differences in transformed units are shown below in Figure 4-66. The average value is shown in Table 4-21, along with the estimated bias from E-122-2. These values represent the expected amount of disagreement between a CVS dyno test and a PEMS road test for an unbiased (on the dyno) PEMS unit. Because the values are in transformed units and are again level dependent for THC in original units, an example application is given at the median E-134 THC level for each vehicle in Table 4-22, along with a comparison to E-122-2.

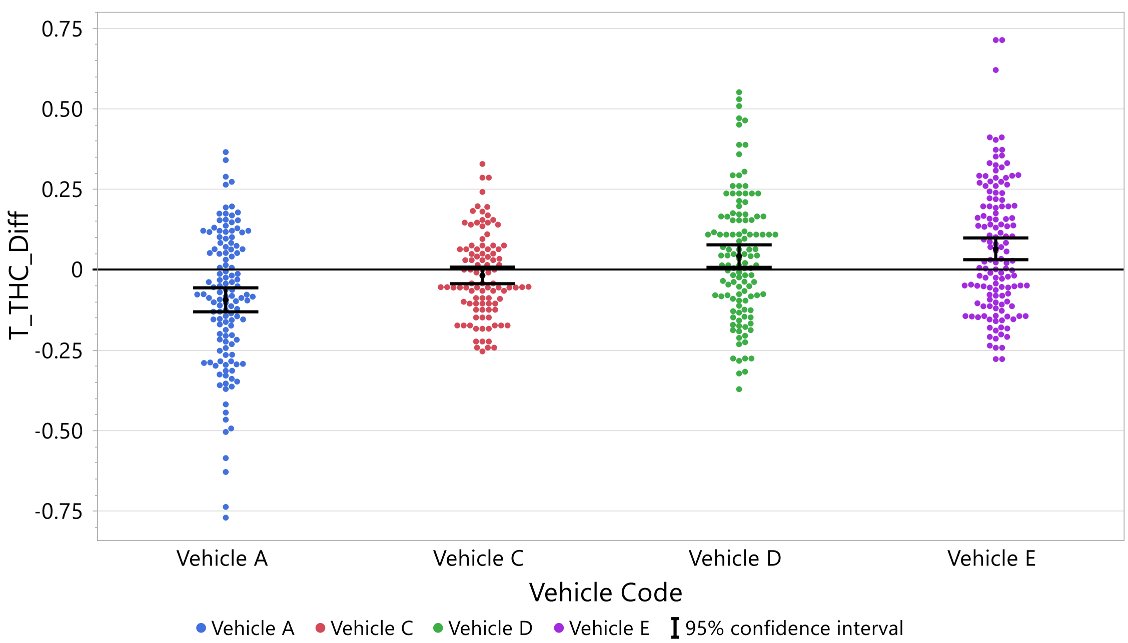


Figure 4-66: Simulated Transformed THC Differences (PEMS Road – CVS)

Table 4-21: T_THC Road Bias Estimates

Vehicle	E-134 PEMS Road Bias	E-122-2 PEMS Road Bias
Vehicle A	-0.0933	-0.1353
Vehicle C	-0.0175*	-0.3942
Vehicle D	0.0426	0.0145*
Vehicle E	0.0651	N/A

*bias was not statistically significantly different from zero

Table 4-22: E-134 Expected THC Difference (PEMS_Road – CVS) based on E-134 Median THC

Vehicle	Median THC (g/mi) E-134 CVS Dyno	Expected THC E-134 PEMS Road (%)	Expected THC E-122-2 PEMS Road (%)
Vehicle A	0.0529	0.0481(-9%)	0.0462(-13%)
Vehicle C	0.0142	0.0139(-2%)*	0.0095(-33%)
Vehicle D	0.0241	0.0251(4%)	0.0245(1%)*
Vehicle E	0.0337	0.0359(7%)	N/A

*based on average bias, but the bias was not statistically significantly different from zero

The road bias is similar in both programs and fairly small in magnitude, with the exception of Vehicle C. Vehicle C showed an additional negative bias for road testing in E-122-2 which was not seen in E-134. Though as a percentage the difference seems large (-33%), the absolute magnitude is small (approx. 0.005 mg/mi). Vehicle E was the only vehicle in either test program to show a significant positive bias for road testing. This unique aspect of Vehicle E may be due to THC produced during the steep highway grade; significant THC was observed during most road tests during this period (see Section 3.4.3.3 for some insight) but consistently less THC was observed during all chassis dyno tests.

4.3.3 PEMS Accuracy and Bias for CO (g/mi)

4.3.3.1 PEMS Instrument Bias for CO: Dyno Testing

Figure 4-67 is a plot of the E-134 CO data in untransformed units which show that CO results appear similar between the PEMS dyno results and CVS results. The model based on paired differences between PEMS dyno and CVS was run, and the model indicated a statistically significant negative bias for Vehicles A and D, as can be seen in Figure 4-68 and Table 4-23. A plot showing the data for E-122-2 is provided for reference following the model results.

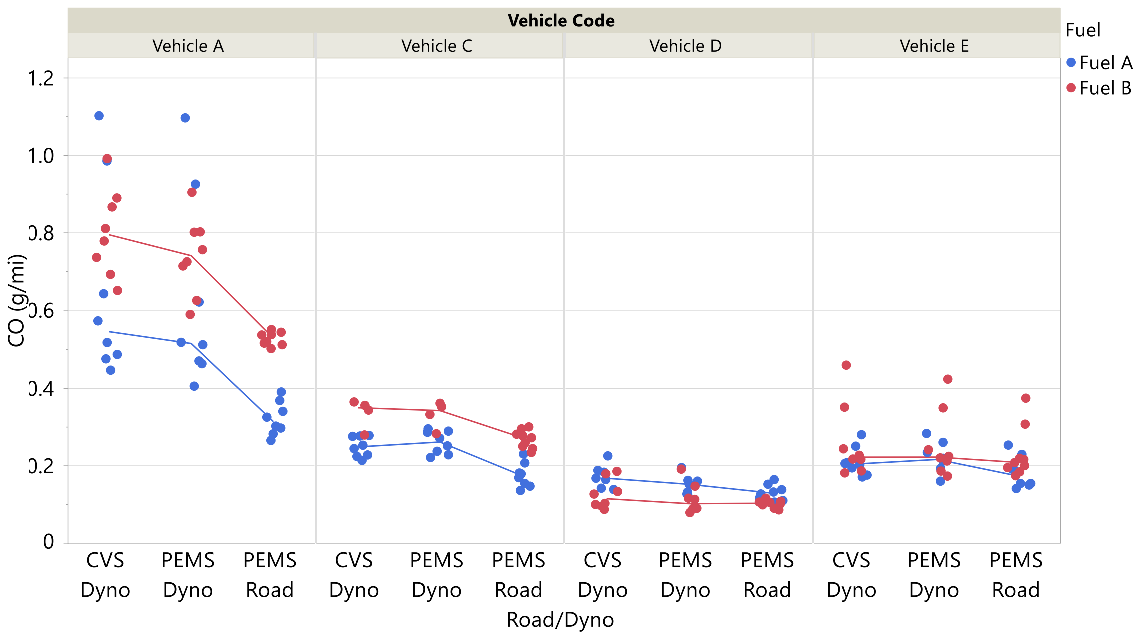


Figure 4-67: E-134 CO (g/mi) by Vehicle and Measurement Method

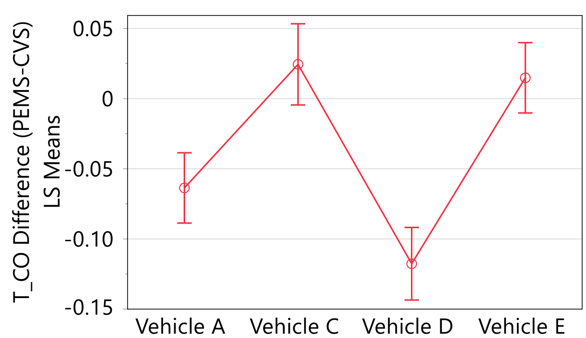


Figure 4-68: LS Mean Ln(CO) Differences with 95% CI by Vehicle (PEMS – CVS)

Table 4-23: LS Mean Ln(CO) Differences with 95% CI by Vehicle (PEMS – CVS)

Level				Least Sq Mean	Lower 95%	Upper 95%
Vehicle C	A			0.0243	-0.0046	0.0533
Vehicle E	A			0.0148	-0.0103	0.0398
Vehicle A		B		-0.0637	-0.0887	-0.0386
Vehicle D			C	-0.1177	-0.1435	-0.0918

Levels not connected by same letter are significantly different.

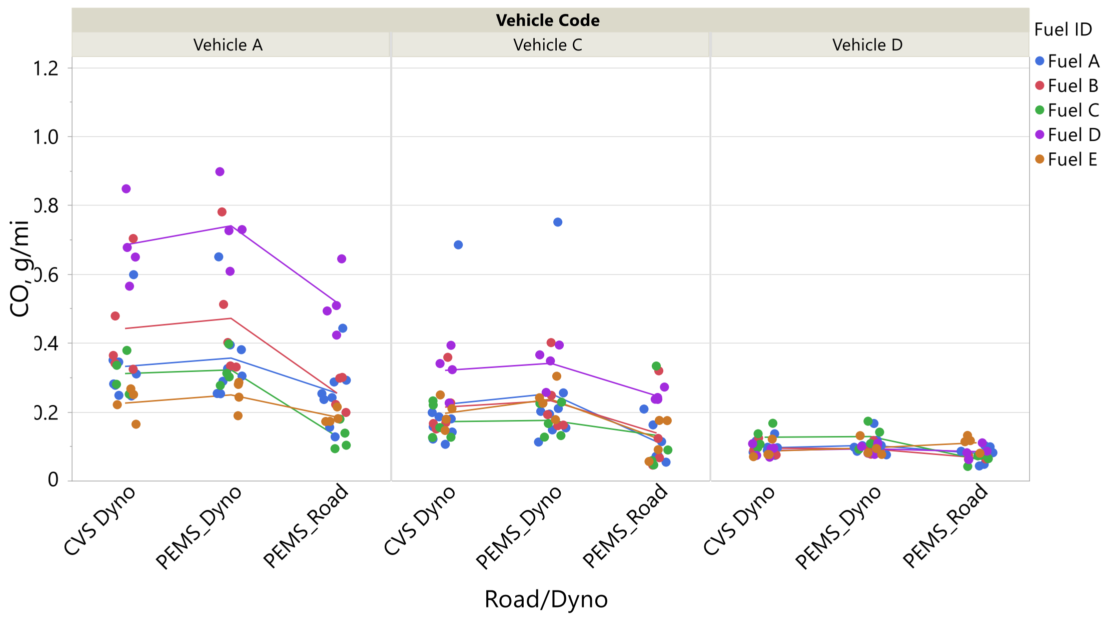


Figure 4-69: E-122-2 CO (g/mi) by Vehicle and Measurement Method

Because the model LS mean differences are given in transformed units and are level dependent for CO in g/mi, Table 4-24 provides an example of the expected CO differences at the median CO result measured by the CVS in E-134. Estimates are given for both projects, with asterisks given for differences which were not significantly different from zero. Similar to THC, there is a difference in the bias between the two projects. In E-122-2, there was a consistent positive bias for the PEMS which was either not present or changed to significantly negative in E-134.

Table 4-24: Expected CO Difference (PEMS – CVS) based on E-134 Median CO

Vehicle	Median CO (g/mi) E-134 CVS Dyno	Expected CO E-134 PEMS Dyno (%)	Expected CO E-122-2 PEMS Dyno (%)
Vehicle A	0.715	0.671(-6%)	0.774(8%)
Vehicle C	0.278	0.285(2%)*	0.310(11%)
Vehicle D	0.142	0.126(-11%)	0.151(7%)
Vehicle E	0.212	0.215(1%)*	N/A

*based on average bias, but the bias was not statistically significantly different from zero

4.3.3.2 PEMS Accuracy for CO: Road Testing

Each possible pairwise difference between a CO road test result and a CVS dyno result was simulated, and all simulated differences in transformed units are shown below in Figure 4-70. The average value is shown in Table 4-25, along with the estimated bias from E-122-2. These values represent the expected amount of disagreement between a CVS dyno test and a PEMS road test for an unbiased (on the dyno) PEMS unit. Because the values are in transformed units and are again level dependent for CO in original units, an example application is given at the median E-134 THC level for each vehicle in Table 4-26, along with a comparison to E-122-2.

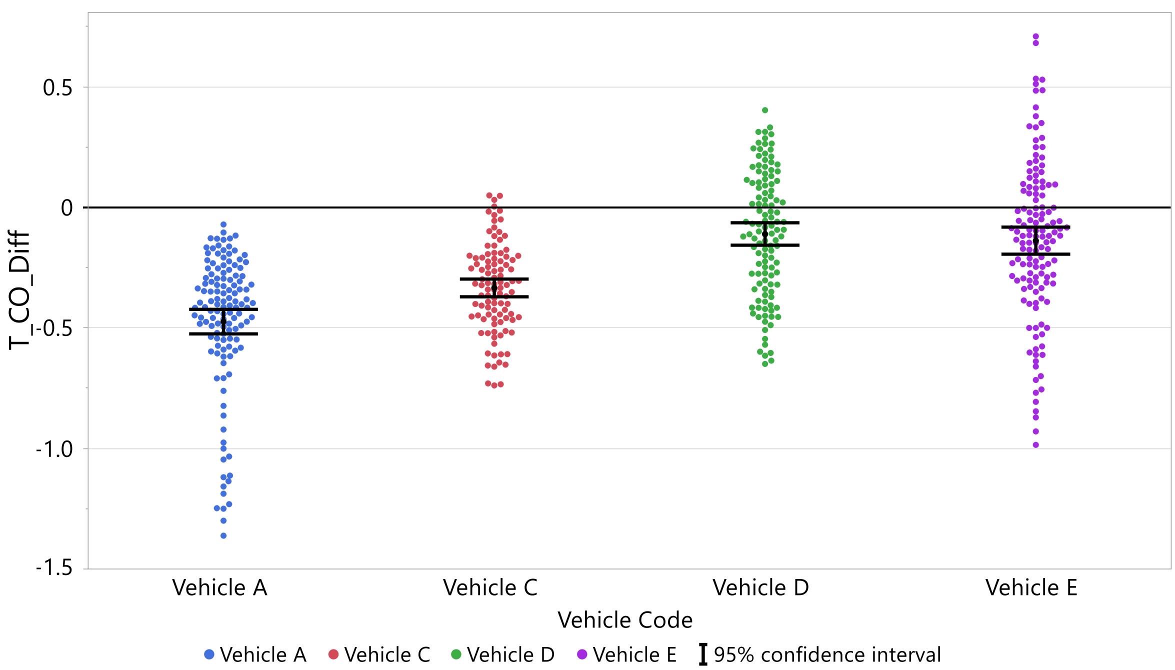


Figure 4-70: Simulated Transformed CO Differences (PEMS Road – CVS)

Table 4-25: T_CO Road Bias Estimates

Vehicle	E-134 PEMS Road Bias	E-122-2 PEMS Road Bias
Vehicle A	-0.4740	-0.2654
Vehicle C	-0.3342	-0.5183
Vehicle D	-0.1104	-0.1598
Vehicle E	-0.1381	N/A

Table 4-26: E-134 Expected CO Difference (PEMS_Road – CVS) based on E-134 Median CO

Vehicle	Median CO (g/mi) E-134 CVS Dyno	Expected CO E-134 PEMS Road (%)	Expected CO E-122-2 PEMS Road (%)
Vehicle A	0.715	0.445(-38%)	0.548(-23%)
Vehicle C	0.278	0.199(-28%)	0.166(-40%)
Vehicle D	0.142	0.127(-10%)	0.121(-15%)
Vehicle E	0.212	0.184(-13%)	N/A

In all vehicles for both programs, there was an additional negative bias for PEMS road tests. For common vehicles, the magnitude of the bias was similar.

4.3.4 PEMS Accuracy and Bias for CO_2 (g/mi)

4.3.4.1 PEMS Instrument Bias for CO_2: Dyno Testing

Figure 4-71 is a plot of the E-134 CO_2 data in untransformed units. The model based on paired differences between PEMS dyno and CVS was run, and the model indicated a statistically significant positive bias for PEMS dyno CO_2 with Vehicles A and E, and a smaller but statistically significant negative bias for Vehicle D, as can be seen in Figure 4-72 and Table 4-27. A plot showing the data for E-122-2 is provided for reference following the model results.

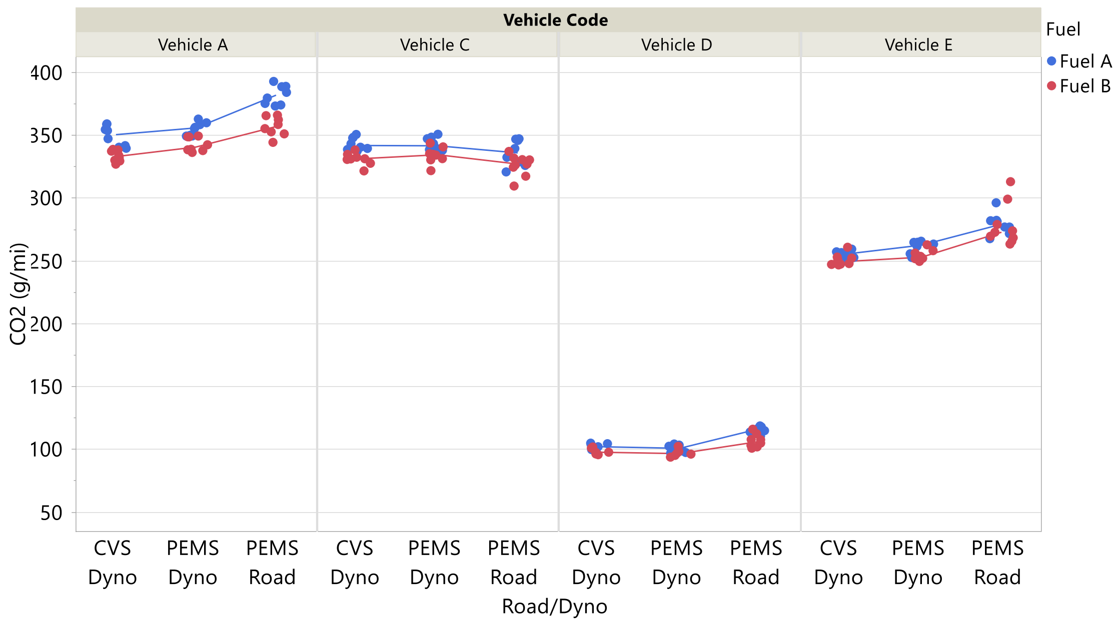


Figure 4-71: E-134 CO_2 (g/mi) by Vehicle and Measurement Method

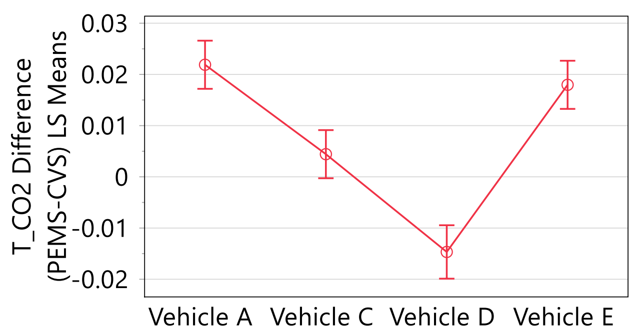


Figure 4-72: LS Mean Ln(CO_2) Differences with 95% CI by Vehicle (PEMS – CVS)

Table 4-27: LS Mean Ln(CO_2) Differences with 95% CI by Vehicle (PEMS – CVS)

Level				Least Sq Mean	Lower 95%	Upper 95%
Vehicle A	A			0.0219	0.0172	0.0266
Vehicle E	A			0.0180	0.0133	0.0227
Vehicle C		B		0.0044	-0.0003	0.0091
Vehicle D			C	-0.0147	-0.0199	-0.0095

Levels not connected by same letter are significantly different.

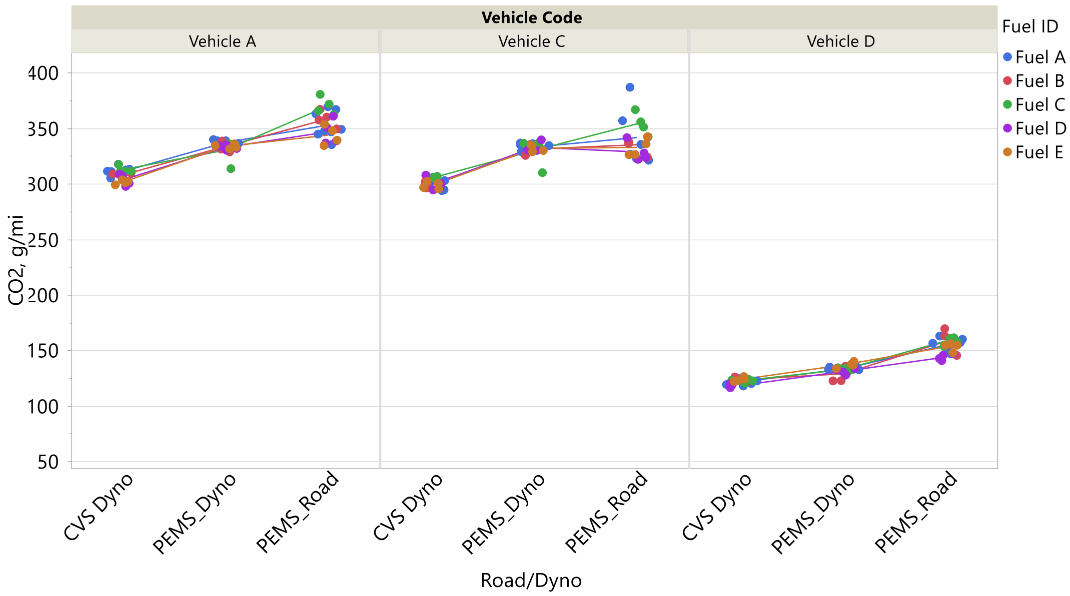


Figure 4-73: E-122-2 CO_2 (g/mi) by Vehicle and Measurement Method

Because the model LS mean differences are given in transformed units and are level dependent for CO_2 in g/mi, Table 4-28 provides an example of the expected CO_2 differences at the median CO_2 result measured by the CVS in E-134. Estimates are given for both projects, with asterisks given for differences which were not significantly different from zero. In E-122-2, there was a consistent positive bias for PEMS dyno CO_2 of a magnitude around 10%. Though there is a statistically significant bias for CO_2 in the E-134 data, it is much smaller (around 1% to 2%) and is not directionally consistent, showing a negative bias for Vehicle D.

Table 4-28: Expected CO_2 Difference (PEMS – CVS) based on E-134 Median CO_2

Vehicle	Median CO_2 (g/mi) E-134 CVS Dyno	Expected CO_2 E-134 PEMS Dyno (%)	Expected CO_2 E-122-2 PEMS Dyno (%)
Vehicle A	339.3	346.8(2.2%)	368.7(8.7%)
Vehicle C	338.0	339.5(0.4%)*	373.4(10.5%)
Vehicle D	100.0	98.6(-1.5%)	109.4(9.4%)
Vehicle E	252.9	257.5(1.8%)	N/A

*based on average bias, but the bias was not statistically significantly different from zero

4.3.4.2 PEMS Accuracy for CO_2: Road Testing

Each possible pairwise difference between a CO_2 road test result and a CVS dyno result was simulated, and all simulated differences in transformed units are shown below in Figure 4-74. The average value is shown in Table 4-29, along with the estimated bias from E-122-2. These values represent the expected amount of disagreement between a CVS dyno test and a PEMS road test for an unbiased (on the dyno) PEMS unit. Because the values are in transformed units and are again level dependent for CO_2 in original units, an example application is given at the median E-134 CO_2 level for each vehicle in Table 4-30, along with a comparison to E-122-2.

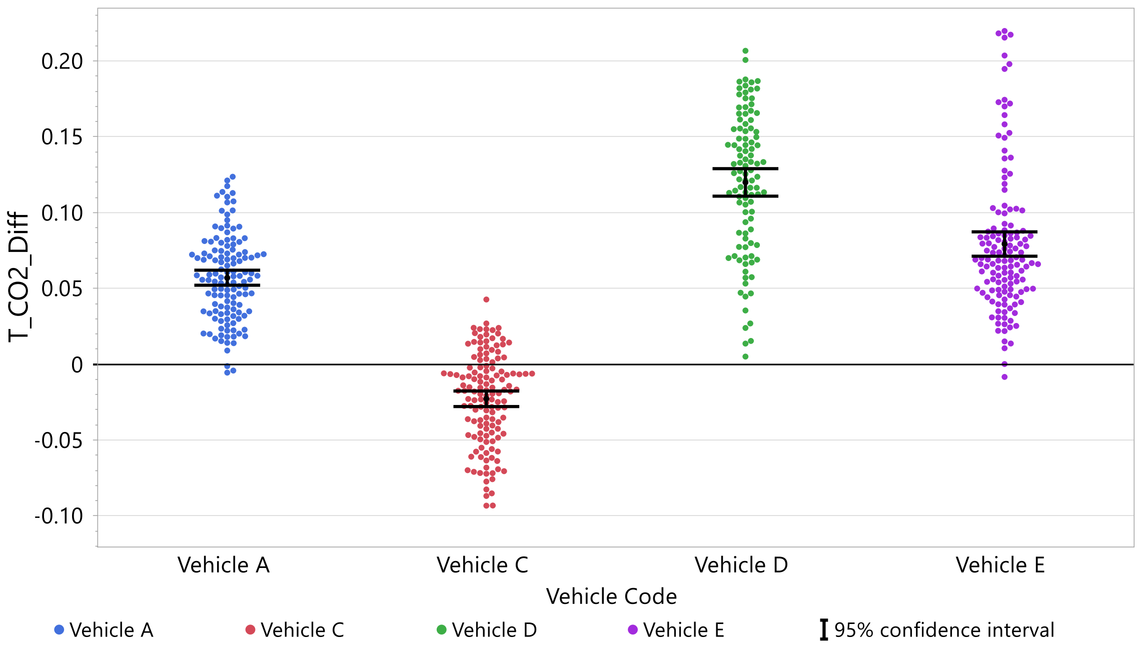


Figure 4-74: Simulated Transformed CO_2 Differences (PEMS Road – CVS)

Table 4-29: T_CO_2 Road Bias Estimates

Vehicle	E-134 PEMS Road Bias	E-122-2 PEMS Road Bias
Vehicle A	0.0570	0.0544
Vehicle C	-0.0228	0.0124
Vehicle D	0.1199	0.1458
Vehicle E	0.0793	N/A

Table 4-30: E-134 Expected CO_2 Difference (PEMS_Road – CVS) based on E-134 Median CO_2

Vehicle	Median CO_2 (g/mi) E-134 CVS Dyno	Expected CO_2 E-134 PEMS Road (%)	Expected CO_2 E-122-2 PEMS Road (%)
Vehicle A	339.3	359.2(5.9%)	358.2(5.6%)
Vehicle C	338.0	330.4(-2.3%)	342.2(1.2%)
Vehicle D	100.0	112.8(12.7%)	115.7(15.7%)
Vehicle E	252.9	273.8(8.3%)	N/A

Vehicles A and D both indicated a positive bias for road testing in both projects, with Vehicle A showing an approximate 6% increase in CO_2, and Vehicle D, approximately 13%-16% higher. Vehicle E, the vehicle unique to E-134, was right in between these two vehicles, showing an 8% increase in CO_2. Vehicle C appears to behave differently from the other vehicles in both projects. This vehicle showed very little positive road-testing bias in E-122-2 and was slightly negative in E-134. Each vehicle appears to have a rather unique on-road bias which is consistent across projects. These biases may be due to the EPA database road load models used for chassis dynamometer testing which do not incorporate the weight and aerodynamics impacts of the installed PEMS equipment.[21] Naturally these impacts would be incorporated into the on-road testing.

[21] E-122-2 Section 3.2.3 includes a demonstration of how a change in road load can effect emissions performance for Vehicle A. It is clear that CO_2 is a primary emissions component that is impacted.

