CRC Report No. E-122

LIGHT DUTY PEMS VALIDATIONS/ CHASSIS DYNAMOMETER CORRELATION

June 2018

COORDINATING RESEARCH COUNCIL, INC.

5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

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Eastern Research Group, Inc.

Light Duty PEMS Validation / Chassis Dynamometer Correlation

Final Report

Project E-122

Prepared for:

Coordinating Research Council

Prepared by:

Eastern Research Group, Inc.

June 6, 2018

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Project E-122

Light Duty PEMS Validation / Chassis Dynamometer Correlation

Final Report

Prepared for:

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

Prepared by:

Alan Stanard
Eastern Research Group, Inc.
3508 Far West Blvd., Suite 210
Austin, TX 78731

LEGAL NOTICE

June 6, 2018

FOREWORD

This report covers development and testing conducted by Eastern Research Group, Inc. (ERG) for the Coordinating Research Council (CRC). Testing was performed in cooperation with Southwest Research Institute (SwRI), which provided the emissions test lab and chassis dynamometer for testing. The project, performed under CRC contract E-122, was performed between October of 2016 and April of 2018. Test route development was performed during the winter of 2016-2017. Emissions testing was performed between June 29, 2017 and September 28, 2017. The project was based on ERG's technical proposal to CRC dated July 19, 2016. The internal ERG project code was 4043.00.001.001. The CRC project oversight was led by Dr. Christopher Tennant and Amber Leland. The ERG project manager was Alan Stanard, assisted in testing and development by Michael Sabisch, Sandeep Kishan, and Chris Krejci of ERG as well as Andrew Burnette of InfoWedge. The SwRI tasks of the project were managed by Peter Lobato, Matt Blanks, and Kevin Whitney, and laboratory emissions tests were overseen by Jeff Mathis.

Table of Contents

Appendices

Appendix A. Test Fuel Properties
Appendix B. Test Route Turn-by-Turn Directions
Appendix C. Span and Audit Gas Specifications
Appendix D. Test Checklists for Lab/Road and Track for each PEMS
Appendix E. Individual Fuel Economy and Emission Mass Results
Appendix F. Continuous Mass Emission Traces from On-Road and Cold-Start Track Tests
Appendix G. Unballasted Test Results
Appendix H. Filter Blank Log

List of Figures

List of Tables

List of Acronyms and Abbreviations

CFR ....Code of Federal Regulations
CO ....Carbon Monoxide
CO_2..................................Carbon Dioxide
CRC..................................Coordinating Research Council
CVS ....Constant Volume Sampler
DCS ....Diffusion Charger System (Horiba continuous PM measurement)
DTC..................................Diagnostic Trouble Code
FID ....Flame Ionization Detector
HC ....Hydrocarbon, or Total Hydrocarbon
MAP ....Manifold Absolute Pressure
MSS..................................Microsoot Sensor (continuous PM measurement type)
NDIR................................Nondispersive Infrared
NMOG ....Nonmethane Organic Gas
NO....................................Nitric Oxide
NO_2 ....Nitrogen Dioxide
NOx..................................Oxides of Nitrogen (NO + NO_2)
NTE..................................Not-to-Exceed (type of emissions standard)
OBD ....On-Board Diagnostic
PEMS ....Portable Emission Measurement System
PID ....Process ID (OBD parameter)
PM....................................Particulate Matter
PM_{10} ....Particulate Matter less than or equal to 10 micron in diameter
PSN ....Particle Synchronization Number (3DATX PM Measurement)
QA....................................Quality Assurance
SAO..................................Smooth Approach Orifice
SCFM...............................Standard Cubic Feet per Minute
SLPM ....Standard Liters per Minute
SwRI ....Southwest Research Institute

Executive Summary

This report documents a project conducted by ERG on behalf of the Coordinating Research Council (CRC), with the assistance of Southwest Research Institute (SwRI). The project was performed to conduct an evaluation of the state of light-duty Portable Emission Measurement System (PEMS) testing by evaluating the measurements made by three different commercially-available PEMS of the emissions of a single test vehicle operating on a chassis dynamometer, on a given on-road route, and on a closed test track.

Interest in the development and use of PEMS to evaluate the pollutant emissions from light duty vehicles has increased in recent years. PEMS allows for the types of exhaust pollutant emission measurements that are typically made in a laboratory, such as the measurements used for new-vehicle certification, to be made on a vehicle during actual on-road use. These measurements can include measurement or estimation of exhaust flow rate, and the measurement of mass emissions of hydrocarbons (HC), oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter mass (PM), among others. European legislation has mandated the use of PEMS for new light-duty vehicle certification, requiring measurements of NOx and particulate number. In the US, PEMS is not a part of light duty certification; however PEMS devices from multiple manufacturers are in use by various entities in support of research or vehicle screening.

The conduct of the project included the following steps:

1. **Test cycle development**, in which an on-road driving route was developed and a dynamometer speed trace was developed to be representative of the route
2. **PEMS training and installation**, in which representatives from each participating PEMS manufacturer instructed ERG staff on proper equipment setup and use
3. **Chassis dynamometer testing**, in which the test vehicle was operated over the speed trace with concurrent measurements collected by the lab and one PEMS unit at a time
4. **On-road drives**, in which the selected on-road route was driven with the test vehicle operated normally with a single PEMS installed and measuring emissions
5. **On-track drives**, in which the same speed trace that was used on the dynamometer was followed on a track with a single PEMS installed and measuring at a time; on-track tests over the same speed trace were conducted both on smooth and rough/potholed surfaces.
6. **Data reduction and analysis**, in which logged data from each PEMS was post-processed and, for chassis dynamometer tests, compared to the lab results

Five repeat dynamometer tests were conducted with each PEMS, five on-road tests were conducted with each PEMS, and six on-track test pairs were conducted with each PEMS. The single test vehicle used for this work was a 2013 Hyundai Santa Fe Sport 2.0T, fueled with a commercially-available E-10 pump gasoline. Dynamometer testing was conducted on an SwRI 48” single-roll chassis dynamometer. Emissions were sampled by the laboratory both in batch over the whole cycle, and instantaneously. Batch measurements were made from a dilution tunnel by bag for gaseous pollutants and on gravimetric filters for PM. Continuous measurements were made on undiluted samples for gaseous pollutants as well as PM via a microsoot sensor (MSS). On-road tests were conducted on a public road route near SwRI in San Antonio, TX, and track tests were conducted at Continental Proving Grounds in Uvalde, TX.

The test route for this project was developed to have an approximately 42 minute duration and has an approximate length of 26.7 miles. GPS logged altitude from the repeated drives was averaged to develop a road grade profile for use by the dynamometer for all lab tests.

Three PEMS were evaluated in this project, the Horiba OBS-ONE, the GlobalMRV Axion, and the 3DATX parSYNC. The PEMS devices evaluated in this work covered a range of measurement capability, size, and complexity. The three systems generally used different measurement principles for the different gaseous and PM measurements, and not all systems measured all exhaust constituents. The intention of ERG staff was to use the equipment just as recommended by the manufacturer whenever possible. ERG created test checklists for the use of each PEMS, and these were iteratively improved with the assistance of each manufacturer’s staff during the first few weeks of testing (the test checklists used in this work are included in Appendix D). The different PEMS units and their accompanying batteries weighed significantly different amounts, so the test vehicle was ballasted to weigh nominally the same amount during all tests.

Results in this report are blinded to the different PEMS units. Because the systems did not all measure the same exhaust constituents, the presentation of each result has a different set of blinded labels so that the identifiers are not obvious due to a given unit being omitted from the result for a given exhaust constituent (i.e. the label letters for each of the three PEMS increment in every successive plot). The average mass emission results for overall measured NO/NOx mass are presented in Figure ES-1. Error bars are included that represent the 95% confidence interval based on the variability of the measurements within each group of repeat measurements. The figure depicts that, for the laboratory tests, two of the PEMS systems measured significantly different average masses than the laboratory system. It can be seen that, for two of the PEMS, variability in the track results was much higher than for the dynamometer tests.

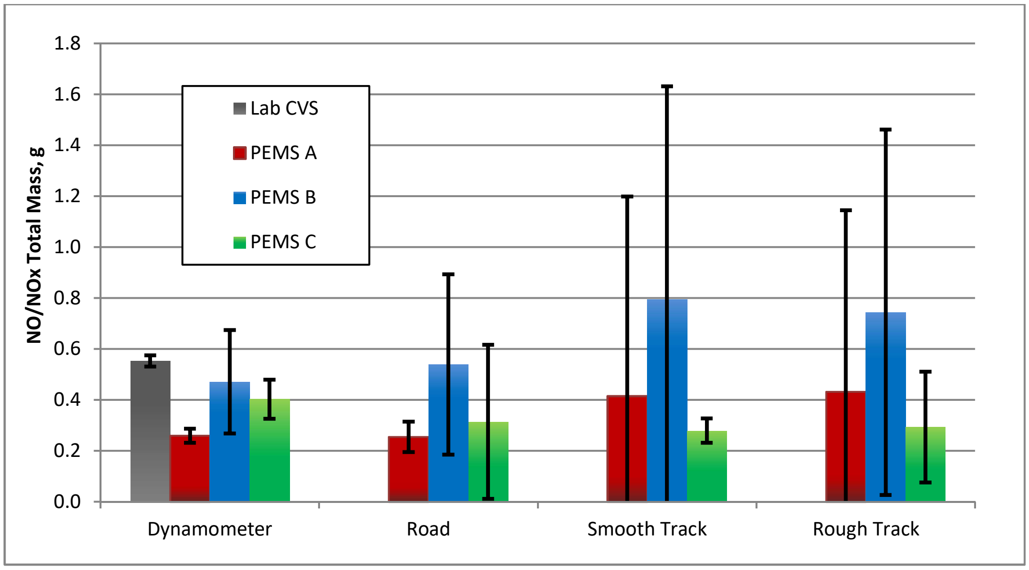

Figure ES-1. Average NO/NOx mass emissions for all measurement and test types.

CO mass results are presented in Figure ES-2. Averages for the lab and the two PEMS are presented for the different test types conducted during the study. For the dynamometer tests, both PEMS in this group agreed statistically with the lab CVS measurements. One of the PEMS units agreed fairly well between dynamometer measurements and road/track measurements, and the other tended to measure higher values over the road and track tests than the dynamometer. Average mass emissions for HC are presented in Figure ES-3. One of the PEMS is significantly different in results than the lab measurement and the other is not conclusively different. The variability in measurements of both PEMS tended to be noticeably higher for both the road and track measurements.

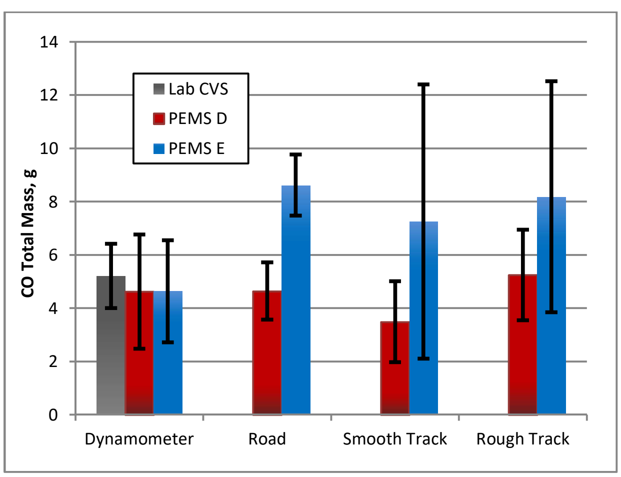

Figure ES-2. Average CO mass emissions for all measurement and test types.

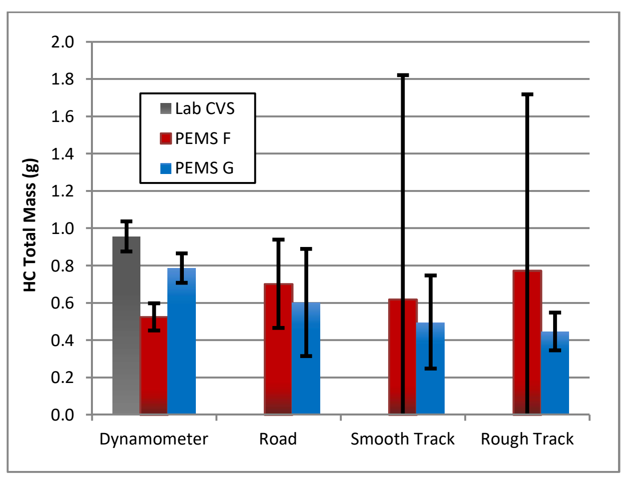

Figure ES-3. Average HC mass emissions for all measurement and test types.

1.0 Introduction

Interest in the development and use of Portable Emissions Measurement Systems (PEMS) to evaluate the pollutant emissions from light duty vehicles has increased in recent years. PEMS allows for the types of exhaust pollutant emission measurements that are typically made in a laboratory, such as the measurements used for new-vehicle certification, to be made on a vehicle while it is in actual on-road use. These measurements can include measurement or estimation of exhaust flow rate, and the measurement of mass emissions of hydrocarbons (HC), oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter mass (PM), among others. The measurement of NOx is taken as the sum of the nitric oxide (NO), and the nitrogen dioxide (NO_2) present in the exhaust.

European legislation has mandated the use of PEMS for new light-duty vehicle certification, requiring measurements of NOx and particulate number. In the US, PEMS is not a part of light duty certification; however PEMS devices are in use by various entities in support of research or vehicle screening. Multiple companies now actively produce and market a variety of PEMS devices with measurement capabilities ranging from those found in a complete emissions testing lab down to simple gas concentration analyzers.

This project was conducted in order to compare the measurement and operational performance of three PEMS devices with different capability levels to that of a complete emissions test lab. Three different commercially-available PEMS units were evaluated by comparing their performance to lab measurements of a vehicle operating on a chassis dynamometer. Additionally, the test vehicle was used as a basis for evaluation of all three PEMS systems as the vehicle was operated over a given on-road route as well as a fixed speed trace on a closed test track. The project was managed and conducted by ERG, with the assistance of Southwest Research Institute (SwRI), which provided equipment and staff support for the chassis dynamometer tests.

The conduct of the project included the following steps:

1. Test cycle development, in which an on-road driving route was developed, data from multiple drives were logged, and a single speed trace was selected as representative of the route
2. PEMS training and installation, in which one or more representatives from the manufacturer of each evaluated PEMS device instructed ERG staff on proper use of the

device and ensured that the installation layout, equipment setup, calibration, operation and data processing performed by ERG personnel was appropriate

3. Chassis dynamometer testing, in which the test vehicle was operated over the developed test speed trace with concurrent measurements collected by the lab and the PEMS units, with a single PEMS installed and operational for each test
4. On-road drives, in which the selected on-road route was driven with the test vehicle operated normally and within the normal traffic flow with a single PEMS installed and operational for each test
5. On-track drives, in which the same speed trace that was used on the chassis dynamometer was followed on a closed track; on track testing included cold-start and hot-running tests over both smooth and potholed surfaces in which the same speed trace was followed
6. Data reduction and analysis, in which logged data from each PEMS was post-processed as appropriate and, for chassis dynamometer tests, compared to the lab results

Testing took place from June through September of 2017. Dynamometer and on-road tests took place at and around SwRI in San Antonio, TX, and track testing took place at Continental Proving Grounds in Uvalde, TX. Five dynamometer tests were conducted with each PEMS, five on-road tests were conducted with each PEMS, and six on-track test pairs were conducted with each PEMS.

2.0 Project Setup

The light-duty emissions lab at SwRI served as the base of operations for this project. ERG assembled support equipment, installation tools, batteries and chargers, and other necessary hardware at SwRI. The test vehicle and test fuel were stored at SwRI throughout the project, with the exception of the approximate 1-month time period in which testing was conducted at the test track.

2.1 Test Vehicle

The test vehicle used for this work was a 2013 Hyundai Santa Fe Sport 2.0T. This vehicle is equipped with a 2.0 liter turbocharged, direct-injected, 4-cylinder gasoline engine, and is certified to Tier 2 Bin 5 emissions standards. At the start of the study, the vehicle had approximately 23,800 miles on the odometer. At that time, the battery was replaced and the engine oil was changed, and more than 300 miles of run-in on the new oil was performed prior to the start of emissions testing.

The test vehicle was modified in order to facilitate the test program. A trailer hitch receiver was installed to facilitate mounting exhaust tubing, PEMS flowmeters, and sample lines at the rear of the vehicle. A cargo carrier was installed into the hitch receiver and modified for this use. The cargo carrier was installed and present for tests of all three evaluated PEMS units, and served to both support the PEMS equipment as well as to protect it in the event of a low-speed rear end collision. A 90° elbow and extension were fitted to the vehicle's tailpipe, and all three PEMS systems sampled at the downstream end of this extension. A photograph of the test vehicle, with the cargo carrier and exhaust pipe extension installed, is shown in Figure 2-1.

Figure 2-1. The test vehicle with attached exhaust extension and support carrier.

A quick-disconnect line was added to the fuel rail at the engine to facilitate fuel draining. A tee-junction was added to an underhood evaporative system tube, with a quick-disconnect installed in order to facilitate canister loading as in CFR certification tests. Figure 2-2 is a picture of the engine in the test vehicle, including the modifications to the fuel rail and evaporative system. No On-Board Diagnostic (OBD) codes were caused by these modifications, nor was the check-engine light illuminated for a diagnostic trouble code (DTC) at any time in the program. No further maintenance, modifications, or repairs were performed during the duration of testing.

Figure 2-2. The engine compartment of the test vehicle including the installed fuel drain adapter (silver quick-disconnect at left) and canister loading tube (black tube and quick-disconnect at right).

2.2 Test Fuel

A single test fuel was used throughout this test program. This fuel was a commercially-available E10 pump fuel, collected from a commercial refueling station in the San Antonio, TX area. The fuel was pumped from a single batch into 13 drums (nominally 715 gallons) during the week of June 5, 2017, corresponding to a time period in which summer fuel is required to be dispensed in the San Antonio area. The SwRI fuel code for this fuel was GA-9739. SwRI performed various analyses of a sample of this fuel, including carbon to hydrogen ratio, density, and net heating value. Results of all SwRI analyses as well as the specific tests performed are included in Appendix A. Additionally, fuel samples were provided to two CRC members for independent analysis. All emission calculations requiring fuel specifications in this work used the results of the SwRI analysis only.

The test fuel was stored at refrigerated temperatures until being dispensed into the test vehicle during fueling. Approximately two weeks before the start of the emissions testing phase of the program, the vehicle underwent a triplicate fuel drain (through the fuel rail) and fill to convert to the test fuel, and was then refilled with the test fuel only from that time until the end of the test program. The test fuel was refrigerated during storage at all times, with the exception of fuel dedicated to use on the test track. The track fuel was dispensed into non-vented containers in batches large enough to support testing increments of approximately one week. These batches were not refrigerated at the test track as there were no facilities to do so.

2.3 Test Laboratory

Testing was conducted at a single chassis dynamometer site at SwRI. Central to this site is a Horiba 48-inch single-roll chassis dynamometer. The dynamometer electrically simulates vehicle road loads and inertia over varying vehicle speeds, and can also include simulation of programmed road grade. This dynamometer was programmed with the test cycle’s speed trace, grade trace, vehicle road load coefficients, and vehicle inertia for this work. A photograph of the test vehicle installed on the chassis dynamometer is shown in Figure 2-3.

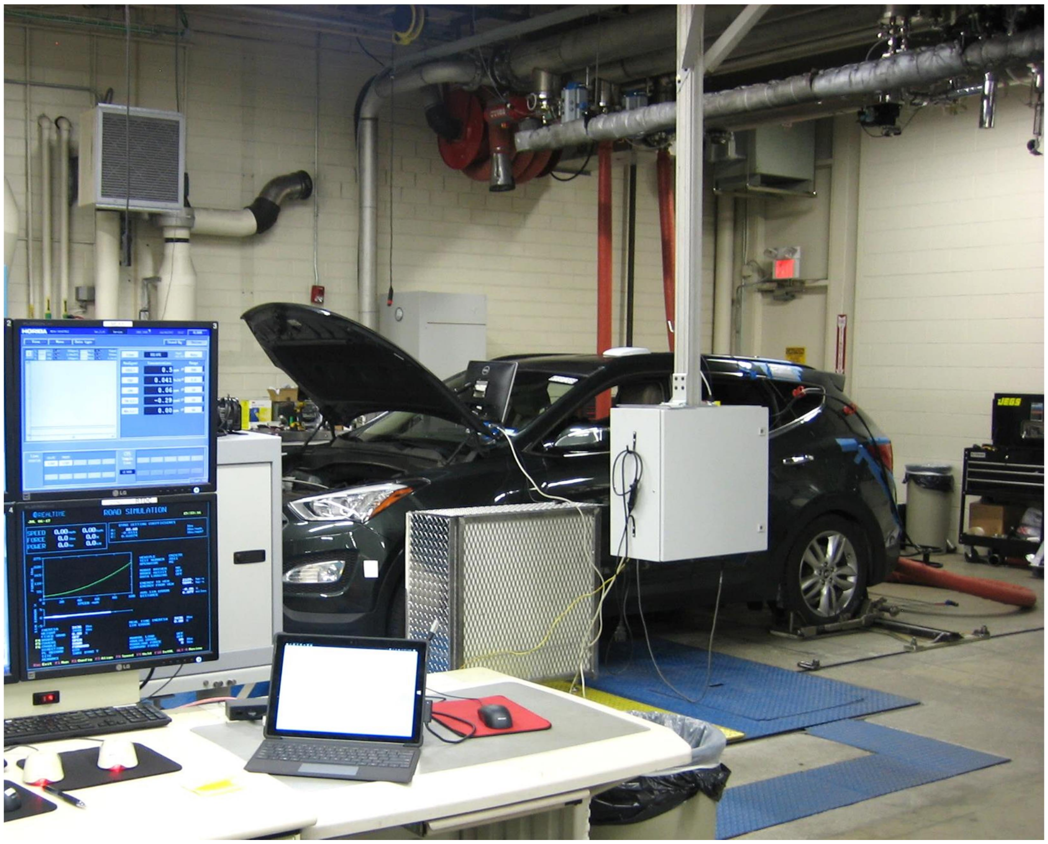

Figure 2-3. The test vehicle installed at the chassis dynamometer test site.

The exhaust measurement equipment consisted of a Horiba CVS-7000 and Horiba MEXA 7400 to collect and measure vehicle tailpipe exhaust emissions. Measurement of HC, CO, NOx, and CO_2 was performed in a manner consistent with light-duty vehicle testing protocols given in 40 CFR Part 1066. The vehicle exhaust was connected to a transfer pipe that led to the lab's constant volume sampler (CVS) tunnel. In the CVS, the exhaust flow mixes with dilution air in the tunnel, and the mixture is then sampled by PM and gaseous sample probes. The dilute gaseous sample as well as the background sample were collected in Kynar bags to give an overall single measurement for each test cycle. Total PM mass was measured from the diluted sample in the CVS tunnel by collecting PM mass on gravimetric filters. All filters in this work, both for the CVS tunnel and the PEMS, used 47 mm TEFLO filters. The CVS tunnel configuration is shown in Figure 2-4; note that this site contains three different dilution tunnels for various types of testing and this program used only the tunnel dedicated to gasoline vehicle testing. The figure depicts the three different vertical transfer pipe extensions, one for each tunnel. To the left of the transfer pipe extensions is a vent blower, in this case used to evacuate the exhaust sample outlet from the PEMS system being tested.

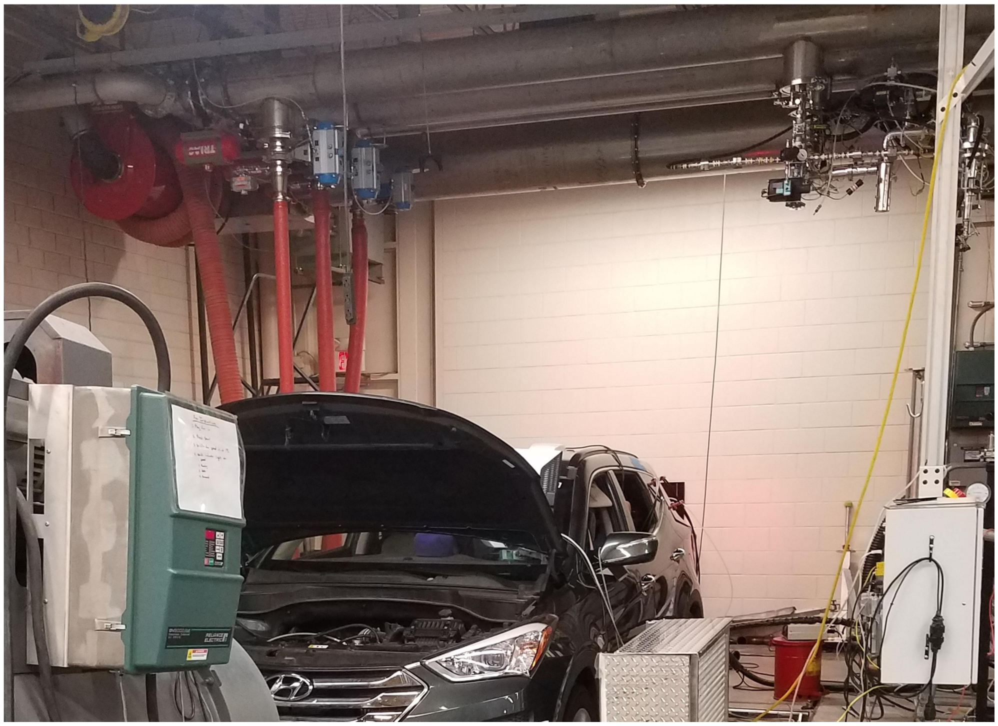

Figure 2-4. The CVS tunnels at the chassis dynamometer test site- the transfer pipes from the vehicle exhaust enter the tunnels at the upper left, and the samples are taken at the upper right.

In addition to Part 1066-type testing, additional raw (undiluted) continuous measurements, known as modal measurements, were sampled just downstream of the vehicle's tailpipe exit in the CVS transfer pipe and collected on a second by second basis yielding a continuous trace of emission mass throughout each test. These measurements also consisted of HC, CO, NOx, and CO_2. Additionally, an AVL micro-soot sensor (MSS) was used to collect raw continuous measurements of the carbon fraction of PM mass in the vehicle exhaust. The MSS employs a photoacoustic sensor which determines the carbon fraction mass. As such, the MSS is expected to measure a lower mass than the total PM, which would include the organic constituents present in PM. The MSS sample was drawn undiluted from the CVS transfer pipe at a location near the modal gaseous sample probe. Exhaust flow rate was estimated continuously based on subtraction of the dilution tunnel inlet flow as measured by a smooth approach orifice (SAO) from the dilution tunnel total flow measured at the tunnel outlet by a sonic venturi. This estimate is not a CFR-specified measurement technique, however it was necessary in order to allow for laboratory calculation of continuous mass emissions for comparison with the continuous mass emission traces measured by each PEMS.

2.4 Test Track

Track testing was conducted at Continental Tire Proving Grounds in Uvalde, TX. The facility consists of a number of paved and dirt roadways and tracks. Two of the facility's tracks were used in this work: the main track, which is an approximately 9-mile oval that runs around the perimeter of the facility, and the ride road, which is a 3-mile oval within the center of the grounds that contains lanes with various pavement characteristics, one of which is a section of bumps and increasing severity potholes. Continental assigned ERG a work bay, which was closed but not environmentally controlled, to house the test vehicle and install, remove, and maintain the PEMS devices. A picture of the test vehicle in the continental bay is presented in Figure 2-5. The test bay was adjacent to the ride road track. A climate controlled office, dedicated to ERG during testing, adjoined to the work bay. The PM filters were stored, closed in cassettes, in this office during testing and prior to return to SwRI for weighing.

Figure 2-5. The test vehicle during a soak at the Continental work bay.

The main track at Continental is comprised of a relatively smooth track with minimal potholes or other roughness. It does, however, have undulations with rises and falls in elevation. The ride road is nearly flat in elevation. Both of the turns of the oval shape, as well as one straightaway, consist of a very flat and smooth paved surface. The lane that ERG used in the other straightaway consists of bumps and potholes designed to evaluate the ride and harshness characteristics of different tires. ERG used this lane to evaluate whether there was an effect of bumps or potholes on the performance of the PEMS units. The ride straightaway consists first of relatively rough pavement, followed by potholes that have been overfilled and so are upward bumps in the surface of increasing severity. Then, the final third of the straightaway consists of unfilled potholes of increasing size and severity. A photograph of the potholed surface is presented in Figure 2-6. The rightmost lane of the straightaway contains the potholes, and they are oriented in rows to alternate the left and right wheels of a vehicle hitting them.

Figure 2-6. The potholed surface of the ride road at Continental Proving Grounds.

3.0 Test Cycle Development

One of the aims of this work was to better understand the effect on test variability when moving from a prescribed trace on the chassis dynamometer to vehicle operation on public roads, even if the route type is nominally equivalent. To achieve this, an on-road test route was selected that would include a variety of driving modes and have approximately equal time spent in low, medium and high speed bins. This driving route would be used for all on-road tests, and a speed recording of the route would serve as the actual speed trace to be followed on the chassis dynamometer and at the test track. Various constraints and targets were used as the basis of the route development. The constraints and targets were as follows:

- Approximately equal time in the following three speed bins in order to capture a variety of driving conditions
  - Less than 35 mph, 35 to 55 mph, greater than 55 mph
- Nominal duration of 45 minutes
  - This is the approximate maximum duration of the CVS system's sample bag fill without modification
- Minimized effect of elevation in order to minimize potential errors in chassis dynamometer load simulation
  - Start and end the route at the same place in order to eliminate the effect of potential energy on the overall cycle energy balance
  - Avoid particularly steep roadways that might have a large effect on engine operation that would be prone to error when simulating on the chassis dynamometer

3.1 Test Route

ERG evaluated a number of routes in order to find a single one that best met the constraints and targets described above. ERG evaluated 6 different routes and drove 4 of them with an OBD and GPS datalogger continuously recording speed and location. ERG presented the resulting statistics from the 4 best routes to CRC. Both ERG and CRC agreed on a single route that best achieved the goals of this work. Figure 3-1 depicts a map of the test route, color coded by the approximate speed range during a drive of the route. Purple indicates speeds under 35 mph, blue indicates speeds between 35 and 55 mph, and red indicates speeds in excess of 55 mph. A list of turn-by turn directions used in following the route is included in Appendix B.

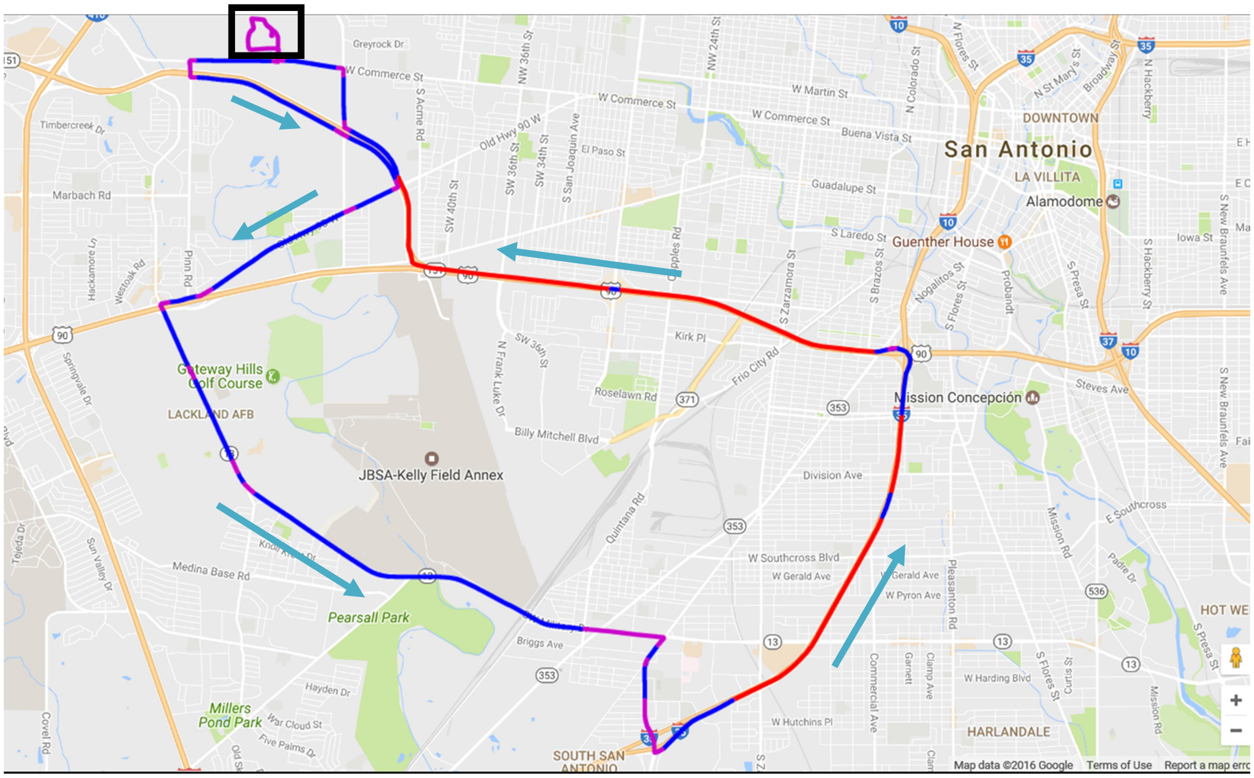

Figure 3-1. The E-122 test route. The black box in the upper left depicts SwRI, the point of the start and end of the route, and the route is color coded by speed.

After selecting this route from those created and reviewed, ERG staff then drove the route repeatedly with the datalogger capturing OBD and GPS signals, primarily to record the speed traces along the route as well as the duration of each drive. Data from the multiple drives was used to select a single speed trace to be followed during all dynamometer and on-track tests. Consideration was given to how best select a single route from the multiple drives of the chosen route. It was determined that the speed trace would be most representative if it came completely from a single drive of the route instead of being based on a mean or median of speed by time or a piecemeal approach. Instead, a number of parameters were calculated for the logged routes, and a single route was chosen based on that which best matched the average of each characteristic for all drives.

The calculated characteristics of each drive, based on the logged speed and time data, are presented in Table 3-1. The logged speed trace from test drive number 3 was taken to be the most like the average of all four repeated drives for all characteristics. Therefore, that logged speed trace was used as the speed trace to be followed during all dynamometer and on-track tests. The actual logged speed traces from the test drives are presented in Figure 3-2. The selected trace, from the third drive, is presented in bold red. While the data was logged on a time basis, the traces are presented on a distance basis to facilitate comparison (i.e., so that given stoplights and turns overlay on each).

Table 3-1. Characteristics of the repeated test logger drives of the E-122 Route

Test Drive #	1	2	3	4	Average
Distance (mi)	26.73	26.71	26.70	26.70	26.71
Time (s)	2417	2494	2418	2360	2422
Average Speed	38.6	37.4	38.6	39.5	38.52
# of Stops	8	9	10	7	8.50
% idle	6.87%	9.78%	8.31%	8.86%	8.5%

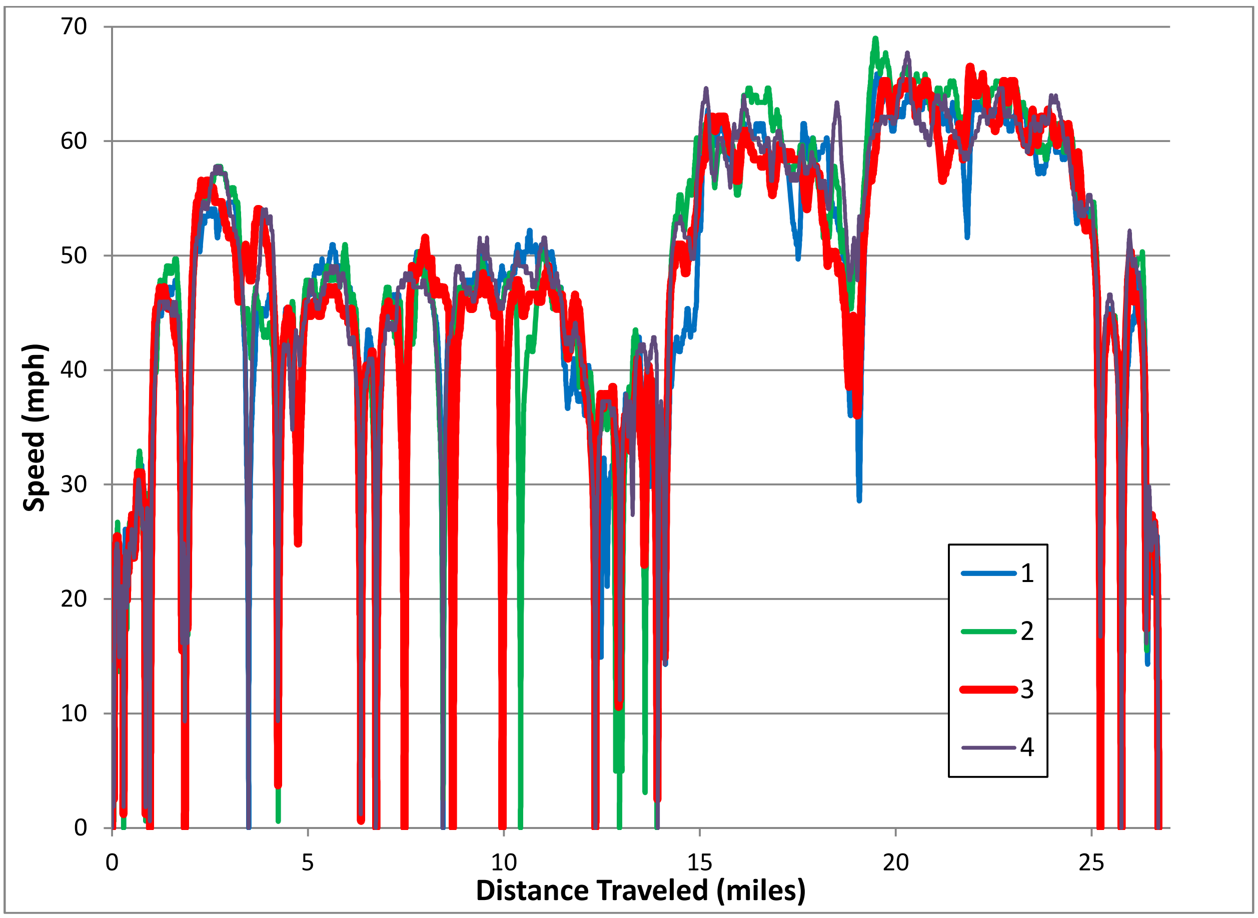

Figure 3-2. The logged speed traces for each test drive of the E-122 route, presented on a distance basis. Drive 3 was selected as most representative.

3.2 Additional Test Cycle Considerations

Vehicle speed sensor error. The datalogger used during the test drives recorded vehicle speed on a second-by-second basis from two sources, the internal GPS as well as the vehicle's OBD data bus. ERG compared the distances traveled over the route based on GPS and OBD and found them to disagree by approximately three percent. Evaluating the route using internet mapping software yielded a trip distance that agreed with the distance based on GPS, indicating that it was likely that the test vehicle's speed sensors were in error. This error may be due to variation in tire diameter. In order for the traces driven on the chassis dynamometer to agree in actual distance over the on-road route, the OBD speed trace was corrected to account for the speed sensor error. The correction was based on the average ratio of GPS-sourced speed to OBD-sourced speed. The OBD-sourced speed was increased by 3.1 percent in order to agree with the GPS data as well as the distance from the online mapping of the route.

Road grade over the route. In order to maximize the consistency of the route driven on the road to the cycle driven on the chassis dynamometer, the road grade over the cycle was estimated for simulation on the dynamometer. As a detailed road survey was outside of the scope of the project, ERG used a combination of topographical maps as well as the GPS altitude logs from the four test drives in order to estimate the road grade along the route. GPS fixes are generally most accurate in terms of latitude and longitude (i.e., horizontal location) as compared to altitude (i.e., vertical location). As a result, a single GPS altitude track is not generally accurate enough for the practical assignment of road grade in emissions testing. However, by calculating the altitude along the route from GPS logs of four different drives of the same trip, ERG was able to improve upon this level of accuracy and develop a single best elevation trace from which road grade could be calculated. The steps in estimating the route's elevation profile were as follows:

1. Calculate the GPS altitude trace from the four test drives on a distance basis (so that, in the absence of any GPS altitude error, all traces would lie exactly on top of each other even though the actual speeds and times were different).

2. Review each GPS altitude trace for apparent errors, such as sudden jumps or discontinuities. The traces were manually smoothed or corrected to minimize any obvious errors. Any sudden discontinuity in which the signal had a sudden excursion in altitude and then return back to or near the original value was edited and the excursion was removed, with linear interpolation in its place. In a few

instances, the signals would have a sudden jump to a new value. In these cases, 20 seconds of data were removed before and after the discontinuity, and a linear interpolation was substituted. This happened on four instances in the data from all four drives.

3. The median altitude, as a function of distance, was calculated from each of the four drives for horizontal segments traveled along the route. The horizontal segments each consisted of travel of one thousandth of a mile- approximately 5 feet. The vertical distance traveled for each successive segment was then calculated from the median altitude.

4. The trace of the vertical distance traveled for each segment was smoothed by averaging the five points centered around each point to be evaluated (i.e., a 5-second smoothing). This was done to minimize the effect of any short-term oscillations in the GPS signal.

5. The smooth trace was then plotted on a distance basis. ERG then reviewed an available topographical map of San Antonio including roadways. Notable or otherwise easily identified locations along the route were picked off the map along with their elevation. The distance from the start of the route to each of the notable points was calculated, and then these points were plotted against the smoothed elevation trace as a cross check for the accuracy of the method. Twelve points were selected to verify the accuracy of the method. This plot is shown in Figure 3-3. No alterations to the altitude trace were made from the topographical charts; it was only used for verification.

6. Finally, the actual grade, in percent, was calculated for each vertical distance increment on the route, based on dividing by the vehicle speed at that point. This yielded a trace of grade percent vs. time (which was again smoothed using a three second average) that could be entered with the speed trace in the dynamometer software to be simulated during lab tests. As a result of dividing by vehicle speed, this calculation tended to have a relatively high amount of error at low speeds, especially at times when the vehicle was approaching or accelerating from a stop. To account for this error, ERG capped all grades at eight percent during these times (based on measurements of maximum route grade made by project staff using a handheld inclinometer). As a check of this process, ERG recalculated the

elevation trace based on the second-by-second grade (with the eight percent cap and the mathematical smoothing) and found an equivalent level of agreement with the topographical cross check values as the original trace had.

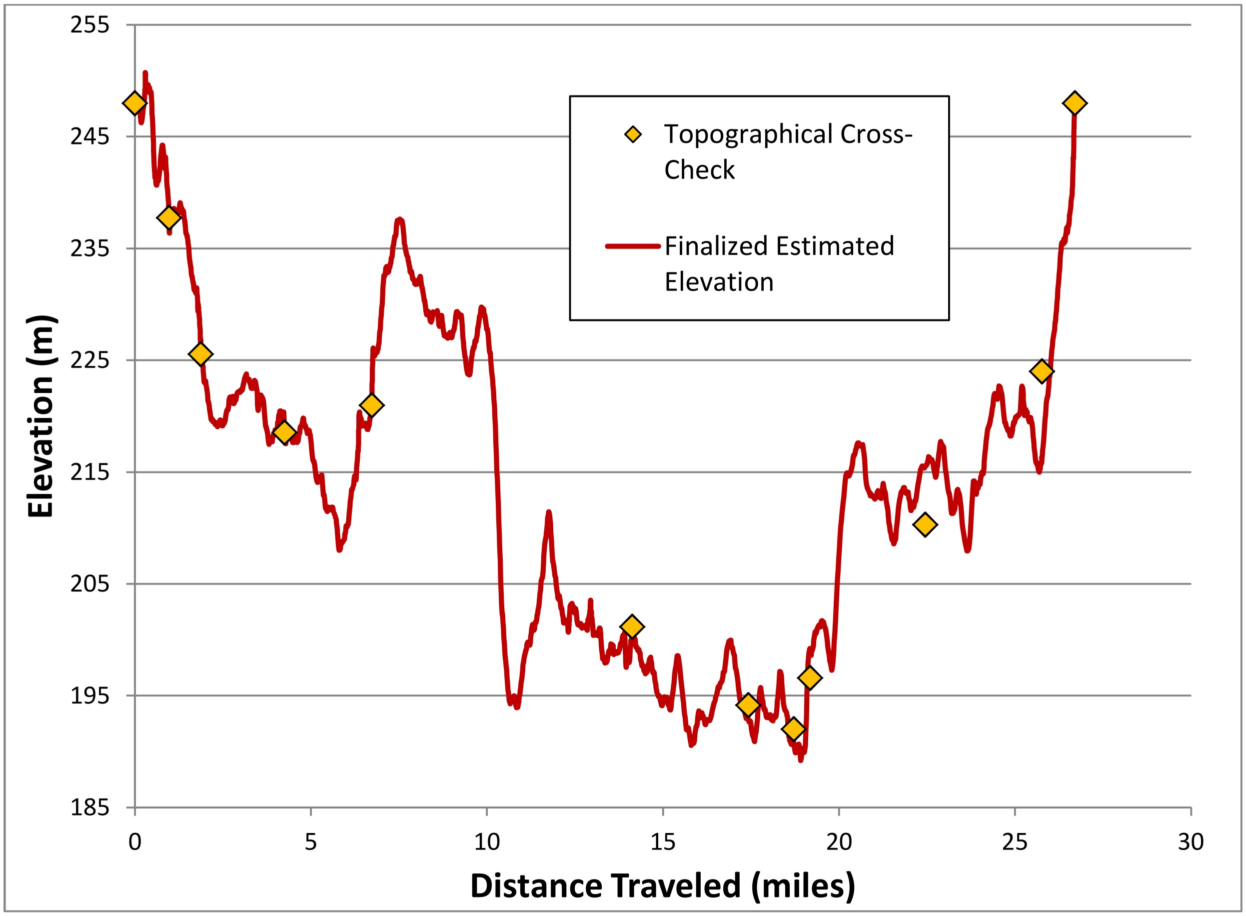

Figure 3-3. The finalized estimated elevation along the route, by distance, along with selected points from a topographical map as a cross check.

4.0 PEMS Devices Evaluated

Three PEMS were evaluated in this work. The manufacturers of all three provided the equipment on loan throughout the term of testing. Each manufacturer also provided on-site training personnel for at least one week to assist ERG with setup, installation, and use of the equipment. Manufacturers' staff were invited to view any or all SwRI-based tests of their own equipment; two of the manufacturers had personnel on site for four tests each, and the other manufacturer did not have personnel on site beyond their setup and training week. Due to personnel accessibility constraints at the test track, ERG did not invite manufacturers to observe on-track testing, and no manufacturer requested the option to do so.

The intention of ERG staff was to use the equipment just as recommended by the manufacturer whenever possible. ERG created test checklists for the use of each PEMS, and these were iteratively improved with the assistance of the manufacturer's staff during the first few weeks of testing. Generally, the same checklist was used for dynamometer and on-road tests, and a different checklist was developed for on-track tests due to the different test procedures in place at the track.

The PEMS devices evaluated in this work covered a range of measurement capability, size, and complexity. The following subsections describe the characteristics, capabilities, and limitations of each unit as well as operational observations of each. A table is provided at the end of this section that has an overview of the measurement principles employed by each unit. The devices are described in the order of their initial arrival at SwRI.

4.1 Horiba OBS-ONE PEMS

The Horiba OBS-ONE was the only participating PEMS device capable of conducting emissions tests per 40 CFR 1065. The unit is modular in terms of the types of measurements that can be conducted. The unit used in this work was configured in a manner similar to that which would be used for heavy-duty in-use PEMS testing for the not-to-exceed (NTE) standards. The NTE feature was not used in this work, rather the device sampled continuously from the beginning to the end of each test cycle. The Horiba PEMS, installed in the test vehicle, is shown in Figure 4-1.

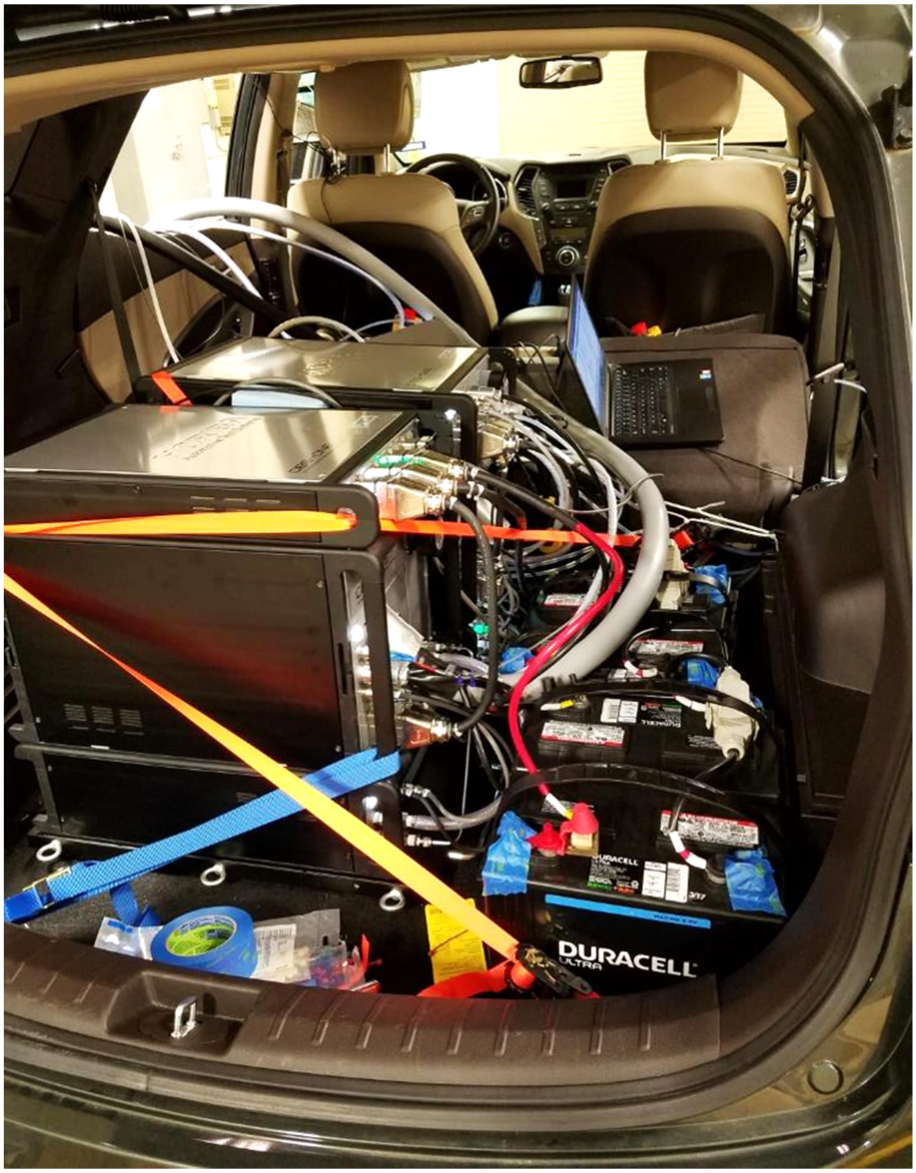

Figure 4-1. The Horiba OBS-ONE PEMS installed in the test vehicle in the configuration used throughout the program.

The Horiba system consists of two main modules, a gaseous sampling module (known as the GA), and a PM sampling module. The systems run on 24V DC power. ERG provided four lead-acid 12V deep cycle batteries for use in this work; one pair of batteries was wired in series to power the GA module, and the other pair was wired in series to power the PM module. The other key component of the system is the exhaust flowmeter tube, which was connected to the full exhaust stream by Marman flange just downstream of the mounted 90 degree exhaust elbow and extension. The flowmeter performs a pitot-based flow measurement continuously on a 10 Hz basis, and the flowmeter tube also provides the mounting point for the GA sample line, the PM sample probe, and an exhaust thermocouple probe. The outlet of the flowmeter provided an attachment point to the transfer tube to the CVS tunnel during dynamometer tests. The sample lines and wiring were routed along the left rear quarter of the vehicle and entered the vehicle through the rear driver's side window. The Horiba system is controlled by a separate laptop computer, connected via a LAN cable. The system is designed so that a temporary or intermittent problem with the laptop or network connection does not cause the equipment to fail or the test data to be lost.

The GA module was equipped for the measurement of HC by flame ionization detector (FID), which is contained in a separate module from the rest of the GA cabinet. Measurements of CO and CO_2 are performed by non-dispersive infrared (NDIR). Both NO and NOx are measured concurrently by chemiluminescence. NOx is measured via a NOx converter, in which the NO_2 in the sample is converted to NO, and then the total sample is measured as NO. The system has a built in zero/span and drift correction feature that takes place any time an emissions test is performed. The system prompts the user to connect zero and span gases at the time a test is initiated, and the internal adjustment for the zero/span takes place automatically. At the conclusion of the test, the system prompts the user to reconnect the zero/span lines to do a post-test drift check. The system then automatically applies the drift correction to the data per 40 CFR 1065.672. In order for the zero/span features to function automatically, a quad blend span gas (consisting of HC, CO, CO_2, and NO/NOx) must be used. Specifications of the span gases used in this project are summarized in Appendix C.

The Horiba's PM module consists of two types of PM measurement. PM mass is measured gravimetrically in batch on a 47mm filter. The cabinet can hold a single filter which is loaded in place prior to the test. A real time particulate measurement is also taken using a diffusion charger system (DCS). This measurement is roughly proportional to the total particle length raised to the 1.13 power. Both measurements are taken by an exhaust flow-proportional partial-flow diluted sample. The sample for both measurements also travels through a cyclonic separator to sample particles under 10 microns. The DCS measurement, because it is proportional to the intended measurement, is "calibrated" to the total PM mass over the test as calculated based on the mass of PM collected on the filter. This calculation is done during data post-processing.

The Horiba system includes an integrated OBD interface. The control software can be configured to sample 16 different OBD signals to assist in data review and post processing. The user can readily assign the logged OBD parameter IDs (PIDs) within the control software. The OBD data is then integrated with the continuous data file output from each test.

Another picture of the Horiba system, taken during prior to installation into the test vehicle, is presented in Figure 4-2. Note that, because of the modular design of the system, the installation involves a relatively complex quantity of tubing and wiring running between each component.

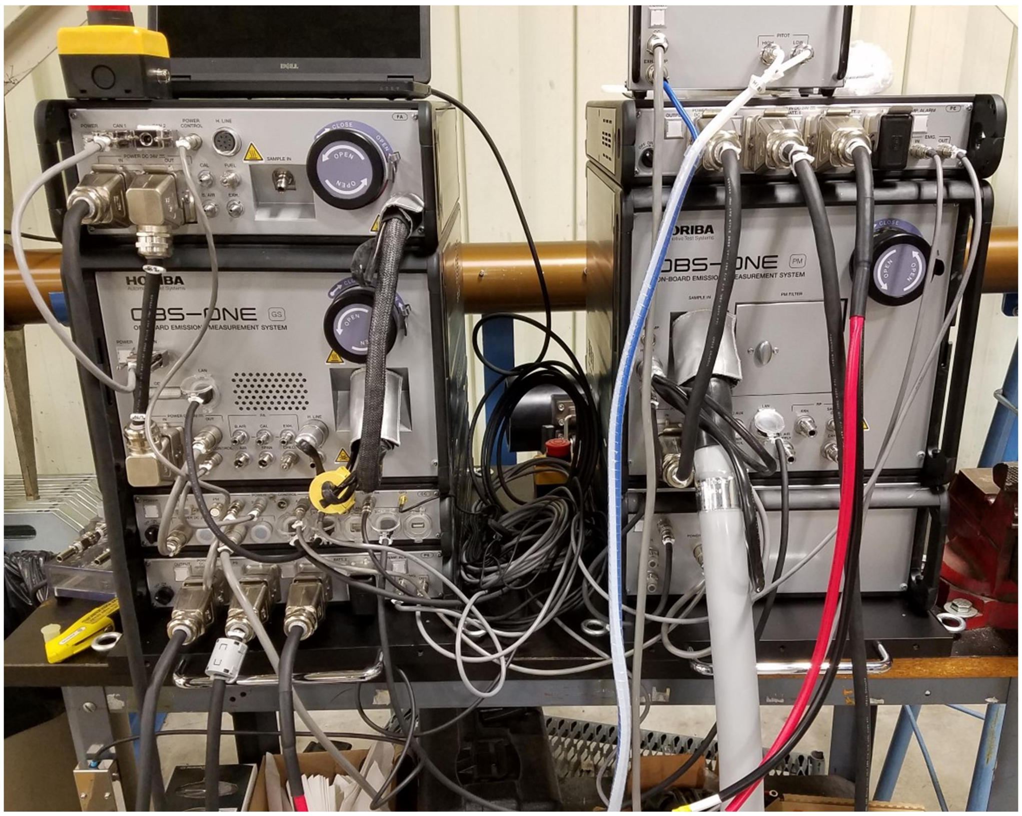

Figure 4-2. The Horiba PEMS system with wiring and tubing being mocked up prior to installation into the test vehicle.

The total system weight of the OBS-ONE-PEMS, including the necessary gas bottles, laptop, and all components as evaluated in this work was approximately 575 lbs. About 205 lbs of this total weight was in the deep cycle batteries. These batteries were specified to allow for approximately two hours of testing, which was needed during the on-track tests in which the test cycle was repeated twice with time in between each to move between tracks as well as to end and restart the test sequences. The FID is a significant user of electric power as both the inner cabinet and heated line are held at 191°C to prevent condensation and keep the HC sample stable, as per

Part 1065 requirements. The gaseous system is designed to operate at 95°C when a FID is not used, meaning the energy requirement, and therefore total battery weight, would be reduced for these types of tests. The approximate weight breakdown of the various components and accessories of the system as tested in this work is presented in Table 4-1.

Table 4-1. Weight of Various Components of Horiba System

Component	**Weight (lbs.)**
Horiba Accessories (laptop, controller module, cabling)	32
Gaseous Measurement Cabinet (CO, CO_2, NOx)	93
FID for HC Measurement and Heated Line	50
Continuous and Batch PM Measurement Cabinet	140
Flow Measurement Equipment (excluding exhaust tube flowmeter, which was equivalent to the sample pipes of the other PEMS)	10
ERG-Specified External Accessories (Deep Cycle Batteries, Gas Bottles)	250
Total	**575**

4.2 GlobalMRV Axion

The Axion system is designed to allow for non-certification emission concentration and mass tests to be conducted using a system with a lighter weight, reduced size, and reduced energy demand as compared to a full 1065-capable system. It is roughly the size of a suitcase, with an external chiller for the PM sample. GlobalMRV provided a single 12V lithium ion battery for use during this work, which was readily capable of powering the system for more than the two hours per day necessary during this program. The Axion system as installed in the test vehicle during this work is shown in Figure 4-3.

Figure 4-3. The GlobalMRV Axion system as installed in this work. The unit was strapped to the right rear passenger seat, and the chiller was strapped in to the floorboards just in front of the unit.

All of the Axion analyzers are located within the single unit. HC, CO, and CO_2 are measured by NDIR. The use of NDIR in the measurement of CO and CO_2 is typical in a wide range of lab and PEMS systems; however NDIR is known to have different levels of sensitivity to HC depending on the composition of the HC molecules being detected.[1] This sensitivity can have an adverse effect on measurement accuracy for measurements over different engine operating modes. NOx measurement consists of NO only, and is measured by an electrochemical detector. PM is measured by laser scattering, and the system utilizes an internal transfer function

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[1] Springer, George. *Engine Emissions: Pollutant Formation and Measurement.* Springer Science & Business Media, 2012

to convert the laser scattering measurement signal to an estimate of PM mass on a second-by-second basis.

The Axion contains two parallel gas analyzers. Generally, the system reports the average values of both analyzers. However, the system periodically re-zeros one analyzer at a time and measures from the other analyzer during this process in order to provide uninterrupted measurements. This feature operates seamlessly with no input from the user.

The Axion does not use a flowmeter to directly measure exhaust flow. Instead, the unit uses an integrated OBD connector to read OBD signals and estimates the exhaust flow based on a proprietary calculation using these OBD signals. Two samples are drawn from the tailpipe, one for the gaseous sample and one for PM. GlobalMRV typically uses two BAR97-style handheld tailpipe probes for emissions tests. Because this work involved full-flow exhaust sampling through the lab's dilution tunnel, an airtight connection was needed that would accommodate the BAR97 sample probes. SwRI fabricated a Marman-flanged mounting tube with welded ports to accommodate the geometry of the BAR97 sample probes while still allowing the exhaust transfer pipe to make an airtight connection. This device is shown in Figure 4-4, and was in place downstream of the test vehicle's exhaust elbow and extension during all tests. The probe tip end mounted to the vehicle's exhaust extension tube downstream of the 90° elbow, and the downstream end had a Marman flange to mate to the lab CVS transfer pipe (similar in size and mounting position to the Horiba flowmeter). GlobalMRV staff assisted in the assembly of the sample probe mounting tube to ensure that its geometry matched their intended sample probe design.

Figure 4-4. The exhaust sample probe mounting tube used for GlobalMRV tests. The two probe tips within the tube point into the oncoming exhaust flow.

The Axion does not allow direct, user selectable choices of OBD parameters to record. Instead it is equipped with approximately ten to fifteen baseline parameters that are automatically logged. For this study, GlobalMRV programmers modified the software code at ERG's request to add a few additional desired parameters (described further in Section 5.1). The programmers sent ERG a replacement parameter file and ERG copied it onto the GlobalMRV system manually. Once this change was made, the OBD parameter list was unchanged for the duration of the project.

The gaseous sample line for the Axion is not heated or chilled. Some water condenses out of the sample in the line, but any liquid water that enters the Axion is pumped out separately via a water trap so as not to clog the system or otherwise damage the sensors. The PM sample is run through a chiller to drop water out of the exhaust sample prior to the laser scattering measurement. The software in the unit, when estimating exhaust mass flow from the OBD data, estimates the quantity of exhaust mass that is water and the quantity of exhaust mass that is the remaining dry exhaust on a second-by-second basis. Prior to the start of a test, the Axion allows the user to conduct a zero/span of the analyzers, which automatically adjusts the system gains to match the zero and span signal levels. The system does not have an integral option to check or perform a drift correction, however. In order to track drift, ERG conducted an audit just before and just after each test in which ambient air followed by quad blend span gas were drawn into the analyzer.

The Axion total installed weight was approximately 65 lbs. Of this, the battery weighed 14 lbs, and the remaining 51 lbs was divided between the chiller and the Axion unit itself. The Axion is controlled via an integrated monitor and USB-connected input devices. The system can be controlled remotely via Bluetooth connection by a tablet computer, if desired.

4.3 3DATX parSYNC

The 3DATX parSYNC is a lightweight PEMS system that can be easily carried by one person and is intended to perform non-certification emissions tests of a limited number of gaseous exhaust constituents as well as PM. It is roughly the size of a shoebox, and utilizes an internal battery so that is can be readily installed in or on a test vehicle. The internal battery can power the unit for over six hours, so its battery capacity was not challenged during this work. The parSYNC analyzer and prototype sample chiller are shown in Figure 4-5. The unit was installed by strapping it down on the vehicle’s left rear seatback, which was folded flat for tests of this system.

Figure 4-5. The 3DATX parSYNC (right) and exhaust sample chiller (left).

The parSYNC contains a gaseous measurement module and a PM module, accessible by a removable cover on the unit. The unit used in this testing was equipped with a gaseous module that could measure NO and NO_2 by electrochemical detector, as well as CO_2 by NDIR. The system was not equipped to measure CO or HC. The PM module measures PM by three concurrent methods, laser scattering, ionization, and opacity. The system internally performs a calculation on the three PM signals and reports a unitless second-by-second particle synchronization number (PSN). There is no integral zero/span feature for the gaseous analyzers for this unit. To zero and span, ERG flowed zero and quad-blend span gas and recorded the data. The datafile lists both internal signal voltage as well as the calculated pollutant concentration for each second of operation. To span, the user averages the voltage signal during the zero and again during the span, and then enters these voltages in the configuration screen of the unit, along with the span gas concentrations. To track drift, ERG used a process similar to that used for the GlobalMRV unit; ambient air followed by quad-blend span gas were flowed prior to the start and immediately after each test so that the level of drift could be calculated from the logged data.

The parSYNC uses a single unheated sample line which directs the sample flow through a chiller to remove water vapor prior to entering the unit. The system is not designed to tolerate liquid water entering the sensors; they are not likely to be damaged by liquid water however it could cause signals to be affected or lost. The system is set up to use a BAR97-style tailpipe probe, so SwRI fabricated a second probe mount tube for the parSYNC similar to that created for the Axion system.

The parSYNC does not include provision for exhaust flow measurement as it does not have an exhaust flowmeter or an internal OBD reader. Instead, ERG used an OBD datalogger (similar to that used during the driving route test drives) to capture OBD and GPS data for this system. The logged OBD signals were then used by project staff to estimate the instantaneous exhaust flow rate during each emissions test using an SwRI-developed transfer function, which could then be used to estimate pollutant mass flow rates in a manner similar to the other two units. These calculations are further described in Section 5.3.

The parSYNC and chiller weigh approximately 16 lbs together. The parSYNC battery is internal and is included in this total. The parSYNC is controlled via a tablet computer connected via a Bluetooth connection. The Bluetooth connection must be kept live throughout the test to prevent loss of data.

4.4 PEMS Operational Observations and Issues Encountered

This section discusses some of the usability aspects of the different PEMS in this study, as well as some of the issues that were encountered with the PEMS during the test program. In general, the PEMS systems were fairly reliable, and tended to have fewer failures than the lab equipment on a per test-day basis (though the lab measured more parameters and had a greater general complexity than did any PEMS).

Time to learn and setup PEMS. As described previously, each PEMS manufacturer provided one or two representatives for a week-long period at the start of the project for training and setup. Generally, the time required to learn and become familiar with each PEMS unit was related to its complexity and number of measurements that it was capable of making. The time required to learn each PEMS is described in this section. For reference, the ERG staff members present at the training had engineering backgrounds with years of experience with emissions testing. Test checklists were developed initially with the help of each manufacturer and then continuously improved throughout the project. This use of test checklists was critical for the correct use of each of the PEMS. With all systems, it would be easy to overlook certain steps or potentially affect the repeatability or accuracy of measurements if not following a checklist. The development of test checklists is discussed further in Section 5.1.

Horiba staff were present for a week of setup and training, and were present to observe the first week of actual testing with the unit as well. It took almost the entire first week for ERG staff to develop the test checklist and become familiar with the proper operation of the unit and the post-processing software. The initial installation of the Horiba system into the test vehicle took approximately two days, however Horiba staff was also instructing ERG staff on the usage of the equipment and the principles of operation in parallel during this time. As a result, it would probably take only one complete day to install this equipment (including both the gaseous, FID, and PM units) into a new test vehicle by staff already knowledgeable about its operation. During this installation, extra time was spent laying out the locations of each component to facilitate the many installations and removals of wiring and tubing that were necessary to complete the multi-month project (the components were placed in a similar location for all tests).

GlobalMRV provided a single staff member to be on-site to assist with training and initial installation. The initial installation was completed on the first day, and the rest of the first week was spent developing the test checklist and learning about the operation and necessary maintenance of the unit. Approximately one day was used to determine the time alignment parameters to be used with the setup on the test vehicle- though the default values for the system were fairly close to those that were finally used. It took approximately two to three days for ERG staff to become proficient in using the system.

One staff member from 3DATX was present for a week to assist with initial setup and training for the parSYNC. The initial installation of the system into the test vehicle took less than an hour. It took approximately two days for ERG staff to become proficient with the system, however additional days were spent developing the test checklist and the zero/span procedures given that the system did not have an internal or automated zero/span function and the procedure to be followed was developed during this time.

Daily installation and setup. Just as the time to become proficient with each PEMS varied with complexity, the time to install each unit also varied with complexity. After determining the best layout for the installation of each PEMS (each chosen with the assistance of the manufacturer representative), the same installation layout was used for all remaining tests. As a result, re-installation of each PEMS while rotating through the various units became less time-consuming throughout the project.

In general, when installing the Horiba system during testing, it took about two to three hours to reinstall the wiring and hoses back into the PEMS to ready it for a test the following day. Installation was facilitated by having two staff members present, especially for handling the relatively heavy heated sample lines. The batteries and main cabinets of the Horiba system were left in place in the test vehicle for most tests of the other PEMS in order to minimize the amount of ballast weight to be added or removed in order to maintain a consistent vehicle weight during all tests. If the complete cabinets had needed to be installed or removed, two staff members would almost certainly have been required. Installation of the system required connections of all plumbing and wiring that was removed when switching between tested PEMS. This included the heated sample lines, the flowmeter and its pressure and thermocouple lines, sample exhaust lines, OBD and GPS wires, and the battery wires. These connections were made readily as most connections have different sized fittings or plugs and were well labeled so that it would be difficult to connect them incorrectly once a user was familiar with the system. The most complicated and numerous connections of this system are the smaller tubes and wiring running between each of the separate modules of the unit. For this work, most of these were left in place throughout testing of all three PEMS. Four 12V lead-acid batteries were used for this system and were charged after every day of testing. The system is designed to be hot-swappable when moving between shore power and battery power and no issues were encountered relating to the power or electrical connections.

Installations of the GlobalMRV system back into the test vehicle after a rotation took approximately one to two hours to complete. Installation could be readily performed by a single project staff member. All connections of the GlobalMRV system were removed when rotating between PEMS; installation required making connections of the sample lines, chiller sample transfer line, exhaust/drain lines, GPS wiring, OBD wiring, and weather station wiring. All electrical connections are unique so it was not possible to install them incorrectly. The sample lines can be installed readily, however their connections need to be made and then removed during the leak check procedure at the start of a test, and there is some risk of leaving the PM line off at the start of the test; the system will not warn the user if this is left off. Otherwise, the system can be installed readily by a user with a few days of experience with the system. The GlobalMRV system was furnished with a 12V rechargeable lithium battery which was charged after every day of testing and easily plugged into the Axion unit. The unit has a small internal battery that allows for hot-swapping between shore power and the battery.

The 3DATX system generally took less than a half an hour to install into the test vehicle, however the developed zero/span and audit steps for this system took longer than for the other systems, generally taking at least another 30 minutes. The zero/span procedure developed for this system in this project required the use of a tedlar bag to allow the system to draw the span gas out at as close to atmospheric pressure as possible (the other systems allowed direct tubing connections of zero and span gasses from their respective bottles). Filling, emptying, and purging the bag required extra time as compared to the other systems. Due to the very portable nature of this system, the warmup and zero/span procedures were performed with the parSYNC outside of the vehicle. During the warmup, the sample line was installed and run into the rear window of the test vehicle. Once the zero/span was complete, the parSYNC and chiller were installed and secured, and this generally took less than 10 minutes. All operation of this PEMS required only a single project staff member. There were few connections that needed to be made, including only the sample line run through the chiller, the transfer line to the parSYNC, and the exhaust line. The internal battery was charged after every day of testing, and the charger could be installed or removed while the system was powered on.