4.3.5 PEMS Accuracy and Bias for Fuel Economy (mpg)

4.3.5.1 PEMS Instrument Bias for Fuel Economy: Dyno Testing

Figure 4-75 is a plot of the E-134 fuel economy data in untransformed units. The model based on paired differences between PEMS dyno and CVS was run, and the model indicated a statistically significant negative bias for PEMS dyno fuel economy with Vehicles A, C, and E, and a positive bias for Vehicle D, as can be seen in Figure 4-76 and Table 4-31. A plot showing the data for E-122-2 is provided for reference following the model results.

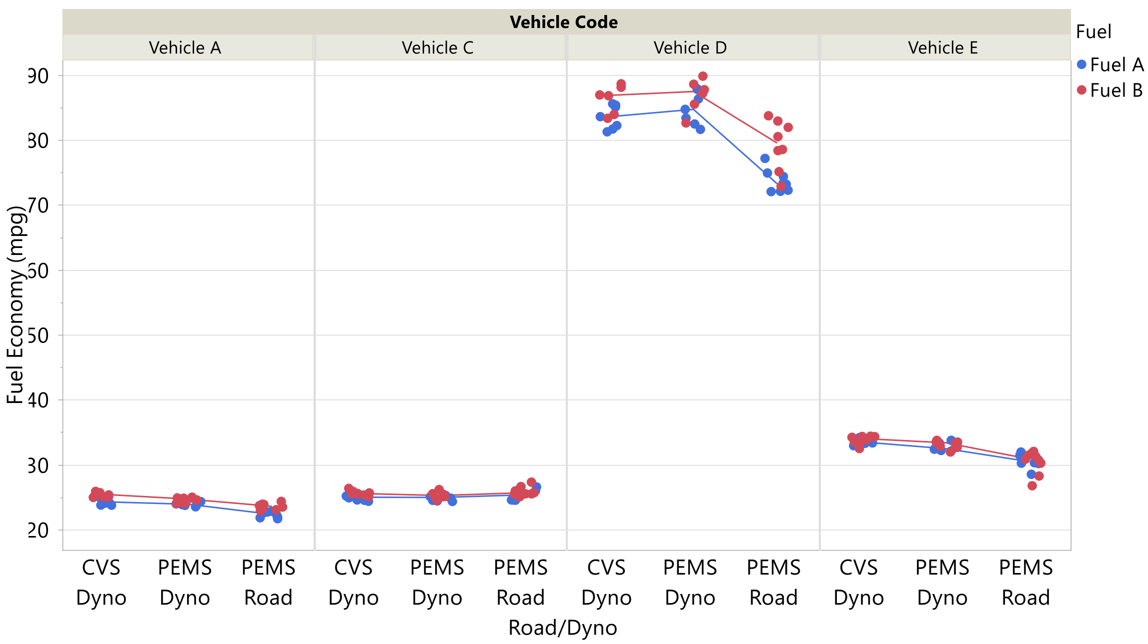


Figure 4-75: E-134 Fuel Economy (mpg) by Vehicle and Measurement Method

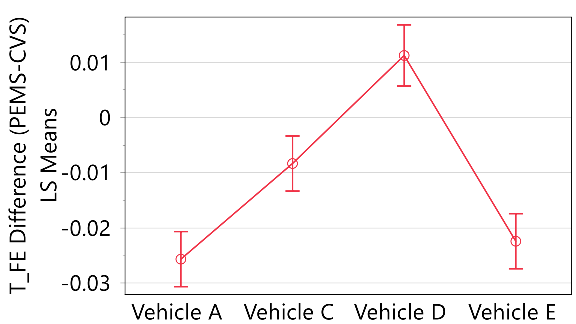


Figure 4-76: LS Mean Ln(Fuel Economy) Differences with 95% CI by Vehicle (PEMS – CVS)

Table 4-31: LS Mean Ln(Fuel Economy) Differences with 95% CI by Vehicle (PEMS – CVS)

Level				Least Sq Mean	Lower 95%	Upper 95%
Vehicle D	A			0.0112	0.0057	0.0168
Vehicle C		B		-0.0083	-0.0133	-0.0033
Vehicle E			C	-0.0224	-0.0274	-0.0174
Vehicle A			C	-0.0257	-0.0307	-0.0207

Levels not connected by same letter are significantly different.

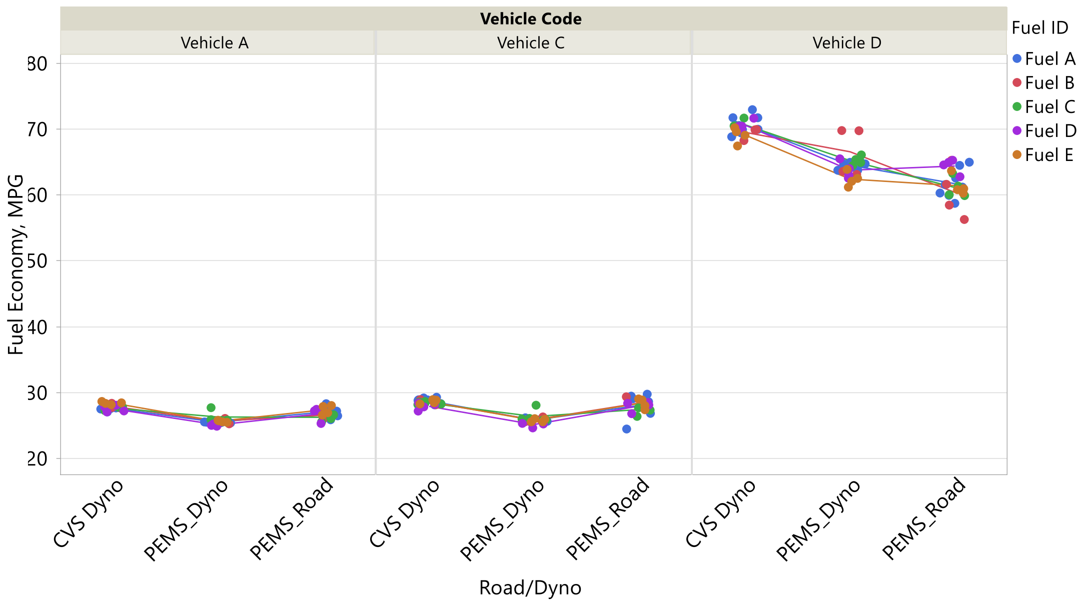


Figure 4-77: E-122-2 Fuel Economy (mpg) by Vehicle and Measurement Method

Comparisons between projects mirror what was stated in the previous section covering CO_2 PEMS instrument bias, as we see E-122-2 PEMS dyno fuel economy results were consistently biased low around 10%, and this bias is much smaller in magnitude for E-134.

Table 4-32: Expected F.E. Difference (PEMS – CVS) based on E-134 Median F.E.

Vehicle	Median Fuel Economy (mpg) E-134 CVS Dyno	Expected Fuel Economy E-134 PEMS Dyno (%)	Expected Fuel Economy E-122-2 PEMS Dyno (%)
Vehicle A	25.1	24.4(-2.5%)	23.0(-8.2%)
Vehicle C	25.3	25.1(-0.8%)	22.9(-9.5%)
Vehicle D	85.4	86.4(1.1%)	78.2(-8.4%)
Vehicle E	33.7	33.0(-2.2%)	N/A

4.3.5.2 PEMS Accuracy for Fuel Economy: Road Testing

Each possible pairwise difference between a fuel economy road test result and a CVS dyno result was simulated, and all simulated differences in transformed units are shown below in Figure 4-78. The average value is shown in Table 4-33, along with the estimated bias from E-122-2. These values represent the expected amount of disagreement between a CVS dyno test and a PEMS road test for an unbiased (on the dyno) PEMS unit. Because the values are in transformed units and are again level dependent for fuel economy in original units, an example application is given at the median E-134 fuel economy level for each vehicle in Table 4-34, along with a comparison to E-122-2.

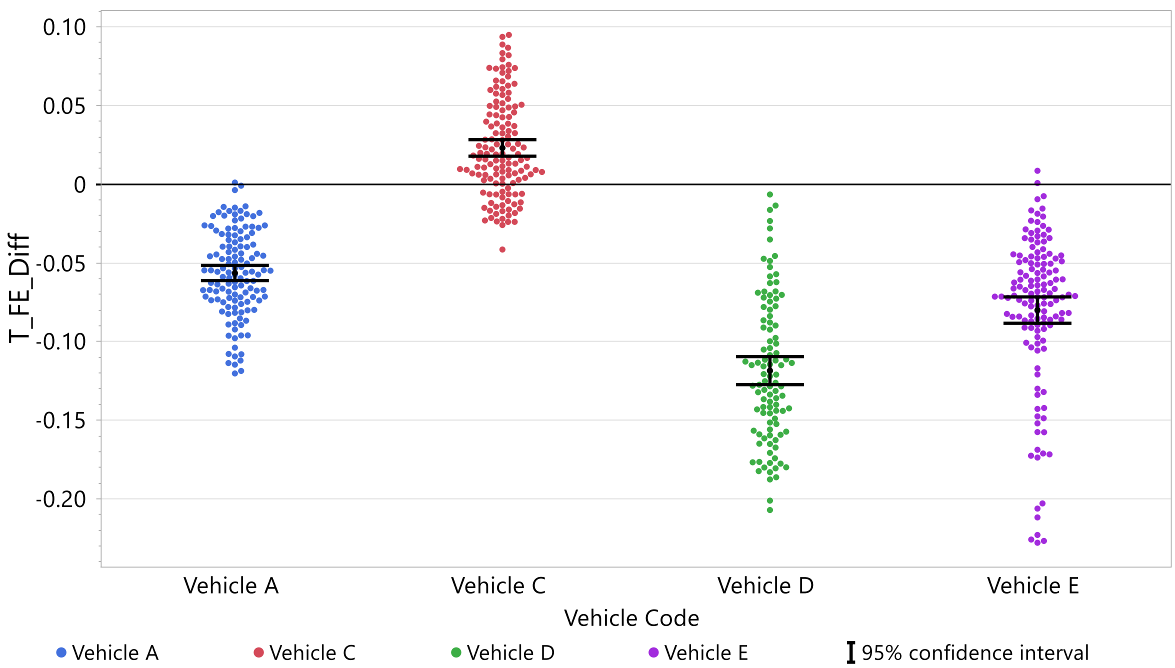


Figure 4-78: Simulated Transformed Fuel Economy Differences (PEMS Road – CVS)

Table 4-33: T_FE Road Bias Estimates

Vehicle	E-134 PEMS Road Bias	E-122-2 PEMS Road Bias
Vehicle A	-0.0564	0.0543
Vehicle C	-0.0231	0.0905
Vehicle D	-0.1185	-0.0432
Vehicle E	-0.0800	N/A

Table 4-34: E-134 Expected F.E. Difference (PEMS_Road – CVS) based on E-134 Median F.E.

Vehicle	Median F.E. (mpg) E-134 CVS Dyno	Expected F.E. E-134 PEMS Road (%)	Expected F.E. E-122-2 PEMS Road (%)
Vehicle A	25.1	23.7(-5.5%)	26.5(5.6%)
Vehicle C	25.3	24.8(-2.3%)	27.7(9.5%)
Vehicle D	85.4	75.9(-11.2%)	81.8(-4.2%)
Vehicle E	33.7	31.1(-7.7%)	N/A

The E-134 fuel economy on road tests showed a consistent negative bias, ranging from -2% to -11%. Vehicle D showed a directionally similar but smaller negative bias for road test fuel economy in E-122-2. Vehicles A and C behaved differently for E-122-2 road tests, showing a positive bias of about 6% and 10%, respectively, even though these vehicles showed a positive bias for CO_2 in the same program. It is thought that the CO and THC biases for E-122-2 had a significant impact on the resulting E-122-2 fuel economy bias.

4.3.6 PEMS Accuracy and Bias for NO_x (g/mi)

4.3.6.1 PEMS Instrument Bias for NO_x: Dyno Testing

Figure 4-79 is a plot of the E-134 NO_x data in untransformed units. The model based on paired differences between PEMS dyno and CVS was run, and the model indicated a statistically significant positive bias for PEMS dyno NO_x for all four vehicles, as can be seen in Figure 4-80 and Table 4-35. A plot showing the data for E-122-2 is provided for reference following the model results. For this parameter, the observed bias was similar across both projects.

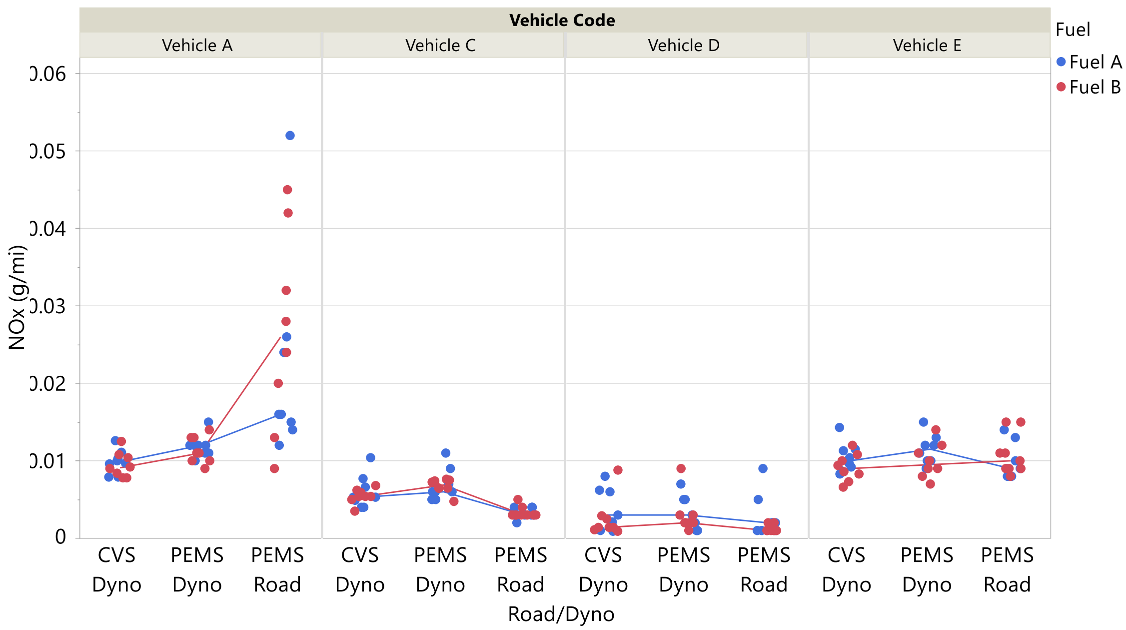


Figure 4-79: E-134 NO_x (g/mi) by Vehicle and Measurement Method

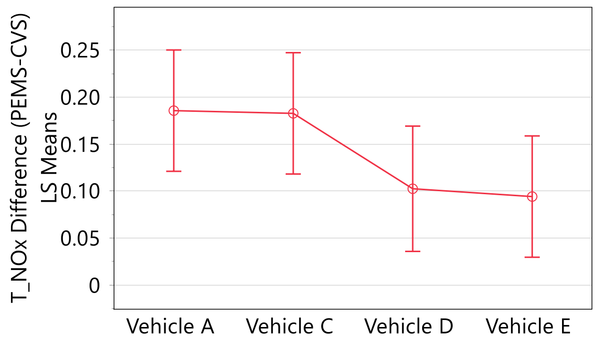


Figure 4-80: LS Mean Ln(NO_x) Differences with 95% CI by Vehicle (PEMS – CVS)

Table 4-35: LS Mean Ln(NO_x) Differences with 95% CI by Vehicle (PEMS – CVS)

Level			Least Sq Mean	Lower 95%	Upper 95%
Vehicle A	A		0.1856	0.1211	0.2502
Vehicle C	A	B	0.1827	0.1182	0.2473
Vehicle D	A	B	0.1025	0.0358	0.1692
Vehicle E		B	0.0942	0.0296	0.1587

Levels not connected by same letter are significantly different.

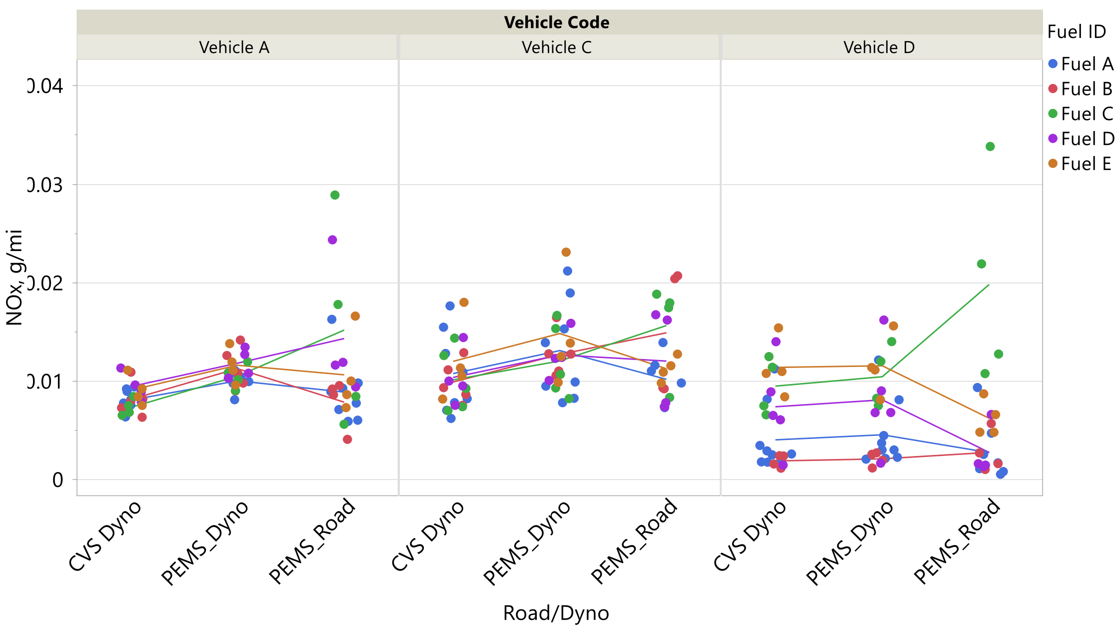


Figure 4-81: E-122-2 NO_x (g/mi) by Vehicle and Measurement Method

Table 4-36: Expected NO_x Difference (PEMS – CVS) based on E-134 Median NO_x

Vehicle	Median NO_x (g/mi) E-134 CVS Dyno	Expected NO_x E-134 PEMS Dyno (%)	Expected NO_x E-134 PEMS Dyno (%)
Vehicle A	0.0097	0.0116(20%)	0.0126(30%)
Vehicle C	0.0054	0.0065(20%)	0.0067(24%)
Vehicle D	0.0021	0.0023(11%)	0.0023(11%)
Vehicle E	0.0095	0.0104(10%)	N/A

4.3.6.2 PEMS Accuracy for NO_x: Road Testing

Each possible pairwise difference between a NO_x road test result and a CVS dyno result was simulated, and all simulated differences in transformed units are shown below in Figure 4-82. The average value is shown in Table 4-37, along with the estimated bias from E-122-2. These values represent the expected amount of disagreement between a CVS dyno test and a PEMS road test for an unbiased (on the dyno) PEMS unit. Because the values are in transformed units and are again level dependent for NO_x in original units, an example application is given at the median E-134 NO_x level for each vehicle in Table 4-38, along with a comparison to E-122-2.

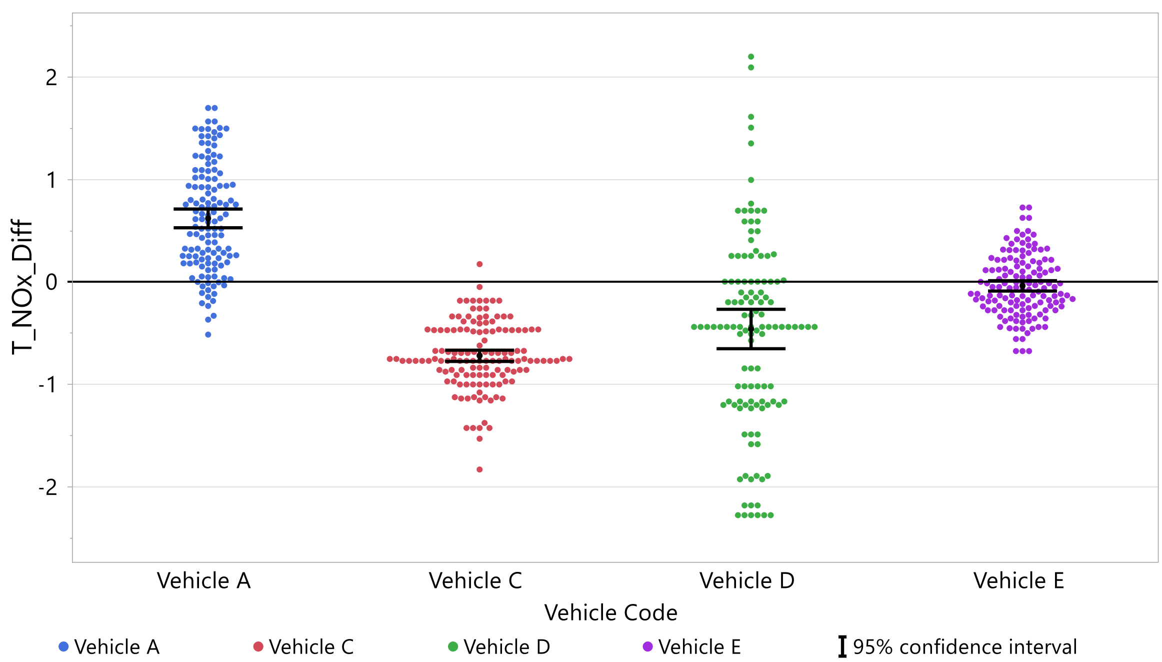


Figure 4-82: Simulated Transformed NO_x Differences (PEMS Road – CVS)

Table 4-37: T_NO_x Road Bias Estimates

Vehicle	E-134 PEMS Road Bias	E-122-2 PEMS Road Bias
Vehicle A	0.6206	-0.1892
Vehicle C	-0.7211	-0.0872
Vehicle D	-0.4593	-0.5247
Vehicle E	-0.0383*	N/A

*bias was not statistically significantly different from zero

Table 4-38: E-134 Expected NO_x Difference (PEMS_Road – CVS) based on E-134 Median NO_x

Vehicle	Median NO_x (g/mi) E-134 CVS Dyno	Expected NO_x E-134 PEMS Road (%)	Expected NO_x E-122-2 PEMS Road (%)
Vehicle A	0.0097	0.0179(86%)	0.0080(-17%)
Vehicle C	0.0054	0.0026(-51%)	0.0049(-8%)
Vehicle D	0.0021	0.0013(-37%)	0.0012(-41%)
Vehicle E	0.0095	0.0091(-4%)*	N/A

*based on average bias, but the bias was not statistically significantly different from zero

Vehicle E, the vehicle unique to E-134, showed no significant bias for road tests. Vehicle D showed a small negative bias consistent in both projects. Vehicle A and C showed a different bias for road tests than that which was observed in E-122-2. Vehicle C had very little bias and road testing for E-122-2 but showed a consistently negative bias for E-134 data. Vehicle A showed a small negative bias in E-122-2, but exhibited a very clear positive bias for road-tests in E-134.

4.4 PEMS Sensitivity to Fuel Property Changes

The final task of this project was to determine if the PEMS responds to fuel and fuel property changes in a similar manner to what is observed on the chassis-dyno CVS test results. The two fuels in the project were chosen due to their differences in fuel PMI, with Fuel A being a higher PMI fuel than Fuel B. It is acknowledged by the authors that any differences in emissions results between fuels cannot be solely attributed to fuel PMI differences, as other fuel properties are not being held constant and are therefore confounded. Some key fuel properties were shown in Table 3-3 for both test Fuels: A and B.

To achieve this final task, only a comparison of PEMS Dyno to CSV Dyno is required. In fact, the PEMS road data is not usable for this task because there is no directly correlated CVS result for on-road tests. However, PEMS Road results will still be included throughout this section and on-road fuel differences will be calculated. The fuel differences between PEMS Dyno and PEMS Road can then be compared to assess the impact of real-world factors.[22]

To determine if the PEMS emissions measurements respond to fuel changes similar to CVS-based measurements, a model was run separately by measurement method (CVS Dyno, PEMS Dyno, and PEMS Road). The emissions results were modeled for each measurement method using the transformations described previously, with vehicle, fuel, and the interaction vehicle*fuel as factors in the model. The estimated fuel difference for each vehicle is compared across methods for PM, THC, CO, CO_2, Fuel Economy, and NO_x.

4.4.1 PM Differences Between Fuels

A plot of the PM data is shown again, colored by fuel, in Figure 4-83. The least squares (LS) mean PM data with 95% confidence intervals from the regression models follows in Figure 4-84, with model estimates back-transformed into original units. Table 4-39 provides a numerical summary. In the table, comparisons are made based on fixing the PM at the level observed with Fuel A, and then estimating the expected Fuel B PM difference based on the LS Mean contrast estimate and its 95% confidence interval. To account for absolute level differences when comparing measurement methods to one another, one should use the transformed PM difference (T_PM Diff) column of the table.

[22] This comparison is used to elaborate on observations made in earlier sections such as those in Sec 4.3 for PEMS Road bias.