Test conclusion and PEMS removal. After the completion of a test, ERG staff followed the PEMS shutdown procedure described in the test checklists for each system. Each system required a purge to clear out exhaust gases and/or water vapor from the components and lines. The Horiba system has an automatic purge feature at the conclusion of each test and that was set to 10 minutes for this work. The GlobalMRV and 3DATX training representatives requested a 30 minute purge of their systems, and project staff followed this by leaving the sample pump on for this duration. ERG staff also blew out the sample lines of those two systems with compressed nitrogen to ensure that the lines would be free of water or other contaminants prior to the next test, but blowing out the sample lines was not specified by Horiba for their heated lines as water did not condense in them.

Removal of each PEMS system after completing the purge procedure and preparing to rotate to the next PEMS was generally fairly rapid. The 3DATX and GlobalMRV systems generally took about a half hour or less to remove and store, and the Horiba system hoses and wiring generally took about one hour to remove. So, including the purge time requirements, the time required after a test to remove the previous PEMS system and be ready for the next system took approximately 1.5 hours for all three PEMS. However, it should be noted that the Horiba cabinets and batteries were left secured in the test vehicle (as a part of the ballast needed for testing of the other two PEMS), so complete removal of the Horiba system would likely take at least one additional hour for a two-person team.

Exhaust condensation. The GlobalMRV and 3DATX systems relied on unheated sample lines to direct the sample from the exhaust probe to the PEMS analyzers. One of the systems chilled only the PM sample and the other chilled both the gaseous and PM samples. In both systems, water is lost in the sample lines and not necessarily quantified accurately. As a result, the concentration measurements performed by the analyzer are not necessarily completely on a dry basis or completely on a wet basis. This causes a potential inaccuracy as the measured concentration is not necessarily equivalent to the concentration that was in the wet exhaust. The GlobalMRV system does estimate the water concentration in the exhaust based on calculations from the OBD signals, however this is not a direct measurement nor is the water lost in the gaseous sample line always a constant amount. The chiller in the 3DATX system was not controlled to a target temperature, but rather utilized a frozen thermal storage material that was prone to rise in temperature as it thawed during the test, further confounding the issue of the amount of water in the sample. This was a prototype chiller, however, and future versions may control to a steady temperature. Also, both of these PEMS directed their PM samples through the chiller where liquid water condenses. Some PM may contact and become entrained in this liquid water and not reach the measurement location in the sample train. The Horiba system had heated sample lines and no issues relating to condensation were encountered with that system, nor was there any reason to suspect that measurements were affected by the water content of the exhaust.

Issues encountered. Minor problems were encountered with each of the PEMS evaluated in the project. The following summarizes each issue encountered:

- One manufacturer elected to travel back to their headquarters with a PEMS component at the conclusion of the training week. Apparently, a supplier had changed a specification unbeknownst to the manufacturer and this caused erroneous readings to occur during zero and span checks. The component was repaired or adjusted and returned for the commencement of testing. While the start of testing was delayed for this unit, no lost days of downtime occurred to the project as the schedule for the other two PEMS was rearranged accordingly.
- The control software or operating system for one PEMS appeared to have a glitch in the operating system during a single test. The screen flashed on and off periodically and the

cursor control was extremely erratic and made it very difficult to select the intended commands. As this occurred during a track test with limited available track time, there was no time available to restart the equipment and meet the warm-up time requirements. The data collected during this test was not lost and did not appear to have been affected.

- One of the systems developed an issue with a gaseous transfer line quick disconnect fitting. The fitting was able connect and disconnect in a way that seemed normal, however the internal components of the fitting blocked the flow when it was connected. This effectively prevented zero and span procedures to be completed properly with the unit. ERG performed troubleshooting of the unit with assistance from the manufacturer in discovering the cause; however the process did result in two lost days of downtime.
- An internal thermocouple failed in one of the PEMS. The manufacturer was easily able to diagnose the problem. A spare was shipped to SwRI and ERG staff installed it into the system. No days were lost to downtime.
- For one of the PEMS that utilized optical PM measurement, the PM measurement was pegged at zero throughout the entire test on one of the test days. The manufacturer indicated that this could have been due to liquid water condensing or otherwise entering the measurement chamber. All PM data for that test day was lost and there was no indication of the problem visible to the user until the data was reviewed.

4.5 Review of the Measurement Principles and Capabilities of Each PEMS

This section contains a review of the pertinent aspects of each PEMS evaluated in this study. Table 4-2 presents the capabilities and characteristics of each of the three PEMS, and Table 4-3 presents the measurement principles and sample conditioning employed by each PEMS and the measurement equipment used in the lab.

Table 4-2. Capabilities and Characteristics of each PEMS

	Horiba	GlobalMRV	3DATX
CO_2 Measured	✓	✓	✓
HC Measured	✓	✓	
CO Measured	✓	✓	
NO Measured	✓	✓	✓
NOx Measured	✓		✓
Exhaust Flow Measurement	✓ - Measured	✓ - Estimated	
40 CFR 1065 Capable	✓		
Weight as Tested (including battery)	575 lbs.	65 lbs.	16 lbs.
Key Advantage	1065-capable measurements using laboratory techniques	Wide range of pollutant concentrations measured and capable of mass estimates, lightweight	Very lightweight and easy to install for NO/NOx, CO_2, and PM concentration/ threshold measurements

Table 4-3. Measurement Principles and Sample Conditioning of the Evaluated PEMS

Measurement	Horiba	GlobalMRV	3DATX	SwRI Lab
HC	FID	NDIR	N/A	FID
NOx	Chemiluminescence	NO only-Electrochemical	NO & NO2 Separately - Electrochemical	Chemiluminescence
CO/CO2	NDIR	NDIR	CO2 only, by NDIR	NDIR
Exhaust Flow Measurement	Pitot-Based Flowmeter	Proprietary OBD-based exhaust flow estimation	None- SwRI/ERG developed an OBD-based curve fit to SwRI-collected exhaust flow data	CVS tunnel-based measurement of tunnel outlet (sonic venturri) minus tunnel inlet (SAO)
Gaseous Sample Conditioning	Heated line (all samples wet)	Line is neither heated or cooled. Any water that condenses is separated but pumped through system.	Entire sample is run through a chiller which captures condensed water.	Bag measurements are made dilute, raw measurements are made on a dry basis except THC, which is wet
PM Sample Conditioning	Heated line. Cyclonic separator upstream of both filter and continuous measurements separates sample to PM_{10}	Sample is passed through a chiller to remove water (which is pumped out of the system separately). Sample measures PM_{10}	Entire sample is run through a chiller which captures condensed water.	Batch sample is separated by cyclone to PM_{10} and smaller only. Continuous (MSS) does not have a separator.
PM Measurement	Gravimetric filter for batch and diffusion charger for continuous. Diffusion charger scaled to match PM mass.	Laser scattering, w/proprietary mass estimation	No Batch Measurement. Continuous separate measurements of Opacity, Ionization, and Laser Scattering. No mass estimation	Gravimetric filter measurement sampled from CVS dilution tunnel. Continuous (MSS by photoacoustic) measured from tailpipe sample probe
OBD Data	Integral measurement included	Integral measurement included	Not included. ERG provided a separate HEMData logger and manually time-aligned the data	N/A

5.0 Exhaust Emissions Testing

This section describes the test procedures that were in place for the dynamometer, on-road and track tests in this work. This includes specifics of test setups, preconditioning, vehicle operation, as well as the differences and specific procedures that differed between the three main types of tests.

5.1 Test preparations and setup

Vehicle test weight/test inertia. As described in Section 4.0, the PEMS units differed significantly in total weight. The intent of this work was to evaluate PEMS measurements under conditions that were as consistent as possible. For this reason, the approach used was to test the vehicle with as consistent a weight as possible. After completely installing the heaviest of the PEMS units, ERG weighed the vehicle at a commercial vehicle weighing facility. With all equipment installed and a driver and passenger on board, the vehicle was found to weigh 4,640 lbs, and this was the test weight that would be used for all tests, whether as an input to the inertia simulation of the chassis dynamometer or the weight of the vehicle during road and track tests. Ballast weights were added to reach the intended test weight for the two lighter PEMS. For most on-road tests, a passenger was not on board and approximately 180 lbs were added to the passenger floorboards of the test vehicle as ballast. During the closed-track tests only, a passenger was always on board in order to assist with steering the vehicle while the driver followed the test's speed trace. For dynamometer tests, the weight of 4,640 lbs was entered into the dynamometer controller software. From this weight value, the dynamometer then calculated the inertia that would be simulated. This value was calculated to be 4,710 lbs, which is higher than the vehicle weight to account for the rotational inertia of the vehicle's non-driven wheels. The main components of the heaviest PEMS, including the batteries, were generally left on board for tests of all three systems. This facilitated switching between tests of each unit as the quantity of ballast to be added or removed was reduced.

Dynamometer road load settings. The electric dynamometer simulates three different types of load on the vehicle, the load due to drag (including aerodynamic, driveline, and tire resistances), the loads due to inertia (which only have an effect when the vehicle is accelerating or decelerating), and, in this work, load due to simulated road grade. The development of the loads due to inertia and grade have been discussed previously (inertia loading was described in the preceding paragraph and grade simulation was described in Section 3.2). The road loads due to drag are simulated by the dynamometer as three dynamometer coefficients in the following equation:

$$F_{RL} = A + Bv + Cv^2$$

Where A, B, and C are the road load coefficients, v is the vehicle speed at a particular time, and F_{RL} is the road load force. The A coefficient can be primarily thought of as the rolling resistance, and C can be thought of as representing the aerodynamic drag. The B coefficient primarily represents the relatively small effect of speed on rolling resistance, and is usually the term with the lowest magnitude in the equation. Note that the equation above describes only the drag-related road load force (i.e., at steady speed) and does not include the forces related to acceleration or grade. There are two types of dynamometer road load coefficients, the target coefficients, which describe the actual load on a vehicle traveling down flat pavement, and the set coefficients, which describe the load that a dynamometer must apply such that the vehicle experiences the same road load on the dynamometer as it would when traveling along level pavement. These two types of coefficients are different because there is a greater amount of drag associated with the drive tires on the interface with the 48” dynamometer roll than there is when they are traveling on level ground.

The EPA publishes the road load coefficients that are used during dynamometer tests for new vehicle emissions and fuel economy certification. These values are generally provided by the manufacturer, but are sometimes determined or verified by EPA. Both the target and set coefficients associated with a vehicle’s certification are published by EPA. For this work, ERG used the EPA-published target coefficients for the test vehicle as the source for dynamometer road load setting. SwRI entered these values, and then used the dynamometer’s internal set coefficient derivation feature to conduct iterative dynamometer coastdowns with the test vehicle in order to derive the set coefficients that would be used during all testing. The dynamometer coefficients for the test vehicle are shown in Table 5-1. The target coefficients are sourced from the EPA published values, and the set coefficients are derived from the target values using dynamometer coastdowns with the test vehicle.

Table 5-1. Target and Set Road Load Coefficients

	Target Coefficient	Derived Set Coefficient
Coefficient A (lbs)	26.347	7.19
Coefficient B (lbs/mph)	0.40519	0.2798
Coefficient C (lbs/mph^2)	0.021578	0.02185

Unfortunately, during the analysis part of this program after testing was completed, ERG discovered that the published road load coefficients for this test vehicle are likely to inaccurately describe the test vehicle's true road load curve. After publishing the certification data for the 2013 model year, EPA investigated Hyundai-sourced road load coefficients used for certification of 2012 and 2013 model year Hyundai vehicles and alleged that Hyundai had underestimated road load coefficients for most models.[2] This investigation ended with a significant civil penalty to the manufacturer, as underestimating the coefficients during dynamometer tests results in higher reported vehicle fuel economy as well as, in general, lower reported pollutant emissions. It is likely that the engine loads encountered during chassis dynamometer testing in this program were somewhat less than the actual on-road engine loading as a result of these underestimated road loads. Corrected road load coefficients for the affected model years were not published, however, based on the case settlement, published coefficients for model year 2015 Hyundai vehicles should be accurate. The Santa Fe body style was unchanged from 2013 to 2015, so the coefficients should be comparable. ERG calculated the target road load horsepower at 50 mph for coefficients from both model years, and the 2013 road load power at 50 mph is approximately 17 percent less than the equivalent horsepower for the 2015 coefficients.

Logged OBD Parameters. As described in Section 4, two of the PEMS included integrated OBD loggers, and, for the third PEMS, ERG supplied a separate OBD datalogger to capture ECM data concurrently with PEMS data collection. The capabilities and customizability of each OBD system was different, so ERG was not able to capture the same parameters with all three systems. However, in large part, most of the same OBD parameters were logged during tests with all three PEMS units in use.

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[2] U.S. EPA, Hyundai and Kia Clean Air Act Settlement. Retrieved 11/1/17, from https://www.epa.gov/enforcement/hyundai-and-kia-clean-air-act-settlement

ERG prioritized and selected OBD PIDs based on perceived usefulness in terms of evaluating the differences in accuracy and repeatability of the PEMS devices. This included a prioritization of the OBD-logged environmental parameters. Secondarily, the remaining parameters were chosen in order to evaluate and understand the operation of the test vehicle. Table 5-2 contains the OBD parameters that were logged during tests of each of the PEMS devices.

Table 5-2. The logged OBD parameters recorded by each PEMS

OBD PID Description	Horiba	GlobalMRV	3DATX (via HEMdata)
Absolute Load Value (%)	X	X	X
Absolute Throttle Position (%)	X	X	X
Ambient Air Temperature (Deg C)	X	X	X
Bank 1 - Sensor 1 lambda (Wide Range)			X
Barometric Pressure (kPa)	X	X	X
Calculated LOAD Value (%)	X	X	X
Commanded Equivalence Ratio ()	X	X	X
Commanded Evaporative Purge (%)	X	X	X
Engine Coolant Temperature (C)	X	X	X
Engine RPM (RPM)	X	X	X
Engine Timing Advance for cyl #1 (deg)		X	X
Evap System Vapor Pressure (Pa)	X	X	X
Fuel Level Input (%)	X	X	X
Fuel Rail Pressure (absolute) (kPa)	X	X	X
Fuel System Status 1	X		X
Intake Air Temp (Deg C)	X	X	X
Intake Manifold Absolute Pressure (kPaA)	X	X	X
Vehicle Speed (km/hr)	X	X	X

Driver aid for track tests. SwRI developed a driver aid to assist the driver in following the E-122 speed trace during the on-track tests. The system consisted of a laptop computer with software to show the E-122 cycle's speed trace, the speed tolerance range at any given second, and the vehicle's current speed in a strip-chart type design. The system used an OBD Y-connector to interface with the vehicles OBD data bus while still allowing each installed PEMS to interface with the OBD as well. The PEMS systems transmitted their data requests to the vehicle's data bus, and the driver aid was programmed to "listen" to the speed signal output. As such, the driver aid did not interfere with the OBD datalogging of each PEMS, but could still receive continuously-updated vehicle speed. A screen capture of the driver aid software is shown in Figure 5-1. The red line depicts the actual speed trace, and the grey line on each side depicts the tolerance range outside of which driver errors could accrue according to 40 CFR 86.115. The blue crosshair indicates the vehicle's current speed. The system was also capable of logging the speed data throughout a test.

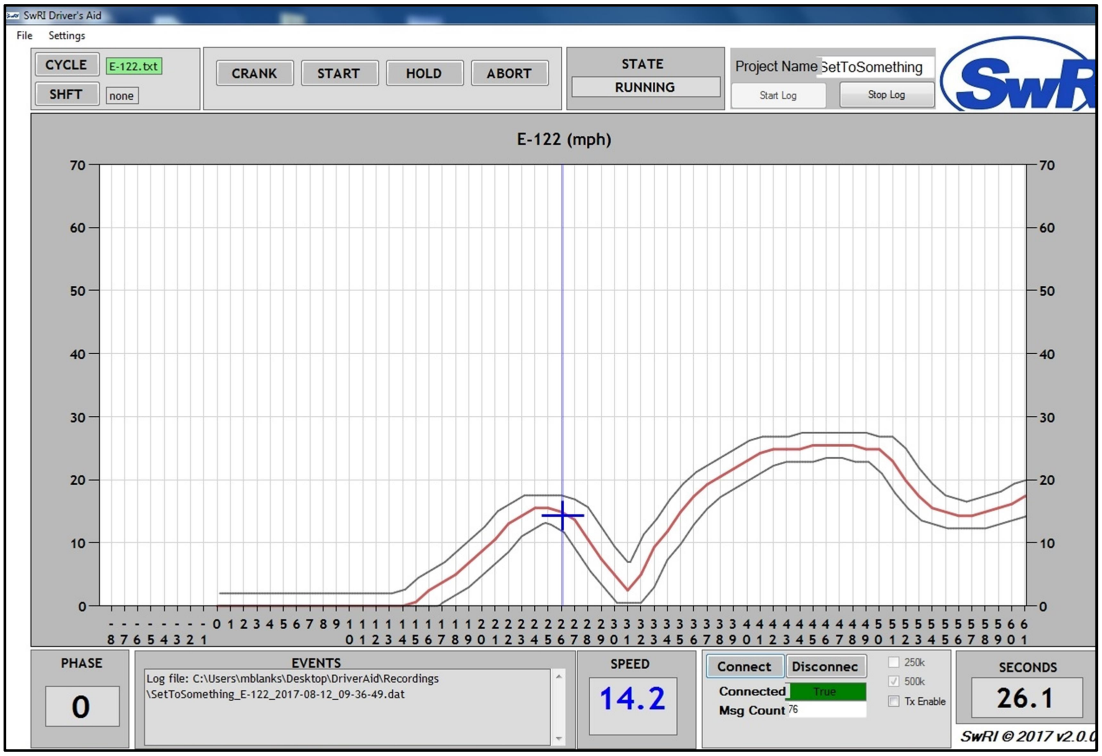

Figure 5-1. The SwRI driver aid software used during track tests.

Trip fuel economy dash panel readout. One of the features of the test vehicle is a running estimate of the trip fuel economy, displayed on the dashboard. This fuel economy log can be reset at any time, and then it will begin a new running estimate of fuel economy since the time of the reset. This readout was reset prior to each test cycle, and was logged at the conclusion of each test. This was done to keep an independent metric of each test cycle, as the vehicle's fuel economy readout was from an independent perspective than each of the PEMS units or to the lab. The dash panel fuel economy readings are generally included with the other fuel economy measurements in this work as a reference. No claim is made as to the accuracy of this reference, nor did ERG perform any specific evaluations or calibrations of this measurement.

PEMS time alignment. Certification tests of light duty vehicles use the principle of batch measurements of emissions samples collected in bags. Emissions of each phase of a test cycle are collected in bags, and then the mass associated with the total emissions is presented on a per-mile basis. This approach does not require any time alignment as it simply uses the total exhaust flow, the overall sample pollutant concentration, and the total miles traveled to yield a single final result. Conversely, PEMS measurements are taken continuously, both for exhaust flow and for pollutant concentrations in a manner similar to lab modal measurements. These types of measurements allow for the calculation of emission mass on a second-by-second basis. Because mass is calculated every second, time alignment between the exhaust flow rate and each pollutant concentration trace is important in order for the mass measurement to be accurate. Because PEMS calculate total emissions over a cycle as the sum of each instantaneous mass estimate, the accuracy of the cycle total is dependent on the accuracy of the mass measurement at each instant. There are various sample delay times for each type of measurement taken within each PEMS, especially between the flowmeter and gaseous analyzers, and the sample routing within a gas analyzer can cause different delay times for the measurement of each exhaust constituent.

The Horiba and GlobalMRV systems include integral methods of specifying the time delays for each measurement that the systems make. The user enters time delay values into the system, and the output data files are automatically time aligned based on those values. The Horiba system accepts the time delays as inputs during post processing, and the GlobalMRV Axion accepts the time delays as inputs during the initiation of a test. The 3DATX parSYNC does not include an integral time alignment feature. ERG worked to create a list of specific time delays for the two systems with integral time alignment features, and these lists were used for all tests of the respective units. To create alignment points, ERG conducted repeated engine starts with the engine and catalyst cold or relatively cool with each PEMS system installed and logging. After each start, ERG reviewed the logged data from the engine start to determine the delays in exhaust flow rate, OBD, and each measured exhaust constituent by looking at the moment that the signals rose above their engine-off values. The integral time delays were edited and another start was conducted until all measurement traces aligned acceptably with the OBD signal indicating the start of the engine (based on RPM). GPS time alignment was determined by performing a few sudden accelerations with the test vehicle and aligning the rise from zero of the

OBD and GPS speeds. For all constituents, the OBD signal was used as the baseline time to which the other measurements would be aligned. The two systems with integral delay features allow for the specification of a single time delay value for each measured parameter; as such, they do not account for the change in time delay resulting from changing exhaust flow rate and its effect on the time required to transport exhaust from the engine to the tailpipe. This is a common limitation on current-generation PEMS. For the 3DATX system, in which OBD parameters were logged separately by an ERG datalogger, ERG manually aligned each test based on the rising signals at the time of engine start.

The time delays used for tests of the Horiba are presented in Table 5-3, and the time delays used for tests of the GlobalMRV are presented in Table 5-4. Note that the GlobalMRV system utilizes two parallel gaseous analyzer modules so some of the measurements have two values given for each of the parameters to account for the time difference between the two modules. No equivalent values exist for the 3DATX system because ERG performed time alignment with the external datalogger manually for each test.

Table 5-3. The time delays used for time alignment of tests of the Horiba System

Measurement	Entered Time Delay (s)
GPS Speed	0
Weather Station	0
Exhaust flow rate	0
CO	-1
CO2	0
H20	-2
NO	-1
NOx	-2
NO2	-2
HC	0
PM DCS	-6
OBD	0

Table 5-4. The time delays used for time alignment of tests of the GlobalMRV System

Measurement	Entered Time Delay (s)
RPM (OBD)	0
CO	3.8/3.6
CO2	2.8/2.6
NO	4.4/4.1
C6H14	3.7/3.5
Real-time PM	4.5
GPS	1
Weather Station	0
O2	3.7/3.7

The 3DATX system had very little difference in time delays for the measured parameters. For these tests, ERG manually aligned the OBD signals with the logged parSYNC parameters based on the initial rise at the engine start. Once the two data sources were in alignment, no further alignments were performed.

Test checklists. ERG created specific test checklists for each PEMS. These were created with the assistance of each manufacturer's representative during the training week with each PEMS, and then updated throughout the project in order to streamline the test process and prevent any errors that might require impact test results. The test checklists included:

- Ballasting of test vehicle
- Checking of vehicle tire pressures
- PEMS equipment warmup
- Any necessary operational or performance checks on the PEMS
- The procedure to initiate an emissions test
- Zero/span or audit procedures
- A prompt to note and reset the in-vehicle dash fuel economy
- Steps needed to retrieve the logged data and properly shut down the equipment

Separate checklists were developed to accommodate the procedures required to do two repeat tests each day at the test track. A new test data collection form sheet was printed and filled out for each test. Copies of the finalized test checklists for each PEMS for lab/road tests and track tests are included in Appendix D.

Vehicle starting and operation. The vehicle was operated as consistently as possible throughout all tests. The vehicle air conditioning, defroster, and heater were kept off for all tests, whether on the dynamometer, road, or track. The PEMS sample and exhaust lines were routed to and from the units through one or both rear windows, which were opened just enough to accommodate the sample lines. As the tests were performed during summer months, the front windows were kept open when on road or track at lower speeds, and raised to be opened just 1 to 2 inches when at higher speeds (i.e., above approximately 40 mph). The goal was to keep the aerodynamic drag as close as possible to the certification coefficients (which would have been developed with the windows closed), but also to allow the vehicle interior to stay at a safe temperature. The engine was always started using the same sequence. The ignition was keyed on, followed by a 5-second pause, followed by the engine start and beginning of the driving cycle. This 5 second period was included as it was found to be the typical duration necessary to allow OBD communications to begin between the PEMS units and the vehicle. Establishing OBD connectivity at the time of engine start was necessary because two of the three PEMS depended on OBD parameters for exhaust flow rate estimation and therefore exhaust mass measurements. The test vehicle is equipped with a heated oxygen sensor, which begins heating when the vehicle is keyed on. For this reason, the key-on period was held as closely as possible to 5 seconds in order to minimize any effect on vehicle emissions variability. When moving the vehicle around the lab prior to and after emissions tests, the key was left off and the vehicle's neutral override switch was used to place the vehicle in neutral to allow it to be pushed with the engine and ignition off.

Test scheduling. In total, 5 dynamometer tests, 5 on-road tests, and 6 track test pairs were conducted for each PEMS. One of the original aims of this work was to minimize potential bias in comparing the different PEMS by rotating through the different units while completing the number of scheduled tests for each. This was limited somewhat by the availability of each PEMS unit used in the program; not all units were available throughout the entire duration of testing. The dynamometer tests and on-road tests were generally conducted on alternating days, while all track tests were conducted separately during a period from August through early September, 2017. For most dynamometer and on-road tests, a given PEMS unit was installed for two test days, consisting of a dynamometer test and then an on-road test, prior to the installation of the next PEMS (though there were some exceptions for various reasons). The test vehicle was preconditioned somewhat differently depending on test type (due to facility limitations), but the vehicle was always driven to full warmup between 12 to 36 hours prior to any emissions test.

Pre-test soak periods ranged in duration from 12 to 36 hours but were generally closer to 24 hours.

Table 5-5 contains the procedure for dynamometer and on-road tests, which generally took place on successive days with a given PEMS unit. The table includes a day number to indicate which steps occurred on each day in a sequence. After the completion of step 7, steps 1-3 could be repeated on the same day with the next PEMS installed. By doing this, it was not necessary to lose a day to fueling and preconditioning if testing continued on successive days. For these tests, the vehicle was always soaked indoors between 68°F and 86°F at the SwRI facility. The dynamometer preconditioning cycle consisted of the Hot 505-second phase of the FTP-75 test cycle. The test vehicle's evaporative canister was then purged and loaded as a part of the preconditioning for each dynamometer. The canister was purged with air at 0.8 standard cubic feet per minute (SCFM) for a total flow of 300 canister volumes. Then, the canister was loaded with a 50/50 mix of butane and nitrogen to 1.5 times the working capacity of the canister during the soak period prior to the dynamometer test. The procedure was developed based on the dynamometer preconditioning portion of 40 CFR 86.132-96.

Table 5-5. Preconditioning and Test Steps for Dynamometer and Road Tests

Step	Day	Action
1	1	Fuel Drain and Fill
2	1	Preconditioning over Hot 505
3	1	Canister Loading
4	1	12-36 hour soak
5	2	Dynamometer test cycle
6	2	12-36 hour soak
7	3	On-road drive

The test track did not have the same facilities to support emissions testing as did the SwRI lab. No climate controlled soak areas were available (though the majority of test days involved overnight low temperatures around 75°F). There was also no specific area for fuel draining, or cold fuel storage at the track. For this reason, the fueling and preconditioning process was somewhat different at the test track than at SwRI. Non-vented cans of test fuel were transported to the test track on approximately a weekly basis. The test vehicle was run to operating temperature the day prior to a test, and then 2-3 gallons of test fuel were added to keep the test vehicle at or just over 40% full during each soak. The test would then serve as the preconditioning for tests taking place on the next day, and fuel was added each day so that the tank would be at the same level prior to each test day. In this way, the fuel properties were kept as stable as possible given cold fuel storage and fuel draining was not feasible at the test track.

5.2 Specific Procedures for Each Test Type

Dynamometer tests. Dynamometer tests in the lab were conducted in keeping with the dynamometer and exhaust emissions portions of the light-duty certification provisions given in 40 CFR 1066 as appropriate. The same driver was used for all dynamometer tests. Generally, the PEMS test data logging was started either immediately before or at the same time as the dynamometer test controller. The PEMS test was stopped at the same time or immediately after the conclusion of the test. The SwRI driver controlled the dynamometer controller and the vehicle, and an ERG staff member controlled the PEMS to start and stop the test.

The PEMS and lab equipment sampled from the exhaust in series. The PEMS sampling point, either the flowmeter and/or sample probe mount tube, depending on the installed system, was most upstream in the exhaust. The lab sample tubes for the modal gaseous measurements as well as the MSS were located immediately downstream from this point. Then, the transfer pipe directed the remaining bulk exhaust flow into the CVS tunnel for dilute gaseous and PM sampling. Figure 5-2 shows a picture of the setup used during chassis dynamometer tests of the test vehicle. The PEMS flowmeter mounts to the elbow and extension pipe that is clamped to the tailpipe. Downstream of this are the probes for the modal gaseous sampling as well as the MSS. The MSS unit is on a cart at the left of the picture. The transfer pipe to the CVS tunnel is in the foreground of the picture, just upstream of the vertical segment that leads to the tunnel. The modal gaseous analyzer is in the background.

Figure 5-2. The exhaust sampling and transfer pipe setup for chassis dynamometer tests.

The CVS dilute measurement technique assumes that all exhaust generated by the vehicle is introduced into the CVS dilution tunnel. However, because raw exhaust was extracted upstream of the CVS tunnel for the PEMS measurement, the modal measurements, and the MSS, the final dilute emission results required adjustment to accurately account for the raw extractions. To calculate the adjustment for the laboratory equipment extractions, the extraction flow rates and pollutant concentrations were recorded for each type of raw measurement. The extracted mass of each pollutant was then calculated and added back to the mass as determined by the dilute CVS emission measurement to give the final dilute emission results. The correction for the PEMS extractions were corrected separately based on the sample flow rate for each PEMS. The Horiba system extracts sample separately for the gaseous and PM modules, and the PM module has an internal flowmeter as it does not operate at a constant extraction rate. This flowmeter measurement was added to the steady gaseous module flow rate, and this sum was used for tests with the Horiba system. For the GlobalMRV and 3DATX systems with steady flow rates, ERG measured their system flow rates prior to testing using a handheld TSI 4000-series flowmeter, and these values were used to calculate the total sample extraction rate for all tests. The nominal sample flow rates for each PEMS are presented in Table 5-6 in units of standard liters per minute (SLPM). All PEMS sample flow rates were very small compared to the average vehicle exhaust flow over the test, which was calculated by the laboratory modal system to average approximately 840 SLPM.

Table 5-6. Nominal Sample Flow Rates for CVS Flow Correction for Each PEMS

PEMS	Nominal Sample Flow Rate (SLPM)
Horiba	2.6
GlobalMRV	14.4
3DATX	2

The laboratory systems included multiple sample extractions as well. The MSS and modal samples were drawn directly from undiluted exhaust, and the PM sample for the filter system was drawn from the dilute exhaust in the CVS tunnel. The MSS sample draw was approximately 0.9 SLPM, and the modal bench sample flow was approximately 3.75 SLPM. Taken in sum, these represent approximately 0.5 percent of the average exhaust flow rate during the tests. The PM filter sample flow, taken from the dilution tunnel, was approximately 47 SLPM, which represented nominally 0.5 percent of the CVS flow rate.

On-road tests. On-road and track tests could not necessarily be conducted as closely to the CFR 1066 requirements as the dynamometer tests, but ERG did conduct those tests in keeping with the spirit of those regulations where possible. After completing the dynamometer test the day before, then soaking overnight, the test vehicle was pushed out of the SwRI dynamometer lab and into the same position in the driveway each time (the same position as was used to begin the route test drives). The PEMS test was started, the vehicle keyed-on for 5 seconds, then the engine was started. After a 10 second idle period (the same as on the dynamometer trace), the vehicle was put into motion and the route was followed. The driver attempted to drive normally, and generally follow along smoothly with traffic. At the completion of the route, the driver returned to the same stopping point each time. After coming to a stop, the engine was allowed to run for 5 seconds and was then shut down and the PEMS test stopped.

No issues with the driving route manifested themselves during testing. The route was never closed or affected by road construction. No particularly significant traffic stoppages occurred during any of the tests, though the amounts of traffic did vary somewhat each day.

Generally, each on-road test was started sometime between 9:30 am and 10:30 am to coincide with the period just after morning commute traffic.

Track test day pairs. Track tests were conducted in pairs so that one test could be conducted on the smooth track, and one could be conducted on the potholed track each day. As such, one test was performed as a cold start, and the other performed as a warm running test. For each PEMS, half of the six track test days began with a cold start on the smooth track, and half began with a cold start on the potholed track. These were generally alternated each day unless there was an overriding scheduling issue with the track administration, as there were other customers at the track with competing scheduling needs.

Track testing required two project staff members, one to sit in the driver seat, and one to sit in the passenger seat. The driver was responsible for holding and watching the driver aid computer, starting and stopping the engine, and following the speed trace using the throttle and brake pedals. The passenger held the steering wheel and steered the vehicle around the track and, when on the ride road, over the potholes. Because of the stop-and-go nature of the drive cycle and the split driving duties, it was necessary for ERG to have the ride road dedicated for these tests with no other vehicles present and, when on the main track, a single lane was dedicated for these tests. In this way, the complete trace could be followed without interference from other vehicles which might have required the driver to slow down and drop off the speed trace.

The work bay used at the track was adjacent to the ride road (i.e., potholed) track. For cold starts on that track, the test vehicle was towed out of the bay and into the same position on the test track for each test. The test was then started with a 5 second key on period, followed by simultaneous engine start and driver aid trace start. Then, the trace was followed through to the end. For tests that began on the main track (the entrance to which was about 3 miles from the work bay), the test vehicle was left in a parking lot adjacent to the track entrance to soak overnight. Prior to the test, the vehicle was pushed into the main track entrance lane, and the test was then started similarly to those on the ride road.

After the completion of the cold start test cycle, the vehicle was driven into the work bay and switched off. The previous test was concluded, either by stopping the test or performing a post-test zero/span or audit. For systems so equipped, the PM filter was changed at this time. For the GlobalMRV and 3DATX systems, the post-test audit served as the pre-test audit for the hot running test. Then, the vehicle was started and driven to ensure the engine was completely warm and positioned at the start position on the next track. Here, it was allowed to idle for 10 minutes in order for the engine temperature and operational conditions to stabilize. At the conclusion of the idle, the PEMS test and driver trace were started and the test cycle followed to completion. After the test, the vehicle was returned to the work bay for the post-test zero span.

For tests on the potholed ride road track, an accelerometer was used to log the points in the test cycle that the bumps and potholes were hit. The accelerometer data log was separate from the driver trace and the PEMS units, and needed to be manually inserted into the data for each test. The accelerometer data time alignment was facilitated by having the passenger "bump" the accelerometer a single time at the start of the trace. In this way, a visible point was inserted in the data that could readily indicate the test start. The accelerometer was only used during tests on the potholed track, and was located on the same place on the vehicle's console for every test.

5.3 Calculations Applied to PEMS Data

In order for PEMS-measured parameters to be compared to the results of the lab measurements, and to facilitate comparisons across the different PEMS units, ERG applied some of its own calculations to the different PEMS datafiles while leaving the original PEMS data intact. This section describes these calculations and why they were necessary. Each different PEMS had its own output format and basis of measurement, and for appropriate cross comparisons, certain calculations were necessary. One calculation that was applied to data from all 3 PEMS was a correction to the OBD speed signal, as described in Section 3.2.

Horiba OBS-ONE. This system is designed to conduct PEMS tests under 40 CFR 1065, with a focus on heavy duty vehicle engine testing. However, the test output sheet includes all data fields needed for these analyses, including total emission mass over the cycle for various exhaust constituents. The system is designed to operate in a similar fashion to lab analyzers, and as such, no calculations were necessary to convert the outputs to the same basis as the lab measurements.

GlobalMRV Axion. The Axion outputs top-down files containing the second-by-second parameters, including the pollutant masses as calculated within the GlobalMRV proprietary code. To calculate total emission masses over the test cycles, ERG summed the fields for each pollutant for the time period of the test and these values were directly used as the results for this system. Similarly, the vehicle speed was integrated and then corrected to total miles, with an adjustment made for the vehicle speed sensor error.