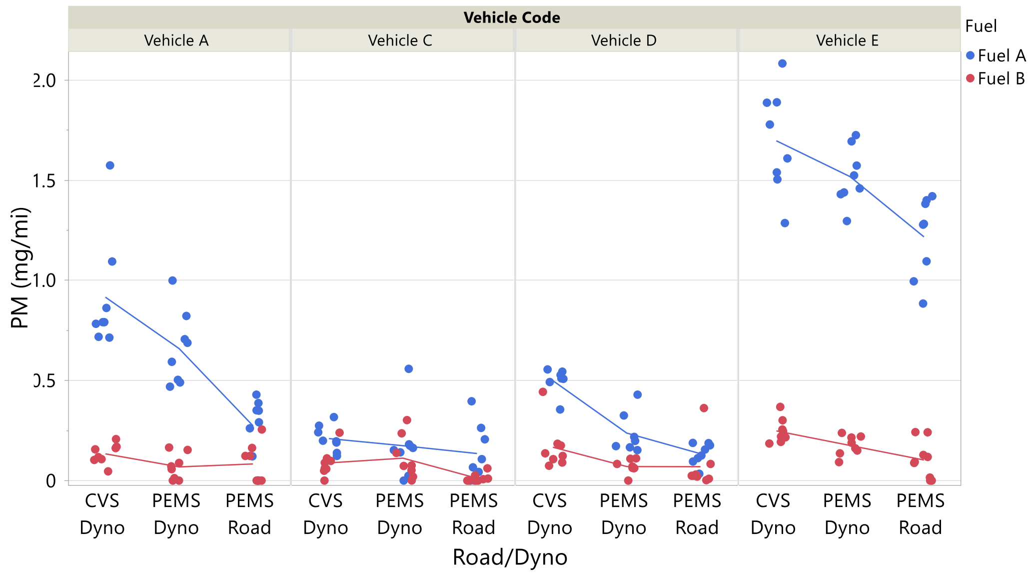


Figure 4-83: PM (mg/mi) by Vehicle and Measurement Method

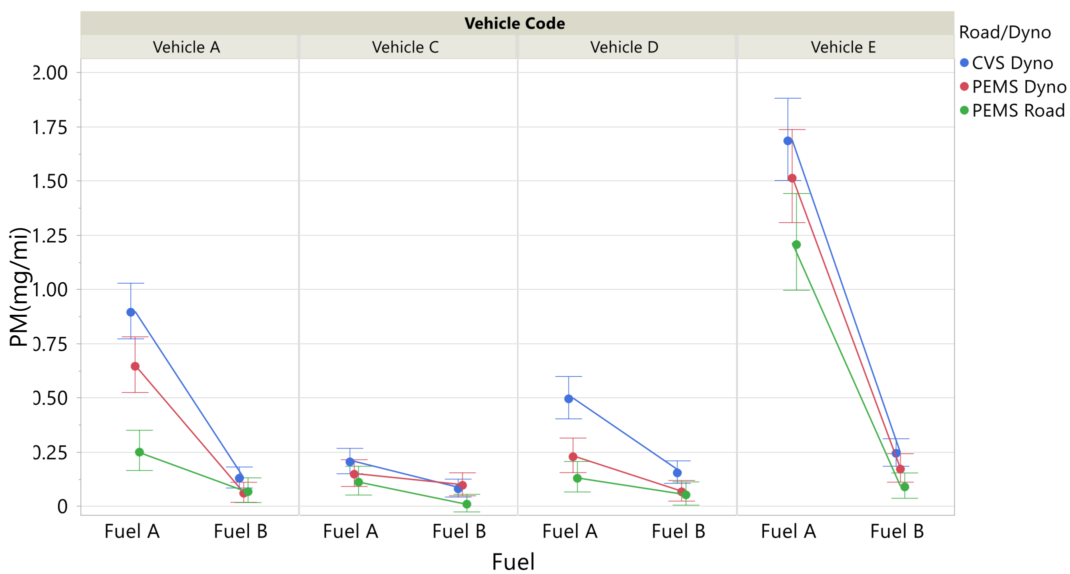


Figure 4-84: LS Mean PM (mg/mi) by Fuel

Table 4-39: Estimated PM Differences Between Fuels with 95% Confidence Intervals

Vehicle	Method	Fuel A Predicted PM (mg/mi)	Fuel B Predicted PM (mg/mi) [95% Conf. Int.]	PM Difference Fuel A – Fuel B (mg/mi) [95% Conf. Int.]	T_PM Difference (Fuel A – Fuel B) [95% Conf. Int.]
Vehicle A	CVS Dyno	0.90	0.13 [0.07, 0.21]	0.77 [0.69, 0.83]	0.39 [0.33, 0.45]
	PEMS Dyno	0.65	0.06 [0.00, 0.14]	0.59 [0.51, 0.64]	0.36 [0.29, 0.44]
	PEMS Road	0.25	0.07 [0.00, 0.16]	0.18 [0.09, 0.25]	0.15 [0.06, 0.24]
Vehicle C	CVS Dyno	0.21	0.08 [0.03, 0.15]	0.12 [0.06, 0.18]	0.11 [0.05, 0.17]
	PEMS Dyno	0.15	0.10 [0.03, 0.18]	0.05* [-0.03, 0.12]	0.05* [-0.03, 0.12]
	PEMS Road	0.11	0.01 [-0.04, 0.08]	0.10 [0.03, 0.15]	0.12 [0.03, 0.20]
Vehicle D	CVS Dyno	0.50	0.15 [0.09, 0.24]	0.34 [0.26, 0.41]	0.21 [0.14, 0.27]
	PEMS Dyno	0.23	0.07 [0.01, 0.15]	0.16 [0.08, 0.22]	0.14 [0.06, 0.22]
	PEMS Road	0.13	0.05 [-0.01, 0.14]	0.08* [-0.01, 0.14]	0.08* [-0.01, 0.17]
Vehicle E	CVS Dyno	1.69	0.25 [0.16, 0.34]	1.44 [1.34, 1.52]	0.51 [0.45, 0.57]
	PEMS Dyno	1.51	0.17 [0.09, 0.28]	1.34 [1.24, 1.42]	0.52 [0.45, 0.60]
	PEMS Road	1.21	0.09 [0.02, 0.19]	1.12 [1.02, 1.19]	0.52 [0.43, 0.60]

*fuel difference not statistically significantly different from zero

All vehicles saw directionally higher PM levels with the higher PMI fuel, with Vehicle E and Vehicle A producing the largest differences. Although the most notable conclusion from Table 4-39 is that the modeled fuel differences for both CVS dyno and PEMS dyno were similar for all vehicles. This can be assessed by viewing the 95% confidence interval of the T_PM difference. This conclusion indicates that the PEMS can measure the PM impact of different fuels in a similar manner to the chassis-dyno CVS system.

Furthermore, PEMS PM fuel differences for Vehicle C, D, and E were similar on the dyno and the road. However, this was not the case for Vehicle A where the PM results only differed by 0.18 mg/mi for PEMS road which was a statistically different result relative to the 0.59 mg/mi difference observed for PEMS dyno. This discrepancy is related to the results discussed in Section 4.3.1.2.

It is worth noting that neither Vehicle C nor Vehicle D saw a statistically significant difference in PM across the varying PMI of fuels in E-122-2. Similar results were observed in E-134 for Vehicle C, specifically with the PEMS dyno model which did not estimate a statistically significant difference in PM results across fuels. However, on the dyno, Vehicle D did show a statistically significant difference in PM results across fuels in E-134; though this was not the case with the PEMS road model which indicated no statistically significant difference across fuels. Vehicle A demonstrated a statistically significant difference in PM emissions across fuels in both E-122-2 and E-134; although, the largest observed PM difference across any combination of fuels in E-122-2 for Vehicle A was 0.2 mg/mi which is considerably smaller than seen in E-134. Any fuel discrepancies across these two projects cannot be attributed to any one factor as there are many potential factors including: different test cycle, different ambient test conditions, different drivers, and even different test fuels were chosen despite similar naming conventions.

Finally, it is notable that Vehicle E saw the largest and most consistent PM difference between fuels, ranging from 1.1 mg/mi on the road-testing to about 1.4 mg/mi on the dyno. The lower estimate for the road testing is explainable by the lower PM levels observed, as the transformed estimates are very similar to chassis-dyno testing. It is possible that this larger observed PM difference across fuels is related to the unique engine technology employed in Vehicle E.

4.4.2 THC Differences Between Fuels

A plot of the THC data is shown again, colored by fuel, in Figure 4-85. The LS mean THC data with 95% confidence intervals from the regression models follows in Figure 4-86, with model estimates back-transformed into original units. Table 4-40 provides a numerical summary. In the table, comparisons are made based on fixing the THC at the level observed with Fuel A, and then estimating the expected Fuel B THC difference based on the LS Mean contrast estimate and its 95% confidence interval.

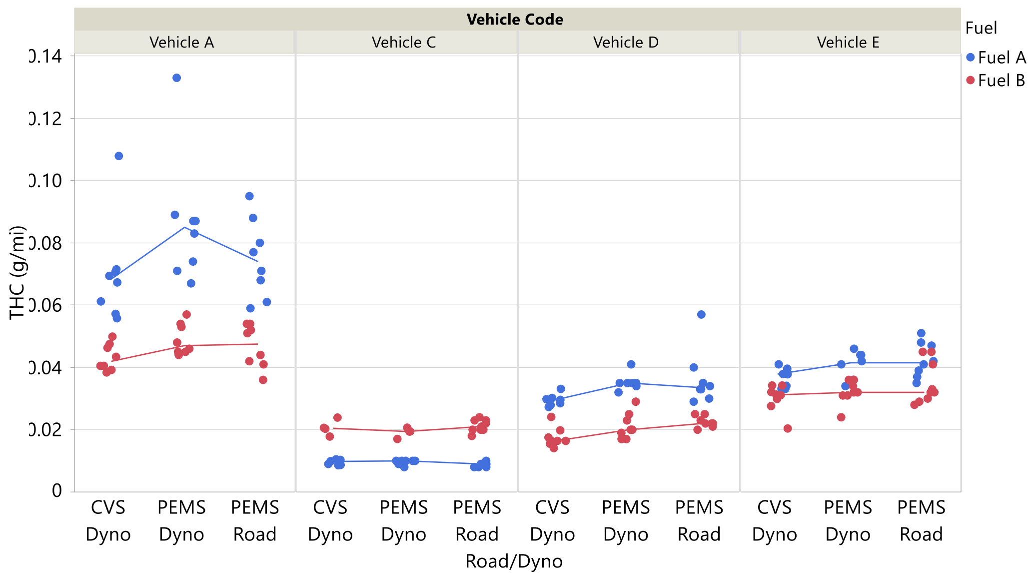


Figure 4-85: THC (g/mi) by Vehicle and Measurement Method

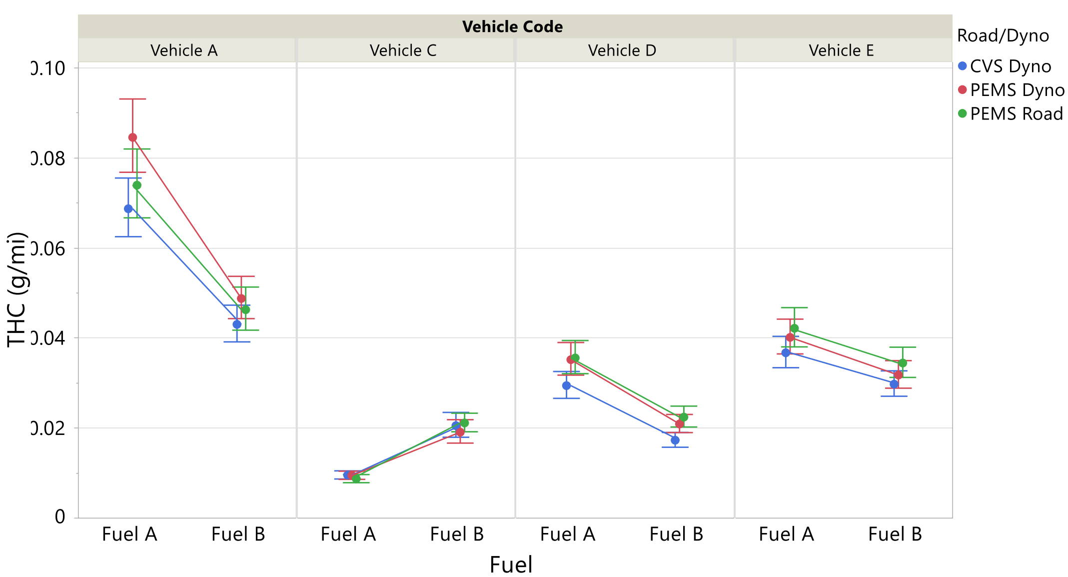


Figure 4-86: LS Mean THC (g/mi) by Fuel

Table 4-40: Estimated THC Differences Between Fuels with 95% Confidence Intervals

Vehicle	Method	Fuel A Predicted THC (g/mi)	Fuel B Predicted THC (g/mi) [95% Conf. Int.]	THC Difference Fuel A – Fuel B (g/mi) [95% Conf. Int.]	T_ THC Difference (Fuel A – Fuel B) [95% Conf. Int.]
Vehicle A	CVS Dyno	0.0687	0.0430 [0.0376, 0.0492]	0.0257 [0.0195, 0.0311]	0.4681 [0.3343, 0.6020]
	PEMS Dyno	0.0846	0.0488 [0.0426, 0.0559]	0.0358 [0.0287, 0.0420]	0.5502 [0.4143, 0.6861]
	PEMS Road	0.0740	0.0463 [0.0400, 0.0536]	0.0277 [0.0204, 0.0340]	0.4685 [0.3225, 0.6145]
Vehicle C	CVS Dyno	0.0096	0.0205 [0.0174, 0.0242]	-0.0109 [-0.0146, -0.0078]	-0.7660 [-0.9300, -0.6020]
	PEMS Dyno	0.0095	0.0191 [0.0162, 0.0225]	-0.0096 [-0.0130, -0.0067]	-0.7010 [-0.8670, -0.5340]
	PEMS Road	0.0087	0.0211 [0.0183, 0.0244]	-0.0124 [-0.0157, -0.0096]	-0.8850 [-1.0270, -0.7430]
Vehicle D	CVS Dyno	0.0294	0.0173 [0.0151, 0.0199]	0.0121 [0.0095, 0.0143]	0.5310 [0.3925, 0.6696]
	PEMS Dyno	0.0352	0.0209 [0.0182, 0.0241]	0.0143 [0.0111, 0.0170]	0.5205 [0.3798, 0.6612]
	PEMS Road	0.0356	0.0224 [0.0194, 0.0260]	0.0132 [0.0096, 0.0162]	0.4611 [0.3151, 0.6071]
Vehicle E	CVS Dyno	0.0367	0.0298 [0.0260, 0.0340]	0.0069 [0.0027, 0.0107]	0.2104 [0.0766, 0.3442]
	PEMS Dyno	0.0402	0.0318 [0.0277, 0.0364]	0.0084 [0.0038, 0.0125]	0.2338 [0.0979, 0.3698]
	PEMS Road	0.0422	0.0344 [0.0299, 0.0397]	0.0078 [0.0025, 0.0123]	0.2023 [0.0604, 0.3442]

Vehicles A, D, and E all saw statistically significant increase in THC with the higher PMI fuel, while Vehicle C saw a statistically significant decrease in THC. In E-122-2, while Vehicle C showed a similar statistically significant decrease in THC with higher PMI fuels, the other two vehicles were not the same. Vehicle A, which increased in THC in this project with the higher PMI fuel, decreased with higher PMI fuels in E-122-2. Vehicle D saw no statistically significant difference in E-122-2. These inconsistencies likely mean that fuel PMI is likely not the main fuel property contributing to differences in THC between fuels, and it is noteworthy that the fuels used in E-122-2 were all different than the two test fuels in E-134.

As for whether or not the PEMS responds similarly to the CVS to changes in fuels, the THC data in this project would suggest that to be true, as the slopes across all measurement methods are very similar, with no significant differences.

4.4.3 CO Differences Between Fuels

A plot of the CO data is shown again, colored by fuel, in Figure 4-87. The LS mean CO data with 95% confidence intervals from the regression models follows in Figure 4-88, with model estimates back-transformed into original units. Table 4-41 provides a numerical summary. In the table, comparisons are made based on fixing the CO at the level observed with Fuel A, and then estimating the expected Fuel B CO difference based on the LS Mean contrast estimate and its 95% confidence interval.

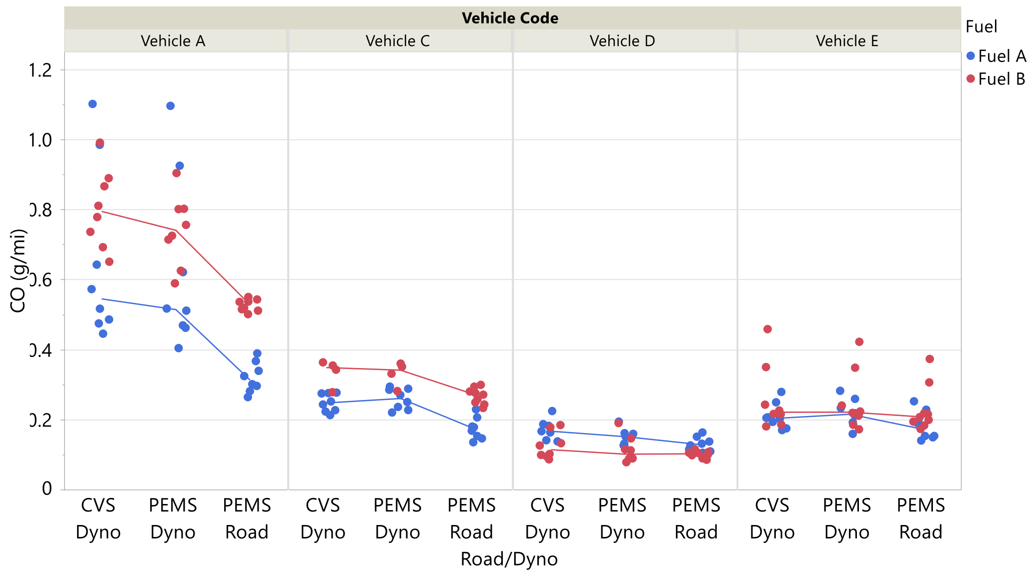


Figure 4-87: CO (g/mi) by Vehicle and Measurement Method

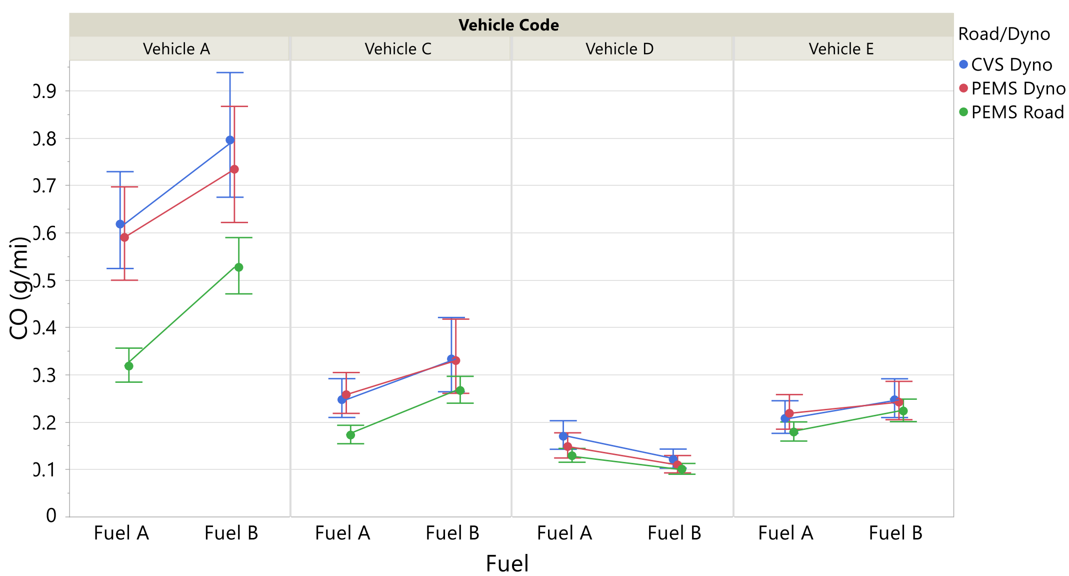


Figure 4-88: LS Mean CO (g/mi) by Fuel

Table 4-41: Estimated CO Differences Between Fuels with 95% Confidence Intervals

Vehicle	Method	Fuel A Predicted CO (g/mi)	Fuel B Predicted CO (g/mi) [95% Conf. Int.]	CO Difference Fuel A – Fuel B (g/mi) [95% Conf. Int.]	T_ CO Difference (Fuel A – Fuel B) [95% Conf. Int.]
Vehicle A	CVS Dyno	0.6186	0.7959 [0.6311, 1.0047]	-0.1773 [-0.3861, -0.0125]	-0.2520 [-0.4850, -0.0200]
	PEMS Dyno	0.5904	0.7342 [0.5805, 0.9288]	-0.1438 [-0.3384, 0.0099]	-0.2180 [-0.4530, 0.0169]
	PEMS Road	0.3187	0.5275 [0.4499, 0.6184]	-0.2088 [-0.2997, -0.1312]	-0.5040 [-0.6630, -0.3450]
Vehicle C	CVS Dyno	0.2477	0.3337 [0.2510, 0.4438]	-0.0860 [-0.1961, -0.0033]	-0.2980 [-0.5830, -0.0130]
	PEMS Dyno	0.2583	0.3303 [0.2477, 0.4406]	-0.0720 [-0.1823, 0.0106]	-0.2460 [-0.5340, 0.0420]
	PEMS Road	0.1730	0.2670 [0.2289, 0.3118]	-0.0940 [-0.1388, -0.0559]	-0.4340 [-0.5890, -0.2800]
Vehicle D	CVS Dyno	0.1704	0.1216 [0.0955, 0.1547]	0.0488 [0.0157, 0.0749]	0.3377 [0.0968, 0.5787]
	PEMS Dyno	0.1487	0.1098 [0.0861, 0.1401]	0.0389 [0.0086, 0.0626]	0.3031 [0.0598, 0.5464]
	PEMS Road	0.1293	0.1010 [0.0861, 0.1184]	0.0283 [0.0109, 0.0432]	0.2472 [0.0882, 0.4063]
Vehicle E	CVS Dyno	0.2082	0.2475 [0.1961, 0.3124]	-0.0393 [-0.1042, 0.0121]	-0.1730 [-0.4060, 0.0596]
	PEMS Dyno	0.2188	0.2426 [0.1917, 0.3068]	-0.0238 [-0.0880, 0.0271]	-0.1030 [-0.3380, 0.1323]
	PEMS Road	0.1794	0.2239 [0.1918, 0.2612]	-0.0445 [-0.0818, -0.0124]	-0.2220 [-0.3760, -0.0670]

Vehicles A and C saw statistically significant decrease in CO with the higher PMI fuel, which aligns with the conclusions drawn in E-122-2. Vehicle D saw a statistically significant increase in CO with the higher PMI fuel, after observing no differences in E-122-2. Vehicle E, not tested in that project, did not show a difference in CO when testing the two fuels in this project. The consistent decrease in Vehicle A and C across both projects may mean that PMI or other correlated fuel properties are affecting CO emissions, but the lack of consistent response across vehicles may also suggest that the relationship is dependent on vehicle technology.

As was seen with THC, the PEMS CO differences when changing fuels are similar, both on the road and the dyno, to the CO changes observed with the CVS, as the slopes across all measurement methods are very similar, with no significant differences.

4.4.4 CO_2 Differences Between Fuels

A plot of the CO_2 data is shown again, colored by fuel, in Figure 4-89. The LS mean CO_2 data with 95% confidence intervals from the regression models follows in Figure 4-90, with model estimates back-transformed into original units. Table 4-42 provides a numerical summary. In the table, comparisons are made based on fixing the CO_2 at the level observed with Fuel A, and then estimating the expected Fuel B CO_2 difference based on the LS Mean contrast estimate and its 95% confidence interval.

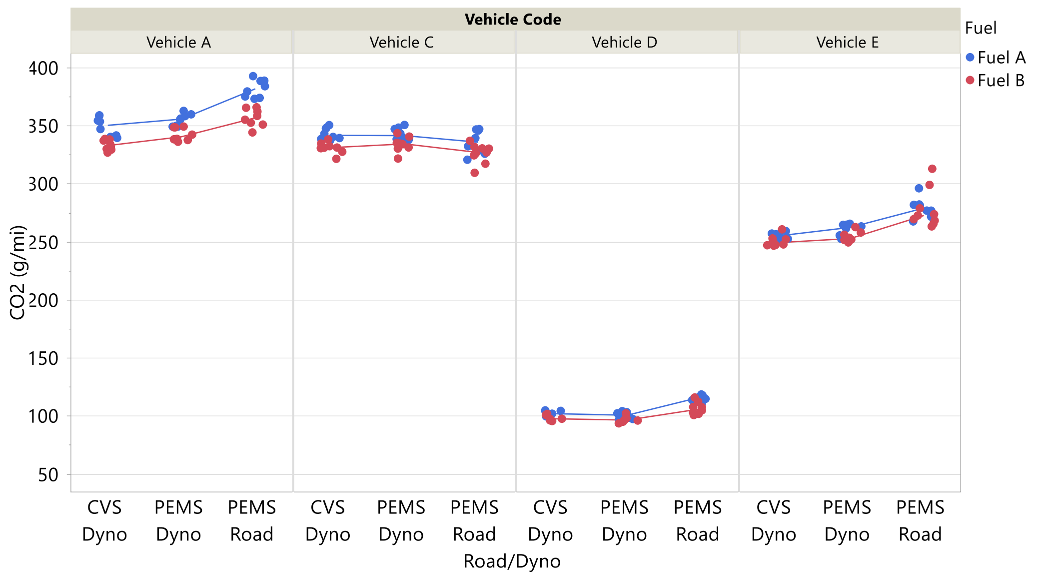


Figure 4-89: CO_2 (g/mi) by Vehicle and Measurement Method

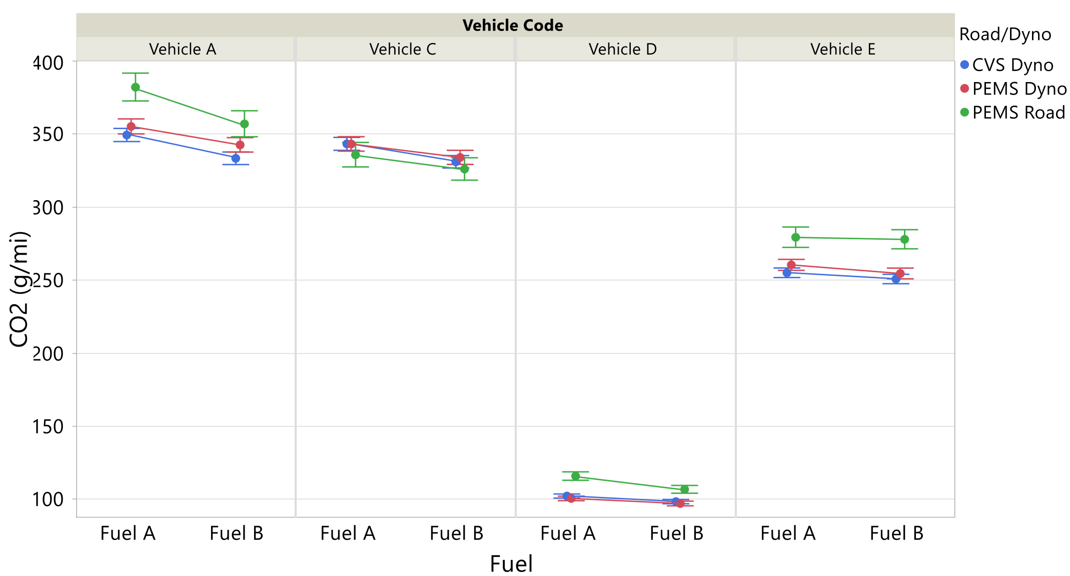


Figure 4-90: LS Mean CO_2 (g/mi) by Fuel

Table 4-42: Estimated CO_2 Differences Between Fuels with 95% Confidence Intervals

Vehicle	Method	Fuel A Predicted CO_2 (g/mi)	Fuel B Predicted CO_2 (g/mi) [95% Conf. Int.]	CO_2 Difference Fuel A – Fuel B (g/mi) [95% Conf. Int.]	T_ CO_2 Difference (Fuel A – Fuel B) [95% Conf. Int.]
Vehicle A	CVS Dyno	349.4	333.4 [327.4, 339.5]	16.0 [9.9, 22.0]	0.0467 [0.0286, 0.0649]
	PEMS Dyno	355.2	342.6 [335.7, 349.7]	12.6 [5.5, 19.5]	0.0362 [0.0158, 0.0566]
	PEMS Road	382.1	357.0 [344.6, 369.8]	25.1 [12.3, 37.5]	0.0680 [0.0327, 0.1033]
Vehicle C	CVS Dyno	343.3	331.0 [325.1, 337.1]	12.3 [6.2, 18.2]	0.0364 [0.0182, 0.0546]
	PEMS Dyno	343.3	334.0 [327.3, 340.9]	9.3 [2.4, 16.0]	0.0272 [0.0068, 0.0476]
	PEMS Road	335.8	326.1 [315.1, 337.5]	9.7 [-1.7, 20.7]	0.0294 [-0.0050, 0.0637]
Vehicle D	CVS Dyno	102.2	98.4 [96.4, 100.4]	3.8 [1.8, 5.8]	0.0380 [0.0178, 0.0583]
	PEMS Dyno	100.6	97.1 [95.0, 99.4]	3.5 [1.2, 5.6]	0.0351 [0.0123, 0.0578]
	PEMS Road	115.9	106.8 [103.1, 110.6]	9.1 [5.3, 12.8]	0.0816 [0.0463, 0.1168]
Vehicle E	CVS Dyno	255.1	250.8 [246.3, 255.3]	4.3 [-0.2, 8.8]	0.0169 [-0.0010, 0.0350]
	PEMS Dyno	260.5	254.6 [249.4, 259.9]	5.9 [0.6, 11.1]	0.0229 [0.0024, 0.0433]
	PEMS Road	279.4	278.0 [268.6, 287.6]	1.4 [-8.2, 10.8]	0.0050 [-0.0290, 0.0393]

Directionally, all vehicles saw an increase in CO_2 with the higher PMI fuel. For Vehicle A, all measurement methods showed a similar difference, and Fuel A was estimated to have about 13 g/mi to 25 g/mi higher CO_2. For Vehicle C, all measurement methods indicated approximately 10 g/mi higher CO_2 with Fuel A. Vehicle D was very similar to Vehicle C, with Fuel A estimating 4 g/mi to 9 g/mi higher CO_2. Vehicle E showed no statistically significant change in CO_2 due to fuel in the CVS dyno model and PEMS model on the road. The PEMS dyno model indicated a 6 g/mi higher CO_2 result on Fuel A, just crossing the line for statistically significance at the 5% significance level. There were no conclusions drawn about CO_2 in E-122-2.

None of the estimates from the different models of CO_2 differences between fuels were statistically different from one another, indicating that the PEMS response to fuel changes in similar to the CVS response.

4.4.5 Fuel Economy Differences Between Fuels

The plot of the fuel economy data, LS mean estimates, and summary table are shown below for reference in Figure 4-91, Figure 4-92, and Table 4-43, respectively, but the data do not reveal any new findings not seen with the CO_2 data shown in the previous section.

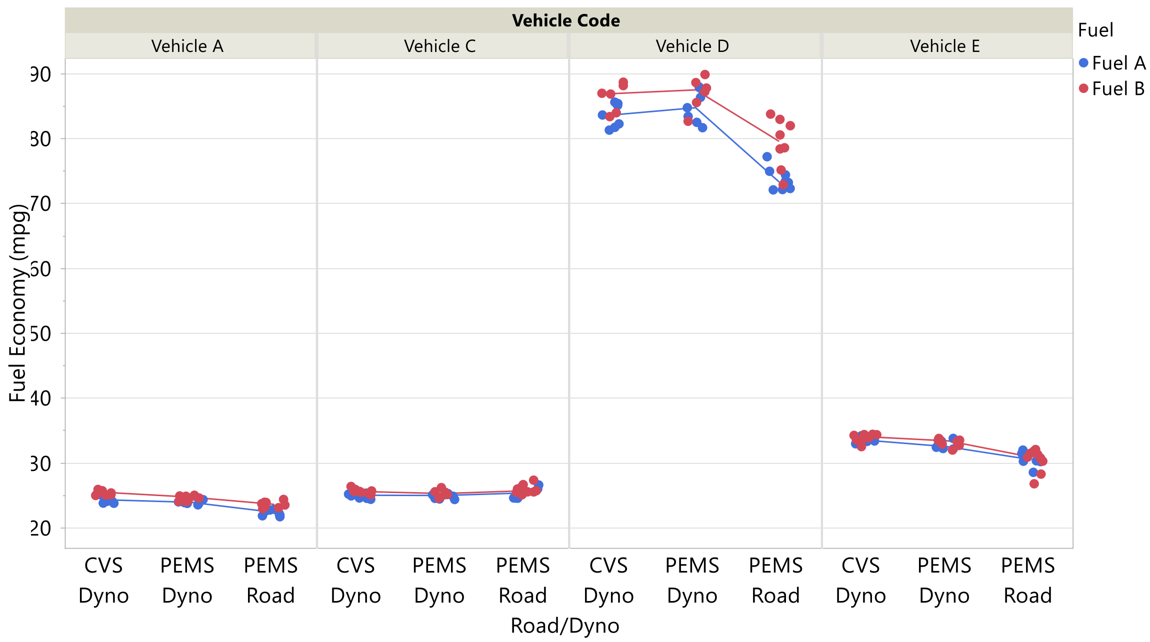


Figure 4-91: Fuel Economy (mpg) by Vehicle and Measurement Method

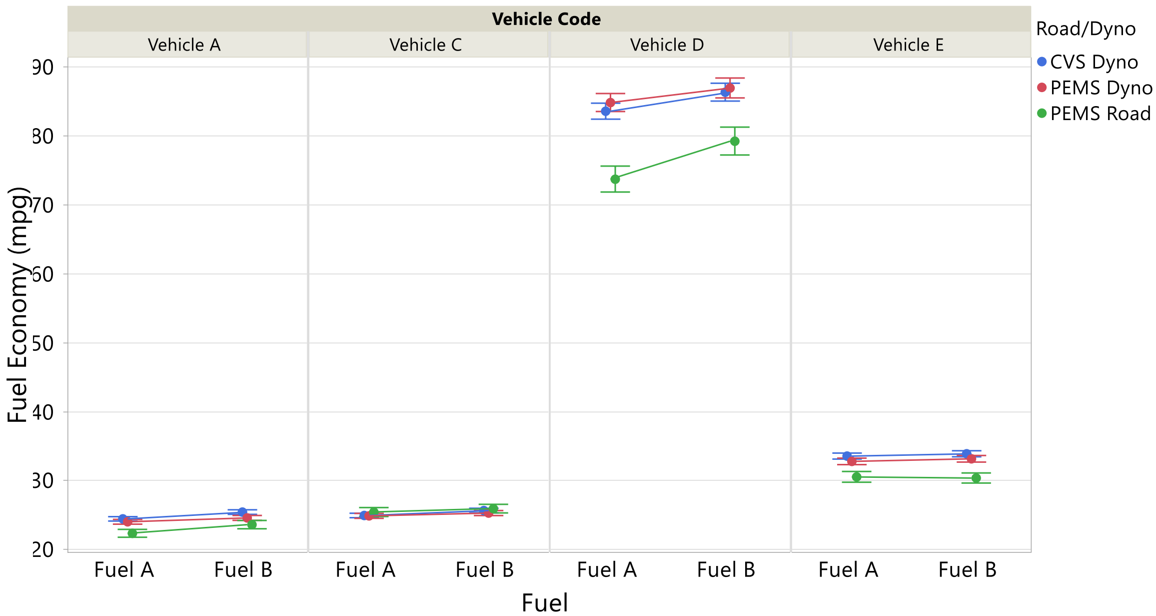


Figure 4-92: LS Mean Fuel Economy (mpg) by Fuel

Table 4-43: Estimated Fuel Economy Differences Between Fuels with 95% Confidence Intervals

Vehicle	Method	Fuel A Predicted FE (mpg)	Fuel B Predicted FE (mpg) [95% Conf. Int.]	FE Difference Fuel A – Fuel B (mpg) [95% Conf. Int.]	T_FE Difference (Fuel A – Fuel B) [95% Conf. Int.]
Vehicle A	CVS Dyno	24.46	25.43 [24.97, 25.92]	-0.97 [-1.46, -0.51]	-0.0390 [-0.0580, -0.0210]
	PEMS Dyno	24.03	24.59 [24.10, 25.09]	-0.56 [-1.06, -0.07]	-0.0230 [-0.0430, -0.0030]
	PEMS Road	22.35	23.62 [22.78, 24.48]	-1.27 [-2.13, -0.43]	-0.0550 [-0.0910, -0.0190]
Vehicle C	CVS Dyno	24.95	25.65 [25.20, 26.15]	-0.70 [-1.20, -0.25]	-0.0280 [-0.0470, -0.0100]
	PEMS Dyno	24.89	25.29 [24.79, 25.83]	-0.40 [-0.94, 0.10]	-0.0160 [-0.0370, 0.0041]
	PEMS Road	25.44	25.93 [25.04, 26.85]	-0.49 [-1.41, 0.40]	-0.0190 [-0.0540, 0.0158]
Vehicle D	CVS Dyno	83.58	86.30 [84.59, 88.13]	-2.72 [-4.55, -1.01]	-0.0320 [-0.0530, -0.0120]
	PEMS Dyno	84.83	86.98 [85.00, 88.92]	-2.15 [-4.09, -0.17]	-0.0250 [-0.0470, -0.0020]
	PEMS Road	73.72	79.22 [76.42, 82.12]	-5.50 [-8.40, -2.70]	-0.0720 [-0.1080, -0.0360]
Vehicle E	CVS Dyno	33.56	33.90 [33.28, 34.51]	-0.34 [-0.95, 0.28]	-0.0100 [-0.0280, 0.0084]
	PEMS Dyno	32.79	33.15 [32.50, 33.86]	-0.36 [-1.07, 0.29]	-0.0110 [-0.0320, 0.0090]
	PEMS Road	30.54	30.38 [29.33, 31.47]	0.16 [-0.93, 1.21]	0.0054 [-0.0300, 0.0405]

4.4.6 NO_x Differences Between Fuels

A plot of the NO_x data is shown again, colored by fuel, in Figure 4-93. The LS mean NO_x data with 95% confidence intervals from the regression models follows in Figure 4-94, with model estimates back-transformed into original units. Table 4-44 provides a numerical summary. In the table, comparisons are made based on fixing the NO_x at the level observed with Fuel A, and then estimating the expected Fuel B NO_x difference based on the LS Mean contrast estimate and its 95% confidence interval.

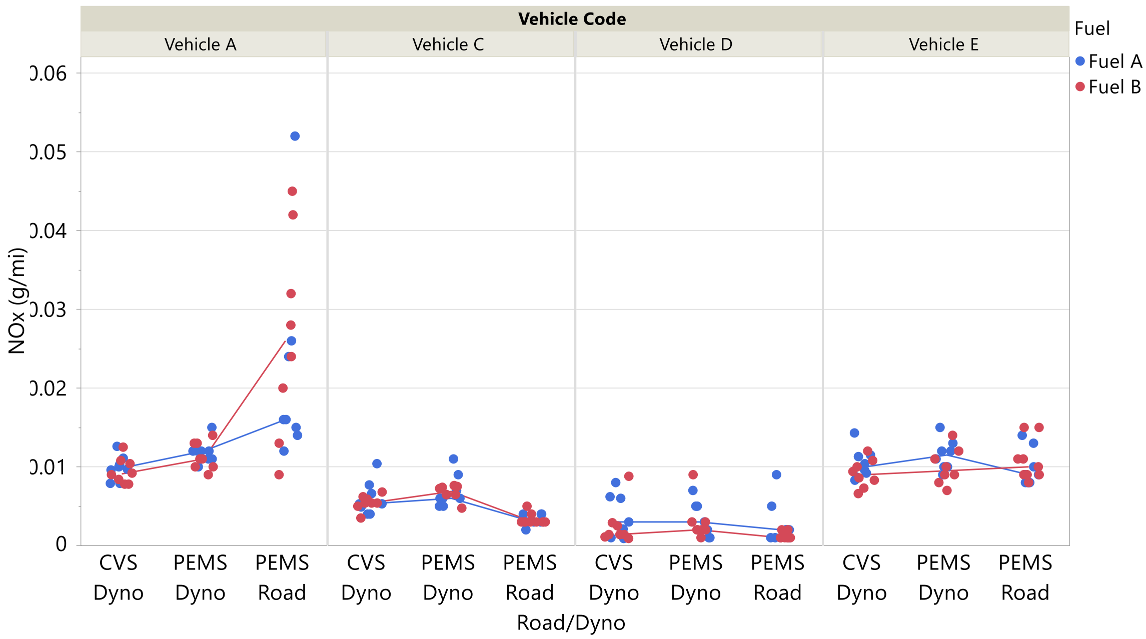


Figure 4-93: NO$_x$ (g/mi) by Vehicle and Measurement Method

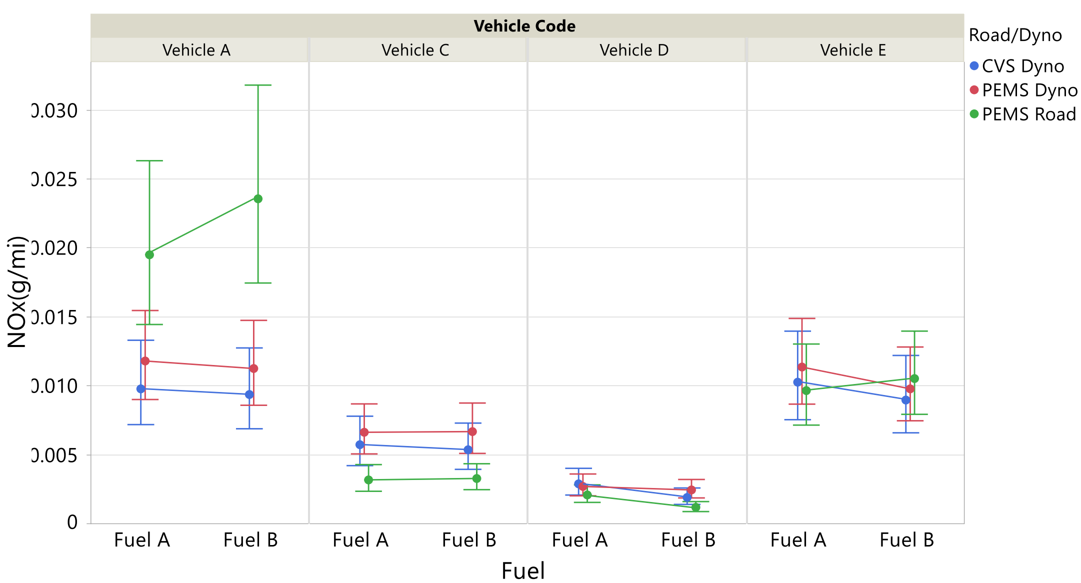


Figure 4-94: LS Mean NO$_x$ (g/mi) by Fuel

Table 4-44: Estimated NO_x Differences Between Fuels with 95% Confidence Intervals

Vehicle	Method	Fuel A Predicted NO_x (g/mi)	Fuel B Predicted NO_x (g/mi) [95% Conf. Int.]	NO_x Difference Fuel A – Fuel B (g/mi) [95% Conf. Int.]	T_ NO_x Difference (Fuel A – Fuel B) [95% Conf. Int.]
Vehicle A	CVS Dyno	0.0098	0.0094 [0.0061, 0.0144]	0.0004 [-0.0047, 0.0037]	0.0429 [-0.3900, 0.4783]
	PEMS Dyno	0.0118	0.0113 [0.0077, 0.0165]	0.0005 [-0.0047, 0.0041]	0.0474 [-0.3350, 0.4294]
	PEMS Road	0.0195	0.0236 [0.0154, 0.0360]	-0.0041 [-0.0165, 0.0041	-0.1890 [-0.6130, 0.2351]
Vehicle C	CVS Dyno	0.0057	0.0054 [0.0035, 0.0083]	0.0004 [-0.0026, 0.0023]	0.0662 [-0.3690, 0.5016]
	PEMS Dyno	0.0066	0.0067 [0.0046, 0.0098]	0.0000 [-0.0032, 0.0021]	-0.0070 [-0.3890, 0.3748]
	PEMS Road	0.0032	0.0033 [0.0022, 0.0050]	-0.0001 [-0.0018, 0.0010]	-0.0320 [-0.4440, 0.3808]
Vehicle D	CVS Dyno	0.0029	0.0019 [0.0012, 0.0030]	0.0010 [-0.0001, 0.0017]	0.4172 [-0.0340, 0.8679]
	PEMS Dyno	0.0027	0.0024 [0.0016, 0.0036]	0.0003 [-0.0009, 0.0011]	0.0979 [-0.2980, 0.4934]
	PEMS Road	0.0021	0.0012 [0.0008, 0.0018]	0.0009 [0.0003, 0.0013]	0.5625 [0.1382, 0.9868]
Vehicle E	CVS Dyno	0.0103	0.0090 [0.0058, 0.0139]	0.0013 [-0.0036, 0.0045]	0.1349 [-0.3010, 0.5703]
	PEMS Dyno	0.0114	0.0098 [0.0067, 0.0143]	0.0016 [-0.0030, 0.0047]	0.1499 [-0.2320, 0.5319]
	PEMS Road	0.0097	0.0105 [0.0070, 0.0159]	-0.0009 [-0.0062, 0.0027]	-0.0870 [-0.4990. 0.3258]

The Vehicle D PEMS Road NO_x data was the only combination to show a statistical difference in NO_x between the fuels, showing slightly higher NO_x with Fuel A. It is clear from Figure 4-93 that this estimate is driven by two higher data points on Fuel A which were not seen on Fuel B. It is possible that this may suggest that Vehicle D is more susceptible to higher NO_x on Fuel A. However, a similar high NO_x data point was observed on a Fuel B chassis-dyno test for Vehicle D. This indicates that, although there were only high NOx data points during on-road tests with Fuel A, the cause of the high NO_x is more likely associated with random chance than the chosen test fuel. In conclusion, there is not thought to be any meaningful impact on NO_x emissions between fuels for all four vehicles. This data also further demonstrates that capability of the PEMS to measure fuel property differences and consistencies in a similar manner as the CVS system.

4.5 Statistical Analysis Conclusions

This project evaluated PEMS performance under "severe" test cycle conditions, including altitude, steep grade, and low temperatures. The statistical analysis assessed PEMS variability, accuracy, and sensitivity to fuel property changes. Because these same objectives were completed in CRC project E-122-2 under “normal” driving conditions, comparisons were made back to this project to determine where cycle conditions may impact PEMS performance. Comparisons could only be made for the three vehicles common across projects: vehicles A, C, and D.

Regarding test variability, only PM and CO appeared to have different conclusions across the two test programs. Variability increased on both chassis-dyno and PEMS results in E-134, though the increase was largest with road-testing. This was primarily driven by Vehicle A and Vehicle D, both of which saw much higher PM levels in this project compared with E-122-2. For CO, all three common vehicles showed a large decrease in PEMS road variability, both when compared to chassis-dyno results in E-134, and when comparing to road results from E-122-2. As this decrease was unexpected, further investigation was conducted to try to understand the cause of the extremely repeatable road results. The investigation revealed a modest correlation between final CO and driver pedal behavior. Smoother accelerations and decelerations for E-134 road-testing likely contributed to some but not all of the differences observed.

CO_2 and fuel economy results were more variable for on-road tests compared to chassis-dyno testing; this observation was consistent between E-134 and E-122-2. NO_x variability was greater with Vehicle A on-road tests compared with chassis-dyno tests, primarily driven by Phase 2 (highest speeds and loads) differences. This increase in NO_x road-testing variability for this vehicle was also observed in both programs.

Other variability differences existed but were thought to be of little practical value and likely only an artifact of low emissions levels.

The PEMS accuracy assessment was broken into two components. First was an assessment of PEMS instrument bias which was conducted by comparing measurements taken simultaneously with the PEMS unit and the CVS for chassis dynamometer tests. The CVS result is taken to be the gold standard “true” value, and any difference in results seen on the PEMS for an identical test is taken to be a “PEMS Instr. Bias.” The second assessment focused on additional road bias, attributed to factors such as environmental differences, traffic, or additional test weight, by comparing the PEMS average emissions measurements taken on the road to the PEMS average emissions measurements for the chassis dynamometer. Because the same PEMS instrument is used for both road testing and chassis dynamometer testing, this “Road Factor Bias” estimate is completely independent of the previous instrument bias estimate. The two independent bias estimates are summarized for each vehicle and emissions parameter below in Table 4-45 for E-134. For comparison, estimates based on the stated bias in E-122-2 are given in Table 4-46. An example baseline value is given in both tables because the biases are dependent on the level of emissions. This baseline value is the median CVS dyno value observed in E-134 and is therefore a representative level to use for comparison. The percentage bias values shown are only applicable at the median emissions level shown and are independent of the other adjacent bias estimate. Therefore, the biases in the table are not meant to be applied consecutively, though for log-transformed parameters, this would be an acceptable application. Negative biases are highlighted in red, indicating the PEMS would measure a smaller value, while positive biases are highlighted in blue, indicating the PEMS would measure a larger value.

Table 4-45: PEMS Bias for E-134

	Vehicle A			Vehicle C			Vehicle D			Vehicle E		
	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias
PM	0.461	-32%	-72%	0.131	-	-49%	0.355	-49%	-49%	0.823	-15%	-23%
THC	0.0529	+18%	-9%	0.0142	-	-	0.0241	+20%	+4%	0.0337	+8%	+7%
CO	0.715	-6%	-38%	0.278	-	-28%	0.142	-11%	-10%	0.212	-	-13%
CO_2	339	+2.2%	+5.9%	338	-	-2.3%	100	-1.5%	+12.7%	253	+1.8%	+8.3%
NO_x	0.0097	+20%	+86%	0.0054	+20%	-51%	0.0021	+11%	-37%	0.0095	+10%	-

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

Table 4-46: PEMS Bias for E-122-2

	Vehicle A			Vehicle C			Vehicle D		
	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias	E-134 CVS Dyno Median	PEMS Instr. Bias	Road Factor Bias
PM	0.461	-34%	-	0.131	-45%	-21%	0.355	-22%	-18%
THC	0.0529	-20%	-13%	0.0142	-27%	-33%	0.0241	-29%	-
CO	0.715	+8%	-23%	0.278	+11%	-40%	0.142	+7%	-15%
CO_2	339	+8.7%	+5.6%	338	+10.5%	+1.2%	100	+9.4%	+15.7%
NO_x	0.0097	+30%	-17%	0.0054	+24%	-8%	0.0021	+11%	-41%

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

The tables indicate that the PEMS instrument bias, as indicated through chassis dynamometer testing, did not stay consistent between programs. However, the PEMS instrument bias tended to be consistent across vehicles in each program. The bias differences across programs may simply be attributable to the multiple years between each program being conducted.

Road factor bias was observed in almost all cases. Interestingly, this road bias tended to be much more similar across projects with a few particularly consistent road tests biases. This includes a negative PM and CO bias for all vehicles except PM for Vehicle A in E-122-2. There is also a consistent positive CO_2 bias, which is seen by all vehicles in both programs, with the exception of Vehicle C in E-134. It was also observed that the road biases tended to be larger in magnitude for E-134.

Finally, PEMS sensitivity to fuel and fuel property changes was assessed. First it is noted that both CVS and PEMS results for all four test vehicles demonstrated higher PM emissions with the higher PMI fuel relative to the lower PMI fuel. The magnitude of difference in PM varied from vehicle to vehicle, but was consistent across measurement methods, with the only exception being Vehicle A PEMS road tests, which showed a much smaller difference between fuels than what was observed with CVS dyno or PEMS dyno testing. The difference in PM emissions also appeared to be greater in this program relative to E-122-2 which used a similar variety of low- and high-PMI fuels.

The conclusion for the fuel property sensitivity analysis was that the PEMS responds very similarly to changes in test fuel compared to the CVS system. Other relevant observations noted during the fuel sensitivity study for gaseous emissions included:

THC

- There were observed discrepancies in the correlation between THC and higher PMI fuels across programs. This indicates that PMI is likely not a key factor in THC emissions.

CO

- Vehicles A and C both produced lower CO emissions with the higher PMI fuel in both programs, but Vehicle D saw an increase in CO with the higher PMI fuel which was not present in E-122-2. No change in CO was observed with Vehicle E when switching fuels.

CO_2

- All vehicles saw directionally higher CO_2 at a marginal significance level (some models slightly yes, some slightly no) with the higher PMI fuel. Vehicle A saw the largest difference, with an estimated 13 g/mi to 26 g/mi difference between fuels, while the other three vehicles were estimated to produce only up to 10 g/mi more CO_2 with the higher PMI fuel.

NO_x

- No differences observed between fuels for any vehicles. This aligns with E-122-2.

APPENDIX A: Emissions Impact of Engine Stop Start Feature of Vehicle C

During the full span of chassis dyno and road emissions tests the ESS feature unique to Vehicle C was disabled by removing the auxiliary power supply battery, Figure A-1.[23] The vehicle was initially received in the same state and an observation of the missing auxiliary battery was not made. The observation was later made after an analysis of test data demonstrated that the ESS feature was not functioning. The decision to complete the remaining tests with ESS disabled was made for the following reasons:

1. The vehicle was able to comply with its certification criteria pollutant emissions standards during its check-in process while the ESS feature was disabled.
2. The test route was not specifically designed in any way to assess the impact of the ESS feature. In other words, there is limited idle time throughout the drive cycle.
3. Voiding and repeating previous tests would cause a significant delay to the project schedule.

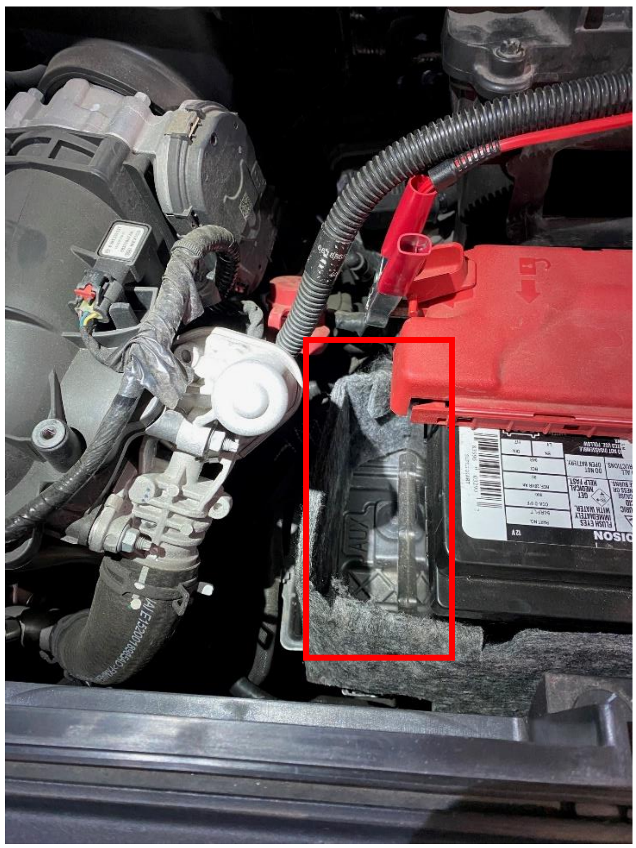


Figure A-1: Missing Pacifica Auxiliary Battery

To support reason #2 stated above, an additional out-of-scope chassis dyno test was commissioned to 1) confirm that replacement of the auxiliary battery reengaged the ESS feature and 2) provide some insight into how Vehicle C's emissions performance may differ on the drive cycle with ESS active. It is very clear that there is a CO_2 benefit during idle periods where ESS is active; however, the mass of CO_2 that is saved is only about 1% of the total CO_2 mass emissions across the full cycle, Figure A-2. No other emissions components appeared to be impacted directly as a result of the active ESS feature.

[23] The auxiliary battery is used to maintain power to essential systems when the engine start-stop feature is active. The engine start-stop feature is deactivated if the auxiliary is not present or otherwise unusable.