The Axion unit calculated the fuel rate in grams per second on a second-by-second basis and this calculation is included in the top-down datafile generated from each test. The method of calculation is not included in the documentation. In order to calculate overall cycle fuel economy, ERG summed the fuel rate over the duration of the test, and then divided by the fuel density in order to get fuel volume. The miles traveled over the cycle (corrected for the vehicle speed sensor error) were then divided by the total fuel volume in order to calculate fuel economy.

3DATX parSYNC. Because the parSYNC does not measure exhaust flow or estimate constituent mass, ERG performed a number of calculations to allow for direct comparisons with the other PEMS systems and the lab results. This included the OBD-based estimate of exhaust flow rate as well as calculation of pollutant mass at each second of operation using a method based on that given in 40 CFR 86.144.

SwRI assisted in the estimate of exhaust flow rate based on OBD signals. This was done by performing a curve fit of logged OBD parameters to dynamometer exhaust flow rate data from the actual dynamometer tests. The fits could be post processed, and the methodology used for all three types of tests. The three relevant OBD parameters that could most significantly determine exhaust flow rate were:

- the manifold absolute pressure (MAP),
- the air/fuel ratio, λ,
- and the engine speed, S.

In order to develop a generic form of an equation using these terms to calculate exhaust flow rate, a simple proof was followed:

- the exhaust mass flow rate is equal to the sum of the intake air mass flow rate and the fuel mass flow rate

$$\dot{m}_{ex} = \dot{m}_{air} + \dot{m}_{fuel}$$

- the fuel mass flow rate is proportional to the air mass flow rate divided by the air/fuel ratio

$$\dot{m}_{fuel} \propto \frac{\dot{m}_{air}}{\lambda}$$

- the exhaust mass flow rate is proportional to the air flow rate plus the air flow rate divided by the air fuel ratio. The air flow rate can be factored, leaving 1 + λ.

$$\dot{m}_{ex} \propto \dot{m}_{air} + \frac{\dot{m}_{air}}{\lambda} = \dot{m}_{air} \cdot \left(1 + \frac{1}{\lambda}\right)$$

- the air mass flow rate is proportional to the manifold absolute pressure and the engine speed.

$$\dot{m}_{air} \propto MAP \cdot S$$

- finally, by substitution, the generic form of the exhaust flow rate equation is as follows:

$$\boldsymbol{\dot{m}_{ex} \propto MAP \cdot S \cdot (1 + \frac{1}{\lambda})}$$

Using the second-by-second logged exhaust flow rate from multiple chassis dynamometer tests, the above equation was calculated on a second-by-second basis using the default OBD engineering units and fit to the exhaust flow rate using a polynomial fit. An example of that fit is shown in Figure 5-3. The final curve fit coefficients used on the calculated generic form were 4.761 x 10-14 for the generic form squared, and 5.747 x 10-8 for the generic form (linear). The intercept was held at zero. The OBD engineering units on MAP were kPA, on engine speed were RPM, and lambda is dimensionless. The CVS-measured exhaust flow is represented at standard temperature and pressure.

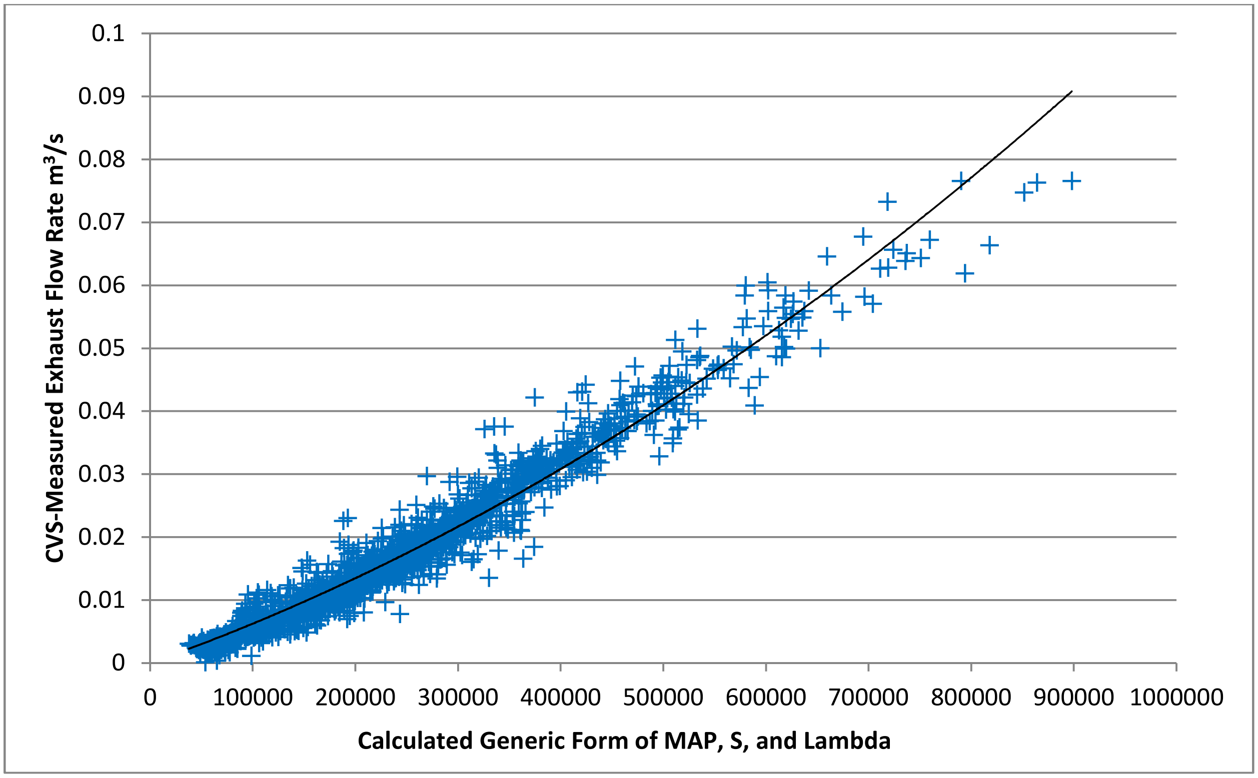

Figure 5-3. Curve fit of the generic form of three OBD parameters to CVS-logged exhaust flow rate for a single dynamometer test (each point is 1 second of the test).

Using the above approach, exhaust flow rate was estimated for each second of operation for 3DATX tests. ERG summed the concentration signals for NO and NO_2 for the estimate of NOx concentration.

ERG followed 40 CFR 86.144 as a guide for the calculation of NOx and CO_2 masses. While 86.144 is written primarily for calculations of batch dilute measurements from a dilution tunnel, some of the equations can be applied with slight modification for second-by-second PEMS data. The equation used for mass calculation of a given pollutant, $\dot{m}_{pol}$, is as follows:

$$\dot{m}_{pol} = \dot{V}_{exh} \cdot \rho_{pol} \cdot X_{i,pol}$$

Where $\dot{V}_{exh}$ is the exhaust volumetric flow rate, m^3/s (corrected to standard conditions),

$X_{i,pol}$ is the volume fraction of the exhaust (i.e., concentration) for a given pollutant at a given second, and ρ_{pol} is the pollutant density at standard conditions, as given in 40 CFR 86.144.

ρ_{pol} for NOx is 1913 g/m^3, and ρ_{pol} for CO_2 is 1830 g/m^3.

The parSYNC does not calculate the vehicle fuel rate or cycle fuel economy by any method. In order to estimate the fuel economy as measured by the PEMS unit, ERG calculated a carbon balance fuel economy for each test with the parSYNC system. This calculation was based on the fuel economy calculation method described in 40 CFR 86.600. Because the parSYNC does not measure CO or HC, only the CO_2 term of the fuel economy equation was used, however this should cause a relatively small amount of error as CO_2 represents by far the greatest amount of carbon in the exhaust. The equation for fuel economy is:

$$mpg = \frac{5174 \cdot 10^4 \cdot CWF \cdot SG}{(CWF \cdot HC + 0.429 \cdot CO + 0.273 \cdot CO_2) \cdot (0.6 \cdot SG \cdot NHV) + 5471}$$

Where:

mpg is the fuel economy, miles per gallon,

CWF is the carbon weight fraction of the fuel (0.8276 for this fuel),

SG is the specific gravity of the fuel (0.7542 for this fuel),

HC, CO, and CO2 are the grams per mile of hydrocarbon, carbon monoxide, and carbon dioxide, respectively, over the cycle,

and NHV is the net heating value of the fuel in BTU/lb (17,444 BTU/lb for this fuel)

6.0 Test Measurements and Results

This section presents the results of the various types of measurements made by the different PEMS systems for comparison against the laboratory measurements. Included are a discussion of the QA checks applied by ERG to the test results, the fuel economy results, and the exhaust emissions measurement results for the different types of tests conducted during the program. A complete log of individual fuel economy and emission mass results for each test is presented in Appendix E.

At the request of CRC, the specific PEMS instruments have been blinded in these results. Additionally, because not all systems can measure all exhaust constituents, the results for each exhaust constituent or measurement type are blinded using a different anonymous identifier in successive analyses to avoid the identity of the devices being apparent based on absence from certain result plots. So, for example, PEMS A, B, and C will only appear in the first group of plots, and for the next, the names will be redefined as any one of PEMS D, E, and F, etc. The identifiers are reset to A as necessary and do not necessarily follow the same blinding order after being reset.

To put the pollutant mass emissions in context, the test vehicle was certified to Tier 2, Bin 5 emissions standards, and had certification limits over the FTP-75 cycle of 0.05 g/mi NOx, 3.4 g/mi CO, and 0.075 g/mi nonmethane organic gas (NMOG). The NMOG standard is a hydrocarbon standard that can be thought of as approximately the total HC mass minus the methane mass fraction. The HC measurements evaluated in this work were on a total HC mass basis, which, for a given test, will be higher than the NMOG. The published FTP-75 emission results for the engine family of the test vehicle (DHYXV02.01TE) were 0.023 g/mi NOx, 0.27 g/mi CO, and 0.018 g/mi NMOG. Where the total mass emissions over the cycle are shown in this section, references are also made to the total emission mass equivalent of the certification standard emission rate multiplied by the number of miles in the project test route (26.7) for comparison. It should be noted that this is a very approximate comparison given that the test cycle in this work was completely different than the FTP-75 certification test cycle and is presented only as a point of reference.

6.1 Data Review and Quality Assurance

ERG performed rigorous in-field test monitoring and performed a number of data reviews to ensure that testing was conducted properly and that final results are calculated and presented in a manner that reflects the procedures recommended by each PEMS manufacturer. This section describes the various quality assurance (QA) checks and reviews that ERG applied during this project.

At the conclusion of each test, project personnel reviewed any PEMS software errors or alarms in order to note whether the systems detected any potential problems that could affect the recorded measurements. After the test was concluded and the data written to file, ERG generated and reviewed overall plots of each pollutant concentration trace to look for outliers, clipping, or loss of signal. Observations of any of these instances were noted in the project log for further review. The goal of this data review was to note whether tests may have been impacted by problems with the PEMS units, procedural problems, or other situations that could affect test data. Tests in which the systems were set up and tests begun correctly were voided and not repeated. Conversely, tests in which lab equipment failed or procedural errors were made by project staff were repeated and the original data removed from further consideration.

One test was voided and not repeated due to loss of signal during the driving route as the PEMS sampling system clogged with water and sampling stopped. Four chassis dynamometer tests were voided and repeated due to lab errors during the program; one case had excessive driver error time and three others had sample train hardware failures that caused loss of data. Visual checks showed no evidence of clipping elevated concentration values for any measured pollutant. No PEMS traces indicated discontinuous outlier values.

At the conclusion of the program, data logged by each PEMS was sent to the respective PEMS manufacturers for review if the manufacturer chose to do so. Any manufacturer comments were discussed and considered for inclusion in the analysis for the report.

During the analysis phase, ERG conducted numerous spot checks for data transcription errors (for those PEMS outputs that required data entry). ERG used a secondary QA staff member to independently review all calculations to ensure that equations and calculations were correctly and appropriately applied and results were reasonable. The calculations of statistics involving test-to-test repeatability and error bars were separately reviewed by an additional ERG staff member. The goal of all QA checks was to be sure that the results in this report reflect, as accurately as possible, the intended operation of each PEMS, and that calculations necessary for cross-comparisons among the different PEMS units were appropriately applied to best capture the intent of the regulations in 40 CFR 86, 1065, and 1066.

6.2 Fuel Economy Measurements

Fuel economy results are presented in this section, averaged by measurement type and test type. The different measurement types are the lab CVS calculated by carbon balance (for the dynamometer tests only), the dash display from the vehicle, and the values measured by each of the three PEMS.

The average fuel economy from all measurement types and over the three different test types is presented in Figure 6-1. Error bars are presented for 95% confidence intervals calculated based on the variability of each set of repeated measurements. Variability is calculated for each group of test type (dynamometer, road, smooth track, or rough track) and each instrument (lab and the different PEMS). Note that there were a different number of tests for each measurement type. There were 15 total lab measurements of fuel economy on the dynamometer, but each PEMS only has 5 fuel economy measurements on the dynamometer. Likewise, the dash display is the average of all measurements of each type and so does represent three times as many measurements than the bars for each of the PEMS units. So, the size of the error bars is affected by the number of measurements as well as the variability within each. In order for the fuel economy to be comparable across all test types, the smooth and rough track tests in the figure refer to cold-start track tests only. The hot-start fuel economy results are presented later in this section.

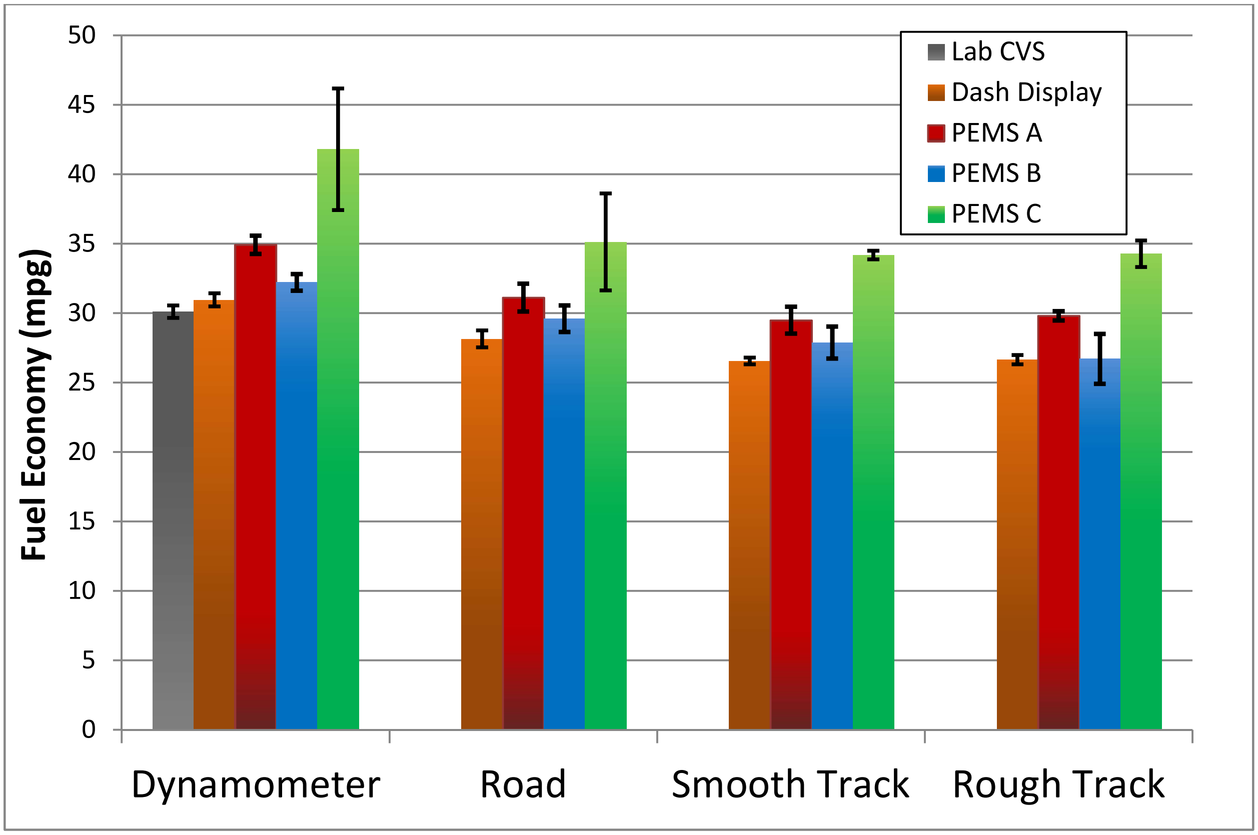

Figure 6-1. Average fuel economy results by measurement source and test type. Error bars represent 95% CI based on variability among repeat tests of each type.

The dash display fuel economy represents a relatively impartial measure of fuel economy over all tests. It shows that the vehicle, in general, operated with the highest fuel economy on the dynamometer cycles, and the lowest fuel economy on the track cycles. For dynamometer tests, all PEMS units reported a fuel economy higher than that reported by the lab CVS or the dash display values.

Half of the on-track tests were conducted as hot-running cycles in which the engine was idling at the start of the test. The fuel economy, as measured by the dash display and the three PEMS for the hot-running track tests are presented in Figure 6-2. The trends among the different measurement types are similar to those observed during cold-start tests. Based on the various measurements, the test vehicle appeared to achieve approximately two percent higher fuel economy during the hot-running tests than the cold-start track tests.

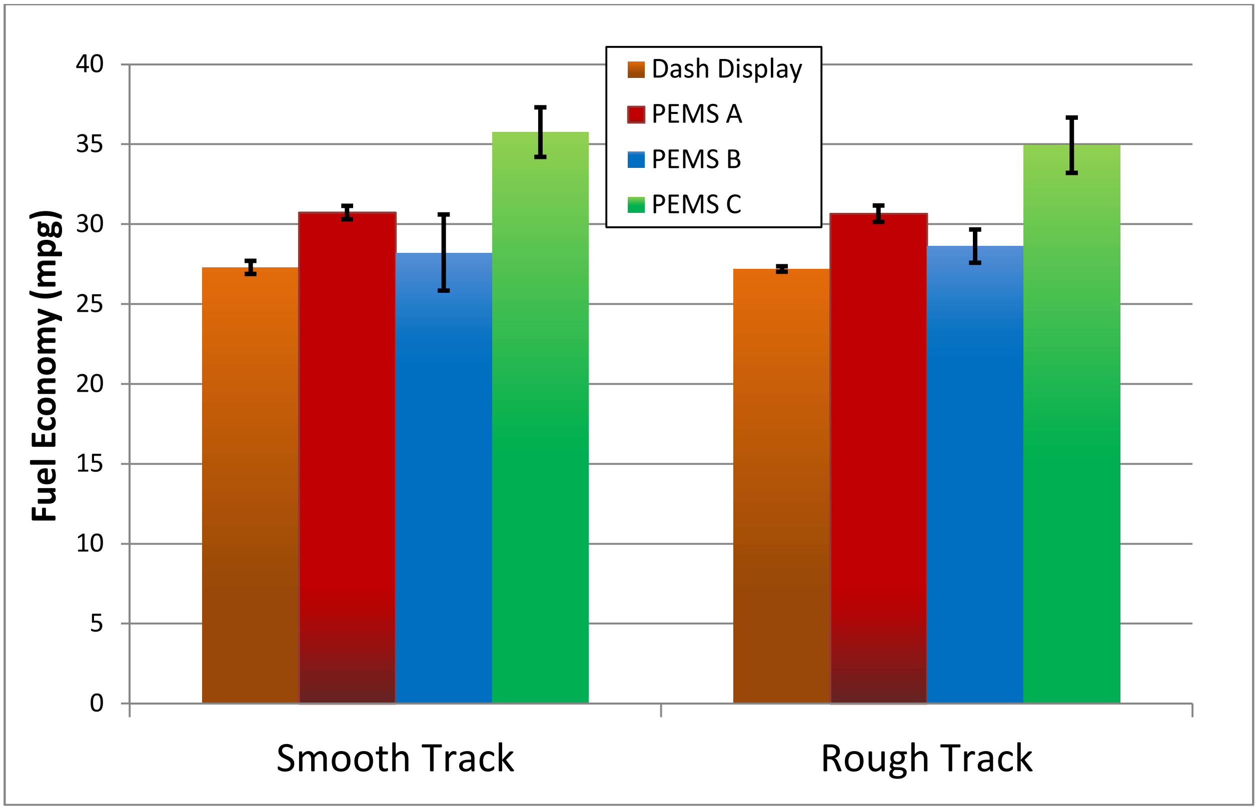

Figure 6-2. Average fuel economy results by measurement source for the hot-running on-track tests.

6.3 Total Pollutant Mass Measurements

This section contains the total mass measurement results over each test as measured by the lab and each PEMS. As in the fuel economy section, error bars are presented for 95% confidence intervals based on the variability among repeat measurements within each test group. As previously mentioned, the lab CVS averages represent all dynamometer measurements, so these confidence intervals represent a different sample size than intervals for the PEMS units.

For the track test results across the different test types, only the cold-start cycles are included so that they are most directly comparable to the cold-start dynamometer and road tests. Hot-running test results from track testing are presented separately at the end of this section. Gaseous measurements from the lab CVS presented in this section are from the bag measurements only (not the lab modal measurements), and PM results are based on the lab's gravimetric filter measurements.

Results for CO_2 mass measurements are presented in Figure 6-3. The averages shown in the figure trend inversely to the fuel economy results shown in the previous section (the letter identifiers are kept the same in this plot as the fuel economy plots). This is to be expected given that the carbon balance fuel economy is inversely proportional to the total carbon mass in the exhaust. It is interesting to note that the trend in total mass emissions for each PEMS hold across all test types, indicating the likelihood of a relative level of bias in a single direction for each system. All three PEMS systems and the lab system use the same type of NDIR measurement of CO_2.

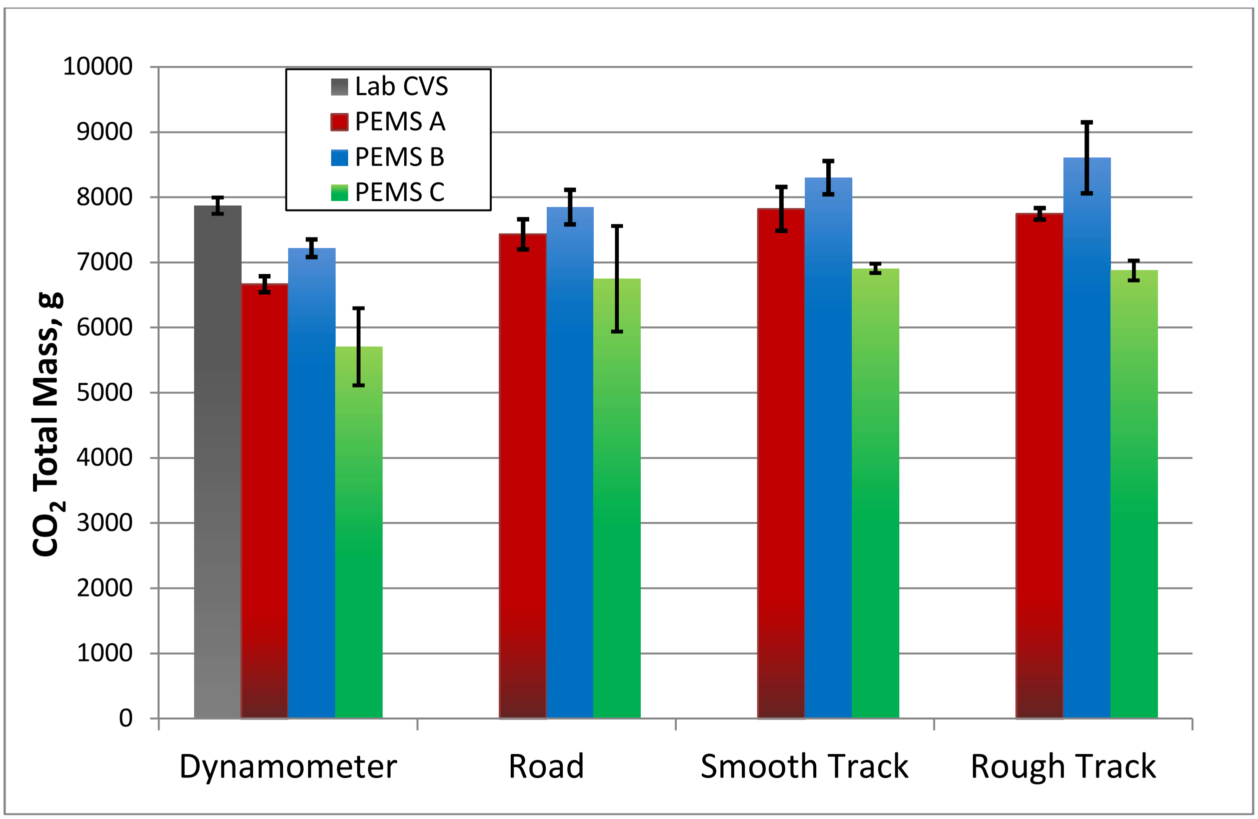

Figure 6-3. Average CO_2 mass emissions for all measurement and test types. Error bars represent 95% confidence intervals based on variability.

The average NOx emissions for all tests are presented in Figure 6-4. The lab CVS measurement and two of the three PEMS units measured NOx, and the other PEMS measured NO. The PEMS measuring NO is included in this plot with the other measurements of NOx in order to preserve the blinding of the results and, as the test vehicle is gasoline-powered, because NO is expected to represent a large majority of the NOx mass.[3] Further, the lab did not have a singular measure of NO (as one is not specified in federal certification regulations), so there is no other direct comparison to lab-measured NO available. For comparison, the NOx emission certification standard for this vehicle was 0.05 g/mi over the FTP-75, and with the test route distance of 26.7 miles, an approximate equivalent NOx total emission would be 1.34 g (note that the test cycle is completely different from the FTP-75, however, so the comparison is only approximate).

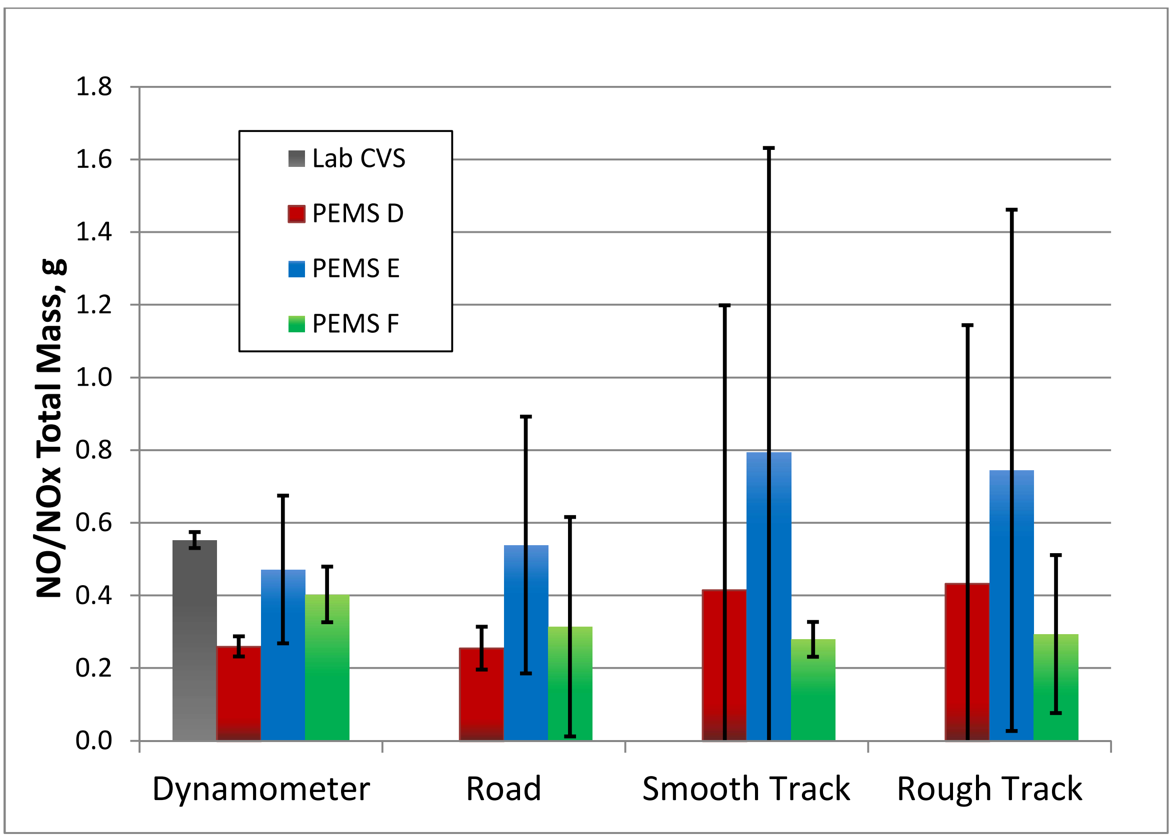

Figure 6-4. Average NO/NOx mass emissions for all measurement and test types.

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[3] One of the PEMS that could measure both NO and NOx reported NO emission masses averaging between 80% to 90% of the reported NOx mass.

No clear trends in NOx emerge from the dynamometer to the on-road or track tests as some PEMS measured higher levels of NOx and some lower. It can be seen that the levels of variability for NOx are notably higher for road and track tests as compared to those performed on the dynamometer. There were only three replicate cold-start track tests for each of the smooth and rough surfaces, so the lower number of replicates results in wider confidence intervals. The vehicle is a notable source of variability as well, especially during the track tests and the less-controlled road tests. The next section presents second-by-second results and it can be seen that occasional short bursts of emissions from the vehicle can significantly affect the total test emission mass. These bursts occur irregularly and not at all in some tests, further widening the error bars. As described in Section 4.0, measurement of NO/NOx is by chemiluminescence for the lab and one PEMS, and by electrochemical sensors for the other two PEMS.

The remaining graphs in this section represent the findings with one of the PEMS excluded due to its measurement capabilities. Average mass emissions for CO are presented in Figure 6-5. For the dynamometer tests, both PEMS in this group agreed statistically with the lab CVS measurements. One of the PEMS units agreed fairly well between dynamometer measurements and road/track measurements, and the other tended to measure higher values over the road and track tests. For comparison, the CO certification standard for this vehicle was 3.4 g/mi over the FTP-75 which, given the length of the E-122 test cycle, is approximately equivalent to 91 g.

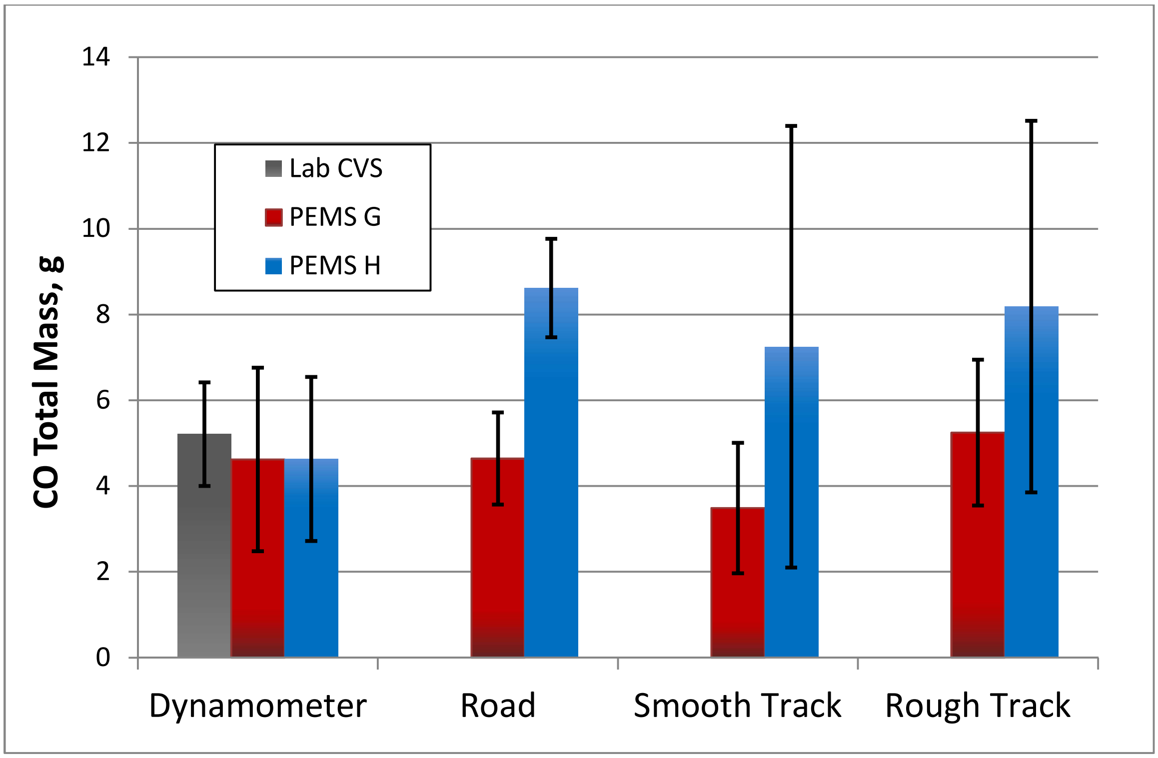

Figure 6-5. Average CO mass emissions for all measurement and test types.

As with NOx, the error bars tend to be wider for the track tests than the dynamometer or road tests, partly because of the fewer replicates. The variability of the track tests was elevated, however. For the smooth track tests of the PEMS with the highest variability, the highest mass measurement of CO mass was nearly double the measurement with the lowest mass. This was not consistent with expectations given that the same speed trace was followed starting from the same place on the track every day, however it appears to be a real effect given that the track variability is elevated across most pollutants and PEMS. All measurement systems represented in the plot utilize NDIR for measurement of CO.

Average mass emission results for HC are presented in Figure 6-6. One of the PEMS is significantly different in results than the lab measurement on the chassis dynamometer, and the other is not significantly different. As observed with NOx emissions, the variability in measurements of both PEMS tend to be noticeably higher for both the road and track measurements. As can be seen in the next section, this is partially due to short-term elevated bursts of emissions that occur irregularly, usually in the higher-speed portion of the test cycle. One of the PEMS has particularly high levels of variability in HC measurement during the track testing on both surfaces. There were no apparent failures or issues that caused this, the measured total emissions simply had a high level of variability ranging between approximately 0.3 and 1.2 grams total over the track tests. The lab and one PEMS use a FID for the measurement of hydrocarbon, and the other PEMS uses NDIR. For comparison, the test vehicle's certification standard for NMOG was 0.075 g/mi, corresponding to 2 g over this test cycle's distance (although the measurement basis of NMOG is different than the basis of HC measured by the PEMS devices and the laboratory equipment).

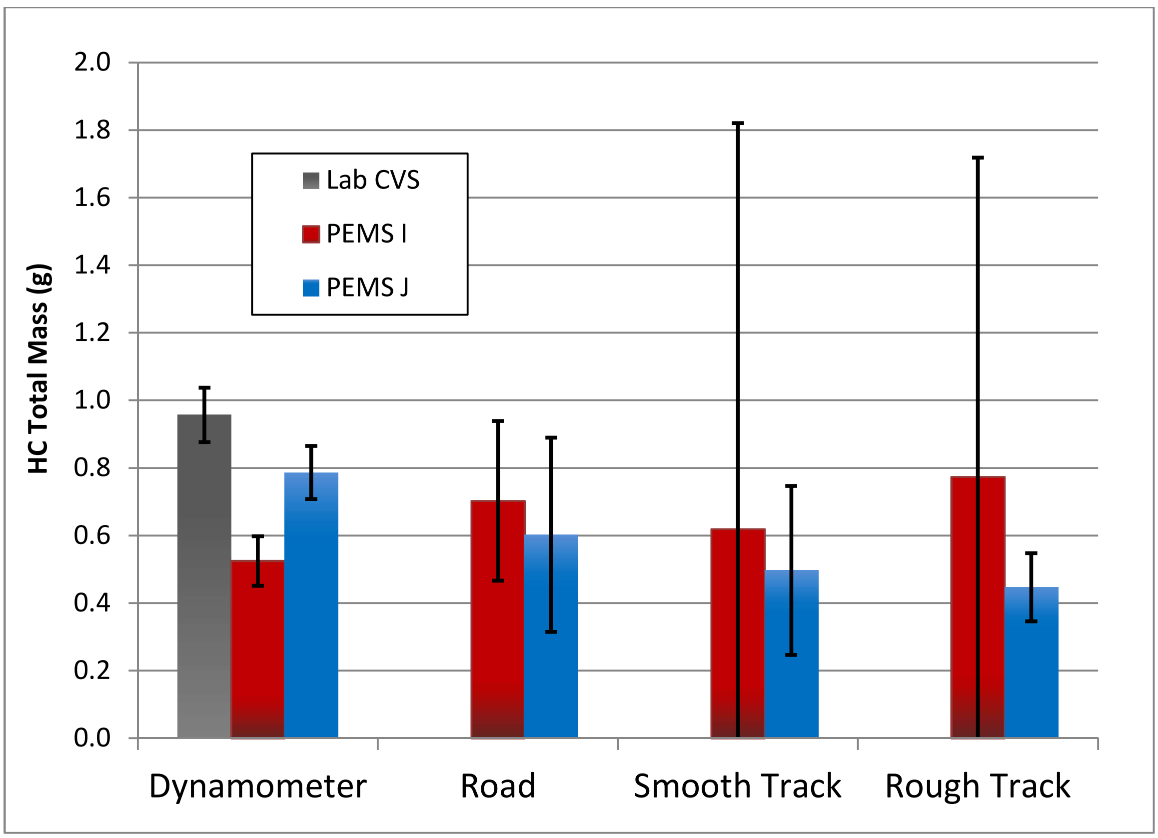

Figure 6-6. Average HC mass emissions for all measurement and test types.

Average mass results for PM are presented in Figure 6-7. For the lab, the PM results represent the PM mass as measured by the gravimetric filter method. Both of the included PEMS report PM mass as outputs, though the two measurement types are different; gravimetric and optical with an internal transfer function. The other PEMS is excluded as it does not report PM emissions on a mass basis that can be compared to the other systems. For the dynamometer tests, it can be seen that one PEMS averaged measurements very close to the laboratory measurements, and the other PEMS underreported PM mass compared to the laboratory measurements.

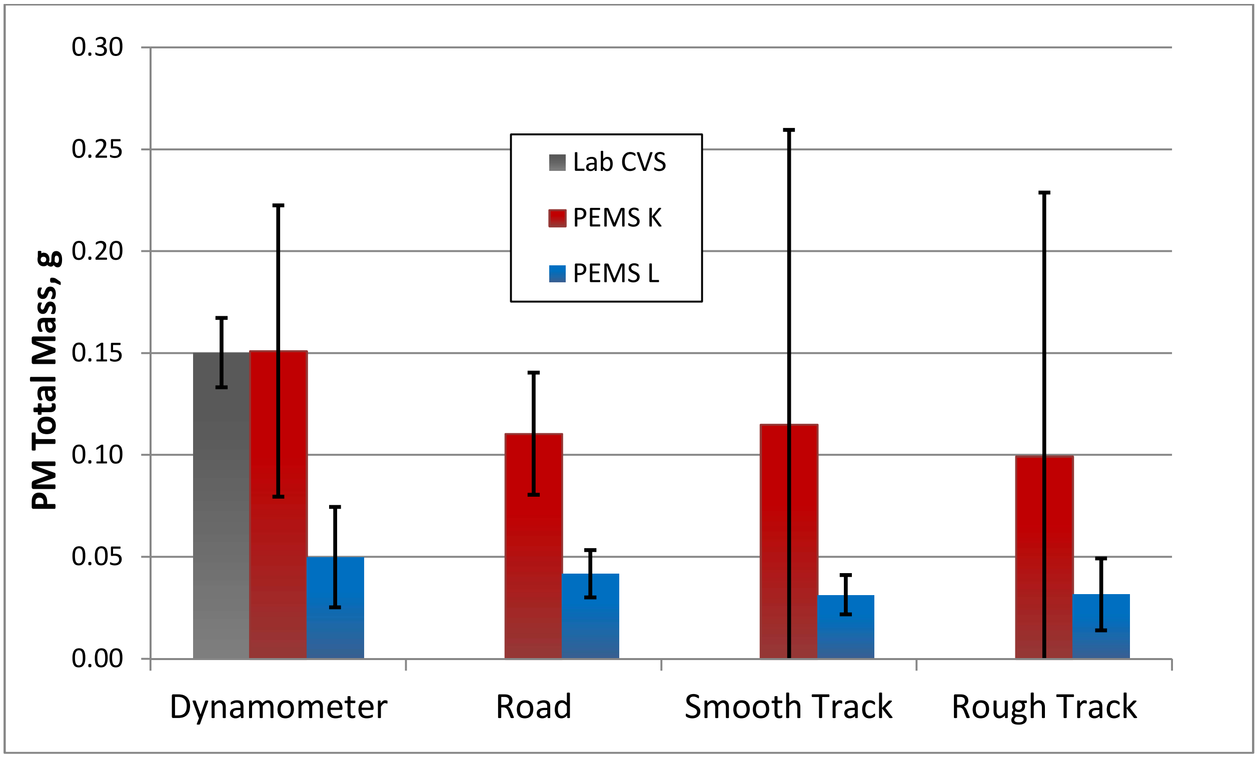

Figure 6-7. Average PM results for all measurements and test types.

Overall, the greatest level of agreement between lab CVS and the PEMS on the dynamometer was for CO. The measured PM mass was particularly variable in comparison from PEMS to lab CVS; this is likely due to the very different measurement techniques employed by the different systems. For the gaseous emissions, most PEMS dynamometer tests resulted in measurements lower than the lab CVS measurement. This is likely due to the trend of most of the PEMS flowmeters/exhaust flow calculations in the study underestimating exhaust flow rate as compared to the CVS. Inaccuracies in time alignment may also cause a bias low for the PEMS system as results tend to get biased low when peaks in exhaust flow do not match up exactly with peaks in emission concentrations.

Interestingly, given that the speeds and accelerations followed on the track were controlled much more tightly than those encountered on the on-road drive, both the smooth and rough track tended to have variability in the results more similar to the on-road tests than the dynamometer tests. One reason for this may be the disparity in grade between the real route, which was modeled on the chassis dynamometer, and the track grade. In general, the track was relatively flat but it did have some steady up and down grades. These did not align with the driving trace, however. The speed trace has gentle accelerations and decelerations that resulted from normal driving over the actual route grades. The track grade did not necessarily align with these, meaning that the throttle and braking was not as natural. For example, a coast on level ground on the actual route may have required braking to stay on the trace during a downhill portion of the track, causing some amount of additional lost energy. This may be why the fuel economy on the track was slightly less, on average, than it was on the road, and may also be a factor in the higher emissions variability at the track given that the second-by-second speed was controlled to match the dynamometer tests.

The emission results from the hot running track tests are presented in the following figures. The plots follow a similar format as the previous plots of average emission mass by PEMS and test type, with error bars representing the 95% confidence intervals of the mean based on variability across multiple tests. Figure 6-8 presents the average NO/NOx (depending on the measurement made by each PEMS) emissions over the hot running track cycles. Averages are calculated for the test on the smooth track surface and the potholed track surface. Taking results for all three PEMS together, the NOx mass results tended be only slightly (~10%) lower during the hot running tests as compared to the cold-start track tests.

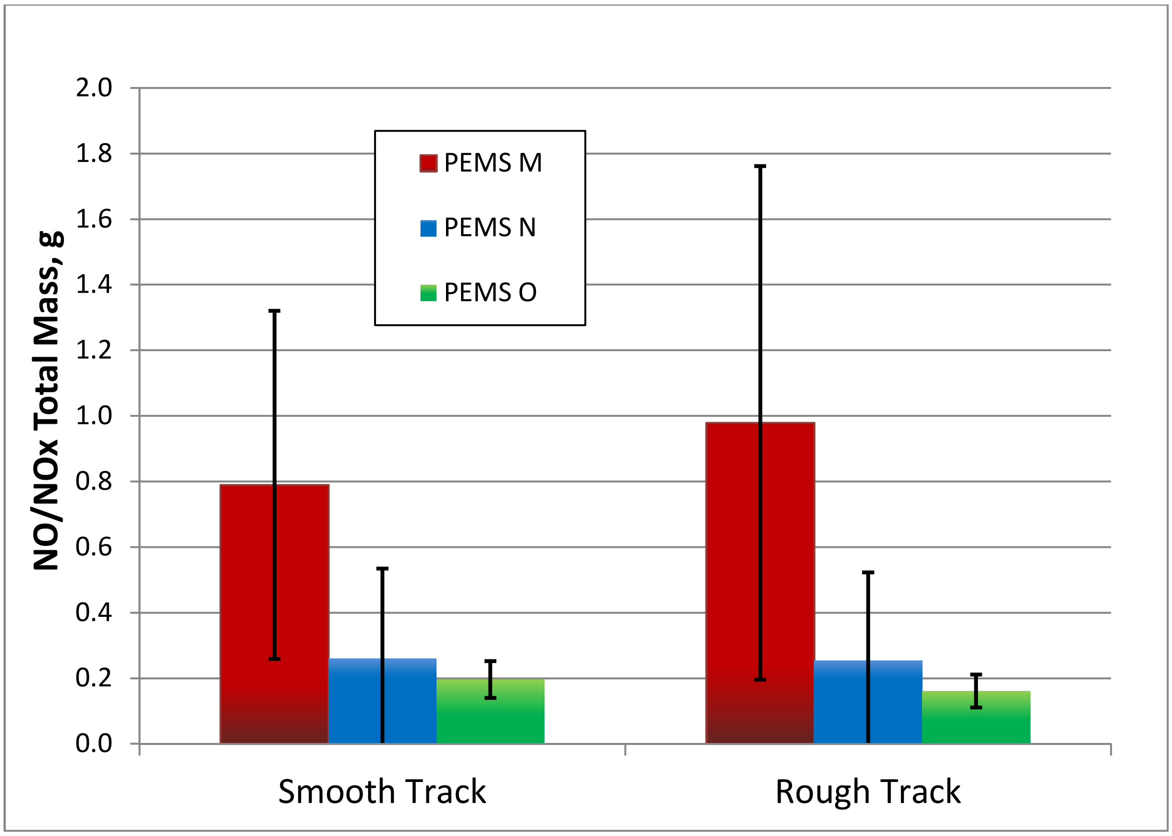

Figure 6-8. The average NO/NOx emission mass over the hot-running track tests.

Figure 6-9 presents the hot-running track test results for CO. The average mass results for CO are, when averaging both PEMS together, approximately 10 to 15 percent lower for the hot running tests than the cold-start tests. The differences between the two track surfaces are not statistically different given the relatively high level of variability observed in the measurements. Figure 6-10 presents the average HC mass emissions for the hot-running track tests. Averaging the results of both PEMS together, the HC results were approximately 50 percent lower during the hot-running track tests as compared to the cold-start track tests.

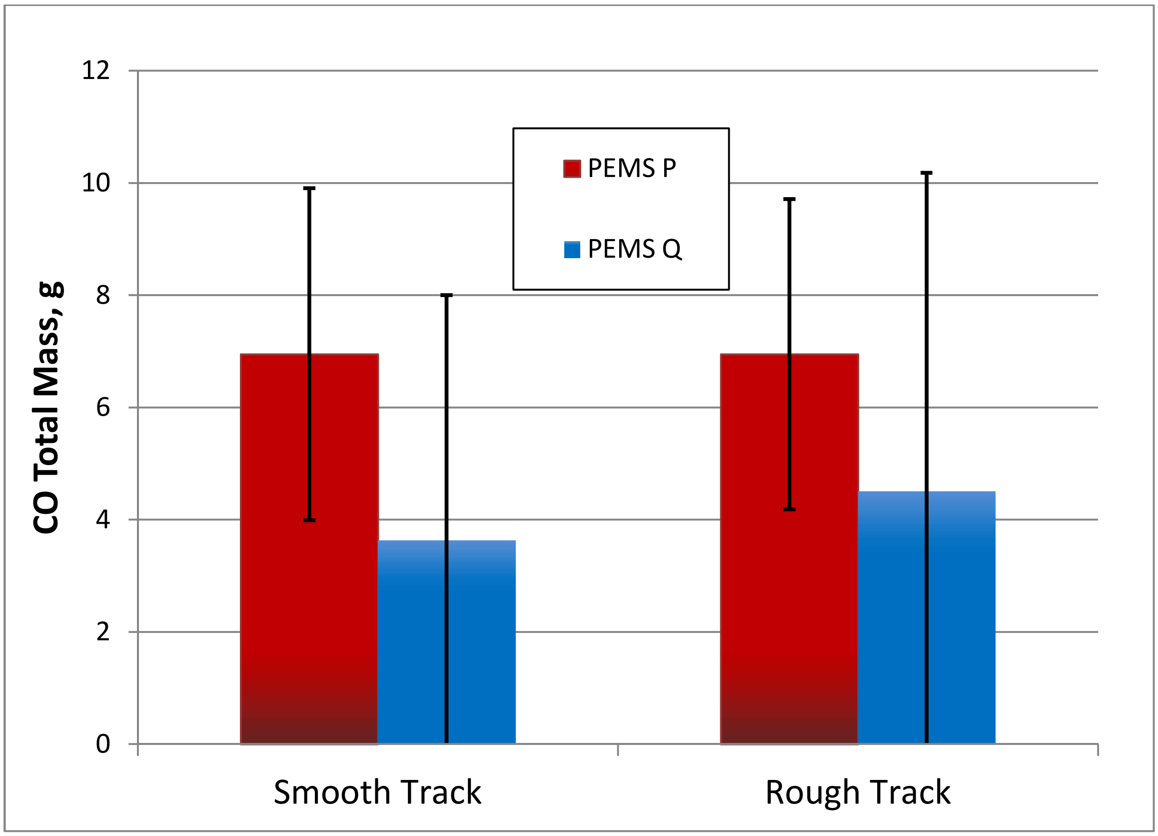

Figure 6-9. The average CO emission mass over the hot-running track tests.

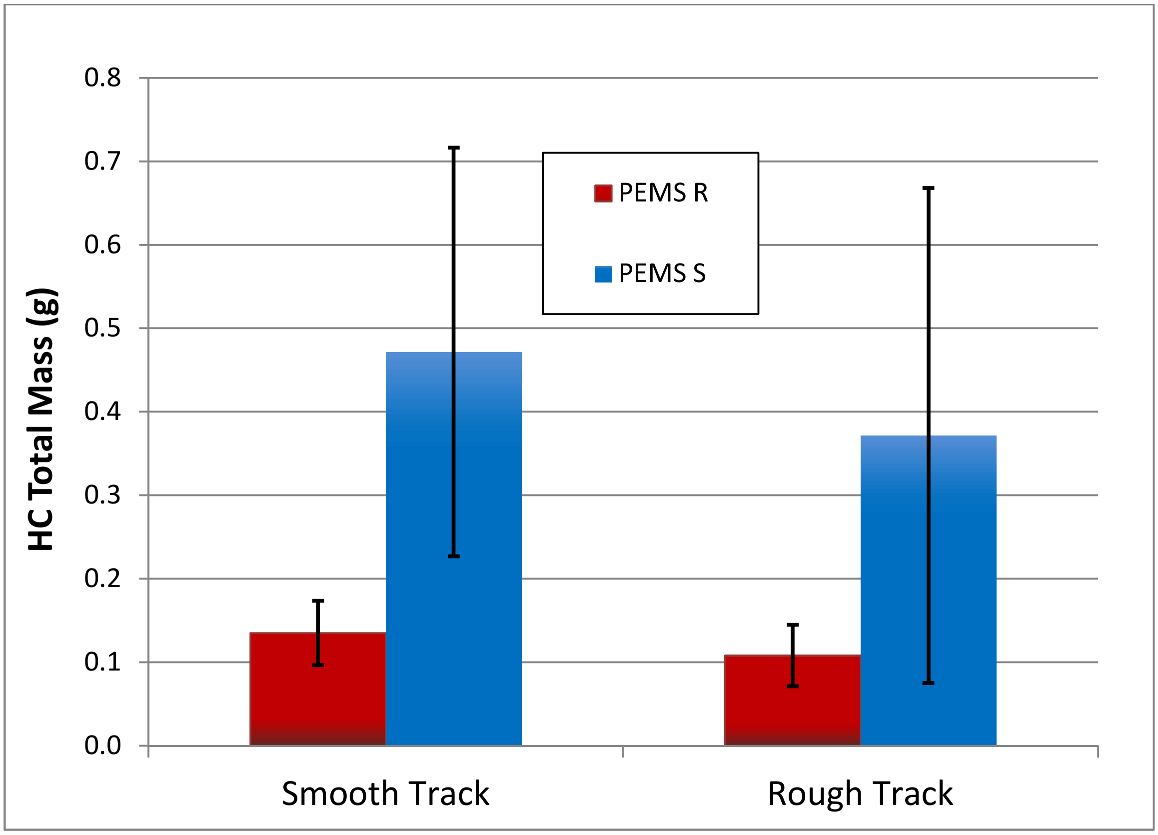

Figure 6-10. The average HC emission mass over the hot-running track tests.

Figure 6-11 presents the hot-running track results for PM. The PM mass emissions trended similarly to HC; hot running test emissions were approximately 50 percent lower than the cold-start tests for the average across both PEMS,.

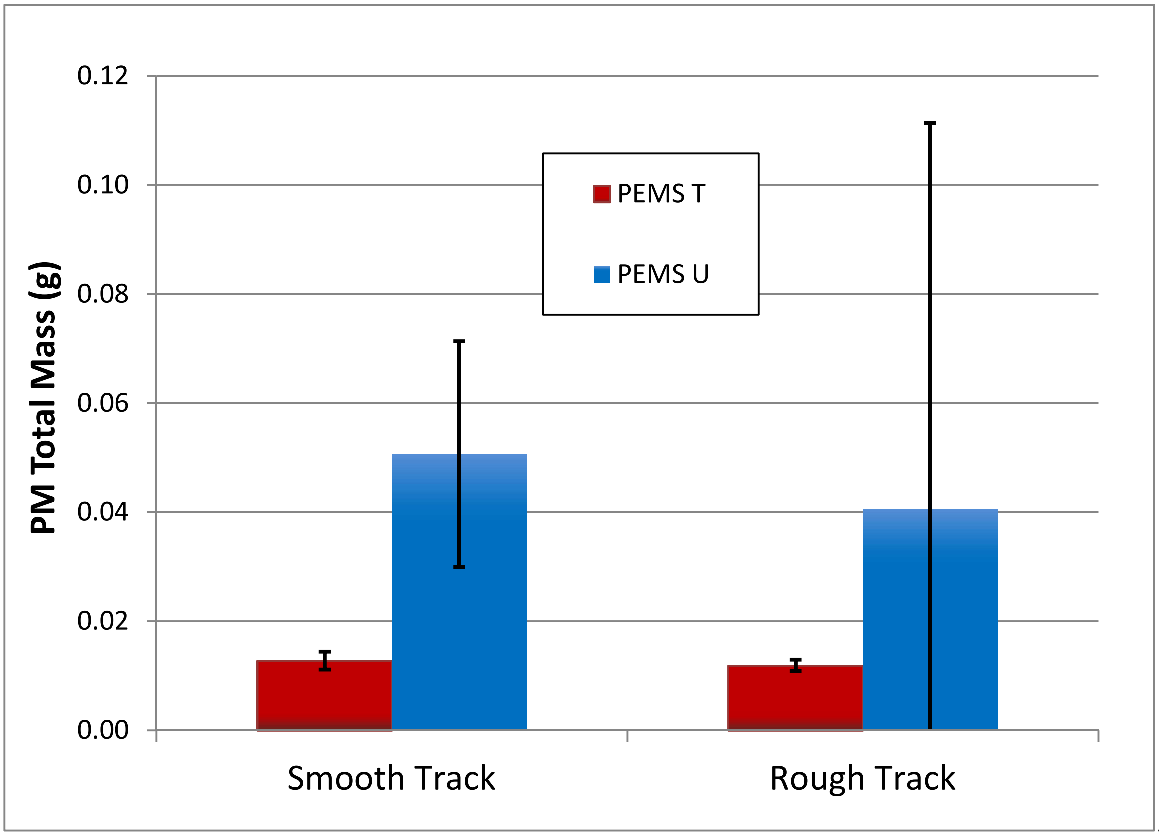

Figure 6-11. The average PM emission mass over the hot-running track tests.

6.4 Second-by-Second Mass Emission Traces

This section presents cumulative plots of continuous mass emissions for all dynamometer tests. The plots allow for the direct comparison of the continuous PEMS and modal mass emission measurements. Plots are presented for CO_2, NO/NOx, CO, HC, and PM. Continuous data is shown only for the dynamometer tests in this section as these tests allow for comparison between the lab and PEMS measurements. The trends in the road and track tests are largely similar, but do not include the opportunity for direct comparisons with the laboratory method of measurement and, as such, are presented in Appendix F. Traces are presented on a cumulative basis to better show how the differences between the PEMS and lab develop and change throughout each test. The instruments are blinded using the same label letters as the previous section to facilitate comparison between the batch and second-by-second results. Note that the PEMS that was not equipped with its own flowmeter, for which ERG calculated exhaust flow based on correlating OBD parameters directly to the lab modal system, may show less bias when compared to the laboratory modal results than the other PEMS for that reason.

In this section, results of the lab measurements are presented based on the lab's full-concentration modal gaseous measurements and the continuous PM measurements from the MSS. This is in contrast to the data presented in the previous section, which were based on the dilute bag gaseous and filter-based PM measurements made using the CVS tunnel. The two separate lab measurement techniques do not necessarily generate identical results. Table 6-1 shows the percent difference between the calculated masses of each gaseous pollutant for the two parallel lab measurement methods. It can be seen that the agreement is best for CO and CO_2, and in particular NOx has a greater average difference which could be related to variability associated with the longer sampling delay associated with this instrument, which includes a NOx converter upstream of the point of measurement. For pollutants except CO_2, the average modal results were lower than the bag measurements (this is shown as a negative percentage). The values in the table indicate why the level of agreement in the total emission masses between the PEMS measurements and the lab measurements differs slightly in this section from the previous section (Note that the previous section contains results from the test methods that are equivalent to those specified for light-duty certification testing).

Table 6-1. Average Differences in Pollutant Mass Between Lab Modal and Lab CVS Bag Measurements

Pollutant	Avg. Total Mass Percent Difference
HC	-13 %
CO	-7.2 %
NOx	-27 %
CO_2	0.46 %

The first group of plots present the cumulative second-by-second CO_2 mass emissions. The same blinding index letters are used in this section as the previous section (as the results for PEMS are identical between both). In the following plots, the PEMS measurements are presented as solid lines and the lab modal measurements are presented as broken lines. Measurements are color coded in pairs to display the two types of parallel measurements presented for each of the five dynamometer tests. The cumulative CO_2 emissions traces for dynamometer tests of PEMS A are presented in Figure 6-12.

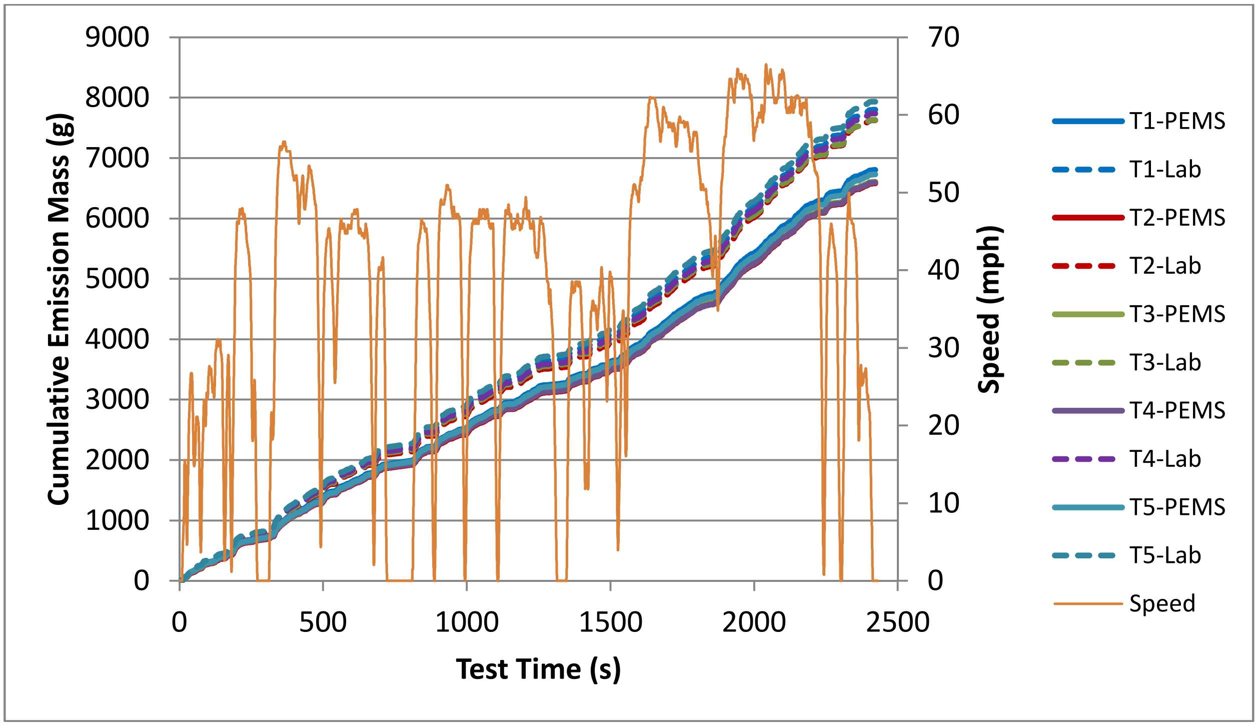

Figure 6-12. Cumulative CO_2 mass for tests of PEMS A on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

The cumulative CO_2 mass traces for dynamometer tests of PEMS B and C are presented in Figure 6-13 and Figure 6-14. The PEMS devices tended to measure a slightly lower CO_2 mass emission rate than did the lab's modal system, and for both the lab and each of the PEMS, the results for the two different measurement types tended to group relatively tightly.

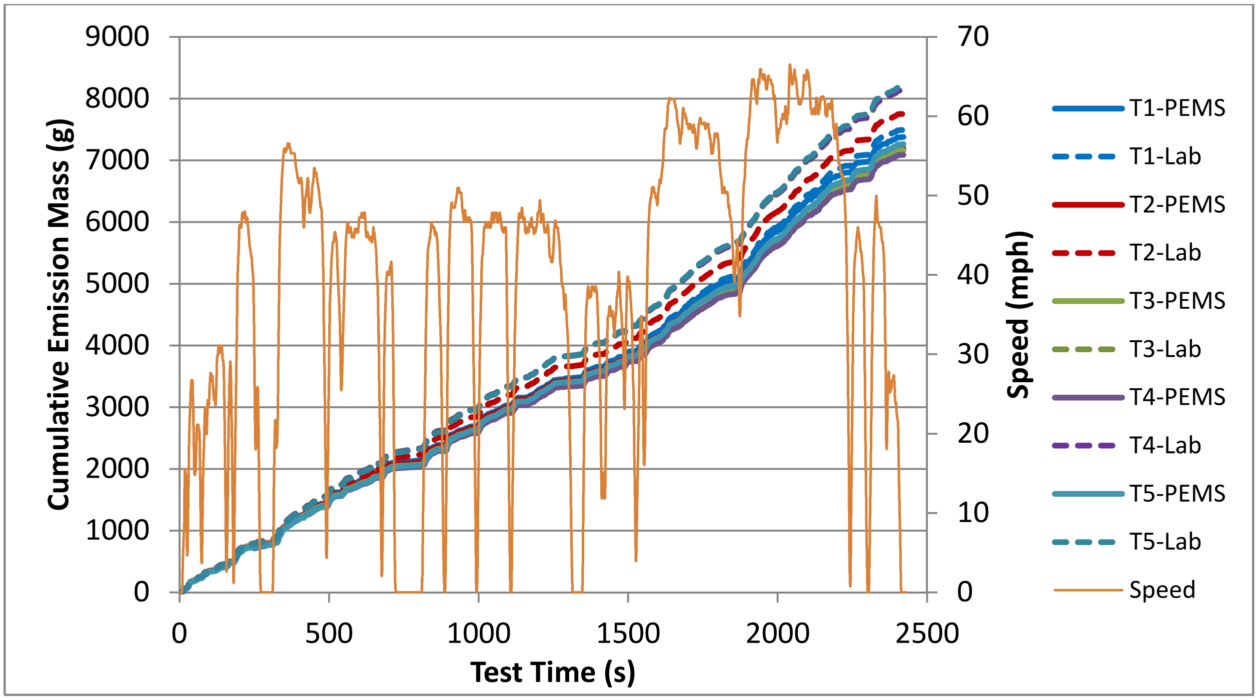

Figure 6-13. Cumulative CO_2 mass for tests of PEMS B on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

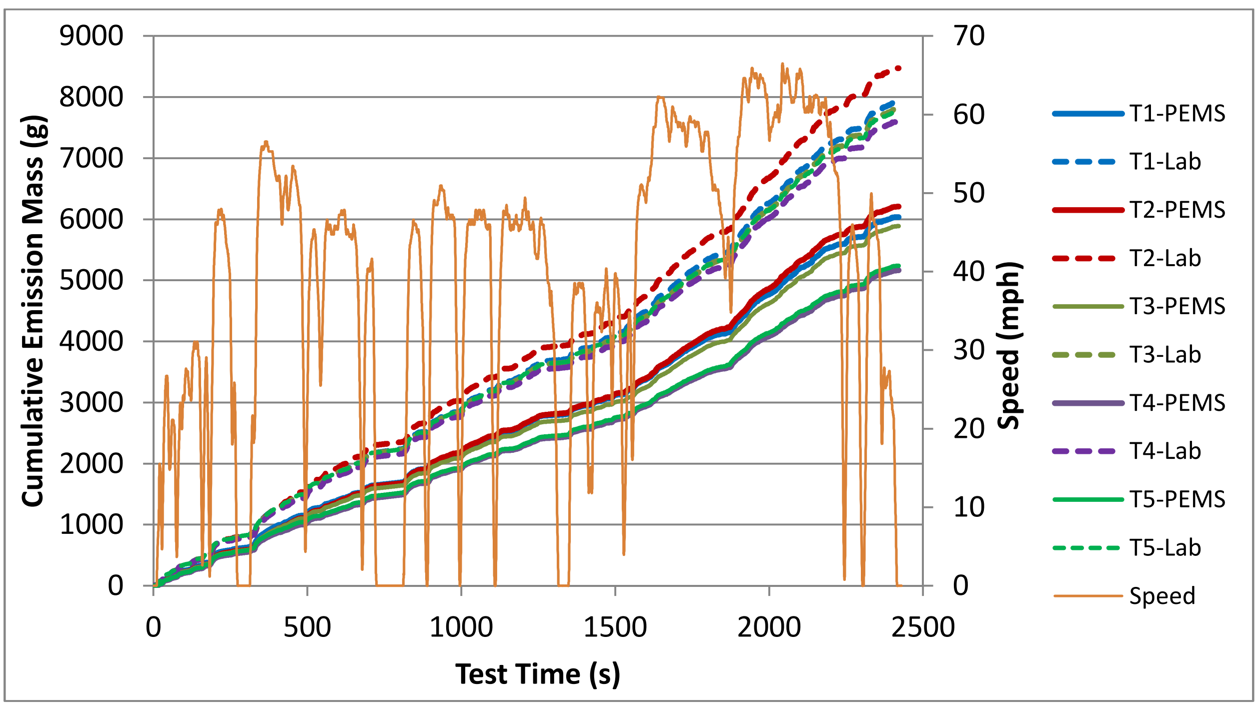

Figure 6-14. Cumulative CO_2 mass for tests of PEMS C on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

As in the previous section, the lab and two of the three PEMS measured NOx (both NO and NO_2), and the other PEMS measured only NO. All results are presented together in this section as NOx for consistency and anonymity. The cumulative NOx emissions traces measured for dynamometer tests of PEMS D are presented in Figure 6-15. In general, this PEMS tended to underestimate the measured NOx mass by comparison to the lab system, but otherwise the trends in both systems are similar. It can be seen that, for both PEMS and lab modal NOx measurement types, approximately half of the total emissions during a test are emitted during the first 30-40 seconds. The NOx emissions during the early to middle portion of the cycle are relatively low. Then, during the latter part of the cycle representing highway driving and a steep underpass transitioning from one highway to another, there are occasional instantaneous bursts of elevated emissions. The exact location within the highway portion of the cycle of these types of instantaneous releases is different for each test, but they occur during the highway portions of most test cycles. Both the PEMS and modal measurements identified and were in agreement regarding the test time of each release; however the two types of measurements generally identified them as being somewhat different in magnitude. As mentioned previously for reference, the equivalent total NOx mass emission for the standard to which this vehicle was certified would be 1.34 g.

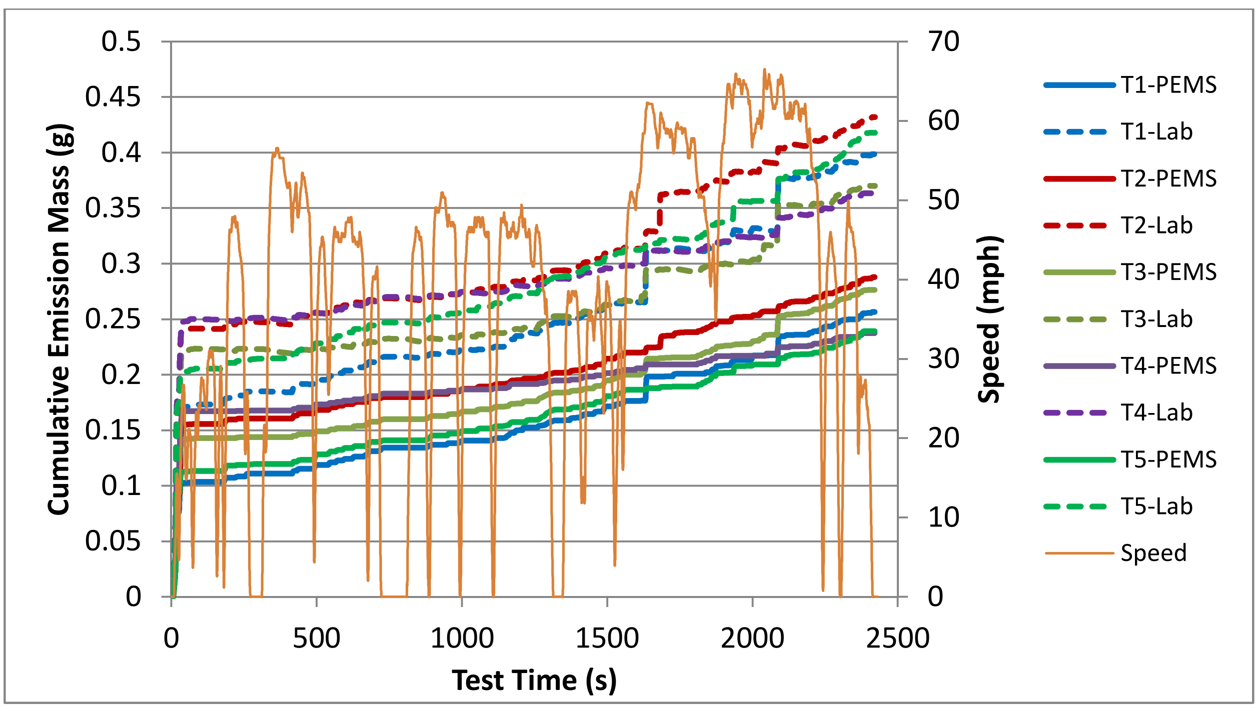

Figure 6-15. Cumulative NOx mass for tests of PEMS D on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

The cumulative NOx traces for dynamometer tests of PEMS E are presented in Figure 6-16. A single test of this unit stands out has having many negative PEMS NOx measurements, which appear as a negative slope in the plot. This indicates either a zero/span issue or a large amount of downward drift during the test.