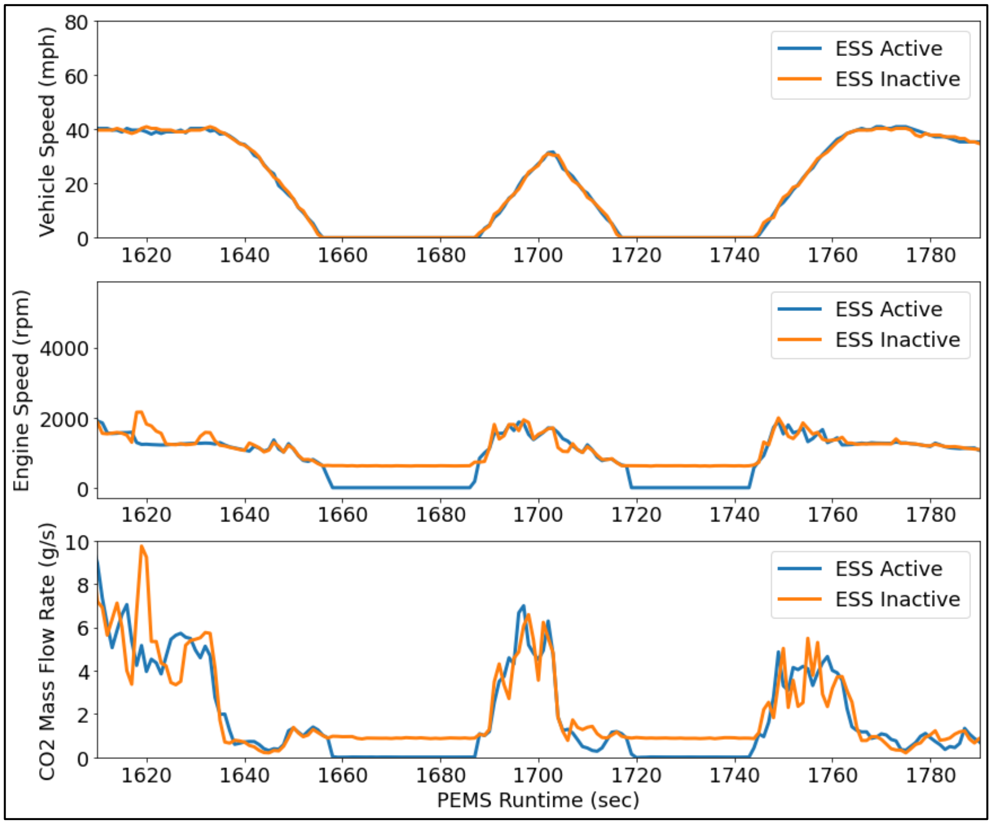


Figure A-2: CO_2 impact of ESS on Vehicle C

APPENDIX B: Additional Test Fuel Characteristics

Table B-1: Detailed Hydrocarbon Analysis Fuel A

New Fuel SampleTest Results 02/2025			MPG2500715.001													
			Fuel A													
			Parrafin		Iso-Parrafin		Aromatics		Napthenes		Olefins		Oxygnenates		Totals	
		Cabon Number	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%
Method	Test Name	Cabon Number														
		2	--	--	--	--	--	--	--	--	--	--	10.174	9.4257	**10.17**	**9.43**
		3	0.0623	0.092	--	--	--	--	--	--	0.0032	0.002	--	--	**0.07**	**0.09**
ASTM D6730	**Detailed Hydrocarbon Analysis (DHA)**	4	5.9369	7.574	0.669	0.8872	--	--	--	--	0.0953	0.116	--	--	**6.70**	**8.58**
		5	6.1059	7.128	9.844	11.615	--	--	0.21257	0.208457	0.9641	1.074	--	--	**17.13**	**20.03**
		6	0.3363	0.372	2.888	3.2068	0.2479	0.207	0.52803	0.511501	0.4898	0.509	--	--	**4.49**	**4.81**
		7	0.4829	0.52	4.966	5.2504	3.8597	3.272	0.68536	0.653586	1.1447	1.172	--	--	**11.14**	**10.87**
		8	0.1828	0.191	14.27	14.879	9.7516	8.194	0.43143	0.410884	0.4254	0.421	--	--	**25.06**	**24.10**
		9	0.1856	0.189	2.039	2.0657	11.155	9.307	0.38529	0.361007	0.154	0.154	--	--	**13.92**	**12.08**
		10	0.0729	0.073	1.158	1.1573	4.9306	4.072	0.11603	0.106102	0.0411	0.041	--	--	**6.32**	**5.45**
		11	0.0673	0.066	2.039	2.0139	1.2695	1.033	--	--	--	--	--	--	**3.38**	**3.11**
		12	0.0527	0.051	0.478	0.4566	0.495	0.408	--	--	0.0054	0.005	--	--	**1.03**	**0.92**
		13	0.0103	0.01	0.269	0.2526	0.0091	0.007	--	--	--	--	--	--	**0.29**	**0.27**
		14	0.0034	0.003	--	--	--	--	--	--	--	--	--	--	**0.00**	**0.00**
		15	0.0073	0.007	--	--	--	--	--	--	--	--	--	--	**0.01**	**0.01**
		16	--	--	--	--	--	--	--	--	--	--	--	--	**0.00**	**0.00**
		Total	13.51	16.28	38.62	41.79	31.72	26.50	2.36	2.25	3.32	3.49	10.17	9.43	100.00	100.00

Table B-2: Additional Fuel Test Results: Fuel A

Ethanol wt% by ASTM D4815	11.63	Ethanol vol% by ASTM D4815	10.80
SG @60°F by ASTM D4052	0.7370		

ASTM D86 (°C)	
IBP	26.2
5	35.5
10	41.3
15	45.8
20	50.1
30	59.3
40	67.3
50	71.3
60	115.8
70	129.4
80	147.6
85	157.8
90	167.5
95	179.9
FBP	206.4

ASTM D7096 - D86 Corr			
	Run 1	Run 2	AVG
IBP	21.4	21.3	21.4
5	27.2	26.8	27.0
10	32.5	32	32.3
20	41.1	40.4	40.8
30	58.6	57.2	57.9
50	103.3	101.2	102.3
70	133.7	132.4	133.1
80	151.8	150.7	151.3
90	170.7	168.4	169.6
95	185.3	181.4	183.4
FBP	210.8	206.4	208.6

ASTM D4814 Driveability Index			
D86		D7096 AVG	
°C	°F	°C	°F
464.5	1012.1	546.1	1159.0

Table B-3: Detailed Hydrocarbon Analysis Fuel B

New Fuel SampleTest Results 02/2025			MPG2500715.002													
			Fuel B													
			Parrafin		Iso-Parrafin		Aromatics		Napthenes		Olefins		Oxygnenates		Totals	
		Cabon Number	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%	Wt%	Vol%
ASTM D6730	**Detailed Hydrocarbon Analysis (DHA)**	Cabon Number														
		2	--	--	--	--	--	--	--	--	--	--	10.931	9.7951	**10.93**	**9.80**
		3	0.0875	0.126	--	--	--	--	--	--	0.0011	5E-04	--	--	**0.09**	**0.13**
		4	4.9914	6.159	0.738	0.947	--	--	--	--	0.1641	0.192	--	--	**5.89**	**7.30**
		5	1.0997	1.242	7.027	8.0195	--	--	0.08174	0.077531	4.0347	4.362	--	--	**12.24**	**13.70**
		6	1.0477	1.121	5.673	6.0805	0.6788	0.548	0.71848	0.6739	2.8143	2.855	--	--	**10.93**	**11.28**
		7	1.0996	1.144	11.28	11.534	3.1685	2.598	0.66705	0.615905	1.1943	1.15	--	--	**17.41**	**17.04**
		8	0.6596	0.668	20.37	20.521	3.9123	3.181	0.38555	0.354559	0.6334	0.604	--	--	**25.96**	**25.33**
		9	0.3523	0.347	4.433	4.3463	2.2675	1.832	0.27086	0.245861	0.1575	0.154	--	--	**7.48**	**6.93**
		10	0.067	0.065	2.795	2.6996	0.5389	0.434	0.06481	0.057537	0.08	0.078	--	--	**3.55**	**3.33**
		11	0.0297	0.028	3.508	3.3578	0.0532	0.042	--	--	--	--	--	--	**3.59**	**3.43**
		12	0.0115	0.011	0.877	0.8147	0.0081	0.007	--	--	0.0038	0.004	--	--	**0.90**	**0.84**
		13	0.0029	0.003	0.41	0.3762	--	--	--	--	--	--	--	--	**0.41**	**0.38**
		14	--	--	--	--	--	--	--	--	--	--	--	--	**0.00**	**0.00**
		15	--	--	--	--	--	--	--	--	--	--	--	--	**0.00**	**0.00**
		16	--	--	--	--	--	--	--	--	--	--	--	--	**0.00**	**0.00**
		Total	9.45	10.91	57.11	58.70	10.63	8.64	2.19	2.03	9.08	9.40	10.93	9.80	100.00	100.00

Table B-4: Additional Fuel Test Results: Fuel B

Ethanol wt% by ASTM D4815	12.18	Ethanol vol% by ASTM D4815	10.95
SG @60°F by ASTM D4052	0.7134		

ASTM D86 (°C)	
IBP	29.4
5	42
10	48.1
15	52.4
20	56.2
30	62.6
40	66.9
50	74
60	102.6
70	111.3
80	121.9
85	130
90	142.5
95	163.5
FBP	195.5

ASTM D7096 - D86 Corr			
	Run 1	Run 2	AVG
IBP	21.8	21.8	21.8
5	27.8	27.7	27.8
10	33.5	33.3	33.4
20	52.3	52	52.2
30	64.1	63.7	63.9
50	95.5	95.1	95.3
70	106.7	105.8	106.3
80	121.7	120.5	121.1
90	144.4	143.4	143.9
95	165.2	165	165.1
FBP	196.2	196.2	196.2

ASTM D4814 Driveability Index			
D86		D7096 AVG	
°C	°F	°C	°F
459.3	1002.9	502.6	1080.8

Table B-5: D7096 Full Analysis Results

°F	Fuel A		Fuel B	
	Run 1	Run 2	Run 1	Run 2
	MPG2501523.001		MPG2501523.002	
IBP	11.2	10.9	11.3	11.4
1	15.3	14.3	15.5	15.3
1.5	27.1	26.5	27.6	27.6
2	28.4	28.1	28.9	29
2.5	29.2	28.9	29.7	29.8
3	29.8	29.5	30.4	30.5
3.5	30.3	30.1	31	31.1
4	30.8	30.5	31.5	31.5
4.5	31.2	30.9	31.9	32
5	31.5	31.3	32.4	32.4
5.5	31.9	31.6	32.8	32.8
6	32.2	31.9	33.4	33.3
6.5	32.6	32.2	34	33.9
7	32.9	32.5	34.8	34.6
7.5	33.4	32.9	36.3	35.7
8	33.8	33.2	48.4	40.3
8.5	34.4	33.6	50.4	50.1
9	35.1	34	51.1	51
9.5	36.6	34.6	51.5	51.5
10	49.4	35.3	51.9	51.9
10.5	50.7	36.7	52.2	52.2
11	51.3	49.4	52.5	52.5
11.5	51.8	50.7	52.7	52.8
12	52.1	51.3	53	53
12.5	52.4	51.8	53.2	53.3
13	52.7	52.1	53.4	53.5
13.5	53	52.4	53.6	53.7
14	53.2	52.7	53.8	53.9
14.5	53.5	53	54.1	54.1
15	53.7	53.2	54.3	54.4
15.5	54	53.5	54.5	54.6
16	54.2	53.7	54.8	54.8
16.5	54.4	53.9	55	55.1
17	54.7	54.2	55.3	55.3
17.5	55	54.4	55.6	55.6
18	55.3	54.6	56	55.9
18.5	55.6	54.9	56.5	56.3
19	56	55.2	57.1	56.8
19.5	56.5	55.5	58.8	57.6
20	57.3	55.8	76	65.8
20.5	70	56.3	77.8	76.9
21	76.4	56.8	78.9	78.4
21.5	77.7	57.8	79.7	79.3
22	78.5	74.4	80.4	80.1
22.5	79.1	76.8	81.1	80.8
23	79.7	77.8	81.6	81.4
23.5	80.2	78.6	82.1	81.9
24	80.6	79.2	82.4	82.3
24.5	81.1	79.7	82.8	82.6
25	81.5	80.2	83.1	83
25.5	81.9	80.6	83.5	83.3
26	82.1	81	83.9	83.7
26.5	82.4	81.4	84.4	84.1
27	82.6	81.8	84.9	84.5
27.5	82.8	82	85.6	85
28	83.1	82.3	86.7	85.7
28.5	83.3	82.5	89.6	86.8
29	83.6	82.7	93.1	89.4
29.5	83.9	82.9	95.1	93
30	84.2	83.2	96.7	95.1
30.5	84.5	83.4	98.1	96.7
31	84.9	83.6	99.5	98
31.5	85.3	83.9	100.9	99.4
32	85.9	84.2	102.5	100.8
32.5	86.8	84.5	104.9	102.3
33	89.2	84.8	106.7	104.6

33.5	93.6	85.2	107.9	106.5
34	94.7	85.7	109.1	107.8
34.5	95.3	86.3	110.8	109
35	95.8	87.4	131.8	110.4
35.5	96.2	92.2	135.3	128.9
36	96.6	94.1	136.7	134.9
36.5	97	94.9	137.6	136.5
37	97.3	95.5	138.3	137.5
37.5	97.6	95.9	139	138.3
38	97.9	96.3	139.7	139
38.5	98.3	96.7	140.2	139.6
39	98.7	97	140.8	140.2
39.5	99.1	97.3	141.4	140.7
40	99.6	97.6	142.3	141.3
40.5	100.4	97.9	144.5	142
41	102.2	98.2	147.2	143.4
41.5	108.5	98.6	148.8	146.7
42	121.6	99	150.8	148.4
42.5	136.7	99.4	154.9	150
43	138.4	100	156.6	154
43.5	139.8	100.9	158.1	156.1
44	140.9	104.7	159.9	157.7
44.5	142.4	110.1	162.7	159.3
45	147.3	133.1	167.2	161.6
45.5	153.1	137.2	172.6	165.5
46	160.9	138.8	174.8	170.9
46.5	174.8	140	175.9	174.3
47	176.7	141	176.7	175.6
47.5	177.8	142.7	177.3	176.6
48	179	147.6	177.8	177.2
48.5	187.8	154	178.4	177.7
49	192.7	161.3	179.2	178.3
49.5	194.1	174.9	180.9	178.9
50	195	176.8	187.8	180.1
50.5	195.7	177.8	189.4	187
51	196.4	179	192	188.9
51.5	197.1	187.9	193.3	191
52	197.9	192.8	193.9	193.1
52.5	199.1	194.2	194.4	193.8
53	201.5	195	194.8	194.4
53.5	203.1	195.8	195.2	194.8
54	203.8	196.4	195.5	195.2
54.5	204.3	197.2	195.8	195.5
55	204.8	198.1	196.1	195.8
55.5	205.1	199.3	196.4	196.1
56	205.5	201.9	196.8	196.4
56.5	205.9	203.3	197.1	196.8
57	206.3	204	197.5	197.1
57.5	206.7	204.5	197.9	197.5
58	207.1	204.9	198.5	197.9
58.5	207.7	205.3	199.1	198.4
59	208.5	205.7	200.3	199
59.5	209.5	206	202.2	200
60	212.6	206.4	203.1	201.9
60.5	220	206.9	203.7	203.1
61	221.7	207.4	204.1	203.7
61.5	223.6	208	204.5	204.1
62	227.4	208.9	204.8	204.5
62.5	228.4	210.1	205.1	204.9
63	229	218.8	205.4	205.2
63.5	229.6	220.9	205.7	205.5
64	230	222.6	206	205.8
64.5	230.3	226.6	206.3	206.1
65	230.6	228.1	206.6	206.4
65.5	230.9	228.9	207	206.7
66	231.1	229.5	207.4	207
66.5	231.6	230	207.8	207.4
67	232.1	230.3	208.4	207.9
67.5	232.7	230.6	209	208.4
68	233.4	230.9	209.6	209

68.5	234.3	231.2	210.4	209.6
69	236	231.7	212.4	210.4
69.5	241.6	232.2	219.2	212
70	248.2	232.8	220.4	219.2
70.5	252.4	233.5	221.4	220.5
71	261.2	234.5	222.4	221.5
71.5	272.1	236.6	224	222.4
72	277.8	243.7	227.1	224.1
72.5	278.7	249.2	227.9	227.2
73	279.5	255.9	228.5	228
73.5	280	265.5	228.9	228.6
74	280.3	277	229.3	229
74.5	280.5	278.3	229.7	229.5
75	280.8	279.2	230	229.8
75.5	281	279.8	230.3	230.2
76	281.3	280.2	230.6	230.4
76.5	281.7	280.5	230.8	230.7
77	282.2	280.8	231	230.9
77.5	283.1	281	231.4	231.2
78	289.5	281.4	231.9	231.7
78.5	291	281.8	232.3	232.1
79	291.8	282.4	232.9	232.6
79.5	292.6	283.5	233.5	233.2
80	293.6	290.2	234.3	233.9
80.5	300.6	291.4	235.5	234.7
81	317.2	292.2	237.7	236.1
81.5	320.5	293.1	241.2	238.7
82	321.9	295.3	245.7	242.5
82.5	323	309.6	247.9	246.6
83	323.9	320	249.6	248.6
83.5	324.9	321.8	251.7	250.4
84	326.1	323	256.6	252.9
84.5	327.9	324	259.4	258.1
85	332.2	325.1	263.4	260
85.5	335	326.5	267.7	265.2
86	338.9	328.6	274.1	270.2
86.5	341.2	333.5	278.5	277.5
87	342	336.2	279.7	279.2
87.5	342.6	340.7	280.4	280.2
88	343.1	341.8	280.9	280.7
88.5	343.7	342.5	281.5	281.3
89	344.3	343.1	282.7	282.2
89.5	345.1	343.7	287	284.5
90	346.1	344.3	290.4	289.3
90.5	351.7	345.2	292.1	291.5
91	352.9	346.7	294.4	293.3
91.5	353.9	352.2	298.7	296.8
92	358	353.3	308	305.2
92.5	360.2	355.9	321.8	319.4
93	361.6	359.4	325.1	324.3
93.5	365.2	361.2	327.6	327
94	370.2	363.8	331.4	330
94.5	373.5	369.6	336.2	335.3
95	376.8	373.4	341.8	341
95.5	386	377.1	344.5	344
96	391.6	387.7	347.7	346.9
96.5	398.9	392.4	353.3	352.8
97	405.1	401.2	359.5	358.8
97.5	409.2	406.6	367.3	366.6
98	420.3	414.9	378.8	376.8
98.5	425.8	422.8	405.4	402
99	449.8	443.7	430	426.9
FBP	493.9	485.5	479.8	477.9

APPENDIX C: Vehicle Coastdown Data

Below are the vehicle coast down results measured during each of the three fuel swaps for each vehicle. Results are the averages of 4 consecutive runs. Coast down times were measured between 70 mph and 30 mph and reported in 10 mph intervals.

Table C-1: Vehicle Coastdown Times

Vehicle	Date	Fuel	70-60	60-50	50-40	40-30	Total
-	-	-	sec	sec	sec	sec	sec
Vehicle D	22-Jan	A	17.26	21.27	26.89	35.51	100.93
Vehicle A	22-Jan	A	16.163	19.964	24.545	31.252	91.925
Vehicle E	29-Jan	B	14.08	17.51	22.28	29.07	82.94
Vehicle C	30-Jan	B	14.28	17.83	22.52	28.76	83.39
Vehicle D	20-Mar	B	17.33	21.31	26.96	35.57	101.17
Vehicle A	21-Mar	B	16.013	19.909	24.317	31.016	91.255
Vehicle E	3-Apr	A	14.09	17.5	22.33	29.17	83.09
Vehicle C	15-Apr	A	14.28	17.83	22.51	28.76	83.38
Vehicle D	8-Jul	A	17.65	22.16	28.8	38.85	107.46
Vehicle E	9-Jul	B	13.69	16.84	21.12	26.82	78.47
Vehicle A	9-Jul	A	16.21	19.88	24.78	31.36	92.23
Vehicle C	9-Jul	B	13.66	16.78	21.12	26.72	78.28

Figure C-1: Vehicle Coastdown Times

APPENDIX D: PEMS Route End Location

To incorporate steeper road grades into the on-road PEMS test route and because of other logistical constraints, the final route was designed such that the PEMS test was concluded at a different location than the test start. This design then introduced one notable issue: the same gas cylinders used for pre-test calibrations could not be available for post-test calibrations at the route end site. Two possible solutions were considered, each with their own pros and cons:

1. Source a second set of gas cylinders to be stored at route end location to perform post-test calibrations and close out test at route end.
   - Minimize data file size
   - Must locate storage space of addition bottles
   - The second set of bottles will not have the exact same component concentrations (±1% NIST traceable concentration uncertainty) as the first, frequent adjustment of calibration parameters in PEMS software to ensure accurate calibration.
2. Adjust procedure to end PEMS exhaust sampling and measurement at route end and return to route start location to perform post-test calibrations before closing out test.
   - PEMS test duration (although not sampling, the PEMS software is still running) is extended by ~30 minutes, additional battery capacity (and increased battery weight) may be needed to mitigate risk of running out of power.
   - Risk of additional PEMS analyzer drift before post-test calibration. Additional drift could impact validity of test.
   - Minimize additional project cost by reducing cost of additional gas bottles (same gas quantity required regardless).

The project team adopted and employed the former solution, and the test route was designed such that the test ended at the storage site for the second set of gas bottles. This decision led to a couple of PEMS testing operational issues. First, it was observed that there was noticeably high THC analyzer "drift". The high drift did not impact the validity of these tests but was a concern for future tests. The source of the issue was found to be the use of a stationary FID fuel bottle being used for pre-test calibrations while the smaller mobile FID fuel bottle was used for the post-test calibrations. By using the same mobile FID fuel bottle for both sets of calibrations the THC analyzer "drift" was reduced significantly. Second, the added complication of manually entering different gas bottle component concentrations for pre- and post-test calibrations introduced a higher likelihood of human error; incorrect bottle concentration values were entered for post-test calibrations for two tests. These errors initially invalidated the two tests, but the data was able to be revalidated after Sensors Inc. was able to make adjustments to the raw data files to correct the bottle concentration values. The full issue was resolved by making adjustments to the PEMS testing checklist used by the operator and by using a Sensors PEMS software functionality to help automate the data entry.

It is first recommended that any future PEMS route development be designed such that the route start and end location are the same. This greatly simplifies testing protocol which can reduce costs by preventing additional materials (e.g. multiple gas bottles), resources (e.g. time required to return to start location even after test concludes), and reducing frequency of errors which may invalidate test data. Should it not be possible to design a PEMS route in this way, as with this project, it is recommended, based on experiences in this project and in retrospect, that the PEMS test still be concluded at the start location and to avoid performing post-test calibrations with a second set of gas cylinders.

APPENDIX E: Chassis vs. On-road Speed Profile and Driving Behavior

Cold Start Speed Profile

Based on general experience, on-road driving style can be influenced by factors such as size of the vehicle, shape of the vehicle (aerodynamic drag), weight of the vehicle (including PEMS equipment), and familiarity with driving the vehicle. These factors impacted the project in a unique way. Because of logistical constraints in needing to develop the test route before test vehicles arrived in Colorado, the test route development was completed using a 44 Energy staff member's personal vehicle. The RWC drive style is therefore representative of how this personal vehicle was driven along the test route whereas the on-road PEMS testing was performed with the test vehicles.

During the test route development, it was recognized that this difference may be impactful and some general guidelines were followed: targeting matching the speed limit, mild accelerations and decelerations, and generally conservative driving style. This type of driving style was also followed during on-road PEMS testing. However, a bias likely still exists with the use of the personal vehicle.[24] As a result, there are some significant differences between the chassis testing drive style and the on-road drive style caused by the design of the RWC.

It has been qualitatively observed that road tests for all vehicles consistently have smoother and more mild accelerations relative to the chassis tests which targets the RWC speed profile. Figure E-1 below shows the start of two example tests for Vehicle A (on Fuel A): one chassis test and one road test. The tests are aligned to the moment of first acceleration. The road test example is intended to be representative of average driving style and performance across all other Vehicle A road tests. Although several small differences exist across the chassis and road test speed traces, these examples are intended to draw attention to two acceleration events that occur around 60 seconds and 80 seconds of the chassis test in Figure E-1. These acceleration events are the source for some emissions discrepancies which are elaborated on below.

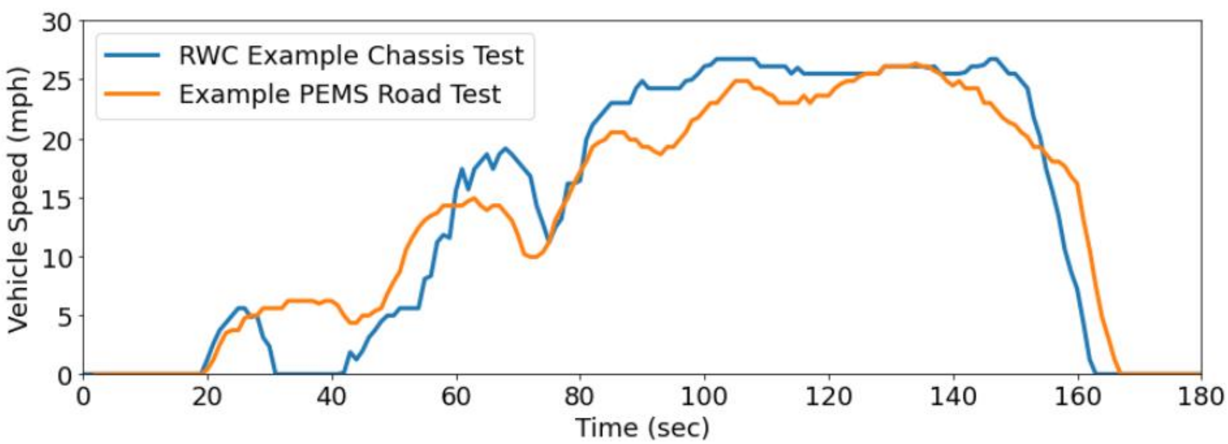


Figure E-1: Chassis Speed Profile vs. On-road Speed Profile

[24] Consider performing mock-testing with a personal vehicle. Consider the differences of performing a PEMS test with a new test vehicle: unfamiliar feel, additional weight from test equipment, expensive equipment extended ~2ft off a rear tow hitch. Despite extensive training and PEMS testing expertise, these factors bias the operator towards a more conservative driving style with the test vehicle relative to a personal vehicle.

Continuing to use Vehicle A as an example, a quantitative assessment of driving style is captured in Table E-1. Average speed, relative positive acceleration (RPA), and the 95th percentile of velocity*positive acceleration are metrics used to demonstrate the relatively more aggressive chassis speed profile compared to the on-road speed profile. Values are calculated for all Vehicle A tests and standard deviations for each of these metrics also showcase the consistency of the speed profile during chassis testing relative to road testing. The mean accelerator pedal position cubed is a unique metric that critically highlights the inconsistency in the accelerator pedal position during chassis testing.[25] The metric is calculated as follows:[26]

$$Mean(Pedal\ Pos\char`^3) = \frac{1}{N}\sum_{i=0}^{N}(accelerator\ pedal\ position\ D_i - 14.901961)^3$$

Table E-1: Chassis vs On-Road Cold Start Driving Metrics[27]

	Average Speed	RPA	vaPOS@95	Mean(Pedal Pos^3)
Vehicle A Chassis Testing Average	13.4 (σ = 0.1)	0.105 (σ = 0.004)	3.49 (σ = 0.34)	339 (σ = 460, med = 212)
Example Chassis Test (Figure E-1)	13.4	0.099	3.89	2089
Vehicle A On-Road Testing Average	13.2 (σ = 0.6)	0.090 (σ = 0.019)	2.73 (σ = 0.71)	114 (σ = 42, med = 108)
Example On-road Test (Figure E-1)	13.3	0.088	3.01	103

The pedal position varies most during the two acceleration events of the chassis speed profile mentioned above; however, during road testing the pedal position is much more consistent during similar accelerations. Figure E-2 shows how outlying accelerator pedal position behavior can impact emissions during cold start operation.[28] Drive metrics for these figure examples are captured in Table E-1 above; note the mean pedal position cubed metric for the example chassis test is nearly +4σ. Tests that exemplify this type of outlying behavior were reviewed and the tests were still validated as the driven speed profiles complied with regulatory boundary requirements.[29]

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[25] Accelerator pedal position measures the physical position of the gas pedal position. This value then influences the throttle position.

[26] The constant "14.901961" is the minimum value output in the OBD data stream for the "accelerator pedal position D" parameter for Vehicle A. This constant is subtracted from the pedal position for two reasons: 1) the subtraction allows a 0 value to represent no external pressure on the accelerator pedal, and 2) the subtraction reduces the magnitude of the result of the cubic function allowing for a more digestible metric. This formula is only applicable to Vehicle A but could be adjusted for other vehicles using a modified constant.

[27] Data only taken for Vehicle A, 32 tests total across road and chassis dynamometer conditions and both test fuels. N = 180 and i = 0 is representative of the data point 20 seconds prior to first acceleration.

[28] It was observed that this type of behavior significantly impacted CO and THC emissions specifically in Vehicle A; the other test vehicles were not so sensitive. This chassis test example was the most extreme. Also note that the accelerator pedal position visualized here was reduced by a constant value of 14.901961 from the raw data.