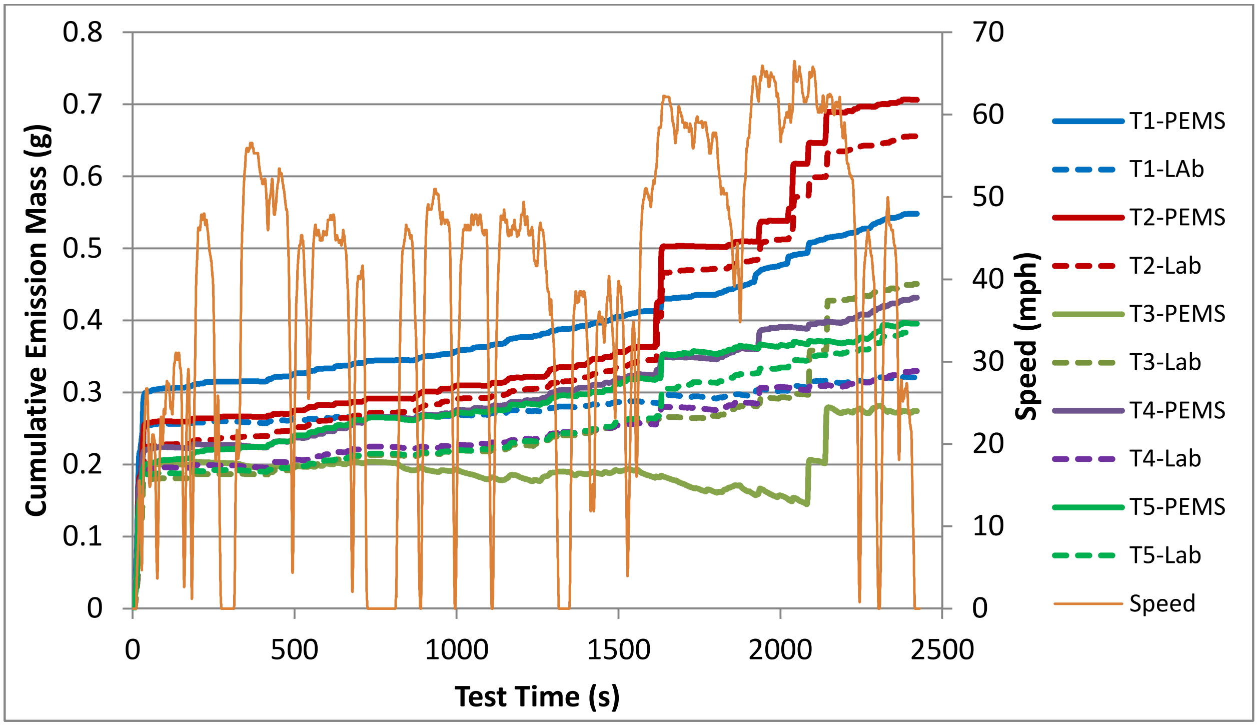

Figure 6-16. Cumulative NOx mass emissions for tests of PEMS E on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

A similar cumulative NOx plot for PEMS F is presented in Figure 6-17. As in the previous plots, approximately half of the total emissions are measured in the first 30-40 seconds, and then the cumulative traces gradually rise until the highway portion of the cycle, in which sudden instantaneous releases contribute significantly to the totals. Both this PEMS and the lab modal systems detected these releases at the same time, however their magnitude was generally different between the two measurements.

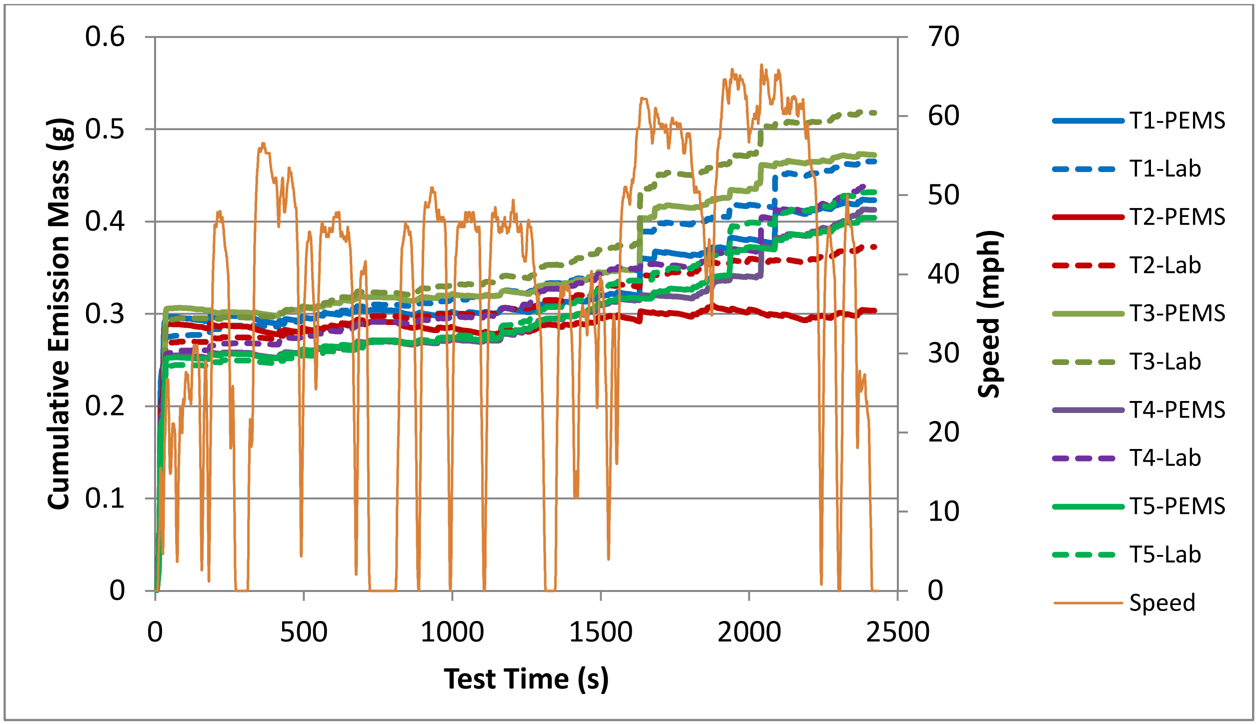

Figure 6-17. Cumulative NOx mass emissions for tests of PEMS F on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

The next group of plots present the cumulative CO mass measurements over each dynamometer test for the two PEMS that measured CO. Cumulative CO emission plots for dynamometer tests of PEMS G are presented in Figure 6-18. One test, T4, immediately stands out as having an extremely large instantaneous emission of CO. This emission was recorded by both systems, albeit with different magnitudes. This point occurs during a period of high engine load during the point in the trace representing the underpass transition from one highway segment to the other. While no driver violation occurred, the driver did use more throttle here to stay on the trace than was typically used in other tests. For the other four tests, the PEMS and lab modal measurements were in general agreement. For comparison, the total mass emission allowed for this vehicle's certification standard would be 91 g.

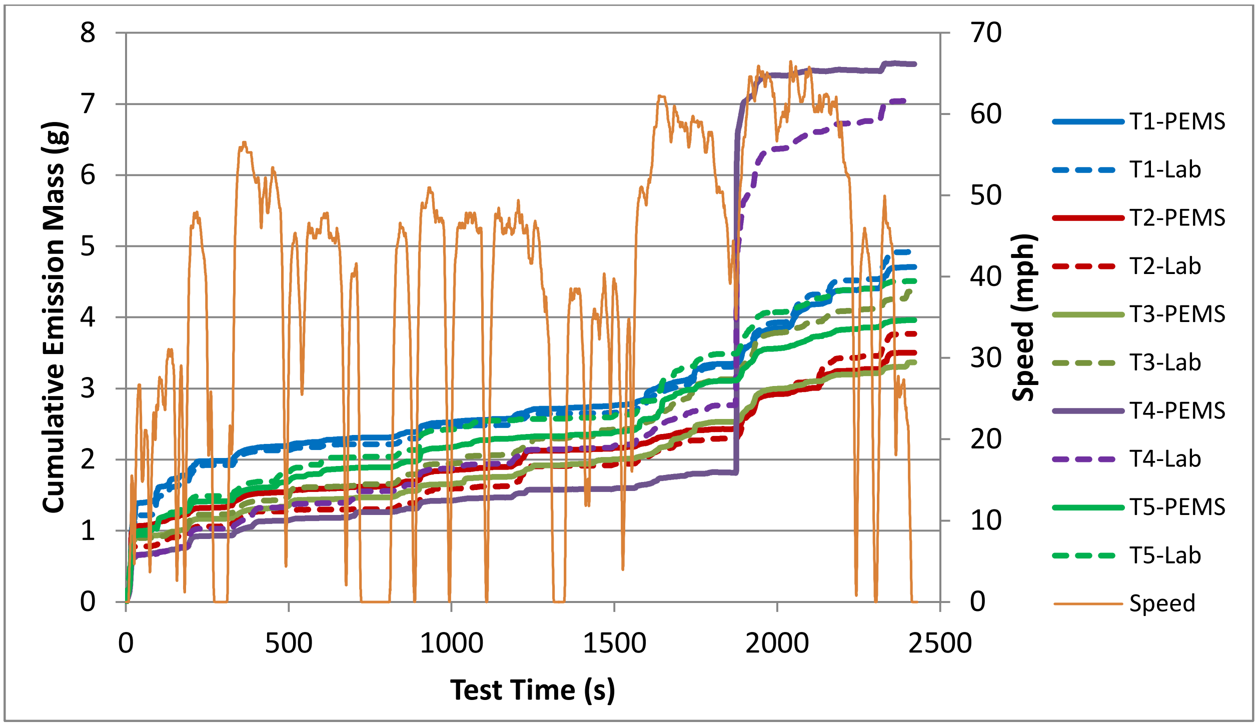

Figure 6-18. Cumulative CO mass emissions for tests of PEMS G on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

The CO measurements for the dynamometer tests of PEMS H are presented in Figure 6-19. During these tests, a smaller proportion of the total mass emissions was measured during the cold-start phase of the tests than was observed for NOx emissions. The CO traces do not reflect the significant instantaneous mass emissions as were observed for the NOx measurements. In these CO measurements, both sources recorded sudden increases in steepness of the cumulative traces that occurred periodically during the tests. Two of these tests, T1 and T3 for this system, had particularly good agreement between the PEMS and lab.

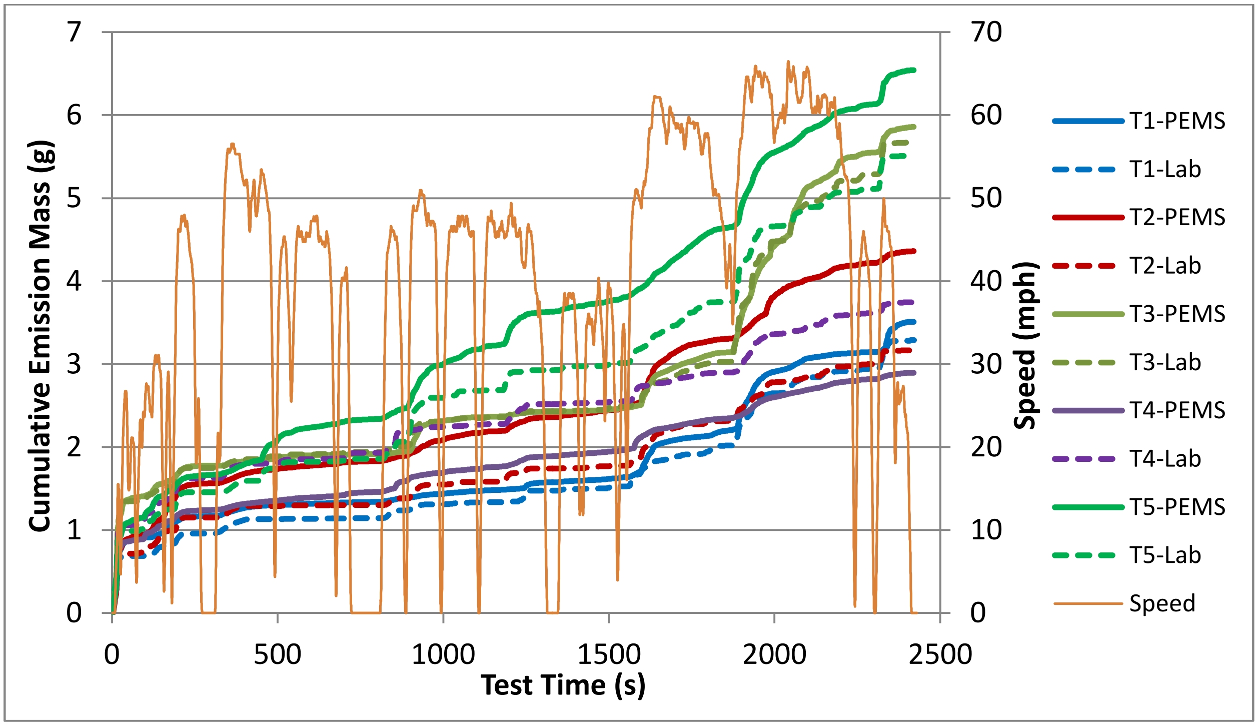

Figure 6-19. Cumulative CO mass emissions for tests of PEMS H on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

The next pair of plots present cumulative measurements of emissions of HC over the dynamometer tests. Figure 6-20 presents the cumulative PEMS and lab modal measurements of HC during the chassis dynamometer tests of PEMS I. It can be seen that this PEMS generally underestimates emission mass as compared to the lab modal system. The lab measures that a great majority of hydrocarbon emissions are released during the cold-start portion of the test, during the first 30-40 seconds. The PEMS measures the cold-start contribution to the total as about half of the cycle emissions, however. Throughout the remainder of each test, the PEMS generally measured a higher amount of HC (i.e., the traces are steeper) as compared to the lab, however the total cumulative emissions measured by the PEMS remain lower than that of the lab at the end of each test. For comparison, this vehicle's certification standard, applied over the test cycle distance, would allow an NMOG emission rate of 2 g.

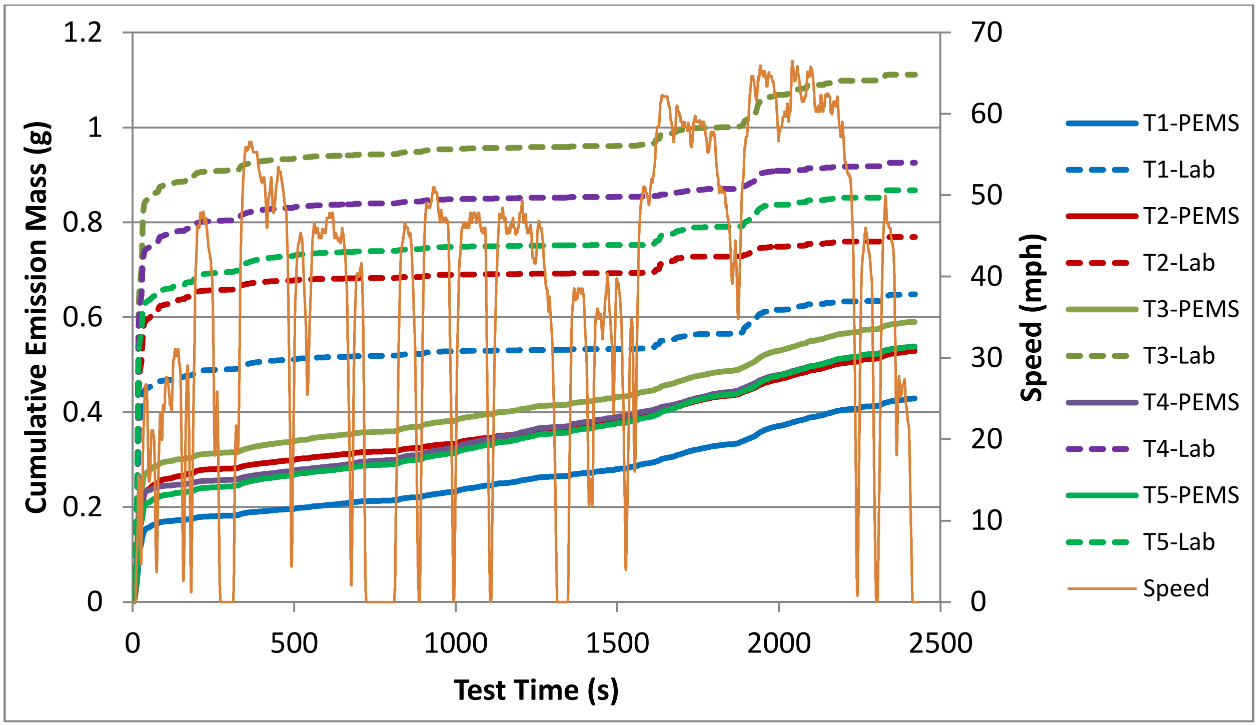

Figure 6-20. Cumulative HC mass emissions for tests of PEMS I on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

Similar cumulative HC traces are shown for tests of PEMS J in Figure 6-21. This PEMS also generally measures lower total HC emissions as compared to the lab modal system. However, the cold-start contribution fraction of total mass as measured by the PEMS is very similar to the cold-start fraction measured by the lab. In tests with this system, the traces for the PEMS and the lab modal system each test appear proportional to one another throughout each test.

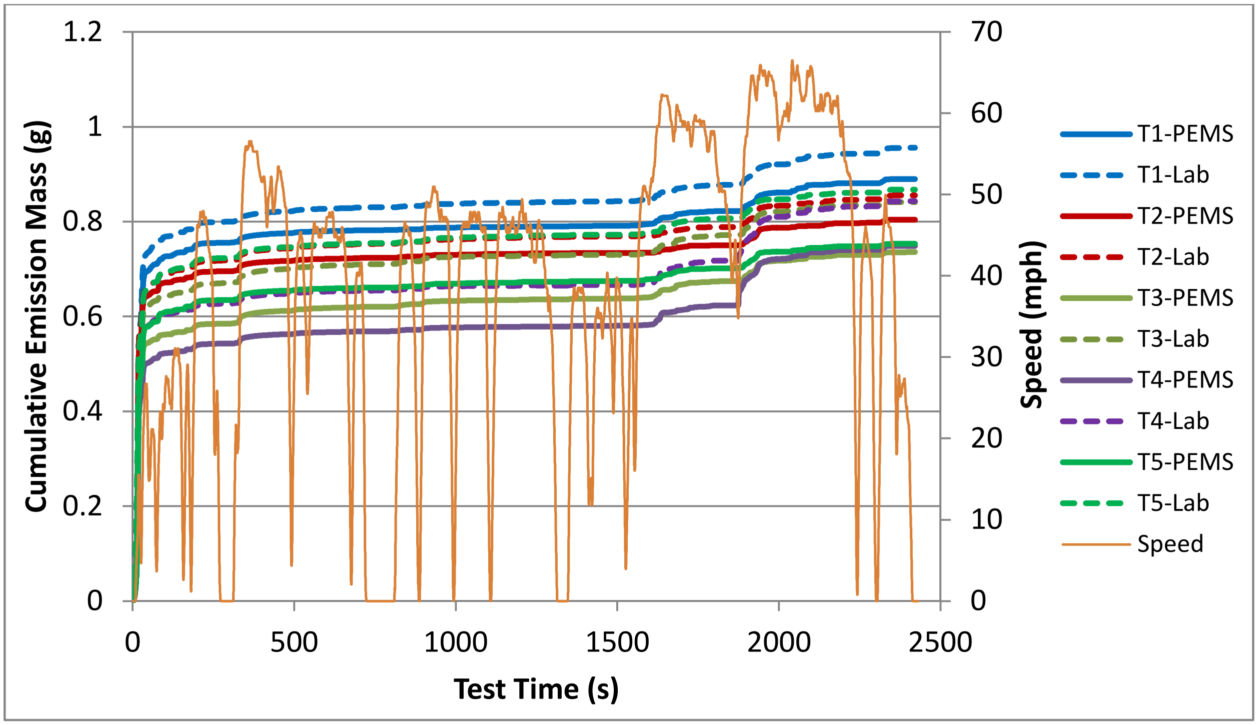

Figure 6-21. Cumulative HC mass emissions for tests of PEMS J on the dynamometer. Measurements are presented in pairs of PEMS and lab modal.

The remaining plots in this section represent the continuous PM mass measurements from the two PEMS units capable of making such measurements. These are presented against the lab measurements from the MSS (which only measures the elemental carbon fraction of PM). Continuous PM mass measurements made during tests of PEMS K are presented cumulatively in Figure 6-22, which shows that the PEMS generally measures lower than the lab MSS. Early in the test cycle, both systems identify the same instantaneous releases of elevated amounts of PM, though the magnitudes are measured differently by the two systems.

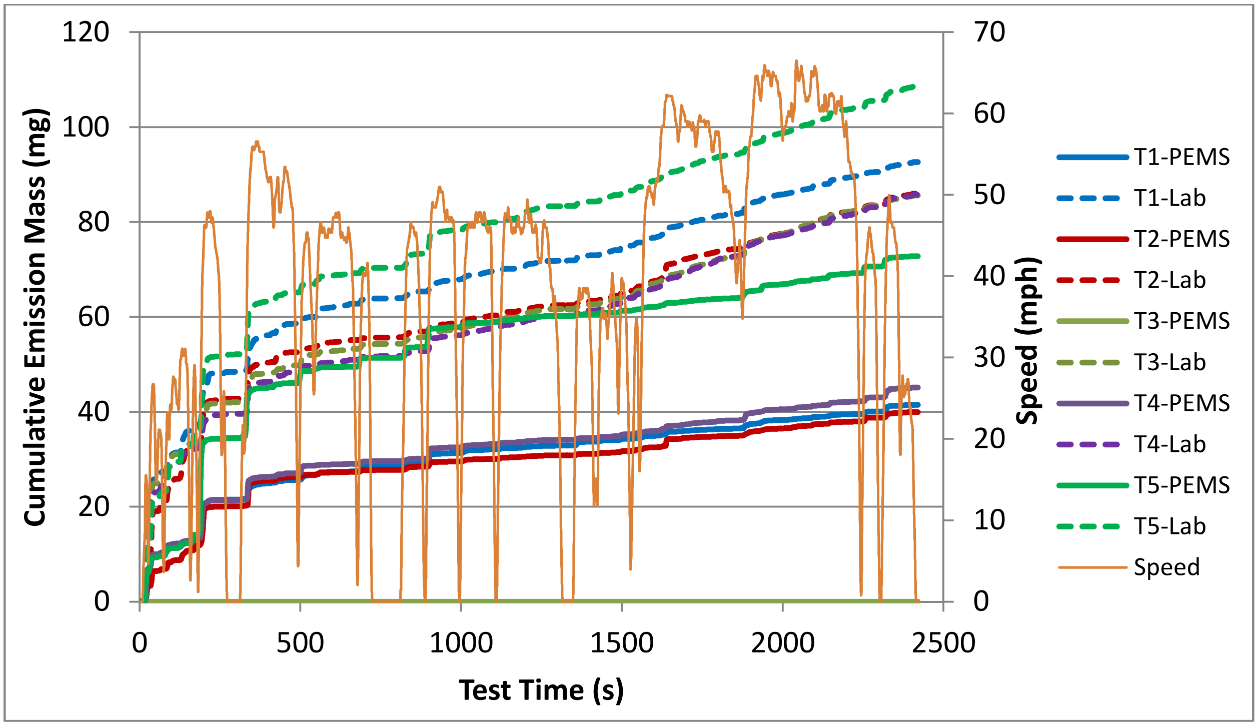

Figure 6-22. Cumulative PM mass emissions for tests of PEMS K on the dynamometer. Measurements are presented in pairs of PEMS and lab MSS.

A similar PM plot for PEMS L is presented in Figure 6-23. One test, T4, stands out as having particularly elevated PM emissions as measured by the PEMS. This elevated release occurs during the high-load highway transition. Both the MSS and the PEMS measure an elevated release at this point, however the scale of the measurement of this release is much different between the two sources. With the exception of T4, the remaining tests agreed fairly well in overall trend between the PEMS and lab MSS measurements. The PEMS tended to measure a somewhat higher total emission mass than did the lab MSS; this may be due to the MSS measuring only the carbon fraction of the PM mass.

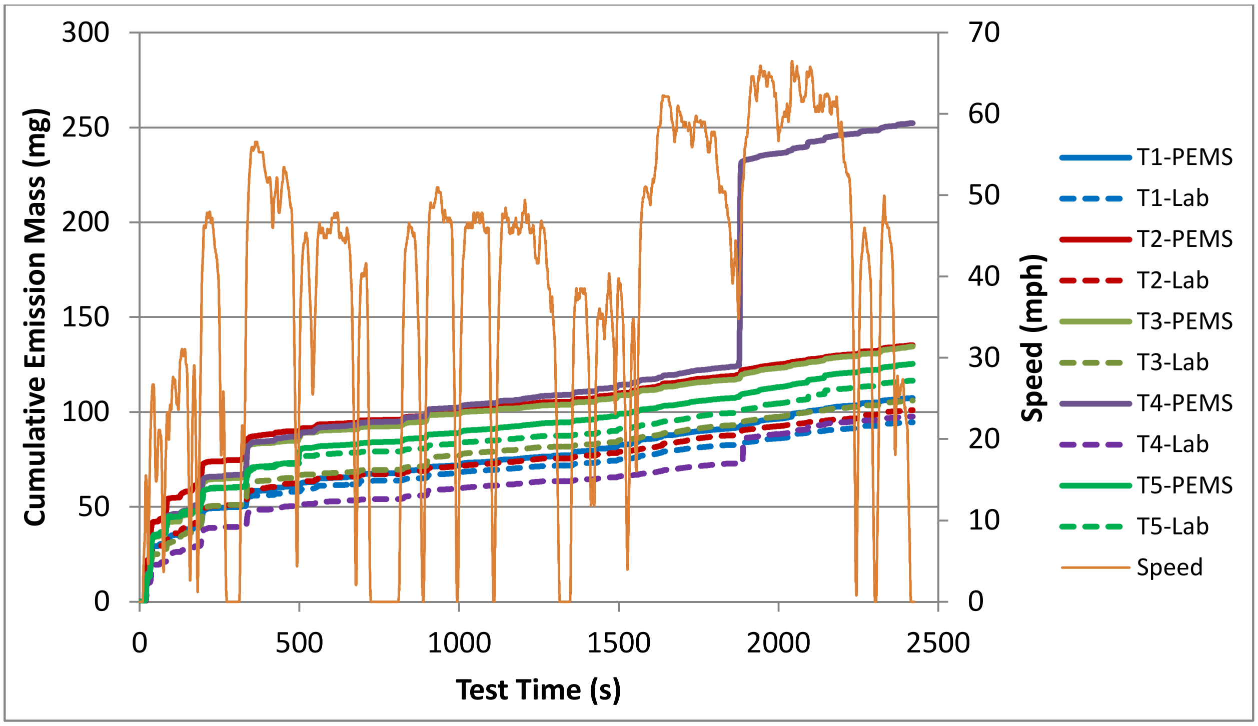

Figure 6-23. Cumulative PM mass emissions for tests of PEMS L on the dynamometer. Measurements are presented in pairs of PEMS and lab MSS.

6.5 Rough Road Findings

One of the project goals was to determine if driving over rough roads has any effect on PEMS performance. To investigate this, ERG conducted half of the on-track tests on the Continental Track's ride road, which contains a stretch of potholed pavement as described in Section 2.4. An accelerometer was used to log vehicle vertical acceleration data so that the times that the test vehicle was passing over the rough section could be flagged in the data logged by each PEMS. ERG analyzed the data from these tests to determine whether the rough pavement had any effect on the accuracy or repeatability of the PEMS measurements. Data from the external accelerometer was time aligned based on the time of the start of each test and appended the data directly into each PEMS' test log file.

Project staff analyzed the data from the potholed track to determine if driving over the potholes had any effect on the PEMS measurements of exhaust flow rate, pollutant concentrations or pollutant masses measured by each PEMS. Measurements of PM were included in the analysis for the two PEMS utilizing continuous optical PM measurement only.

In this investigation, ERG first graphically reviewed all parameters of interest with accelerometer data overlaid on the graphs. Time-series traces were reviewed for evidence of measurements pegging at high or low values or any other erratic behavior when the potholes were encountered. Project staff graphically reviewed the continuous traces for each parameter of interest in the data for all three PEMS from both the cold-start tests and the hot-running tests on the ride road. There was no visual or graphical evidence of any abnormal measurement behavior in any of the parameters of interest for any of the three PEMS.

An example of the data that ERG reviewed is presented in Figure 6-24. The plot shows an excerpt of the measured hydrocarbon traces for the FID-equipped PEMS for three replicate tests (T1-T3), with the signal from the accelerometer overlaid over a duration including two passes over the potholed surfaces. The plot is scaled down from the plots that were visually reviewed for the analysis, but it shows that the HC concentration traces do not have an obviously-apparent response to the two segments of potholes included in the excerpt. The accelerometer data is normalized to be positive from 1g, indicating that typical accelerations over the potholes generally reached a maximum of 1.7g to 1.8g.

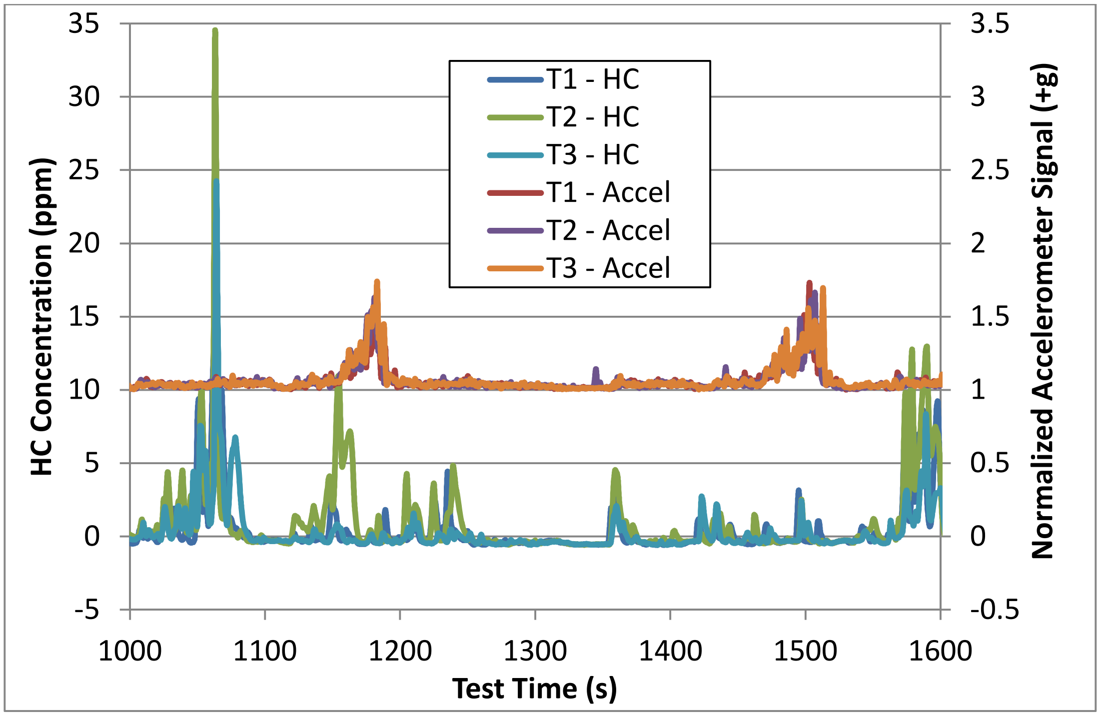

Figure 6-24. Example traces of HC concentration and accelerometer data from the ride road track.

A second investigation involved the review of error bars from the mass results from the smooth and rough tracks. The overall mass results shown previously in Section 6.3 displayed total mass results for each exhaust constituent over tests including those on the smooth track and those on the rough track, presented as the mean of replicates with 95% confidence interval error bars (Figure 6-3 through Figure 6-7). For all pollutants and all PEMS, results for a given pollutant for a given PEMS had overlapping error bars between the results for the two track types (and all but one had error bars overlapping the mean of the measurement of the other track type), indicating that it was not likely to be possible to conclude that there were differences in the measured masses between the two track types. This is in agreement with the findings of ERG's visual review; that no differences due to roughness of the track could be concluded.

The third investigation attempted to perform a further statistical comparison of the corresponding rough and smooth driving segments encountered on the ride road compared to the same two segments of the drive cycle as driven on the main (smooth) track. The accelerometer traces, merged into the test files, were used to assign segments of the drive cycle corresponding to rough and smooth driving on the ride road. Because the tests on the ride road started in the same location each day, the parts of the test in which the potholes were encountered were nominally the same for all runs. ERG determined time ranges of the test cycle that coincided with the potholes and the time ranges that coincided with the smooth part of the track. Each cycle driven on the ride road was thus divided into rough segments and smooth segments. The test cycle required 9 laps of the ride road to complete, however there was one long stop that took place in the middle of a rough segment (in which the operation of the PEMS would then be "smooth" as the potholes had no effect on the vehicle when stopped), so the cycle was divided into a total of 10 rough segments and 11 corresponding smooth segments. The time periods identified for the potholed segments are overlaid on the test's speed trace in Figure 6-25.

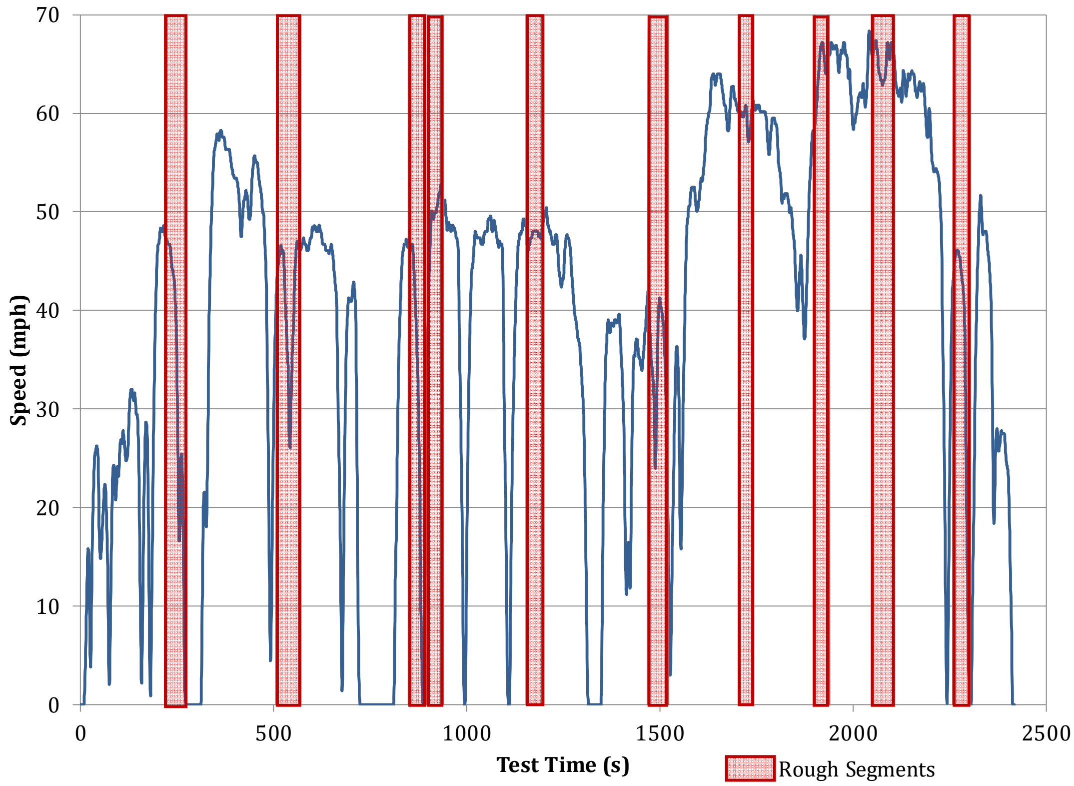

Figure 6-25. The potholed segments of the test (shaded in red), overlaid on the test speed trace.

Each of the potholed segments of each test were then concatenated to represent one total segment type of potholed driving per test, and each of the smooth segments were concatenated to represent one total segment type of smooth track driving per test. In this way, the data from the driving cycle could be divided into one singular rough segment type and one singular smooth segment type by cycle time, and these assignments were made in the same way to tests on both the ride road and the smooth main track, allowing for, comparisons across the two track types of both smooth and potholed surfaces. The smooth segment type allows comparisons of the smooth main track against the smooth part of the ride road (referenced later as Smooth/Smooth), and the rough segment type allows comparisons of the of the smooth main track against the potholed part of the ride road (referenced as Smooth/Potholed).

During testing, three replicate tests were performed on each track for each PEMS. This statistical investigation involved analyses of the different segment types (Smooth/Potholed and Smooth/Smooth) and different track types (the ride road and the main track), each containing the three replicates for each PEMS. These analyses were performed for the hot-running tests only (so that the values would be more comparable across the merged segments and the effect of the cold-start would not be included). Thus, the analysis was based on 2x2 matrices for comparisons (by segment type and track type). The investigation was to determine whether any effect was evident on the means of measurements from each of the three replicate segments as well as the standard deviations found for all data for each parameter within a given track/segment/PEMS combination. Differences in the means would indicate that the average result for a segment was likely changed due to the presence of potholes, and differences in the standard deviations would indicate that the noise or variability in the measurement was changed by the presence of potholes.

ERG performed a Welch's ANOVA test to determine if the results of the means of each parameter were significantly different within a given segment type due to the two tracks. The Welch's comparison was used as it allows for comparison of groups that do not necessarily have the same variance. All comparisons were made at the 5% level of significance. To determine whether the variability in measurements for a given segment type was affected by the presence of potholes, project staff then performed a Levene's test for homogeneity of variance. The results of the analyses for exhaust flow rate, CO_2, and NO/NOx as well as the vehicle operational parameters throttle and engine speed are presented in Table 6-2[4]. These are presented together in one table as all three PEMS included these measurements. The findings of this comparison address the following question: Given that the same two segment types of the trace were driven over both the track with potholes and the track without potholes, was there a difference observed in the measured parameters between the two track types for either of the two segment types?

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[4] Note that the blinded indices for each PEMS are reset to A in this section.

Table 6-2. Statistical Significances of the Effect of Track Type within a Given Segment Type, all PEMS

		PEMS A		PEMS B		PEMS C	
Analysis Type	Parameter	Smooth/ Smooth	Smooth/ Potholed	Smooth/ Smooth	Smooth/ Potholed	Smooth/ Smooth	Smooth/ Potholed
Means of Measur-ements	Throttle (Load)	No Effect	No Effect	No Effect	**Significant Difference**	No Effect	No Effect
	RPM	No Effect	No Effect	No Effect	No Effect	No Effect	**Significant Difference**
	Exh. Flow	No Effect	No Effect	No Effect	**Significant Difference**	No Effect	No Effect
	CO_2 Conc.	No Effect	No Effect	No Effect	No Effect	No Effect	No Effect
	NO/NOx Conc.	No Effect	No Effect	No Effect	No Effect	No Effect	No Effect
Standard Deviation of Measurements	Throttle (Load)	No Effect	No Effect	No Effect	**Significant Difference**	No Effect	No Effect
	RPM	No Effect	No Effect	No Effect	No Effect	No Effect	No Effect
	Exh. Flow Rate	No Effect	No Effect	No Effect	No Effect	No Effect	No Effect
	CO_2 Conc.	No Effect	No Effect	No Effect	**Significant Difference**	No Effect	No Effect
	NO/NOx Conc.	**Significant Difference**	No Effect	**Significant Difference**	No Effect	No Effect	**Significant Difference**

The analysis indicates that it is likely that any effect of the presence of potholes is either minimal or not stronger than the noise in the measurements or the other differences in operation caused by the two tracks. It can be seen that, for PEMS B, there is a significant difference in the throttle values and, likely as a result, the exhaust flow rate on the potholed track. This could have been due to the increased drag on the vehicle from driving over the rough surface or the small differences in grade for the two track types. As a result, the vehicle could not be operated exactly the same way over the potholes as it could on the same driving segments of the main track, so it is not possible to draw a conclusion on whether the cause of any differences observed in measured parameters are due to the driving differences or the presence of potholes. It can also be seen for PEMS A that significant differences were observed between the smooth segments of the two tracks (Smooth/Smooth), indicating that significant noise or variability is present between track types even without the influence of potholes.

Similar results are presented for the measurements of CO and HC for the two PEMS that made these types of measurements in Table 6-3. For PEMS E, significant differences were observed for the standard deviations of measurements of both CO and HC for both

Smooth/Smooth and Smooth/Potholed segments, indicating that the noise in this analysis cannot be attributed specifically to the potholes. There is a significant difference observed in the standard deviation of CO measurements for PEMS D, however as described previously, it cannot be determined whether this difference is due to the potholes or the different driving inputs that were caused by the difference between the two tracks.

Table 6-3. Statistical Significances of the Effect of Track Type within a Given Segment Type for PEMS that Measure CO and HC

		PEMS D		PEMS E	
Analysis Type	Parameter	Smooth/ Smooth	Smooth/ Potholed	Smooth/ Smooth	Smooth/ Potholed
Means of Measurements	CO Conc.	No Effect	No Effect	No Effect	No Effect
	HC Conc.	No Effect	No Effect	No Effect	No Effect
Standard Deviation of Measurements	CO Conc.	No Effect	**Significant Difference**	**Significant Difference**	**Significant Difference**
	HC Conc.	No Effect	No Effect	**Significant Difference**	**Significant Difference**

PM traces were analyzed for the two systems with continuous optical PM measurements, however significant differences were observed in the means for both PEMS on the Smooth/Smooth segment type, indicating that there is enough noise in the PM measurements on smooth segments to preclude conclusions regarding measurement performance on the rough segments.

In this analysis, it was not possible to conclude whether the potholes had a discernable effect on the measurements (either in terms of the measurement level or variability) of the instruments. The throttle inputs required to stay on the speed trace were not necessarily equivalent between the rough segments of the two different tracks, and as a result, there is not enough information to conclude whether the differences observed in the measured outcomes are due to the potholed surface or the different driving inputs necessary on the different tracks. The differences in required throttle inputs were due to both the increased drag on the vehicle due to the presence of the potholes (the added throttle input required to hold speed over the potholes was noticed and reported by the driver), as well as any trends in road grade differences between the two track types. So, because the vehicle could not be driven exactly the same way over the two types of surfaces, it was not possible to statistically determine whether any observed differences were due to the rough surface or the required difference in engine operation necessary to stay on the speed trace. This finding was in agreement with the visual review of the measurement traces as well as the statistical comparisons of the overall tests masses between the two tracks; there is no indication that the potholed surfaces had any effect on any of the measurements for the three PEMS. It should be noted also that no damage was found to have occurred to any of the PEMS as a result of operation over the potholed course.

6.6 Unballasted Dynamometer and On-road Testing

The manufacturer of one of the lighter weight PEMS requested that the project include additional repeat dynamometer and on-road tests of their unit installed in the vehicle without any ballast weight added to the vehicle. One of the advantages of a less complex and lighter-weight PEMS is that the effect on the vehicle’s performance due to the system’s presence is reduced as compared to a heavier system. However, it is also important to note that the heaviest PEMS system in this work is designed primarily to meet the Part 1065 requirements for engine testing (including heavy-duty vehicle PEMS testing) and, if light-duty PEMS were legislated in the US under different requirements, a system designed for that purpose by that manufacturer may end up being lighter.

In order to conduct the testing without ballast on the dynamometer, the test vehicle was re-weighed with only the (lighter-weight) PEMS installed with two passengers present near the end of the testing program. This new weight was entered into the dynamometer software for the calculation of a new dynamometer set inertia, and this configuration was used with no additional ballast for the on-road tests. In total, two additional dynamometer tests and two additional on-road tests were conducted for this lighter-weight condition with this single PEMS.

For comparison of the effect of the test weight on vehicle fuel economy and emissions, the fuel economy as measured by the lab CVS system, dash display, and PEMS are presented in Figure 6-26. On average, the three measurement types reported an increase in fuel economy from the ballasted tests to the tests without ballast, but only the dash display data resolved this difference with statistical significance. Average emission mass results for NO/NOx, CO, HC, and PM are presented in Appendix G for these tests. In general, both the PEMS and lab CVS measured lower emission masses on average during the tests without ballast, however due to the relatively low number of repeat tests in the no-ballast-weight condition, none of these changes were significant.

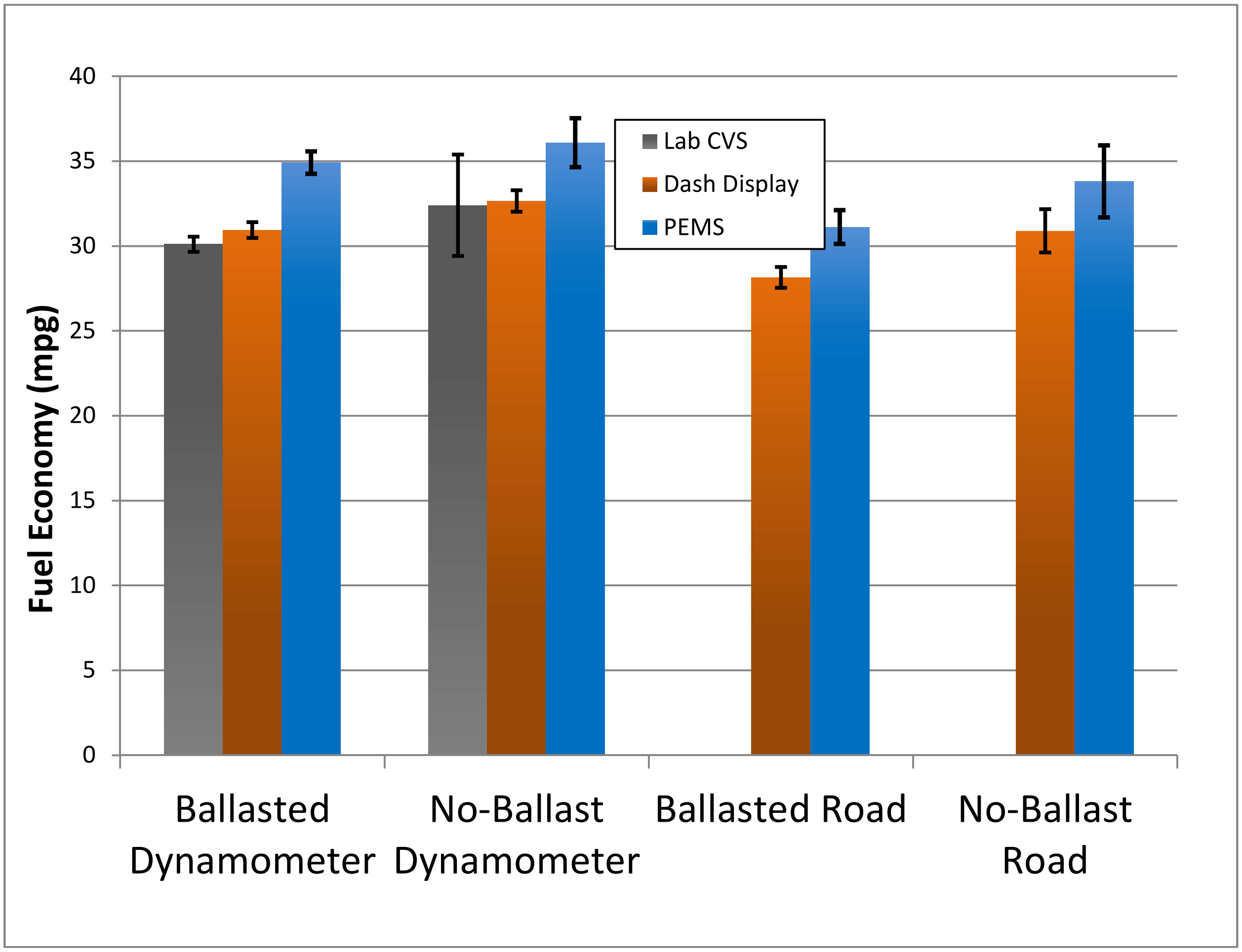

Figure 6-26. Average fuel economy results for ballasted and no-ballast tests with a single PEMS.

7.0 Analysis and Discussion

7.1 Pre- and Post-Test Drift Checks

All gaseous emissions analyzers are subject to some level of measurement drift over time. The 1065-capable PEMS included in this project automatically prompts the user to perform zero and span calibrations at the beginning and end of each test in order to perform automatic drift checks and corrections during post-processing. The other two PEMS do not have this feature, although ERG did conduct zero and span audits by flowing ambient air (as a zero gas) and span gas before and after each test of these units to allow subsequent drift checks. This section summarizes the level of PEMS analyzer drift as well as the relative error in the measurements of the span gas concentration measured by each PEMS during all span gas audits. Only gaseous analyzers were evaluated for drift in this project.

Prior to each emissions test, all three PEMS were subject to a zero and span calibration, in which zero gas (or ambient air, depending on the PEMS system design) and span gas were supplied to the unit for the calibration of the measurement at low and high concentration values for that test. The 1065-capable PEMS automatically then records a brief audit to track the accuracy of the new calibration. For the other two PEMS, ERG manually flowed ambient air and then span gas with the system logging data in order to capture the accuracy of the zero and span. At the end of the test, the 1065- capable PEMS again takes a zero and span measurement and records the measured values to capture the level of instrument drift over the course of the test. For tests of the other two PEMS, ERG manually recorded a post-test audit for the same purpose.

The drift and span accuracy data are presented in this section in three ways. First, the average span errors are presented for each exhaust constituent and each PEMS. The average span error is calculated from the difference between the actual span gas concentration and the span value recorded for each of the pre-and post-test audits conducted on that PEMS. The errors are given as a percentage of the nominal actual span gas concentration used in the audits (two different span gases were used during this project with the same nominal pollutant concentrations, presented in Appendix C). Second, the zero drift is presented for each exhaust constituent for each PEMS. The zero drift refers to the amount of drift in the analyzer response from the pre-test zero audit to the post-test zero audit. The drift is presented on a relative basis; to present relative percentages without dividing by zero, the drift is presented as a percentage relative to the nominal span gas concentrations of each constituent. Third, the average span drift from pre-test to post-test is presented on the same relative basis to the nominal span gas concentration for each constituent. For certification test reporting, often the drift is presented either as a percentage of the span value or a percentage of the individual analyzer's full scale reading. Drift measurements in this report are presented for comparison as a percentage relative to the nominal span gas concentration to allow consistent comparisons to be made across the different PEMS. Each PEMS has different analyzer full-scale ranges so presenting the drift based on those varying ranges would not allow for direct comparisons between the different systems. As in previous sections, CO_2 and NOx emissions are presented together as they were measured by all three PEMS, and CO and HC are presented together as they were measured by two of the PEMS.

Figure 7-1 displays the average span gas error between the actual span gas concentration and the measured concentration during all pre-and post-test audits for CO_2 and NOx[5]. The values in this average represent all pre- and post-test audits during all dynamometer, road, and track tests. Error bars are presented on the 95% confidence interval of the mean based on the variability among all averaged values for a given PEMS and exhaust compound. Note that positive and negative errors are all averaged with their sign unchanged in this analysis. This approach of averaging pre- and post-test span errors is similar in intent to the drift correction equation in 40 CFR 1065.672 in which the correction is applied based on the relative level of error in the pre- and post-test zero and span readings. This review includes only the span error so that values can be presented as a percentage for comparison across the different PEMS. The overall average span error for CO_2 tends to be is somewhat smaller than that for NOx, ranging from +/- 1% for CO_2, and up to nearly 4% for NOx.

[5] The blinding indices of the PEMS units are reset in this section and do not necessarily match with earlier sections.

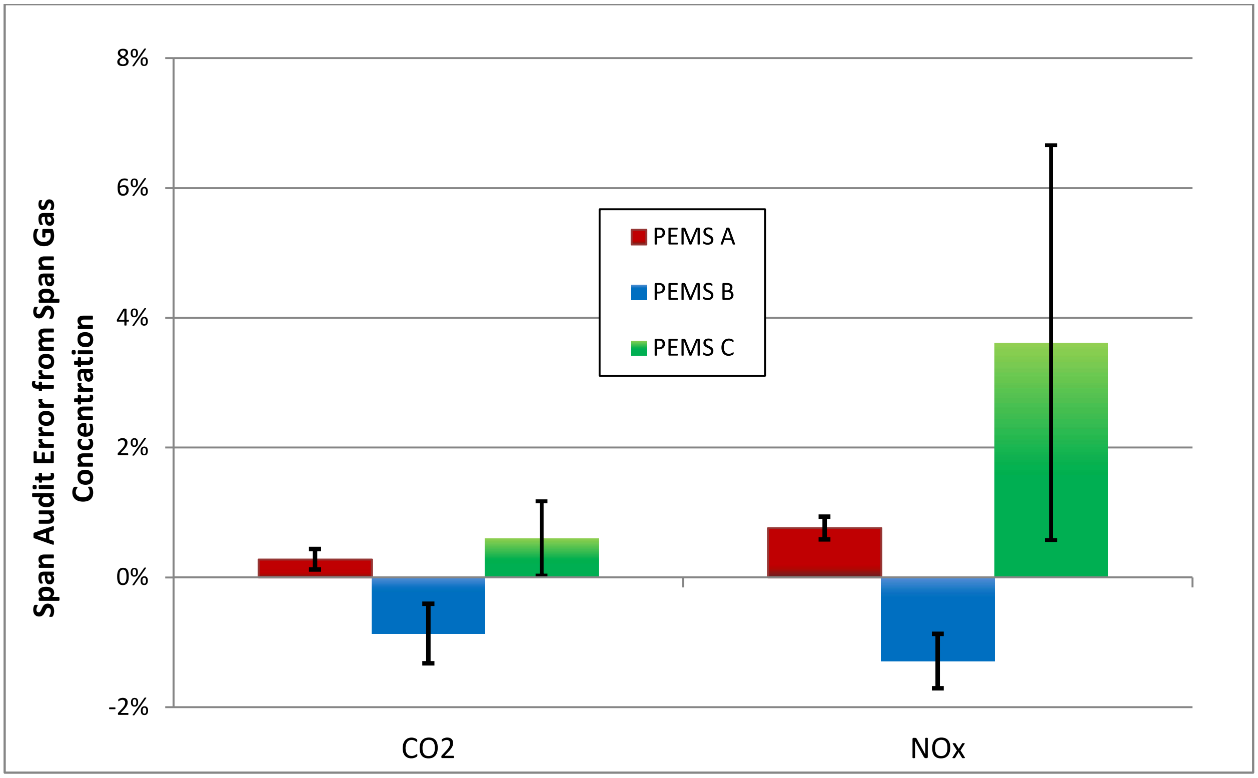

Figure 7-1. Average error from the span gas concentration to the measured audit concentration of CO_2 and NOx for pre- and post-test audits.

A similar plot is presented in Figure 7-2 for measurements of CO and HC for the two PEMS that measured these compounds. The average span errors for these constituents ranged from -1.5% to 1% for CO and HC measurements.

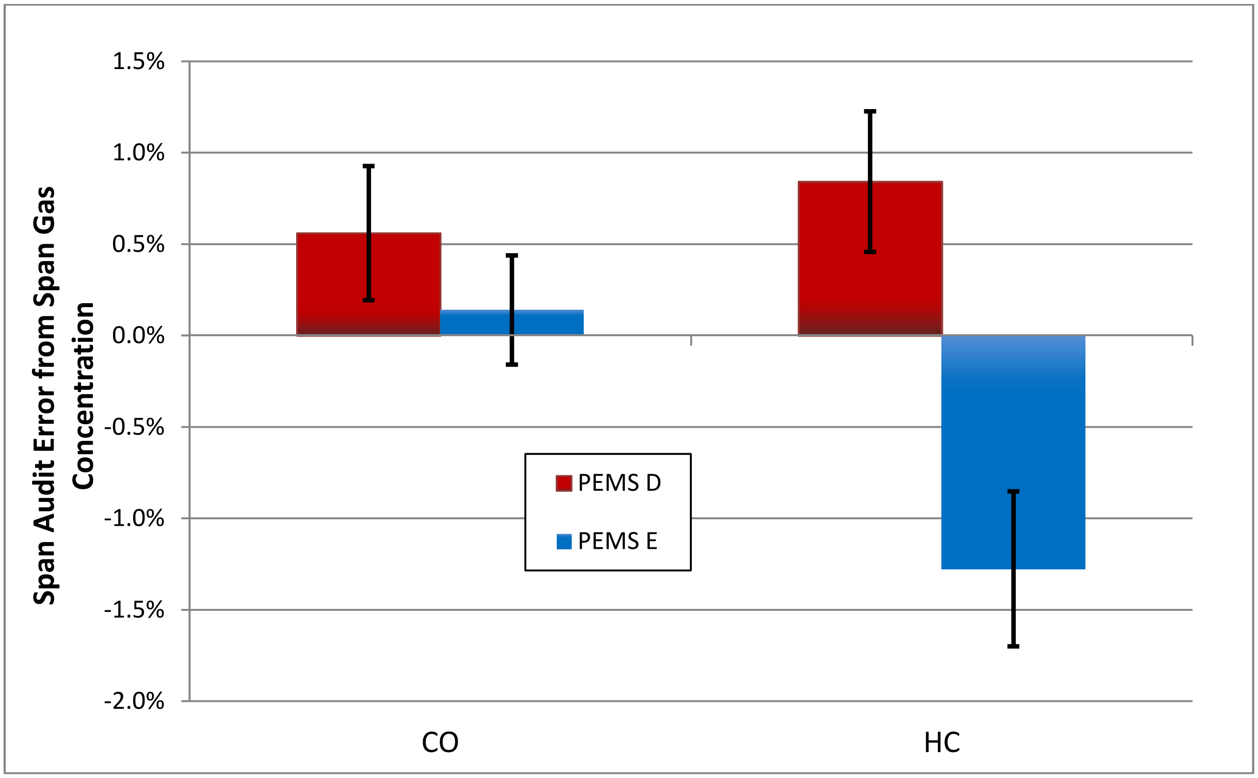

Figure 7-2. Average error from the span gas concentration to the measured audit concentration of CO and HC for pre- and post-test audits.

Figure 7-3 displays the average amount of drift from pre-test to post-test zero audits, given as a percentage of the nominal span gas value. Generally, zero drifts were much less than one percent for audits of CO_2 and NOx, however one PEMS averaged a drift of 1.5% with a relatively high level of variability around this value. This approach to drift analysis is intended to be comparable to the drift requirement description of 40 CFR 86.140, in which drift is calculated as the difference between the post-test measurement and the pre-test measurement. However, instead of being presented on the basis of the full scale readings of the different PEMS, all results are presented on the basis of the nominal concentrations of the span gas used in the project for consistency. The span gas concentration forms the relative basis of both the zero drift results and the span drift results (zero drift is often presented on the basis of full-scale readings, however as mentioned previously that basis was not used as it would be inconsistent across the different PEMS).

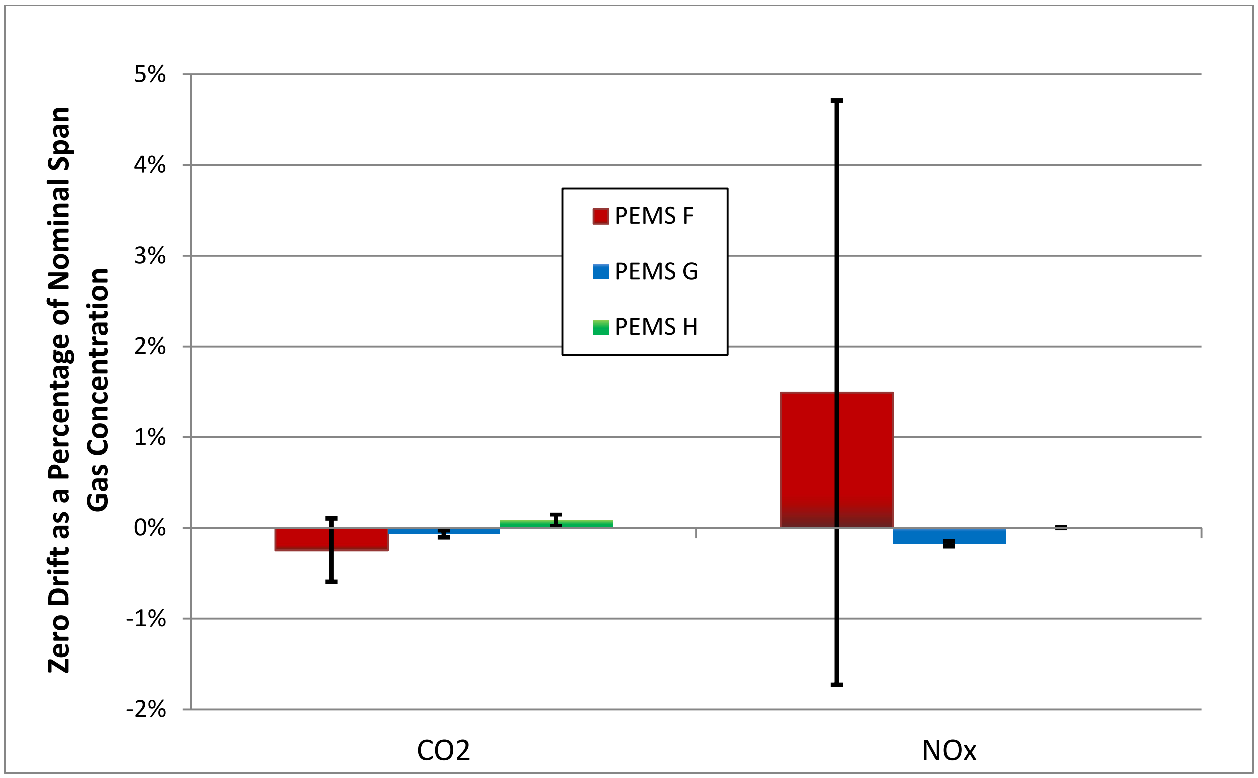

Figure 7-3. Average pre-test to post-test zero drift in CO_2 and NOx audits of all tests. Percentage is calculated relative to the nominal span gas concentration.

Figure 7-4 presents the zero drift averages for audits of CO and HC. These values, presented as a percentage of the nominal span gas values, range for both analyzer types from approximately -0.01% to 0.02%.

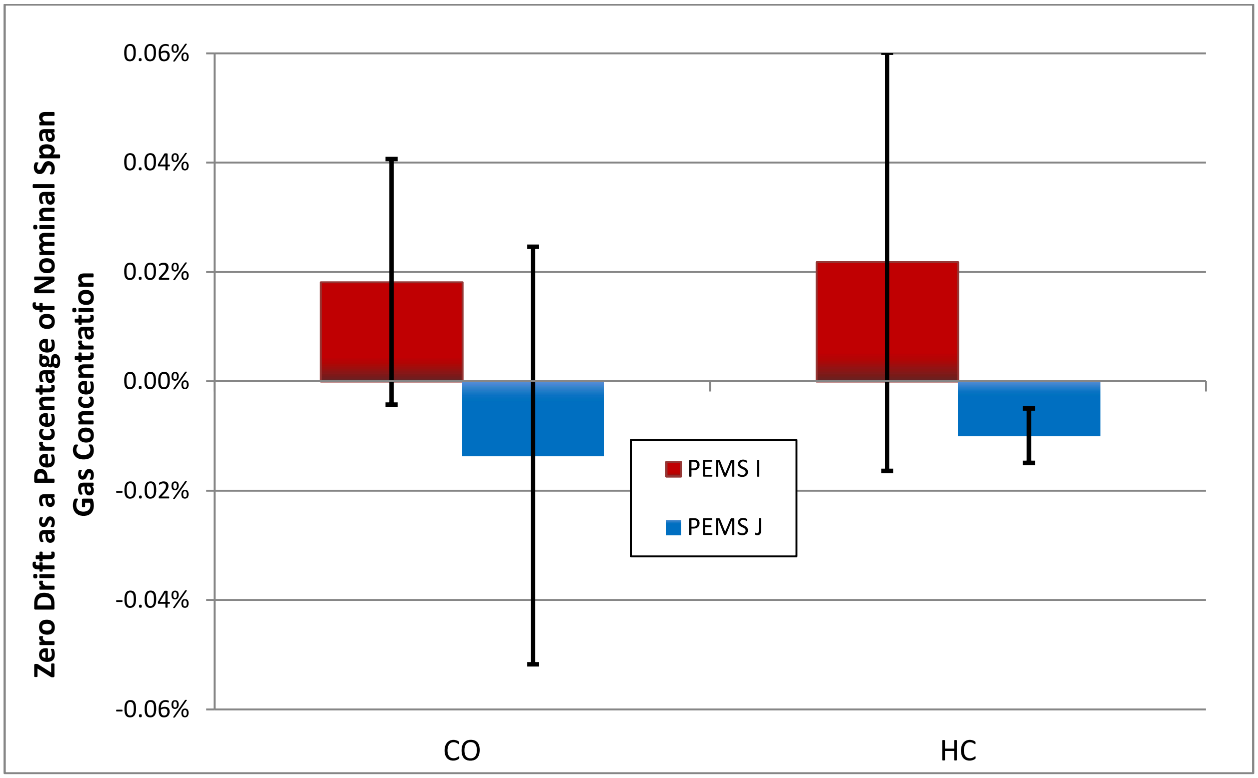

Figure 7-4. Average pre-test to post-test zero drift in CO and HC audits of all tests. Percentage is calculated relative to the nominal span gas concentration.

Average span drift from pre- to post-test audits are presented for measurements of CO_2 and NOx in Figure 7-5. As with the previous plots, these drift amounts are presented as a percentage of the nominal span gas concentrations used in the project for each compound. The average drift for each PEMS ranged from approximately -1% to 0.5% for CO_2, and up to greater than 6% for NOx.

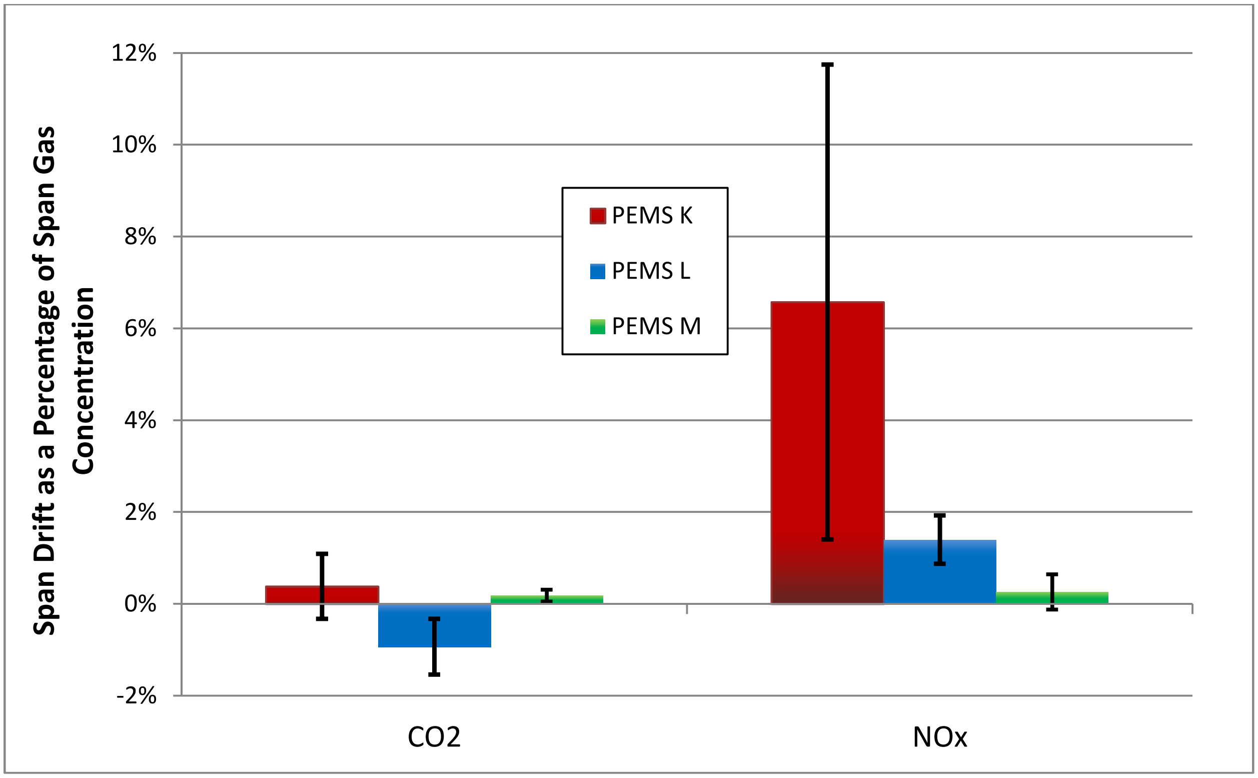

Figure 7-5. Average pre-test to post-test span drift in CO_2 and NOx audits of all tests. Percentage is calculated relative to the nominal span gas concentration.

Average span drift amounts for CO and HC are presented in Figure 7-6. These values generally fall in a tighter range than those observed for CO2 and NOx, ranging from -0.75% to 0.25% on average.