[29] Procedural specifications in SAE J2951 referenced by 40 CFR 1066.425

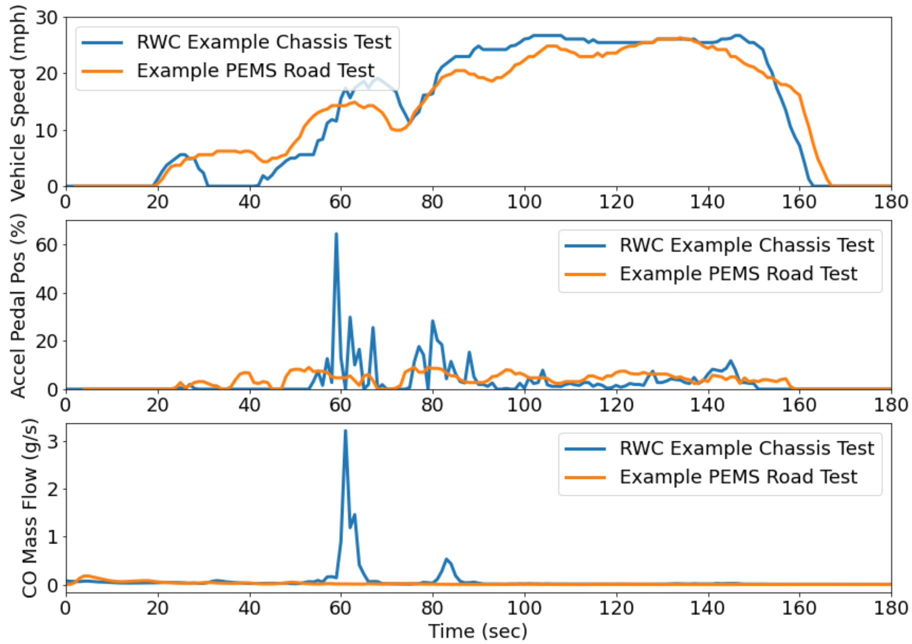

Figure E-2: Impact of Accelerator Pedal Position During Chassis Testing

To some extent, the accelerator pedal position behavior may be related to differences between the chassis test driver and the on-road PEMS test driver.[30] If the driver ever falls behind the speed trace during chassis testing, they might overapply force to the accelerator pedal to catch back up to speed in a way that is not realistic of a "real-world" driving style. This issue is apparent in the cold start acceleration events discussed above. It is possible that the design of the RWC used for chassis testing may have instigated this issue by defining relatively more aggressive accelerations than are observed during the on-road testing. To help avoid this potential impact, it is recommended that, if possible, real-world chassis test cycles be defined using the test vehicle, as opposed to the personal vehicle used in this project, that is also intended to be run on the chassis dynamometer.[31] For future projects concerned with test result variability, a drive metric to account for driver/operator variability, such as the one discussed here, could be applied to validate tests.

Cold Start Idle

It is also notable that the idle procedure for on-road and chassis testing is slightly different. The procedures were intended to be the same but the difference, due to some small oversight in test design, resulted in an additional 14 seconds of idle in drive during chassis tests. The difference wasn't noticed until after a significant portion of the testing was completed.

[30] One driver was dedicated to all on-road PEMS tests. A different driver was dedicated to all chassis tests except for only a few chassis tests run by a third, alternative driver. The alternative driver was not the cause for the outlying pedal position behavior.

[31] It is acknowledged that this issue is unavoidable for this project as four different test vehicles were to be used. Even if one test vehicle was used for development of the RWC, the real-world drive style of the other three vehicles may naturally be different.

An analysis of idle emissions performance was used to justify the continued usage of the differing procedures; in other words, it was found that the additional idle time did not have a critical impact on the emissions results. Figure E-3 shows an example of idle CO emissions for a chassis and road test on Vehicle E, Fuel B. The examples are time aligned to the moment the test begins (@ 0 seconds).

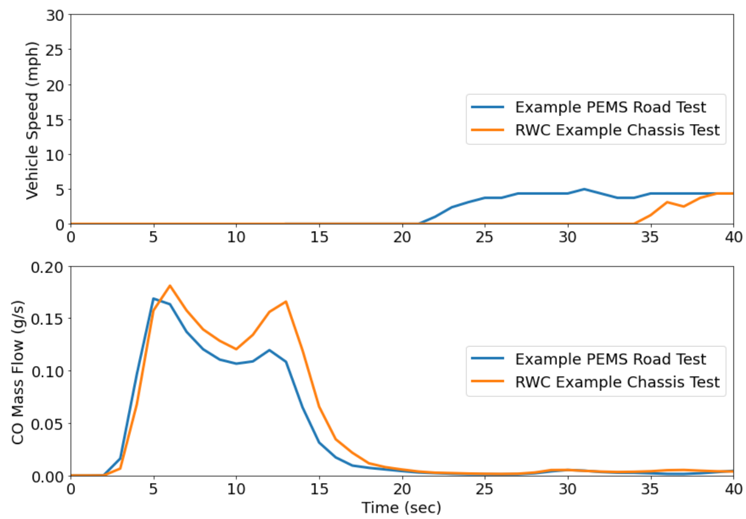

Figure E-3: RWC Extended Idle

APPENDIX F: Route Development Data Smoothing and Concatenation

Data from the three route test runs were used to create speed and grade profiles that would be representative of drive performance during on-road PEMS testing. The urban, rural, and highway speed profiles from each run were qualitatively assessed to determine which individual sections from each run were the most representative. Before this assessment, the speed data was processed to correct brief, 1-3 seconds, GPS dropouts using linear interpolation and then passed through a mild, first-order savitzky-golay filter. An example of this speed data processing is shown in Figure F-1 and processed speed data from all three runs in shown in Figure F-2. It was then determined that all three sections of run three were equally or more representative of the expected PEMS test driving performance and behavior than the other runs.

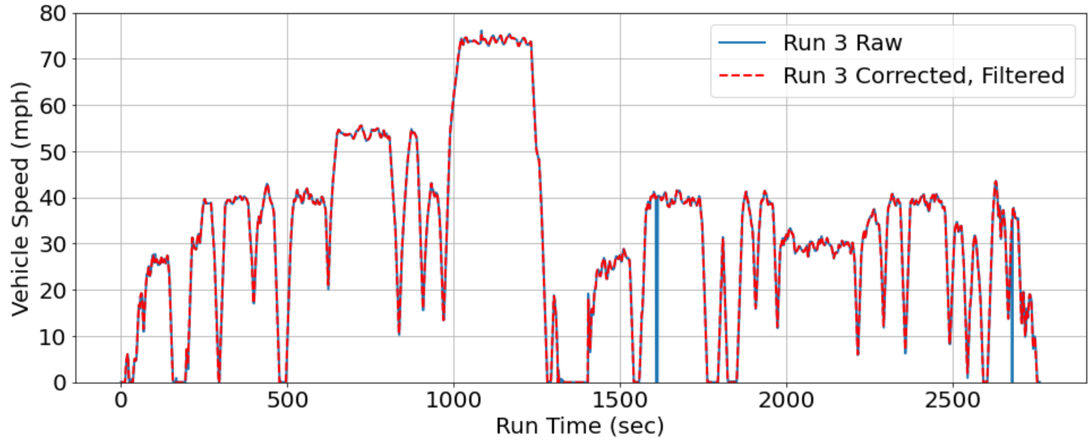

Figure F-1: Run 3 Raw Speed Data vs. Corrected, Filtered Speed Data

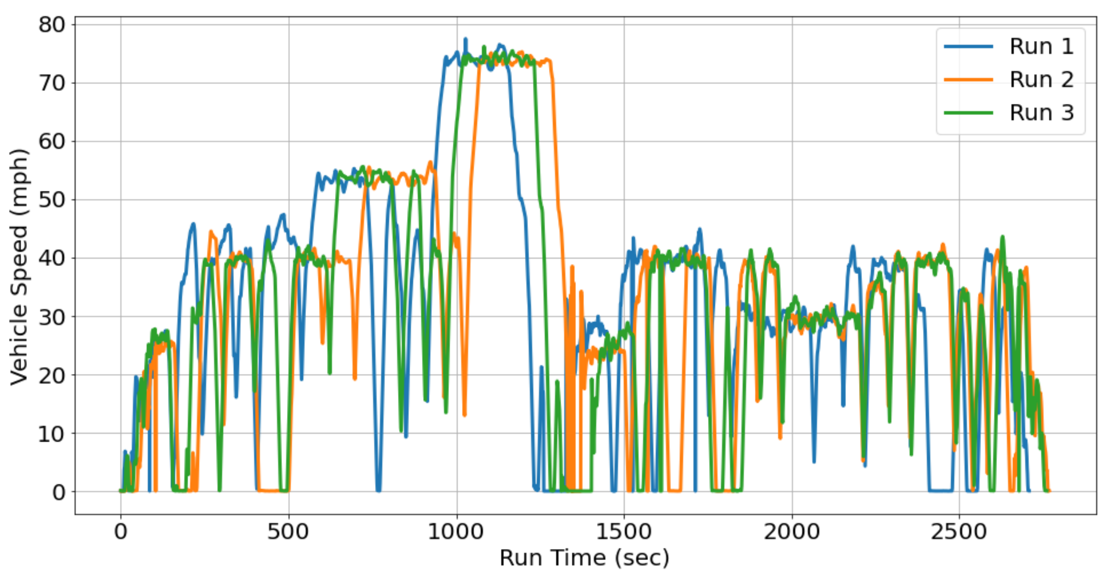

Figure F-2: GPS Corrected, Filtered Speed Data from Test Runs

However, run three still required an adjustment to account for the 2-3 minute GPS dropout directly following the highway driving section. This issue was addressed by collecting GPS data from a modified route test run and splicing it into the section of missing data. The points of concatenation were based on

GPS location such that the resulting GPS profile represents an accurate distance. The vehicle speeds at both concatenation points were similar enough in both speed profiles such that there was no significant instantaneous speed change. Finally, idle periods throughout the speed profile had to be hardcoded to 0 mph as the filtering process was unable to fully reduce GPS signal noise. In summary, the final speed profile was created as follows:

1. For all runs: linearly interpolate across valid speed data points where brief GPS dropouts occurred.

2. For all runs: pass the data through a mild, first-order savitzky-golay filter.

3. Individually select the most representative urban, rural, and highway driving section from each of the three runs. Basis for selection was qualitative assessment of drive style and quantitative assessment of the number of traffic stops. (All sections of run three chosen)

4. Splice data from additional modified run into run three using GPS latitude and longitude to locate accurate concatenation points.

5. Hardcode speed to 0 mph during identified idle periods.

A similar process was used to create a final grade profile; however, heavier filtering was required as there were periods of increased noise throughout the elevation profile, example in Figure F-3.[32] Careful consideration was given to the aggressiveness of the filtering methodology; too light of a filter could cause erroneous dyno load behavior and too heavy of a filter could underrepresent to true extent of the real-world road grades. The final grade profile was calculated as follows:

1. For all runs: linearly interpolate across valid elevation data points where brief GPS dropouts occurred.

2. For all runs: pass the data through a moderate, second-order savitzky-golay filter.

3. For all runs: calculate grade using a 10 second rolling average of the filtered elevation data.

4. For all runs: pass the calculated grade data through a mild, first-order savitzky-golay filter.

5. Splice data from additional modified run into run three using GPS latitude and longitude to locate accurate concatenation points.

[32] Position uncertainty of Vbox 3i single antenna is 0.5m

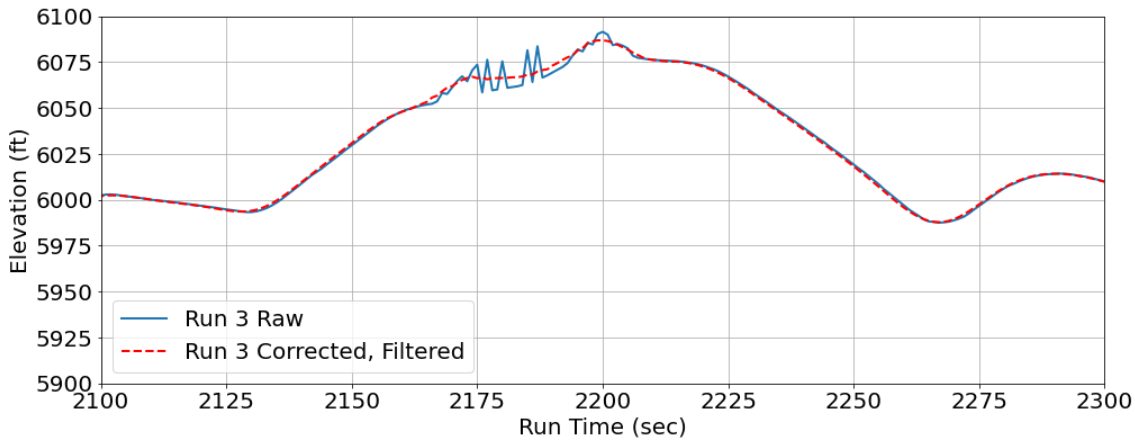

Figure F-3: Raw vs Corrected, Filtered Elevation

APPENDIX G: PM Measurement Methods

Four PM measurement methods were used throughout the project: PEMS gravimetric filter, CVS gravimetric filter, PEMS Pegasor, and AVL MSS. All four measurement methods were employed for chassis emissions tests while only the PEMS pegasor and PEMS gravimetric filter were in use for on-road emissions tests.

Both PM gravimetric filters produce results which can only be used to represent an average value across the full test cycle. The Pegasor and MSS produce modal data, 1Hz and 10Hz respectively, which are useful for data verification. For example, an unusually high PM result in chassis test D-A-4 for Vehicle A was validated by showing that both the MSS and Pegasor captured a large cold start PM spike as a result of a small, but still valid, deviation from the speed trace.

While this modal data can be useful for data verification, it is important to note that the magnitude of PM measured by the MSS, Pegasor, and gravimetric filters can differ. The MSS uses a photoacoustic measurement principal which is capable of measuring soot mass concentration without cross sensitivity to other exhaust components.[33] The soot mass being measured by the MSS is primarily black carbon. The Pegasor uses a corona discharge, and subsequent electrical current differential measurement, to measure PM aerosols including both black carbon and other organic volatiles. Finally, the gravimetric filter also measures large PM aerosols. Finer PM particles may not be caught in the filter. Additionally, the gravimetric filter is cross sensitive to some exhaust components that can react with the filter material. [34] The measurement methods used in this project are summarized in Figure G-1.

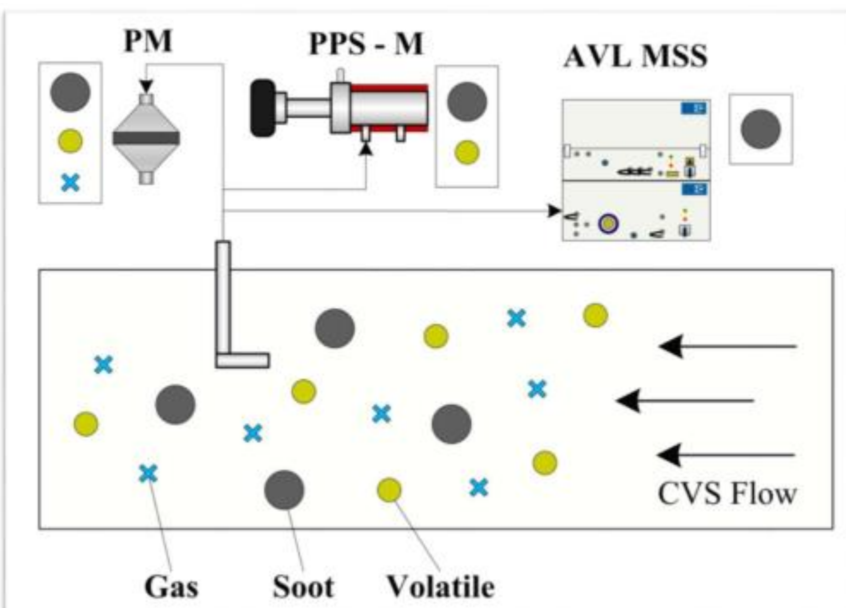

Figure G-1: What is being measured by different PM measurement methods

[33] https://www.avl.com/en-us/testing-solutions/all-testing-products-and-software/emission-analysis-and-measurement/avl-micro-soot-sensor-2

[34] https://pegasor.fi/wp-content/uploads/2024/02/PPS_M_white_paper.pdf

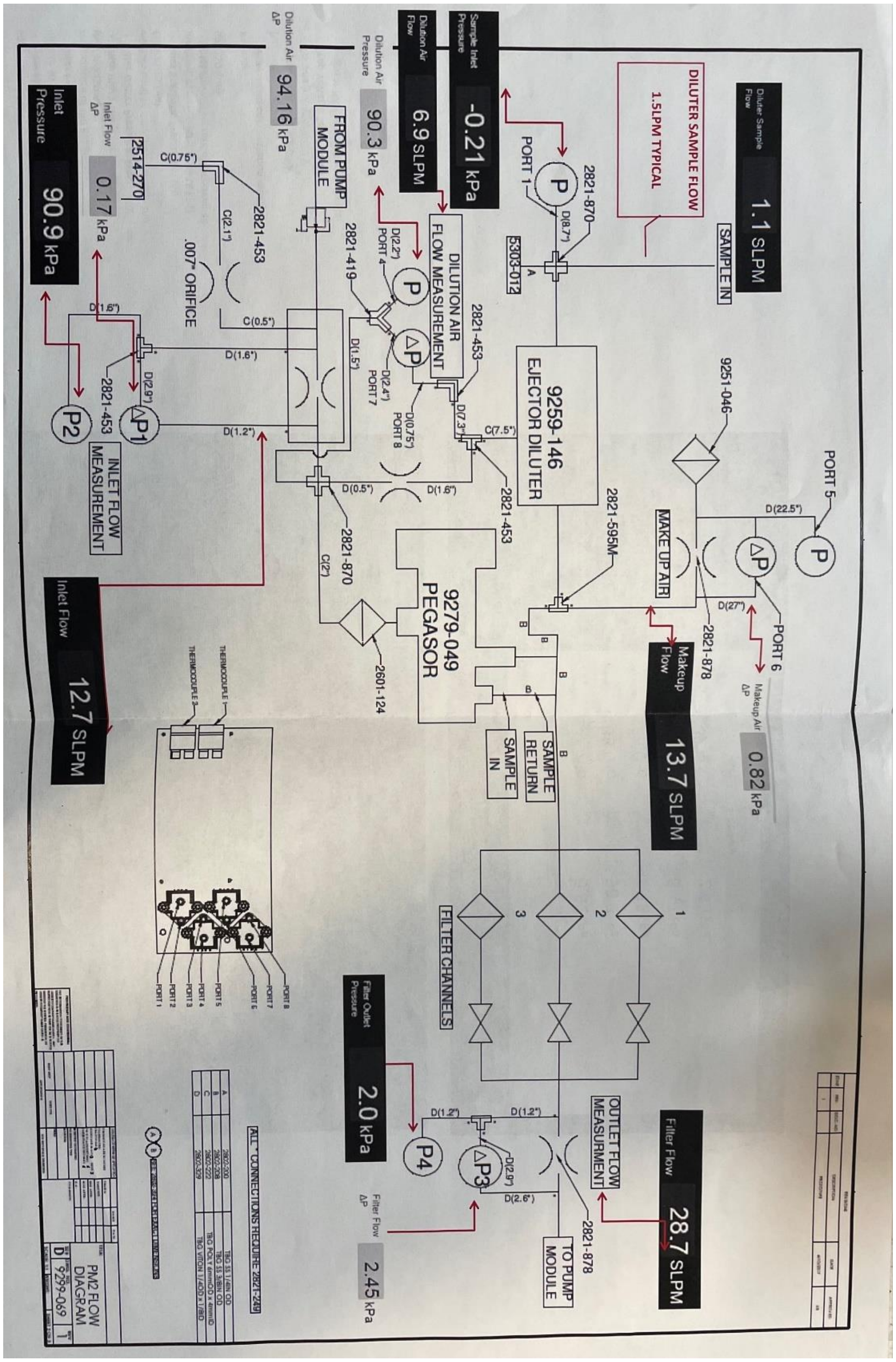

Figure G-2: PM2 Flow Path Diagram

APPENDIX H: Emissions Impact of Engine Start Temperature

As noted in Section 3.5.1, a procedural cold soak period was used to ensure that engine starting conditions were constant across all emissions tests. However, a procedural error was evidenced in the test data for one of Vehicle D's chassis dyno emissions tests. The details of the error are unknown but it is clear that Vehicle D's engine temperature had deviated from the intended target of 50°F (10°C). Figure H-1 below shows the engine coolant temperature profile for the procedurally correct cold start and the procedural error hot start test. Corresponding with the engine temperature deviation is a decrease in THC and CO emissions during the first couple minutes of the test. Both the PEMS and CVS captured the deviation in emissions behavior. The data from this "hot start" test was invalidated and not considered in any further analysis.

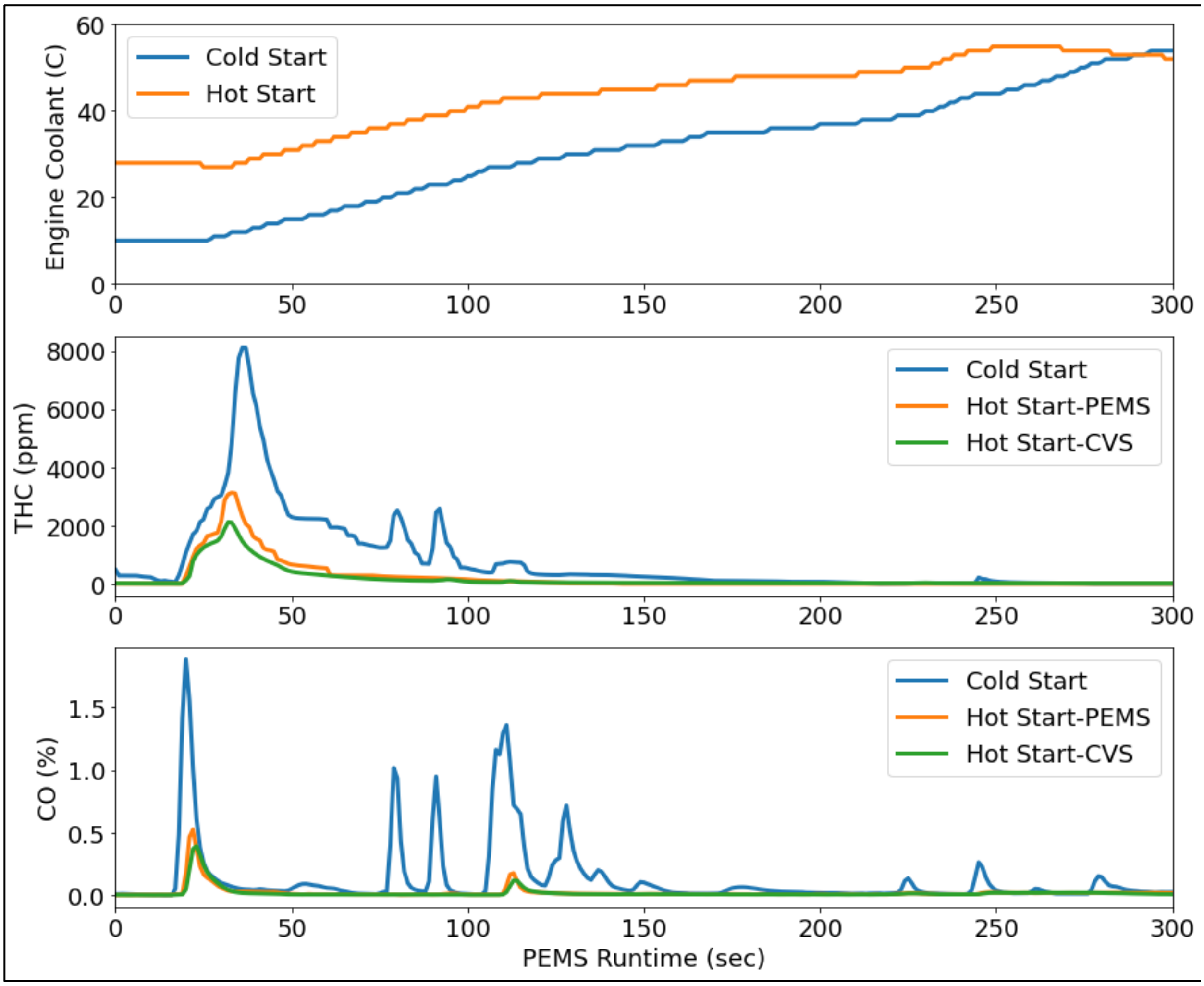

Figure H-1: Vehicle D Emissions Impacted by Engine Temperature

APPENDIX I: PEMS Testing Checklists

Check List On-Road Testing CRC E-134

Test Engineer: ______________________ Test Date: ______________

Test Vehicle: ______________________ Test/Filter #: ______________

Pre-Test Set-up Checks:

- ☐ PEMS and vehicle exhaust attached with clamp and gasket
- ☐ Hitch lock has been tightened
- ☐ SOC set to 50% (PHEV only)
- ☐ Leak check (passing criteria 0.2% oxygen or less when flowing nitrogen) O_2 reading:__________

Pre-Test PEMS Checks:

- ☐ Zero and span gas bottle pressures > 500 psig
- ☐ Web interface gas bottle span values same as bottle certs
- ☐ Web interface shows 13 panes
- ☐ FID heated line set to 191°C

Preparation:

- ☐ Insert pre-weighed filter(s) into filter housing
- ☐ PM2 pump on and in bypass (10 minutes running before start)
- ☐ FID fuel running and flame lit (10 minutes running before start)
- ☐ Test file created on SCS and vehicle details entered

Start test:

Vehicle pre-start:

- ☐ SCS set to record
- ☐ EFM back purged and zeroed
- ☐ Turn on on-board fid fuel bottle, 43 psi
- ☐ Close then unplug shore bottle
- ☐ Confirm flame is on
- ☐ Analyzers zeroed, outlet pressure 20psi
- ☐ Analyzers spanned, outlet pressure 20psi
- ☐ Connect battery
- ☐ Power distribution pane indicates "both inputs attached"
- ☐ Tail lights on
- ☐ Power shifted from wall to battery power
- ☐ >11V on power distribution pane
- ☐ PC charger and calibration gas line in car
- ☐ Fairings (covers) attached to PEMS
- ☐ Start Time ________________________

Vehicle start:

- ☐ SCS set to sample mode
- ☐ PM2 set to filter 1 or filter 2
- ☐ Sample flow between 2.5 to 4.0 L/min
- ☐ No erroneous warning messages on PEMS
- ☐ Vehicle started, trans in Park, start timer
- ☐ HVAC 72°F auto, front and rear defrost on
- ☐ At 15 seconds switch trans to Drive
- ☐ At 20 seconds begin test route
- ☐ Front and rear defrost off at Chambers Street

Mid Test (when able):

- ☐ No check engine lights or alarms
- ☐ Vehicle fuel level checked (full/near full)

Energy Technologies

Check List On-Road Testing CRC E-134

Notes:

Post-drive:

- ☐ SCS set to standby mode, PM to bypass, pump off
- ☐ Vehicle engine stopped
- ☐ Zero and span gas bottle pressures > 500 psig
- ☐ Web interface gas bottle span values set to bottle certs
- ☐ Analyzers zeroed
- ☐ Analyzers spanned
- ☐ Test file closed
- ☐ FID heated line set to 100°C (only if <11V)
- ☐ Extinguish flame via interface
- ☐ Turn off fid fuel flow (close main valve)

Check List Dyno Testing CRC E-134

Test Engineer: ______________________ Test Date: ______________

Test Vehicle: ______________________ Test/Filter #: ______________

Pre-Test Set-up Checks:

- ☐ PEMS and vehicle exhaust attached with clamp and gasket
- ☐ Hitch lock has been tightened
- ☐ SOC set to 50% (PHEV only)
- ☐ Leak check (passing criteria 0.2% oxygen or less when flowing nitrogen) O_2 reading:_________

Pre-Test PEMS Checks:

- ☐ Zero and span gas bottle pressures > 500 psig
- ☐ Web interface gas bottle span values same as bottle certs
- ☐ Web interface shows 13 panes
- ☐ FID heated line set to 191°C

Preparation:

- ☐ Insert pre-weighed filter(s) into filter housing
- ☐ VI module attached
- ☐ PM2 pump on and in bypass (10 minutes running before start)
- ☐ FID fuel running and flame lit (10 minutes running before start)
- ☐ Test file created on SCS and vehicle details entered

Start test:

Vehicle pre-start:

- ☐ SCS set to record
- ☐ EFM back purged and zeroed
- ☐ Analyzers zeroed, 3-3.25 SLPM
- ☐ Analyzers spanned, 3-3.25 SLPM

Vehicle start:

- ☐ SCS set to sample mode
- ☐ PM2 set to filter 1 or filter 2
- ☐ Sample flow between 2.5 to 4.0 L/min
- ☐ No erroneous warning messages on PEMS

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Notes:

Post-drive:

- ☐ SCS set to standby mode, PM to bypass, pump off
- ☐ Zero and span gas bottle pressures > 500 psig
- ☐ Web interface gas bottle span values set to bottle certs
- ☐ Analyzers zeroed
- ☐ Analyzers spanned
- ☐ Test file closed
- ☐ Extinguish flame via interface
- ☐ Turn off fid fuel flow (close main valve)

APPENDIX J: Tabulated Test Data

Table J-1: Distance Weighted Emissions Data

Test Date	Vehicle	Sequence Number	Test Start Time	Distance (mi)	Fuel Economy (mpg)	CO_2 (g/mi)	CO (g/mi)	kNOx (g/mi)	THC (g/mi)	Pegasor PM (mg/mi)	Filter PM (mg/mi)	Avg Ambient Temp (°C)
7-Feb	Vehicle A	D-A-1	N/A	25.90	24.0	355	0.463	0.012	0.074	0.424	0.503	12.7
8-Feb	Vehicle A	D-A-2	N/A	25.92	23.8	360	0.405	0.011	0.087	0.444	0.490	11.2
9-Feb	Vehicle A	D-A-3	N/A	25.93	23.6	363	0.512	0.012	0.089	0.491	0.469	11.7
15-Feb	Vehicle A	D-A-4	N/A	25.89	23.8	358	0.926	0.012	0.133	0.690	0.999	10.9
23-Jul	Vehicle A	D-A-5	N/A	25.81	23.9	356	1.097	0.011	0.083	0.635	0.822	13.1
24-Jul	Vehicle A	D-A-6	N/A	25.83	24.4	349	0.470	0.015	0.071	0.329	0.593	14.0
25-Jul	Vehicle A	D-A-7	N/A	25.84	24.4	350	0.518	0.012	0.067	0.398	0.706	13.7
26-Jul	Vehicle A	D-A-8	N/A	25.83	24.4	349	0.622	0.010	0.087	0.412	0.688	12.7
23-Apr	Vehicle A	D-B-1	N/A	25.76	24.9	339	0.590	0.014	0.048	0.026	0.071	11.4
24-Apr	Vehicle A	D-B-2	N/A	25.86	24.1	349	0.905	0.011	0.053	0.082	0.153	11.3
25-Apr	Vehicle A	D-B-3	N/A	25.87	24.1	349	0.802	0.010	0.054	0.055	0.000	12.0
26-Apr	Vehicle A	D-B-4	N/A	25.84	24.2	349	0.803	0.013	0.057	0.052	0.000	12.3
4-Jun	Vehicle A	D-B-5	N/A	25.92	25.0	336	0.726	0.013	0.046	0.045	0.165	12.8
5-Jun	Vehicle A	D-B-6	N/A	25.86	24.6	342	0.757	0.009	0.045	0.046	0.012	12.3
6-Jun	Vehicle A	D-B-7	N/A	25.83	24.9	338	0.715	0.010	0.045	0.042	0.057	13.0
7-Jun	Vehicle A	D-B-8	N/A	25.86	24.9	339	0.626	0.011	0.044	0.030	0.088	13.1
1-Feb	Vehicle A	R-A-1	11:45 AM	25.50	22.6	380	0.302	0.012	0.088	0.344	0.387	14.1
2-Feb	Vehicle A	R-A-2	11:15 AM	26.07	22.0	389	0.368	0.014	0.095	0.286	0.429	10.5
27-Feb	Vehicle A	R-A-3	10:45 AM	25.54	21.9	389	0.297	0.052	0.077	0.241	0.121	-3.5
28-Feb	Vehicle A	R-A-4	9:30 AM	25.53	22.8	375	0.282	0.024	0.061	0.200	0.291	5.6
7-Mar	Vehicle A	R-A-5	10:45 AM	25.51	22.2	384	0.340	0.015	0.068	0.194	0.000	5.4
8-Mar	Vehicle A	R-A-6	10:00 AM	25.56	22.8	374	0.265	0.016	0.059	0.216	0.261	-2.8
12-Mar	Vehicle A	R-A-7	10:45 AM	25.50	22.9	373	0.390	0.016	0.080	0.217	0.349	12.3
13-Mar	Vehicle A	R-A-8	10:15 AM	25.51	21.7	393	0.325	0.026	0.071	0.228	0.351	8.7
28-Mar	Vehicle A	R-B-1	9:45 AM	25.44	24.0	353	0.544	0.013	0.036	0.024	0.123	11.0
29-Mar	Vehicle A	R-B-2	8:45 AM	25.45	23.0	366	0.516	0.028	0.052	0.033	0.255	7.8
2-Apr	Vehicle A	R-B-3	10:45 AM	25.44	23.7	355	0.551	0.009	0.054	0.022	0.000	9.0
3-Apr	Vehicle A	R-B-4	10:00 AM	25.44	23.9	351	0.537	0.024	0.044	0.025	0.000	14.8
4-Apr	Vehicle A	R-B-5	9:30 AM	25.44	23.1	366	0.538	0.042	0.054	0.029	0.123	15.1
5-Apr	Vehicle A	R-B-6	9:00 AM	25.44	23.5	359	0.502	0.045	0.042	0.040	0.163	13.3
16-Apr	Vehicle A	R-B-7	10:45 AM	25.45	24.4	344	0.512	0.020	0.051	0.022	0.000	13.1
17-Apr	Vehicle A	R-B-8	10:00 AM	25.43	23.3	362	0.520	0.032	0.041	0.031	0.000	19.0
9-May	Vehicle C	D-A-1	N/A	26.53	24.9	343	0.228	0.005	0.010	0.079	0.000	11.9
10-May	Vehicle C	D-A-2	N/A	26.52	24.4	351	0.237	0.011	0.009	0.085	0.024	12.5
14-May	Vehicle C	D-A-3	N/A	26.53	24.5	349	0.295	0.006	0.010	0.090	0.174	12.5
15-May	Vehicle C	D-A-4	N/A	26.50	24.6	347	0.271	0.006	0.008	0.059	0.558	12.4
4-Jun	Vehicle C	D-A-5	N/A	26.46	25.1	340	0.289	0.009	0.010	0.059	0.163	12.6
5-Jun	Vehicle C	D-A-6	N/A	26.48	25.3	338	0.221	0.005	0.009	0.054	0.152	12.1
6-Jun	Vehicle C	D-A-7	N/A	26.43	25.1	340	0.251	0.007	0.010	0.071	0.141	12.9
7-Jun	Vehicle C	D-A-8	N/A	26.52	25.2	339	0.286	0.006	0.010	0.070	0.181	12.8
8-Feb	Vehicle C	D-B-1	N/A	26.22	26.2	322	0.510	0.008	0.029	0.018	0.076	11.4
9-Feb	Vehicle C	D-B-2	N/A	26.25	25.5	331	0.542	0.006	0.027	0.014	0.000	11.8
13-Feb	Vehicle C	D-B-3	N/A	26.24	25.2	335	0.880	0.008	0.059	0.038	0.073	12.3
15-Feb	Vehicle C	D-B-4	N/A	26.26	25.3	334	0.720	0.006	0.033	0.013	0.019	12.1
23-Jul	Vehicle C	D-B-5	N/A	26.20	25.3	335	0.282	0.007	0.017	0.020	0.302	13.1
24-Jul	Vehicle C	D-B-6	N/A	26.21	24.6	344	0.361	0.007	0.019	0.015	0.051	13.9
25-Jul	Vehicle C	D-B-7	N/A	26.07	25.6	330	0.332	0.005	0.019	0.012	0.236	16.8
26-Jul	Vehicle C	D-B-8	N/A	26.24	24.7	341	0.352	0.006	0.021	0.012	0.138	13.4
25-Apr	Vehicle C	R-A-1	10:45 AM	25.97	25.7	333	0.230	0.002	0.010	0.057	0.000	19.1
26-Apr	Vehicle C	R-A-2	9:45 AM	25.97	26.6	321	0.136	0.003	0.008	0.043	0.043	17.2
30-Apr	Vehicle C	R-A-3	12:45 PM	25.97	24.6	347	0.207	0.004	0.009	0.043	0.206	20.0
1-May	Vehicle C	R-A-4	1:15 PM	25.96	24.6	346	0.147	0.003	0.009	0.040	0.263	21.6
2-May	Vehicle C	R-A-5	2:20 PM	26.02	25.2	340	0.154	0.004	0.008	0.047	0.396	15.1
3-May	Vehicle C	R-A-6	11:30 AM	26.01	24.6	347	0.179	0.003	0.008	0.039	0.107	21.0

7-May	Vehicle C	R-A-7	12:50 PM	26.01	26.0	328	0.169	0.003	0.009	0.042	0.066	12.2
8-May	Vehicle C	R-A-8	12:20 PM	26.01	26.3	326	0.181	0.004	0.009	0.064	0.000	12.9
27-Feb	Vehicle C	R-B-1	1:45 PM	25.96	25.7	327	0.295	0.003	0.024	0.013	0.000	-3.5
28-Feb	Vehicle C	R-B-2	12:15 PM	25.98	25.5	332	0.281	0.003	0.023	0.007	0.000	10.3
5-Mar	Vehicle C	R-B-3	1:00 PM	25.97	25.1	337	0.277	0.004	0.020	0.011	0.000	10.7
6-Mar	Vehicle C	R-B-4	2:00 PM	25.97	27.4	310	0.234	0.003	0.022	0.010	0.061	13.7
7-Mar	Vehicle C	R-B-5	2:30 PM	25.99	25.6	331	0.250	0.003	0.020	0.012	0.010	4.4
8-Mar	Vehicle C	R-B-6	1:00 PM	26.02	25.9	326	0.244	0.003	0.018	0.011	0.000	-1.1
20-Mar	Vehicle C	R-B-7	1:30 PM	25.94	25.6	330	0.259	0.003	0.021	0.009	0.026	13.8
21-Mar	Vehicle C	R-B-8	11:30 AM	25.90	26.7	317	0.272	0.003	0.020	0.005	0.000	15.1
22-Mar	Vehicle C	R-B-9	11:15 AM	25.94	26.0	325	0.300	0.005	0.023	0.009	0.007	12.2
7-May	Vehicle E	D-A-1	N/A	25.96	32.2	266	0.283	0.011	0.046	0.659	1.459	10.9
8-May	Vehicle E	D-A-2	N/A	25.92	32.2	265	0.213	0.013	0.044	0.635	1.439	10.9
9-May	Vehicle E	D-A-3	N/A	25.94	32.6	262	0.260	0.015	0.042	0.777	1.694	11.1
10-May	Vehicle E	D-A-4	N/A	25.95	32.4	263	0.219	0.012	0.036	0.782	1.725	11.1
29-May	Vehicle E	D-A-5	N/A	25.93	33.4	255	0.193	0.009	0.041	0.703	1.573	11.9
30-May	Vehicle E	D-A-6	N/A	25.95	33.8	253	0.160	0.010	0.034	0.544	1.296	11.0
31-May	Vehicle E	D-A-7	N/A	25.95	33.4	256	0.212	0.012	0.036	0.672	1.524	11.7
5-Jun	Vehicle E	D-A-8	N/A	26.06	33.1	258	0.228	0.010	0.043	0.605	1.408	11.2
13-Feb	Vehicle E	D-B-1	N/A	25.90	33.3	254	0.349	0.009	0.024	0.103	0.092	10.8
14-Feb	Vehicle E	D-B-2	N/A	25.92	33.5	252	0.186	0.007	0.031	0.119	0.220	11.0
15-Feb	Vehicle E	D-B-3	N/A	25.94	33.5	252	0.173	0.008	0.036	0.146	0.238	9.5
16-Feb	Vehicle E	D-B-4	N/A	25.91	32.7	258	0.224	0.010	0.036	0.118	0.136	9.5
16-Jul	Vehicle E	D-B-5	N/A	25.96	32.0	263	0.423	0.009	0.031	0.088	0.189	12.9
17-Jul	Vehicle E	D-B-6	N/A	25.89	33.5	252	0.241	0.011	0.032	0.056	0.150	13.0
18-Jul	Vehicle E	D-B-7	N/A	25.85	32.9	256	0.220	0.014	0.032	0.058	0.161	12.1
19-Jul	Vehicle E	D-B-8	N/A	25.96	33.8	250	0.212	0.012	0.034	0.039	0.215	12.1
9-Apr	Vehicle E	R-A-1	10:15 AM	25.52	30.2	282	0.229	0.010	0.047	0.495	1.382	9.6
10-Apr	Vehicle E	R-A-2	10:00 AM	25.51	31.5	272	0.154	0.008	0.039	0.497	1.282	10.0
11-Apr	Vehicle E	R-A-3	11:20 AM	25.51	30.7	277	0.191	0.009	0.037	0.421	1.278	11.7
12-Apr	Vehicle E	R-A-4	9:00 AM	25.52	30.4	282	0.150	0.008	0.035	0.374	0.884	14.7
16-Apr	Vehicle E	R-A-5	1:15 PM	25.51	30.8	277	0.154	0.009	0.041	0.524	1.095	15.0
17-Apr	Vehicle E	R-A-6	12:45 PM	25.50	32.0	268	0.141	0.008	0.042	0.452	0.995	20.7
18-Apr	Vehicle E	R-A-7	11:00 AM	25.54	28.6	296	0.253	0.014	0.048	0.546	1.420	0.5
19-Apr	Vehicle E	R-A-8	9:45 AM	25.53	30.3	281	0.193	0.013	0.051	0.568	1.400	2.8
21-Feb	Vehicle E	R-B-1	9:30 AM	25.51	30.3	279	0.216	0.008	0.033	0.034	0.241	12.6
22-Feb	Vehicle E	R-B-2	10:15 AM	25.50	30.7	274	0.208	0.011	0.028	0.033	0.088	2.9
23-Feb	Vehicle E	R-B-3	9:15 AM	25.51	31.8	266	0.219	0.009	0.032	0.033	0.000	6.6
15-Mar	Vehicle E	R-B-4	1:15 PM	25.57	26.8	313	0.374	0.015	0.045	0.050	0.093	3.4
19-Mar	Vehicle E	R-B-5	10:30 AM	25.51	32.1	263	0.174	0.009	0.030	0.052	0.000	11.5
20-Mar	Vehicle E	R-B-6	10:45 AM	25.51	30.9	273	0.195	0.010	0.029	0.062	0.118	8.4
21-Mar	Vehicle E	R-B-7	9:30 AM	26.70	31.3	270	0.184	0.011	0.032	0.037	0.128	12.3
26-Mar	Vehicle E	R-B-8	11:30 AM	25.52	28.3	299	0.307	0.015	0.045	0.076	0.242	2.6
27-Mar	Vehicle E	R-B-9	9:45 AM	25.51	31.5	268	0.200	0.009	0.041	0.053	0.015	6.4
7-Feb	Vehicle D	D-A-1	N/A	26.01	94.0	91	0.033	0.013	0.016	0.100	0.113	11.5
8-Feb	Vehicle D	D-A-2	N/A	26.04	82.5	103	0.162	0.005	0.035	0.252	0.172	10.4
9-Feb	Vehicle D	D-A-3	N/A	26.06	83.4	103	0.132	0.001	0.035	0.200	0.166	10.0
16-Feb	Vehicle D	D-A-4	N/A	26.06	81.7	104	0.195	0.002	0.041	0.310	0.218	9.8
16-Jul	Vehicle D	D-A-5	N/A	25.96	84.8	101	0.160	0.003	0.035	0.287	0.325	11.8
17-Jul	Vehicle D	D-A-6	N/A	25.96	88.0	97	0.125	0.007	0.032	0.247	0.152	11.4
18-Jul	Vehicle D	D-A-7	N/A	26.02	87.3	98	0.127	0.005	0.034	0.252	0.429	11.9
19-Jul	Vehicle D	D-A-8	N/A	26.00	86.4	99	0.152	0.001	0.035	0.196	0.198	11.6
30-Apr	Vehicle D	D-B-1	N/A	25.97	85.6	98	0.147	0.002	0.029	0.047	0.083	11.0
1-May	Vehicle D	D-B-2	N/A	26.03	82.7	102	0.089	0.009	0.017	0.033	0.000	10.4
3-May	Vehicle D	D-B-3	N/A	25.99	88.6	95	0.091	0.001	0.020	0.020	0.109	11.7
14-May	Vehicle D	D-B-4	N/A	25.97	116.8	72	0.113	0.003	0.023	0.032	0.070	11.2
29-May	Vehicle D	D-B-5	N/A	25.87	89.9	94	0.090	0.002	0.019	0.019	0.063	10.6
30-May	Vehicle D	D-B-6	N/A	25.97	87.8	96	0.116	0.003	0.020	0.018	0.111	10.8
31-May	Vehicle D	D-B-7	N/A	26.01	87.2	97	0.079	0.002	0.017	0.024	0.062	11.6
4-Jun	Vehicle D	D-B-8	N/A	26.01	89.8	94	0.191	0.002	0.025	0.018	0.062	10.9
31-Jan	Vehicle D	R-A-1	2:15 PM	25.62	73.4	116	0.116	0.005	0.035	0.248	0.155	13.3

1-Feb	Vehicle D	R-A-2	2:15 PM	25.61	74.4	115	0.106	0.002	0.030	0.234	0.188	14.5
2-Feb	Vehicle D	R-A-3	1:55 PM	25.62	72.2	118	0.152	0.002	0.034	0.196	0.187	11.5
21-Feb	Vehicle D	R-A-4	12:30 PM	25.62	72.1	119	0.132	0.001	0.057	0.145	0.125	15.5
22-Feb	Vehicle D	R-A-5	1:30 PM	25.63	72.3	118	0.127	0.002	0.033	0.173	0.034	6.0
23-Feb	Vehicle D	R-A-6	12:15 PM	25.62	75.0	114	0.138	0.001	0.033	0.158	0.112	9.2
12-Mar	Vehicle D	R-A-7	1:45 PM	25.61	77.2	111	0.164	0.009	0.040	0.214	0.176	12.5
19-Mar	Vehicle D	R-A-8	1:30 PM	25.62	73.2	117	0.110	0.001	0.029	0.097	0.095	13.8
27-Mar	Vehicle D	R-B-1	11:45 AM	25.58	80.6	105	0.101	0.002	0.022	0.076	0.083	8.2
28-Mar	Vehicle D	R-B-2	11:30 AM	25.59	75.2	112	0.090	0.002	0.023	0.071	0.362	13.0
29-Mar	Vehicle D	R-B-3	11:00 AM	25.59	78.4	108	0.105	0.001	0.025	0.062	0.020	9.4
2-Apr	Vehicle D	R-B-4	1:20 PM	25.58	83.0	102	0.086	0.001	0.021	0.056	0.024	11.4
4-Apr	Vehicle D	R-B-5	11:30 AM	25.59	78.6	108	0.116	0.001	0.022	0.037	0.030	19.9
5-Apr	Vehicle D	R-B-6	11:15 AM	25.59	72.9	116	0.108	0.001	0.025	0.034	0.024	20.0
10-Apr	Vehicle D	R-B-7	12:30 PM	25.59	83.8	101	0.099	0.001	0.020	0.024	0.002	12.4
11-Apr	Vehicle D	R-B-8	2:45 PM	25.57	82.0	103	0.106	0.001	0.022	0.031	0.009	14.1

APPENDIX K: Drift Verification

PEMS translates the voltage or current from a sensor into engineering units by means of calibrated coefficients. Over time, changes in the environment surrounding the PEMS cause the response to a particular pollutant concentration to change, or "drift," over time. The amount of drift is quantifiable, and data suspected to have excessive drift can be excluded. The CFR prescribes a methodology for drift-correction and gives criteria for excluding data segments deemed to have excessive drift.[35]

For a test to be valid, the difference between the drift-corrected and uncorrected value of regulated exhaust gas constituents must be either less than ±4% of the uncorrected value, or, for small values, the drift-corrected value must be less than the certification standard by at least two times the absolute difference between the uncorrected and drift-corrected values.[36] The second criterion is necessary when measured emission become small where the relative difference between drift-corrected and uncorrected can easily exceed ±4%. Take the case where the measured emissions for a component are zero. Any modicum of absolute drift would result in an infinite percentage of relative drift.

Drift verification is only necessary for gaseous components with an applicable emissions standard and CO_2. Therefore, for these vehicles, drift verification procedures only strictly apply to CO and CO_2, Table K-1. For other emissions components such as NO_x and THC, best engineering judgement was used to assess relative drift. Figure K-1 and Figure K-2 below show drift points for all PEMS tests; all tests were deemed valid.

Table K-1: Vehicle Emissions Standards (FTP-75)

	CO_2 (g/mi)	CO (g/mi)	NOx (g/mi)	THC (g/mi)	NOx + NMOG (g/mi)
Vehicle A	N/A	2.1	N/A	N/A	0.125
Vehicle B	N/A	1.7	N/A	N/A	0.07
Vehicle C	N/A	1.0	N/A	N/A	0.03
Vehicle D	N/A	1.0	N/A	N/A	0.03

[35] 40 CFR § 1065.672 - Drift correction

[36] 40 CFR § 1065.550 - Gas analyzer range verification and drift verification.

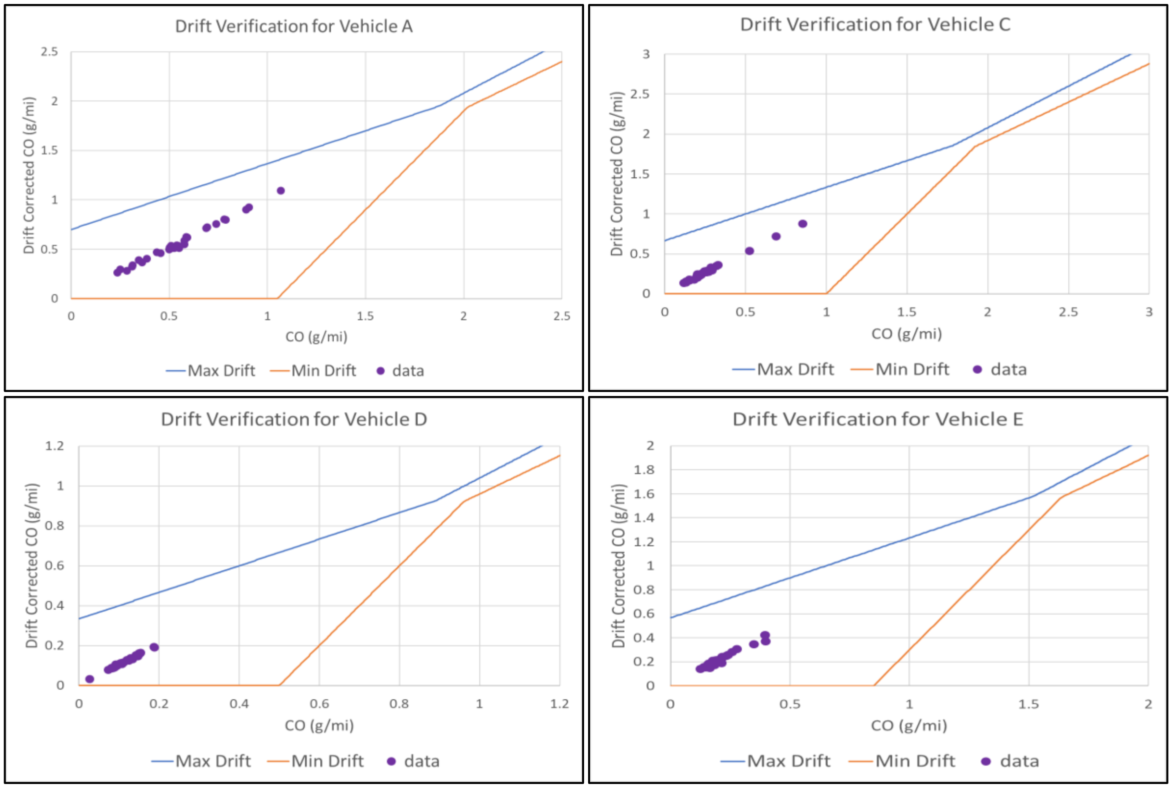

Figure K-1: CO Drift Verification

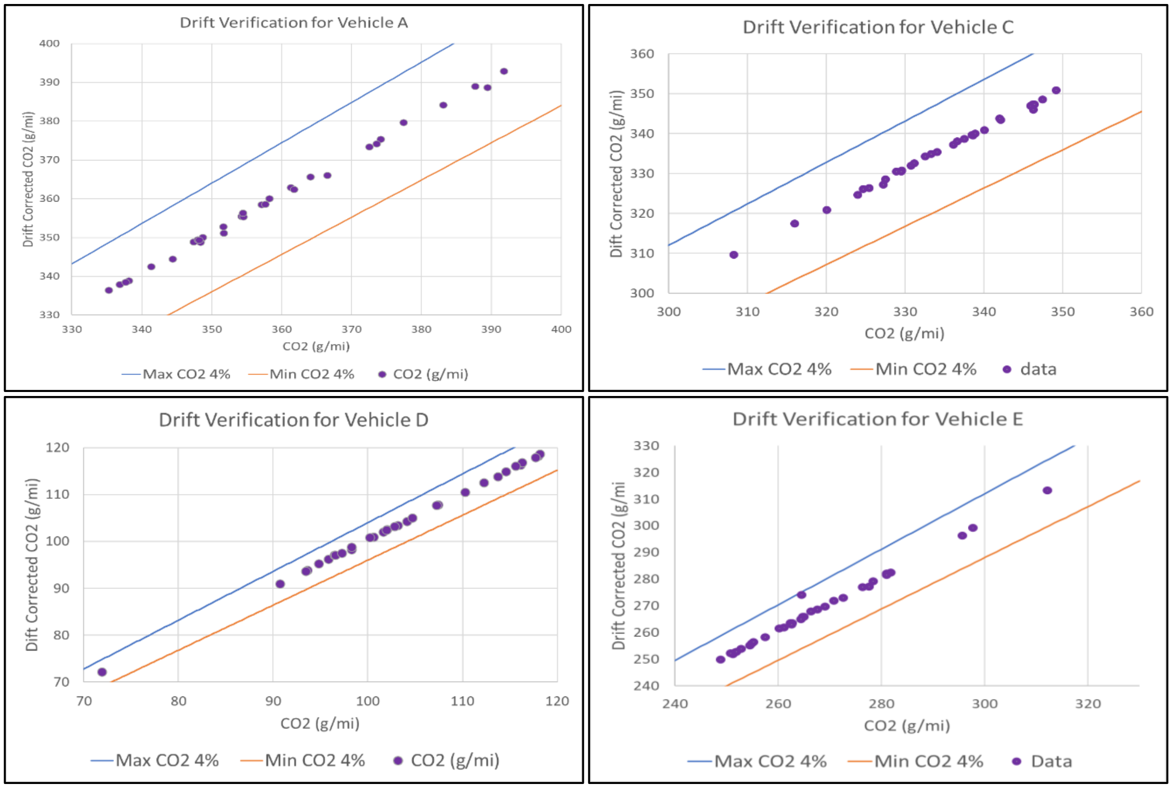

Figure K-2: CO_2 Drift Verification

APPENDIX L: Outlier Analysis

The data was inspected for outliers using both visual inspection of the data and considering studentized residuals from the model described in Section 4.1.1. In total, twelve points were identified as potential outliers for further review, eight of which were for PM, two for CO, one for THC, and two for fuel economy. Of the eight PM outliers, four were from Vehicle C. The full list is shown below in Table L-1.

Table L-1: Outliers and Unusual Data List

Parameter	Vehicle	Vehicle Test ID's
PM	Vehicle A	R-A-5, D-A-4
PM	Vehicle C	D-A-1, D-A-2, D-A-4, D-B-5
PM	Vehicle D	D-B-1, R-B-2
CO, THC	Vehicle A	D-A-4
CO	Vehicle A	D-A-5
CO_2, Fuel Economy	Vehicle D	D-B-4, D-B-8

These results were inspected carefully by 44Energy and reviewed individually with the committee. PM data from the PEMS Pegasor and also soot data from the MSS were used to help better understand the PM outliers where possible. For example, for Vehicle A, test R-A-5, Figure L-1 shows the PM results for Vehicle A as measured by PEMS filter on the road vs. the Phase level PM data as measured by the PEMS Pegasor. Though the PEMS filter indicated this test had no PM, the Pegasor data suggested otherwise. Figure L-2 which follows is a zoomed in plot of lower PM levels including all vehicles. The figure indicates that there were other tests which had positive PM recorded by the Pegasor for Phase 1 which resulted in zero PM as measured by the PEMS filter. The correlation between the PEMS filter and the Pegasor appears poor at these low PM levels.

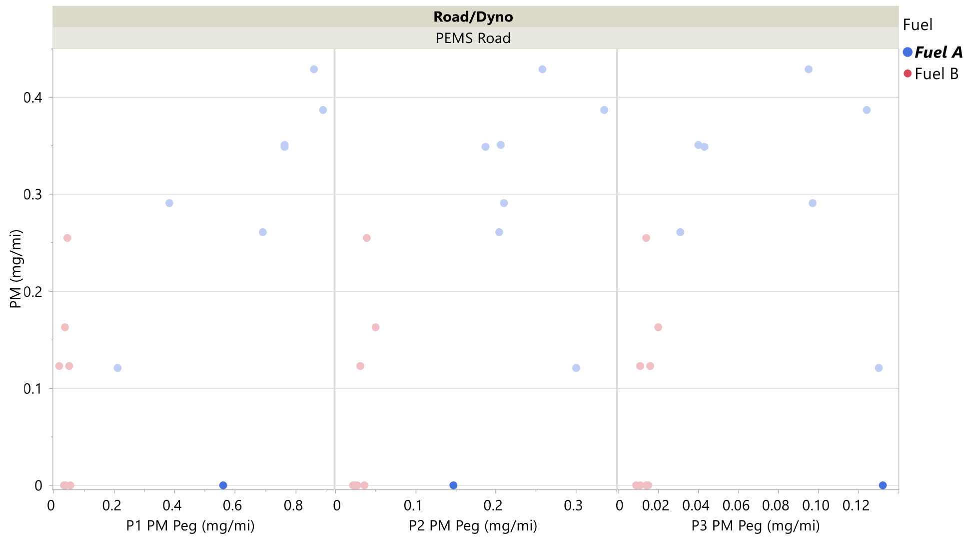

Figure L-1: Vehicle A PEMS Road Filter PM vs. Pegasor Phase-Level PM

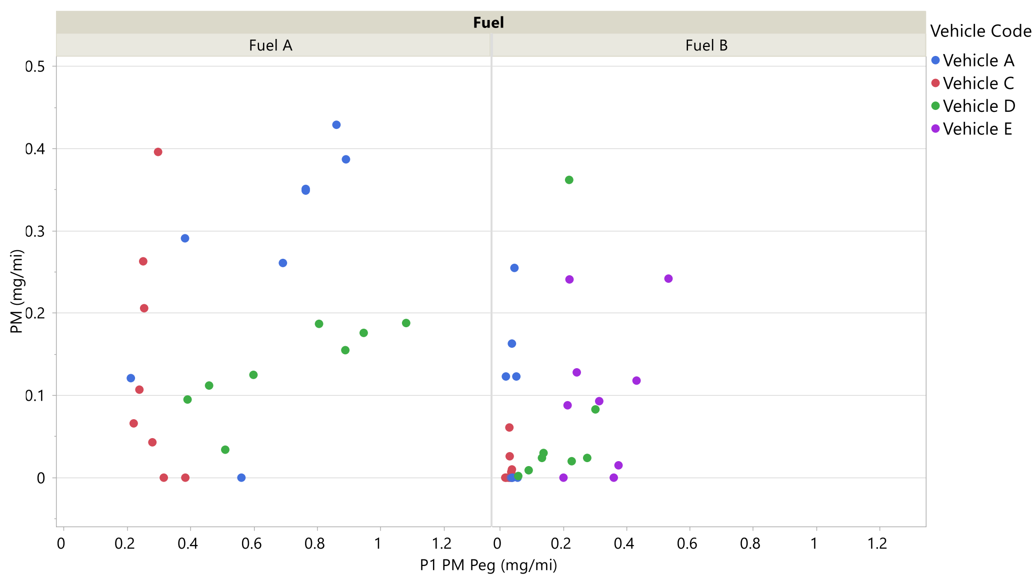

Figure L-2: PEMS Road Filter PM vs. Phase 1 Pegasor PM

The Pegasor PM data does show a good correlation to PEMS filter PM for higher PM levels, as indicated below in Figure L-3. The plot appears to indicate that the slope of the regression line differs by vehicle. Vehicle C data was almost entirely at low PM levels less than 0.5 mg/mi and showed the poorest correlation, while Vehicle E showed a strong correlation, with some PM results near 1.5 mg/mi. The correlation also appeared to be worse on road tests as compared to chassis dyno tests.

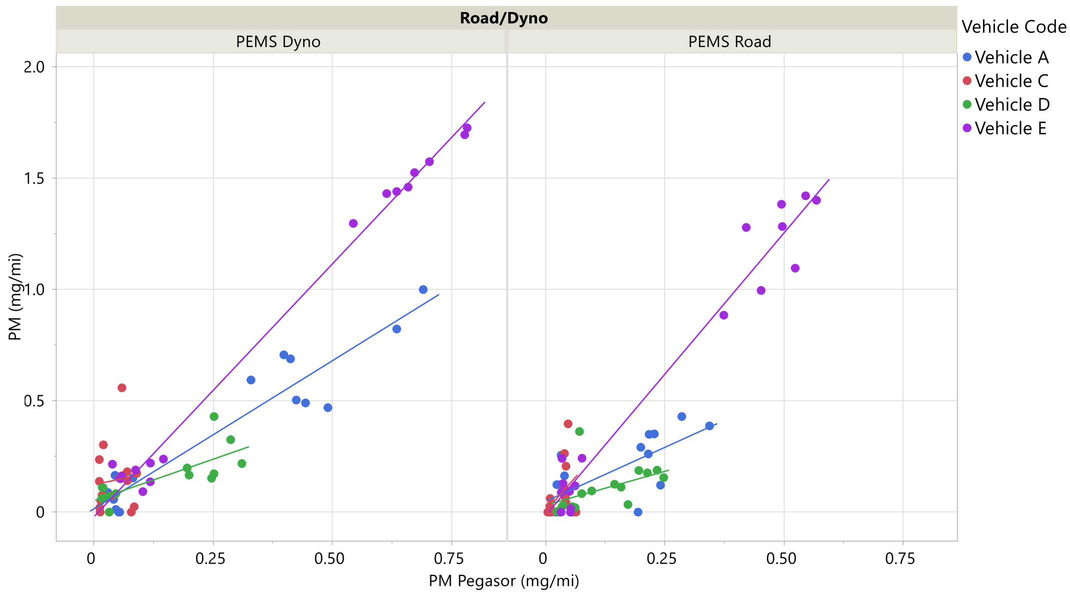

Figure L-3: PEMS Filter PM vs. Pegasor PM

Vehicle C had several data points which indicated discrepancies between the PM measured by the PEMS on the dyno and the PM measured by the CVS. This can be seen by D-A-1, D-A-2, D-B-5, and D-A-5 below in Figure L-4. D-B-7 below was only identified due to its higher PM level on that fuel, but was measured as having this higher PM via both measurement methods. All of the points except for D-A-5 are highlighted in Figure L-5, with PEMS PM on the y-axis, and Phase 1 PM from the Pegasor on the x-axis. The dyno tests on the left-hand side of the plot appear to stick out as having more disagreement than normal compared with other chassis-dyno tests but are not outside the norm for the relationship when also considering road tests, as seen on the right-hand side.

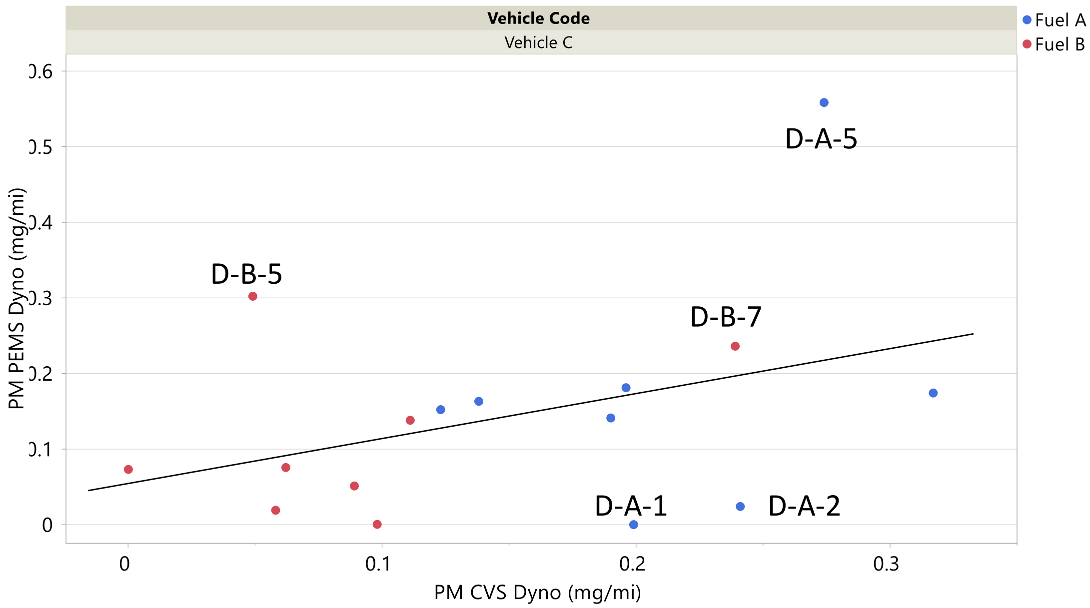

Figure L-4: Vehicle C PEMS Dyno PM vs. CVS Dyno PM

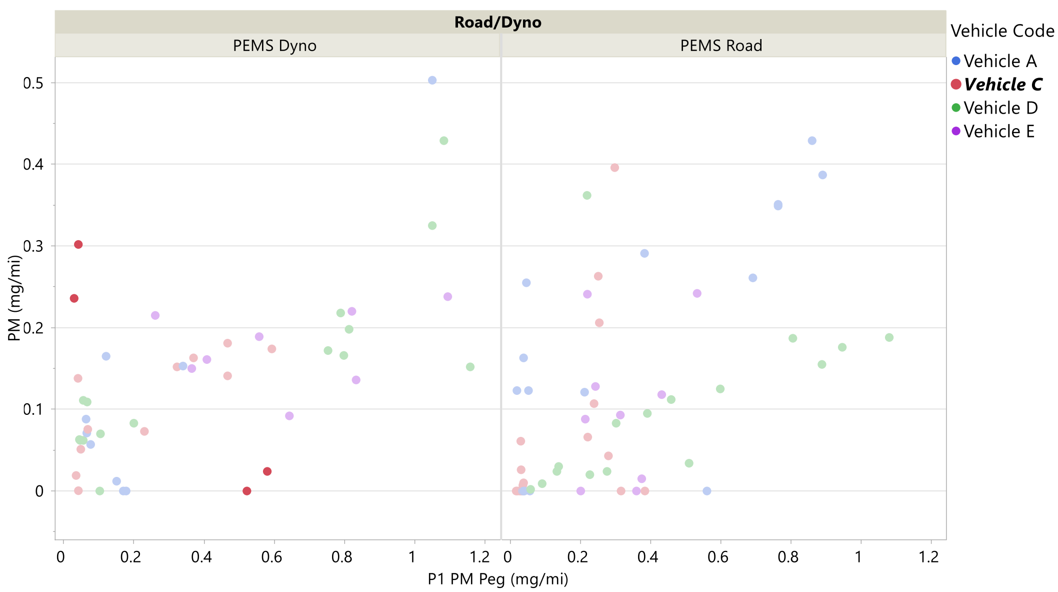

Figure L-5: PEMS PM Filter vs. Phase 1 Pegasor PM

Figure L-6 further demonstrates that higher results on the Pegasor or the MSS do not necessarily indicate higher PM filter results, as evidenced by D-B-3 below. The figure also indicates that a near-zero or zero reading on the Pegasor or the MSS does not necessarily mean zero PM, as evidenced by D-B-7.

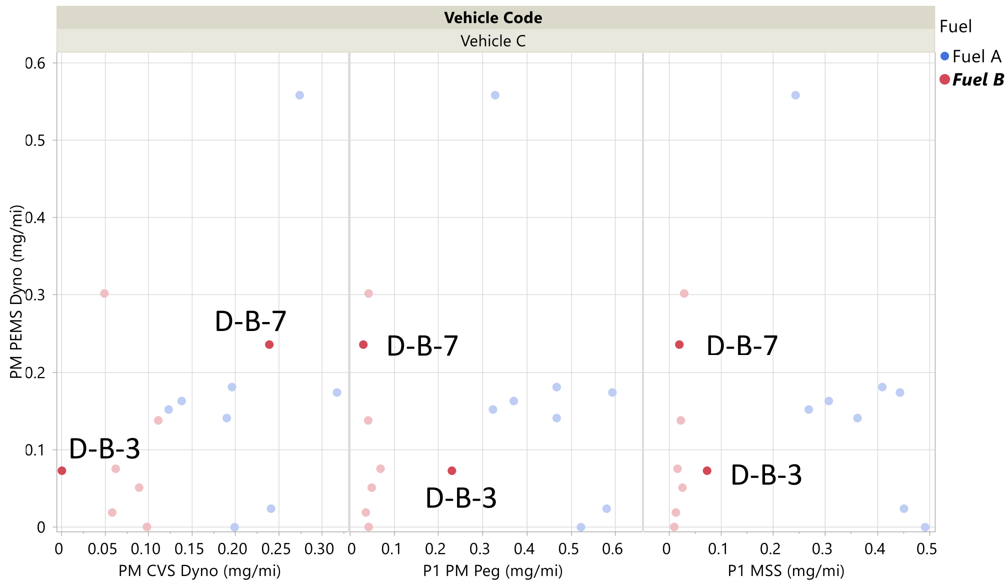

Figure L-6: Vehicle C PEMS Dyno PM vs. CVS Dyno PM, Phase 1 Pegasor PM, and Phase 1 MSS Soot

For CO and THC, there were some differences in variability observed on Vehicle C between the first set of four tests of Fuel B on the dyno and the second set of four tests of Fuel B on the dyno, as shown below in Figure L-7. After review, some problems were identified with the first set of tests, and these tests were eventually deemed invalid and not included in the statistical analysis. More information on these tests can be found in Section 3.1.1, Section 3.6.4.2, and APPENDIX A: Emissions Impact of Engine Stop Start Feature of Vehicle C.

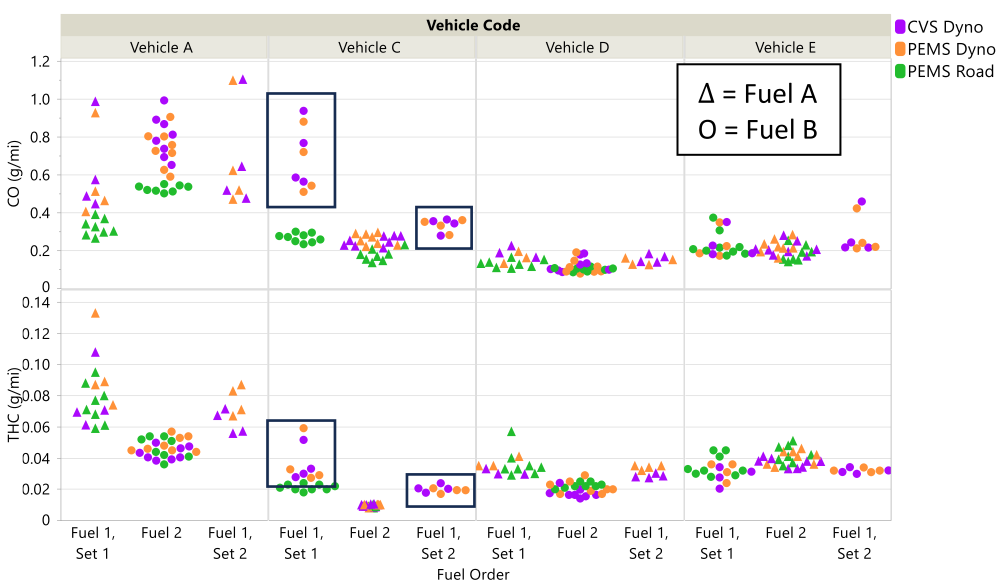

Figure L-7: CO and THC by Vehicle and Test Set

It was also noted that both Vehicle A and Vehicle C exhibited much less variability in CO for road testing as compared with chassis dyno testing, as seen in Figure L-8. Note that the Vehicle C four highest CO data points on the dyno are the same four tests determined to be appropriate for removal as discussed in the previous plot. For Vehicle A data, review of the highest two data points on Fuel A (D-A-4 and D-A-5) indicated sensitivity to differences in vehicle operation by the driver which is discussed more in Section 4.1.2.2.

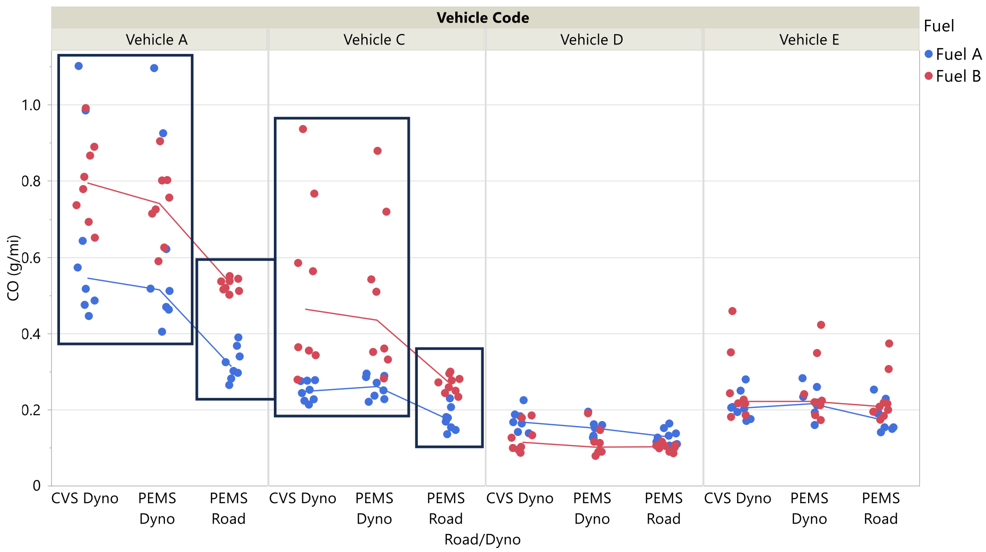

Figure L-8: CO by Vehicle and Measurement Method

Next, Vehicle D had some PM outliers. The first is test D-B-1 which resulted in higher-than-expected PM as measured by the CVS when compared to other results on the same fuel and considering the result as measured by the PEMS. The other outlier result was road test R-B-2. These points are shown below in Figure L-9.

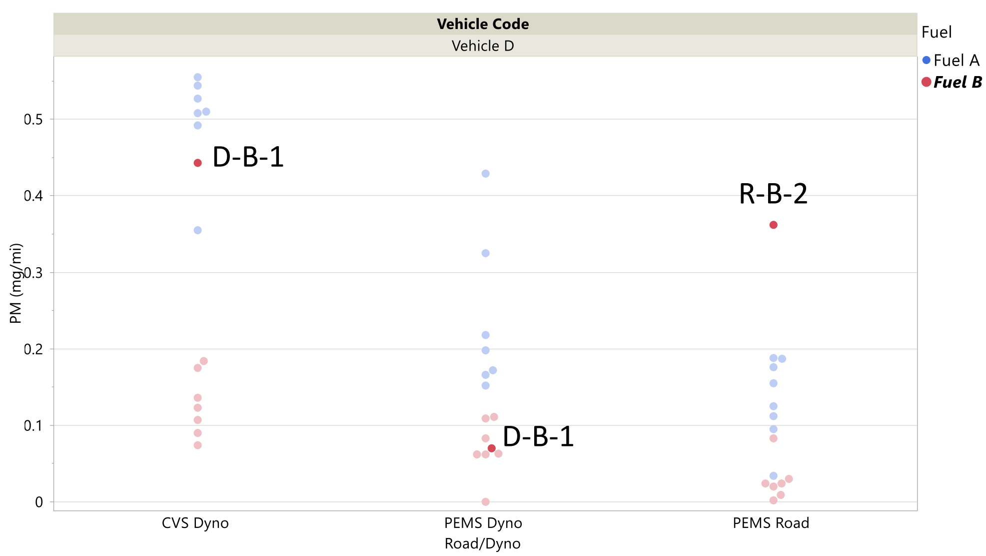

Figure L-9: Vehicle D PM by Measurement Method

Based on Figure L-10 below, using Phase 1 MSS as a comparison, it appears that the result would have in fact been expected to be lower PM near 0.2 mg/mi. However, as pointed out previously, there are multiple other instances where the correlations of the PM filter to the Pegasor or the MSS results are unreliable at low PM levels.

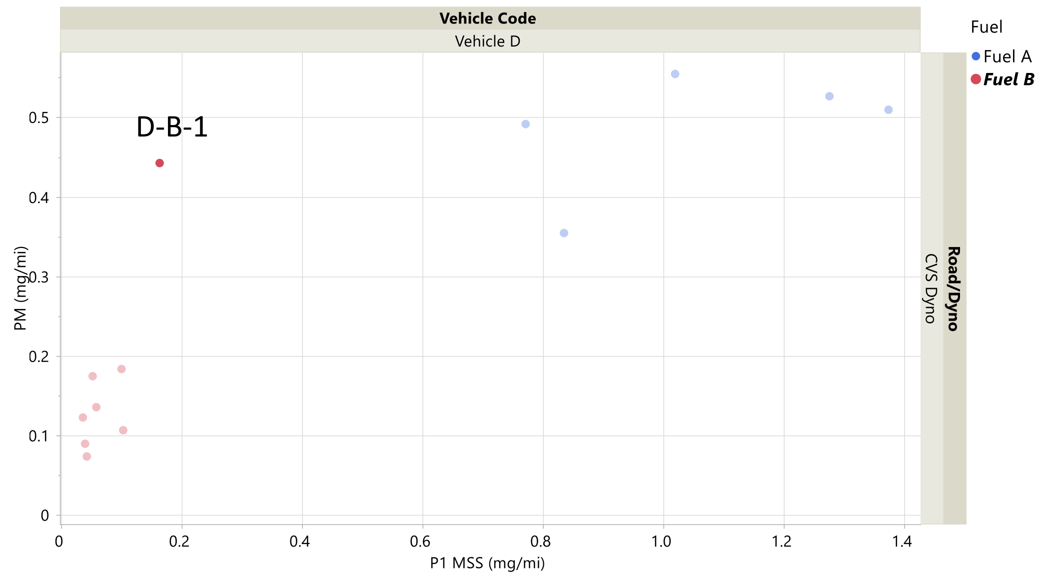

Figure L-10: Vehicle D CVS Dyno PM vs. Phase 1 MSS Soot

Vehicle D Test R-B-2 on the road appeared to be a bit more suspect, however, given the strength of the correlation between the PEMS PM filter results and the Phase 1 Pegasor results for this vehicle. This can be seen below in Figure L-11, where the correlation appears to indicate an expected PM filter result less than 0.1 mg/mi.

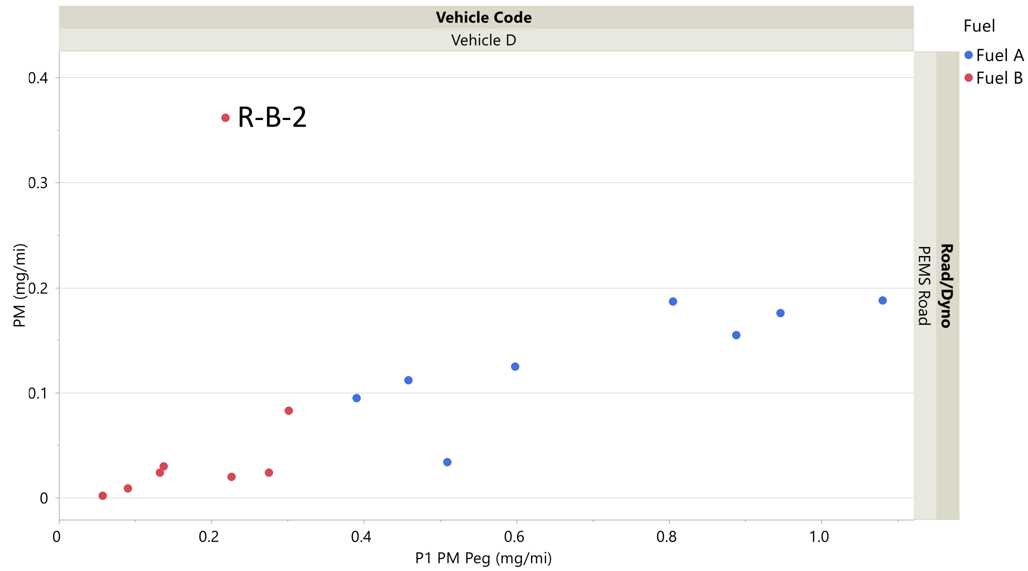

Figure L-11: Vehicle D PEMS Road PM vs. Phase 1 Pegasor PM

Vehicle D also had a pair of unusual fuel economy and CO_2 results, as shown by the green points in Figure L-12 below. The point in the upper-right of the figure (D-B-4) was found to have had unusually low engine-on time in Phase 2 of about 18%, whereas the other tests were all between 25%-38% engine-on time. This phase of the cycle has the highest speeds, loads, and accelerations, and the fuel economy of this phase shows the best correlation to final fuel economy among the three phases. No explanation was found to explain the discrepancy on Test D-B-8, where the CVS fuel economy result was just over 100 mpg and the PEMS fuel economy result was about 90 mpg.

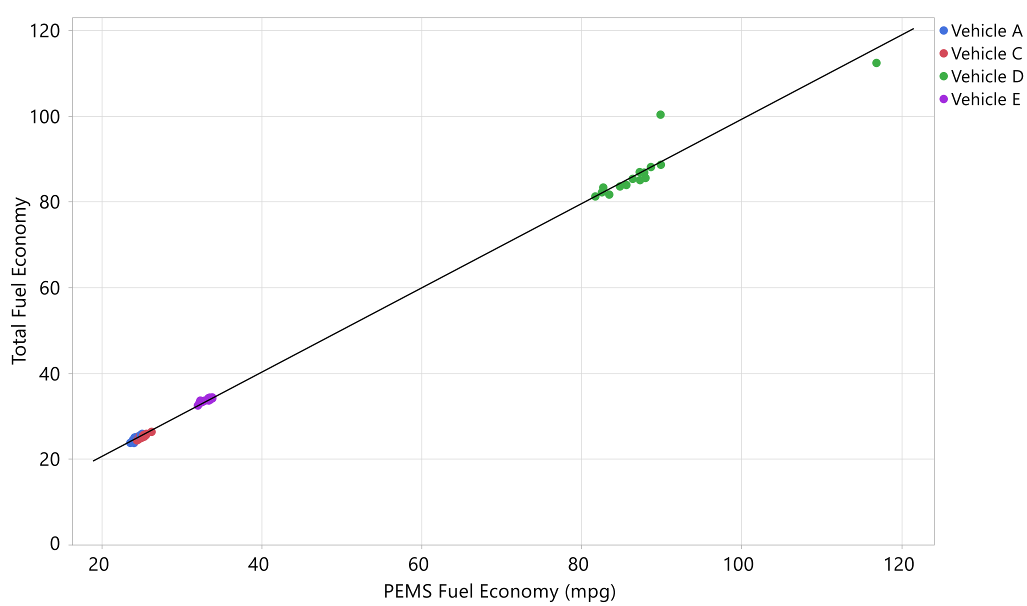

Figure L-12: CVS Dyno Fuel Economy vs. PEMS Dyno Fuel Economy