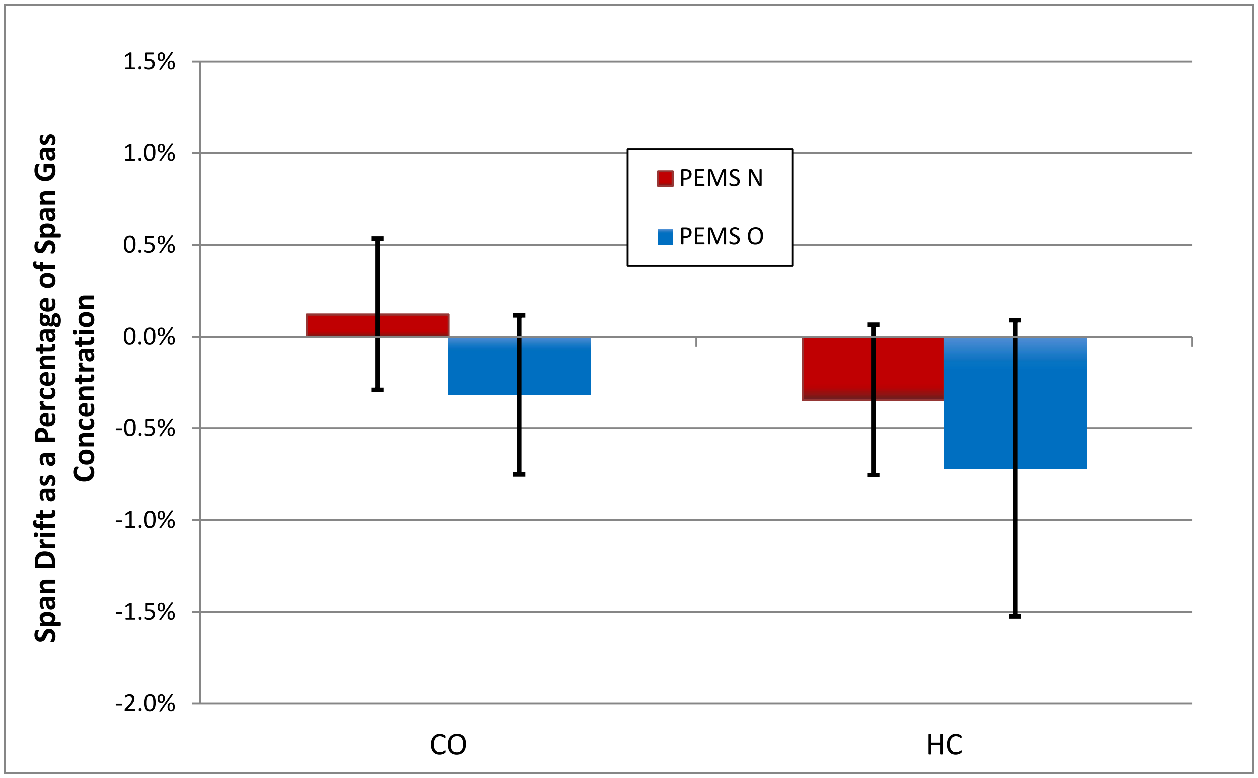

Figure 7-6. Average pre-test to post-test span drift in CO and HC audits of all tests. Percentage is calculated relative to the nominal span gas concentration.

7.2 Filter Blank Analysis

The 1065-capable PEMS unit uses gravimetric filters as a method for the measurement of exhaust PM mass emissions. The use of gravimetric filters involves first weighing an empty filter, then installing it in the PEMS and running the test (in which the filter is exposed to a proportionally-diluted portion of the exhaust flow), and then weighing the filter again after the test. PM emission mass over the cycle is then calculated per 40 CFR 1065.650. This process is subject to filter handling effects from the time of the first weighing to the time that the filter is installed in the PEMS and exposed to exhaust sample flow, and again from the end of the test until the filter is weighed after the test. It is also subject to any lab measurement errors associated with weighing the filters.

In order to quantify the effect of the filter handling procedures and other errors on the PEMS PM data collected in this project, ERG conducted a series of filter blank tests throughout the program. Two types of filter blank tests were performed, field blanks, in which a blank filter was conditioned and weighed, taken from the filter weighing area and installed into the PEMS, then immediately removed and returned to the filter weighing area for stabilization and weighing, and system blanks, in which a filter was taken from the weighing area, installed in the PEMS and the PEMS run in bypass for 30 minutes, and then removed from the PEMS and returned to the weighing area. The PEMS was run in bypass with the filter installed for 30 minutes to simulate the process that was followed for all tests of that PEMS, in which the sample pump is warmed up for approximately 30 minutes prior to a test with the system in standby and test filter installed. The PEMS is designed to bypass all sample flow so the filter should not be exposed to any flow during this time. Filter blanks were taken to simulate the processes of filter handling and weighing during testing at SwRI and at the test track.

The results of the filter blank investigation are presented in Figure 7-7. This figure shows that all blank filters gained weight during the handling in the blank tests. The field blanks appeared to gain more weight than did the system blanks. On average, the blanks gained 0.0023 mg. For tests of this vehicle, this level of filter weight gain corresponds approximately to 0.133 grams over the test cycle. This value represents approximately 11.5% of the average PM mass emission test results for cold-start tests of the vehicle with this PEMS. However, given that the system blanks were the most representative of the actual filter handling during testing, the percentage of test PM mass represented by these blank weight gains is only is approximately 8.2%. A log containing all the filter blank measurements and calculated averages is presented in Appendix H.

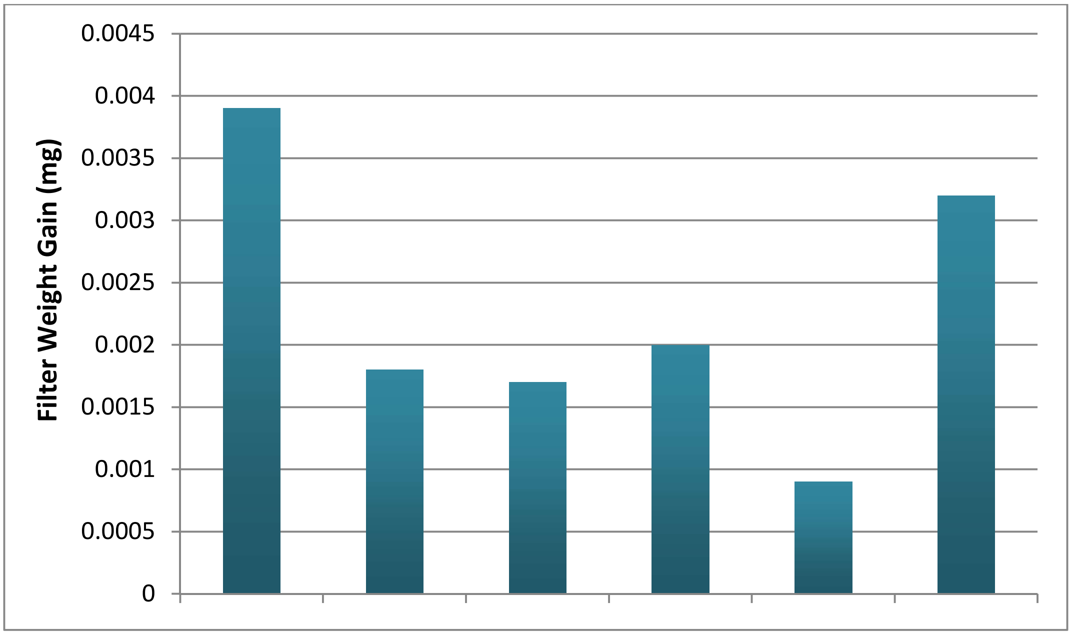

Figure 7-7. The measured change in filter weight for the blank-tested filters for the gravimetric-based PEMS.

Appendix A

Test Fuel Properties

Commercial E10 RUL for ERG Project			
	PSponCd		GA-9739
	SSponCd		Drum 7 of 13 Middle
	MiscCode		dated 6-9-17
	CReqstr		Kevin Brunner
	POTKNum		22751.01.801
	UserCd		FLRD-2032
	Size		gallon
D240 Gross Heating Value	BTUHeat	BTU/lb	18661
	MJHeat	MJ/kg	43.405
	CALHeat	cal/g	10367.2
D240 Net Heating Value	BTUHeat	BTU/lb	17444
	MJHeat	MJ/kg	40.575
	CALHeat	cal/g	9691.1
D4052 Density	API@60F		56.1
	SPGr@60F		0.7542
	Dens@15C	g/ml	0.754
D5291 Carbon/Hydrogen	Carbon	wt%	82.76
	Hydrogen	wt%	13.34
D5453 Sulfur	Sulfur	ppm	25.88
	SulfurWtPct	%	0.0026
D5599 Oxygenates	DIPEVol	Vol%	<0.1
	ETBEVol	Vol%	<0.1
	EtOHVol	Vol%	9.5498
	iBAVol	Vol%	<0.1
	iPAVol	Vol%	<0.1
	MeOHVol	Vol%	<0.1
	MTBEVol	Vol%	<0.1
	nBAVol	Vol%	<0.1
	nPAVol	Vol%	<0.1
	sBAVol	Vol%	<0.1
	TAMEVol	Vol%	<0.1
	tBAVol	Vol%	<0.1
	tPAVol	Vol%	<0.1
	TtlVol	Vol%	9.55
	TtlWt, Oxygen	Wt%	3.49

Appendix B

Test Route Turn-by-Turn Directions

E-122 Driving Route

Start at SwRI Bldg 87 Light-Duty Lab Vehicle Door
Drive North Out of Bldg. 87 Rear Driveway
Left on Tom Slick Ave.
Left on 4th St.
Left on Avenue C/Harold Vagtborg Ave.
Right on Tom Slick Ave.
Right on Commerce Dr.
Left on Pinn Rd.
Left on 151 E Access - Stay on Access
Right on Old 90 West
Stay on 90 Access
Left on Military Dr. S
Right on Somerset Rd. - Becomes Palo Alto
Left on IH 35 N, Merge to Onramp
Exit Hwy 90 West
Exit TX-151 West
Exit Callaghan Rd.
Right on Callaghan Rd.
Left on Commerce Dr.
Right on Tom Slick Ave. - to Bldg 87
Left into Bldg 87 Rear Driveway
Stop and turn off in front of no parking sign

Appendix C

Span and Audit Gas Specifications

Span and Audit Gases used in E-122

Airgas Quad Blends were used to Span the Horiba and 3DATX Systems and to Audit the Global MRV and 3DATX Systems
Bottle 1, used 7/10 - 8/7
Propane, 1471 ppm
NO, 2735 ppm
CO, 5%
CO_2, 15%

Bottle 2, used 8/9 - 9/28
Propane, 1499 ppm
NO, 2752 ppm
CO, 5%
CO_2, 15%

BAR97 High Gases were used to Span the GlobalMRV System. They were also used for the 2 audits of this system prior to 7/10
Bottle #1: (Used for Audits on 7/6 and 7/7)
Propane, 3195 PPM
NO, 3015 ppm
CO, 7.99%
CO_2, 12%

Bottle #2:
Propane, 3195 PPM
NO, 2996 ppm
CO, 7.99%
CO_2, 12%

Airgas
an Air Liquide company

Airgas USA, LLC
9810 BAY AREA BLVD
Pasadena, TX 77507
Airgas.com

CERTIFICATE OF ANALYSIS
Grade of Product: PRIMARY STANDARD

Customer:	S W RESEARCH		
Part Number:	X05NI79P33A0000	Reference Number:	163-400932059-1A
Cylinder Number:	CLM002987	Cylinder Volume:	33.7 CF
Laboratory:	124 - Pasadena (SG06) - TX	Cylinder Pressure:	2216 PSIG
Analysis Date:	Jun 28, 2017	Valve Outlet:	660
Lot Number:	163-400932059-1A		

Expiration Date: Jun 28, 2025

Primary Standard Gas Mixtures are traceable to N.I.S.T. weights and/or N.I.S.T. Gas Mixture reference materials.

ANALYTICAL RESULTS

Component	Req Conc	Actual Concentration (Mole %)		Analytical Uncertainty
PROPANE	1500 PPM	1471 PPM	(entered	+/- 1%
NITRIC OXIDE	2700 PPM	2735 PPM		+/- 1%
CARBON MONOXIDE	5.000 %	5.000 %		+/- 0.02% abs
CARBON DIOXIDE	15.00 %	15.00 %		+/- 0.02% abs
NITROGEN	Balance			
Total oxides of nitrogen		2753 PPM		For Reference Only

Placed into Service
20170710

Approved for Release

Airgas
an Air Liquide company

Airgas USA, LLC
9810 BAY AREA BLVD
Pasadena, TX 77507
Airgas.com

CERTIFICATE OF ANALYSIS

Grade of Product: PRIMARY STANDARD

Customer:	S W RESEARCH		
Part Number:	X05NI79P33A0000	Reference Number:	163-400932059-1A
Cylinder Number:	CAL6664	Cylinder Volume:	33.7 CF
Laboratory:	124 - Pasadena (SG06) - TX	Cylinder Pressure:	2216 PSIG
Analysis Date:	Jun 28, 2017	Valve Outlet:	660
Lot Number:	163-400932059-1A		

Expiration Date: Jun 28, 2025

Primary Standard Gas Mixtures are traceable to N.I.S.T. weights and/or N.I.S.T. Gas Mixture reference materials.

ANALYTICAL RESULTS

Component	Req Conc	Actual Concentration (Mole %)	Analytical Uncertainty
PROPANE	1500 PPM	1499 PPM	+/- 1%
NITRIC OXIDE	2700 PPM	2752 PPM	+/- 1%
CARBON MONOXIDE	5.000 %	5.000 %	+/- 0.02% abs
CARBON DIOXIDE	15.00 %	15.00 %	+/- 0.02% abs
NITROGEN	Balance		
Total oxides of nitrogen		2752 PPM	For Reference Only

Placed into Service 8/9/17

Approved for Release

Appendix D

Test Checklists for Lab/Road and Track for each PEMS

Horiba Test Checklist v1.7 **Date:______________**

ERG Test Personnel: ___________________ **Test No:______________________**

- Ballast vehicle with 170-180 lbs if no passenger will be present (on-road only). Make sure no other ballast weights are present
- Check vehicle tire pressures, set to 33 ± 1 psi
- Make sure dash fuel economy readout has been reset
- Plug in Horiba shore power and turn both PS units on. Flip rotary switches (3) on both PE modules and the CC module. Make sure both green and white lights are on for both
- Connect LAN cable to laptop, wait for all component white lights to be on, wait at least 1 min for GA computer to boot up, start Horiba software (Horiba DMC). Go to system -> connect. No EI or PN for this program.
- Use stream screen to ensure desired components are plugged in (only EI & PN plugged out)
- Check system FID, GA and other filters (FID is most critical), replace if needed.
- Install fresh Teflo gravimetric filter:
    - Note filter #________________________
- Go to device screen – Open one screen for GA tailpipe, under "Menu", select validation
    - After about 1-hour warm-up, do a vacuum decay leak check. Install gaseous sample line cap, select GA View's "Menu Button" -> Validation – Leak Check (vacuum decay), "GA must be in "pause". Select NO -> information box. Watch the pressure decay. Watch for warning indicators (yellow exclamation) in upper right of screen. If we have a leak, inspect O-ring on GA filter, reset both sample line quick disconnects. Note system will fail leak check if it hasn't warmed up (approximately 1 hour).
    - From footer- select GA -> History -> VLeak Check (vacuum decay). Review to verify, look for green "pass" button (analyzer autoswitches to "pause" after leak check)
    - Remove plug and put back into "standby"
- Connect FID fuel and zero air and open bottle valves. Check absolute bottle pressure to ensure we have enough gas, and check output pressure (should be 100-120 kpa).
- Light FID and turn on O_3 generator by going to system standby (in footer) for all components. Note time, test can begin in one hour: __________
- If desired, perform a cursory check of analyzer responses:
    - Connect span gas (output pressure is 100 – 120 kpa) and flow span and then zero gas (through Device screen, "Span" and "Zero" buttons) and verify values are reasonable (everything should upscale).
    - Press the "stop" button to stop gas flow
- Perform calibrations on PM – DLS under Device view
    - Absolute pressure cal.: Select menu -> Cal -> A-Press cal. Enter barometric pressure directly from SwRI dyno screen readout in the 3 locations
    - Differential pressure cal.: Select menu -> Cal -> D-Press cal. Press OK to perform Cal.
    - Flow Cal. Remove PM sample probe from flowmeter. Cover the probe with the small black rubber cap. Select menu -> Cal -> Flow cal.

  - Leak check. Keep black probe cover installed. Remove transfer connection from FS unit, RP sample out. Install quick-connect plug into RP Sample Out. Ensure filter holder is closed. Select menu -> Validation -> Leak check. After check is complete and passed, remove quick-connect plug and re-install transfer tube to RP sample out. Remove black plug from probe and re-install PM sample probe into flow meter.
  - DCS Functionality Check: Select menu -> Validation -> DCS Functionality Check. May need to run this multiple times. Ok if repeatable and near 30. Problem under 20. (Can do next step, HC hangup check, concurrently with this step)
  - From footer- select PM -> History -> Can review all Cals to verify, look for green “pass” button (analyzer autoswitches to “pause” after leak check)
- Perform HC hangup check
  - Disconnect gaseous sample line from flowmeter. Re-route line back into window of test vehicle to GA. Connect an exhaust line to hangup-tee barb fitting. Connect male quick connect of tee to sample line. Make sure span bottle is connected and open.
  - Device View -> GA Menu Button -> Validation -> Hangup Check
  - When prompted, connect female quick connect of the tee to GA (main, not FID) “Check” port. Acknowledge prompt and allow check to complete
  - Remove and replumb sample line
- After approximately ½ hr -45 mins, under PM Device view: Select “Fill” button (turns on pump). Ensure sample bypass button is gray (green means the filter is being loaded). This allows system to stabilize.
- Perform instantaneous z/s. This is a pre-test cursory check to ensure the system is set up correctly:
  - Check initial instrument health by selecting Maintenance -> GA -> Monitor. Press Analyzer Sensitivity. Take screen capture using snipping tool as a reference
  - Ensure span gas is connected and valve open. Device View -> GA -> Cal. <Can use Information Box to assist with troubleshooting. CO screen will show cal gas flow. NOx information view shows NDIR (20), CLA (40). Specific value is not critical but it should be steady during test day>.
  - Check that changes were reasonable by selecting Maintenance -> GA -> Monitor. Press Analyzer Sensitivity. Compare to snipping screen to ensure changes took place but are reasonable.
- Move vehicle to dynamometer or out to driveway, connect transfer pipe
- Connect Horiba OBD plug into dash
- Begin PEMS test sequence. Ensure span gas is connected and bottle is open at the start of this sequence. Press Test button.
  - Select ERG test, click Execute
  - Add test information, then press Ok
    - Note start time: ___________________________
  - In upper right, can select view screen

  - Yellow box indicates current steps in program. Exhaust gas tailpipe window header indicates the specific task being performed. Can select instruments from footer to see plots or tabulated data. System will show as standby when ready
  - Press green “Start Cal” button
  - Remove span bottle once span is complete (system reverts to standby), stow line in car
  - Press green “Start Sampling” button when ready to begin test
  - Start engine and drive route. Start vehicle moving 10 seconds after engine start.
  - Come to a stop and then press “Stop Test”.
  - Bring vehicle inside or off dyno (if desired), reconnect span gas
  - Press Start Drift Check
  - After drift check, but BEFORE Starting cleanup: Remove gravimetric filter
  - <u>After removing grav filter</u>, select “Start Cleanup” (purges system for about 10 mins)
  - Click “End Test” (no need to wait for “cleanup” to complete, it will continue)
- Note then reset in-vehicle fuel economy log
  - Note vehicle-logged fuel economy: ______________________mpg
  - Use page scroll button on steering wheel to find range, return button to reset
- Return to shore power and charge batteries if batteries were used:
  - Connect and power on shore power to both modules
  - Make sure green lights of PS units came on
- Turn off PEMS system
  - Put system into Pause, system will purge
  - Disconnect span gas after drift check complete
  - System -> Disconnect/Power Off
  - Horiba Button -> Exit and Shut Down
  - Turn off the 3 switches on the PS and CC units
- Close all gas bottles
- Connect charger clamps to batteries and then plug in chargers
  - During charging, if the PEMS is powered off, disconnect the battery power cables from the PEMS. They are only isolated from the PEMS if the PEMS is powered on and on shore power
- Return filter and holder to weighing room
- Drain condensation block

Setting Calibration Values

- Device View -> GA Menu Button -> Span Gas
- Enter value as ppmC. SwRI values are listed in ppmC
- To edit OBD PIDS, under “user” menu (upper right of computer screen), move from “normal” to “supervisor”, password is “super”.

Performing zero/span with individual gases

- Ensure correct span values are entered in the Span Gas window
- Device View -> GA
- Press Button for individual gas -> Auto Cal.
- This does not work in a Test Mode. Would need to do a pre-test Z/S calibration. Then log a pre-test read of all bottles. Then do test. Then log a post-test read of all bottles. Enter the pre and post read values in post processor.

Monthly linearity check (do not need linearize for 1065) - Need a 703 gas divider

Horiba Post Processing

- Open HoribaPP
- Open recent test file:
  - Navigator screen -> Horiba PEMS analysis bar (round logo)
  - File Import, select desired file. Opens Data Mapping Dialog
  - Leave section one as default. Can import another datafile in section 2. In section 3, generate 1 Hz data. Use average, not sampling
  - Select "loading"
- Can open Data Portal (white square icon directly under "Settings"). The data portal allows quick review of the logged data, with small preview plots
- Fuel Registration -> Select needed fuel properties/file– no longer required, this is pre-set
- Perform time alignment
  - "View" in left toolbar -> Horiba logo -> Time alignment (upper left logo)
  - Under Channel Group, select MeasData_1Hz (not org, which is 10 Hz)
  - Under Raw Channel, select (by pressing Add) ***(note, save time by only selecting parameter that require change, i.e., non-shaded, retained for documentation)***
    - GPS Speed (0 second delay)
    - WS Ambient Temp, RH, ambient pressure (0 second delays for each)
    - PF_ExhaustFlowRate1 (0 second delay, i.e., 0)
    - GA_COConc (1 second advanced, i.e., -1)
    - GA_CO2Conc (0 second delay, i.e., 0)
    - H2O (2 second advanced, i.e., -2)
    - GA_NOConc (1 second advance, i.e., -1)
    - GA_NOxConc (2 second advance, i.e., -2)
    - GA_NO_2Conc (2 seconds advanced, i.e., -2)
    - GA_THCConc (0 seconds delay)
    - PM_Sensor_PM (6 seconds advance, i.e., -6)
    - OBD_EngineSpeed (0 second delay)
    - Load (same delay and OBD Engine speed)
  - Click Input Delay Time

- Select "OBD Engine Speed" as the cross-correlation reference channel. Under Delay Time Table, select the variable that is desired to change. In the delay column, can adjust the delay for each variable until graph shows acceptable alignment. Use parameter delays listed above. Complete time alignment of all desired parameters. Double click a line to change color. After complete, press apply.
- Analysis Button -> Horiba (Circle) Logo -> Basic Calculation -> Correction Tab
  - Along top, Channel Group to MeasData_1Hz (unless 10Hz calcs are desired)
  - Hit Drift Correction button upper left (ignore the "there is a channel not in group" message)
  - Check Custom at top of Screen (only if using manually-recorded single blends)
  - Make sure all rows are checked at rightmost Selection column
  - Press Correction at bottom (this applies the drift correction)
- Press Basic Calculation (lower left button)
  - Regulation Tab: Select US regulation type
  - Common Tab: Select speed source for Distance Calculation. Can uncheck for full variable list. Enter filter tare and loaded weights. Go through all variables, ensure you select all 1 hz drift corrected, time-aligned variables, if available. Select "drift" corrected variables if available, otherwise "delay", otherwise just the native variable. Can deselect unneeded variables. For exhaust flow, choose PF_exhfl1
  - Calculation Tab: Probably do not need to change anything in this tab
  - TripComposition Tab: Probably do not need to change anything in this tab
  - Correction Tab: Dry to Wet Inactive, Combustion System is Spark Ignition Direct, NOx channel active, PM channel active
  - Press "Calculation" button at lower right to initiate calculations

- View button in left toolbar:
  - The four tabs show different trip stats
- To output a report: Report button in left toolbar -> Horiba (circle) logo -> Emission Report
  - Select Emission_NTE_Eng, then select "OK" button
  - Under "File", select "PDF Export" to save the summary report to a PDF
- Navigator button in left toolbar:
  - Horiba button -> File export (don't use convert, which merely exports the raw binary into a CSV)
  - Select group "EmissionResult_1"
  - Export the csv
  - Exports to C:\Horiba\OBS-PP\Data\ExportData
- To export binary data, go under HoribaDMC main software, select "results" under test menu, then select the file you want to export and export to the desired location…
- CRITICAL: To exit post processor, File –> Exit. ALWAYS select Exit and do not Save. ALWAYS select No when it asks to save.

Horiba Test Checklist v2.2-Track **Date:_______________**

ERG Test Personnel: ___________________ **Test Nos:_____________________**

- — Check vehicle tire pressures, set to 33 ± 1 psi
- — Make sure dash fuel economy readout has been reset
- — Plug in Horiba shore power and turn both PS units on. Flip rotary switches (3) on both PE modules and the CC module. Make sure both green and white lights are on for both
- — Connect LAN cable to laptop, wait for all component white lights to be on, wait at least 1 min for GA computer to boot up, start Horiba software (Horiba DMC). Go to system -> connect. No EI or PN for this program.
- — Use stream screen to ensure desired components are plugged in (only EI & PN plugged out)
- — Check system FID, GA and other filters (FID is most critical), replace if needed.
- — Install fresh Teflo gravimetric filter:
    - o Note filter #________________________
- — Go to device screen – Open one screen for GA tailpipe, under "Menu", select validation
    - o After about 1-hour warm-up, do a vacuum decay leak check. Install gaseous sample line cap, select GA View's "Menu Button" -> Validation – Leak Check (vacuum decay), "GA must be in "pause". Select NO -> information box. Watch the pressure decay. Watch for warning indicators (yellow exclamation) in upper right of screen. If we have a leak, inspect O-ring on GA filter, reset both sample line quick disconnects. Note system will fail leak check if it hasn't warmed up (approximately 1 hour).
    - o From footer- select GA -> History -> VLeak Check (vacuum decay). Review to verify, look for green "pass" button (analyzer autoswitches to "pause" after leak check)
    - o Remove plug and put back into "standby"
- — Connect FID fuel and zero air and open bottle valves. Check absolute bottle pressure to ensure we have enough gas, and check output pressure (should be 100-120 kpa).
- — Light FID and turn on O_3 generator by going to system standby (in footer) for all components. Note time, test can begin in one hour: __________
- — If desired, perform a cursory check of analyzer responses:
    - o Connect span gas (output pressure is 100 – 120 kpa) and flow span and then zero gas (through Device screen, "Span" and "Zero" buttons) and verify values are reasonable (everything should upscale).
    - o Press the "stop" button to stop gas flow
- — Perform calibrations on PM – DLS under Device view
    - o Absolute pressure cal.: Select menu -> Cal -> A-Press cal. Enter barometric pressure directly from SwRI dyno screen readout in the 3 locations
    - o Differential pressure cal.: Select menu -> Cal -> D-Press cal. Press OK to perform Cal.
    - o Flow Cal. Remove PM sample probe from flowmeter. Cover the probe with the small black rubber cap. Select menu -> Cal -> Flow cal.
    - o Leak check. Keep black probe cover installed. Remove transfer connection from FS unit, RP sample out. Install quick-connect plug into RP Sample Out. Ensure filter holder is

closed. Select menu -> Validation -> Leak check. After check is complete and passed, remove quick-connect plug and re-install transfer tube to RP sample out. Remove black plug from probe and re-install PM sample probe into flow meter.

    - DCS Functionality Check: Select menu -> Validation -> DCS Functionality Check. May need to run this multiple times. Ok if repeatable and near 30. Problem under 20. (Can do next step, HC hangup check, concurrently with this step)
    - From footer- select PM -> History -> Can review all Cals to verify, look for green “pass” button (analyzer autoswitches to “pause” after leak check)
- Perform HC hangup check
    - Disconnect gaseous sample line from flowmeter. Re-route line back into window of test vehicle to GA. Connect an exhaust line to hangup-tee barb fitting. Connect male quick connect of tee to sample line. Make sure span bottle is connected and open.
    - Device View -> GA Menu Button -> Validation -> Hangup Check
    - When prompted, connect female quick connect of the tee to GA (main, not FID) “Check” port. Acknowledge prompt and allow check to complete
    - Remove and replumb sample line
- After approximately ½ hr -45 mins, under PM Device view: Select “Fill” button (turns on pump). Ensure sample bypass button is gray (green means the filter is being loaded). This allows system to stabilize.
- Install jumper battery cables between the two battery banks and connect batter banks to PS units
- Perform instantaneous z/s. This is a pre-test cursory check to ensure the system is set up correctly:
    - Check initial instrument health by selecting Maintenance -> GA -> Monitor. Press Analyzer Sensitivity. Take screen capture using snipping tool as a reference
    - Ensure span gas is connected and valve open. Device View -> GA -> Cal. <Can use Information Box to assist with troubleshooting. CO screen will show cal gas flow. NOx information view shows NDIR (20), CLA (40). Specific value is not critical but it should be steady during test day>.
    - Check that changes were reasonable by selecting Maintenance -> GA -> Monitor. Press Analyzer Sensitivity. Compare to snipping screen to ensure changes took place but are reasonable.
- Connect Horiba OBD plug into y-connector with drivers aid, verify function of both
- Tow or push vehicle to test track
- Begin PEMS test sequence. Ensure span gas is connected and bottle is open at the start of this sequence. Press Test button.
    - Select ERG test, click Execute
    - Add test information, then press Ok
        - Note start time: ___________________________
    - In upper right, can select view screen

- Yellow box indicates current steps in program. Exhaust gas tailpipe window header indicates the specific task being performed. Can select instruments from footer to see plots or tabulated data. System will show as standby when ready
- Press green “Start Cal” button
- Remove span bottle once span is complete (system reverts to standby), stow line in car

— Begin recording for accelerometer-

— Open driver trace, select cycle, enter date and test number in logging window, press start log, then press crank

— Engine start procedure:
  - Key on for 5 seconds first
  - Press start on driver trace
  - Horiba: Press green “Start Sampling” button when ready to begin test.
  - Start engine
  - Accelerometer: bump to dash at engine start

— Drive route. Start vehicle moving 10 seconds after engine start.
  - Come to a stop and then press “Stop Test” on horiba.
  - Stop the driver trace log
  - Stop logging accelerometer
  - Bring vehicle inside or off dyno (if desired), reconnect span gas

— Note then reset in-vehicle fuel economy log
  - Note vehicle-logged fuel economy: ______________________mpg

  - Press Start Drift Check
  - After drift check, but BEFORE Starting cleanup: Remove gravimetric filter
  - After removing grav filter, select “Start Cleanup” (purges system for about 10 mins)
  - Click “End Test” (no need to wait for “cleanup” to complete, it will continue)
  - Use page scroll button on steering wheel to find range, return button to reset

— Install fresh Teflo gravimetric filter:
  - Note filter #_______________________

— Check gas bottle pressures

— Move vehicle to next track, begin 10 minute idle

— Begin PEMS test sequence. Ensure span gas is connected and bottle is open at the start of this sequence. Press Test button.
  - Select ERG test, click Execute
  - In upper right, can select view screen
  - Yellow box indicates current steps in program. Exhaust gas tailpipe window header indicates the specific task being performed. Can select instruments from footer to see plots or tabulated data. System will show as standby when ready
  - Press green “Start Cal” button
  - Remove span bottle once span is complete (system reverts to standby), stow line in car

- Begin recording for accelerometer
- Open driver trace, select cycle, enter date and test number in logging window, press start log, then press crank
- Running start for test
    - Reset dash fuel economy
    - Horiba: Press green “Start Sampling” button just before start
    - Accelerometer: bump to dash at test start
    - Press start on driver trace

- Put vehicle in gear and drive route.
    - Come to a stop and then press “Stop Test” on horiba.
    - Stop the driver trace log
    - Stop logging accelerometer
    - Bring vehicle inside or off dyno (if desired), reconnect span gas
    - Press Start Drift Check
    - After drift check, but BEFORE Starting cleanup: Remove gravimetric filter
    - After removing grav filter, select “Start Cleanup” (purges system for about 10 mins)
    - Click “End Test” (no need to wait for “cleanup” to complete, it will continue)
- Note then reset in-vehicle fuel economy log
    - Note vehicle-logged fuel economy: ________________________mpg
    - Use page scroll button on steering wheel to find range, return button to reset

- Return to shore power and charge batteries if batteries were used:
    - Connect and power on shore power to both modules
    - Make sure green lights of PS units came on
- Turn off PEMS system
    - Put system into Pause, system will purge
    - Disconnect span gas after drift check complete
    - System -> Disconnect/Power Off
    - Horiba Button -> Exit and Shut Down
    - Turn off the 3 switches on the PS and CC units
- Close all gas bottles
- Connect charger clamps to batteries and then plug in chargers
    - During charging, if the PEMS is powered off, disconnect the battery power cables from the PEMS. They are only isolated from the PEMS if the PEMS is powered on and on shore power
    - Separate bank jumper cables prior to charging
- Return filter and holder to cooler for storage
- Drain condensation block
- Add 1-2 gallons of test fuel to vehicle

Setting Calibration Values

- Device View -> GA Menu Button -> Span Gas
- Enter value as ppmC. SwRI values are listed in ppmC
-
- To edit OBD PIDS, under "user" menu (upper right of computer screen), move from "normal" to "supervisor", password is "super".
-

Performing zero/span with individual gases

- Ensure correct span values are entered in the Span Gas window
- Device View -> GA
- Press Button for individual gas -> Auto Cal.
- This does not work in a Test Mode. Would need to do a pre-test Z/S calibration. Then log a pre-test read of all bottles. Then do test. Then log a post-test read of all bottles. Enter the pre and post read values in post processor.

Monthly linearity check (do not need linearize for 1065) - Need a 703 gas divider

Horiba Post Processing

- Open HoribaPP
- Open recent test file:
  - Navigator screen -> Horiba PEMS analysis bar (round logo)
  - File Import, select desired file. Opens Data Mapping Dialog
  - Leave section one as default. Can import another datafile in section 2. In section 3, generate 1 Hz data. Use average, not sampling
  - Select "loading"
- Can open Data Portal (white square icon directly under "Settings"). The data portal allows quick review of the logged data, with small preview plots
- Fuel Registration -> Select needed fuel properties/file– no longer required, this is pre-set
- Perform time alignment
  - "View" in left toolbar -> Horiba logo -> Time alignment (upper left logo)
  - Under Channel Group, select MeasData_1Hz (not org, which is 10 Hz)
  - Under Raw Channel, select (by pressing Add) ***(note, save time by only selecting parameter that require change, i.e., non-shaded, retained for documentation)***
    - GPS Speed (0 second delay)
    - WS Ambient Temp, RH, ambient pressure (0 second delays for each)
    - PF_ExhaustFlowRate1 (0 second delay, i.e., 0)
    - GA_COConc (1 second advanced, i.e., -1)
    - GA_CO2Conc (0 second delay, i.e., 0)
    - H2O (2 second advanced, i.e., -2)

        - GA_NOConc (1 second advance, i.e., -1)
        - GA_NOxConc (2 second advance, i.e., -2)
        - GA_NO_2Conc (2 seconds advanced, i.e., -2)
        - GA_THCConc (0 seconds delay)
        - PM_Sensor_PM (6 seconds advance, i.e., -6)
        - OBD_EngineSpeed (0 second delay)
        - Load (same delay and OBD Engine speed)
    - Click Input Delay Time
    - Select "OBD Engine Speed" as the cross-correlation reference channel. Under Delay Time Table, select the variable that is desired to change. In the delay column, can adjust the delay for each variable until graph shows acceptable alignment. Use parameter delays listed above. Complete time alignment of all desired parameters. Double click a line to change color. After complete, press apply.
    - Analysis Button -> Horiba (Circle) Logo -> Basic Calculation -> Correction Tab
        - Along top, Channel Group to MeasData_1Hz (unless 10Hz calcs are desired)
        - Hit Drift Correction button upper left (ignore the "there is a channel not in group" message)
        - Check Custom at top of Screen (only if using manually-recorded single blends)
        - Make sure all rows are checked at rightmost Selection column
        - Press Correction at bottom (this applies the drift correction)
    - Press Basic Calculation (lower left button)
        - Regulation Tab: Select US regulation type
        - Common Tab: Select speed source for Distance Calculation. Can uncheck for full variable list. Enter filter tare and loaded weights. Go through all variables, ensure you select all 1 hz drift corrected, time-aligned variables, if available. Select "drift" corrected variables if available, otherwise "delay", otherwise just the native variable. Can deselect unneeded variables. For exhaust flow, choose PF_exhfl1
        - Calculation Tab: Probably do not need to change anything in this tab
        - TripComposition Tab: Probably do not need to change anything in this tab
        - Correction Tab: Dry to Wet Inactive, Combustion System is Spark Ignition Direct, NOx channel active, PM channel active
        - Press "Calculation" button at lower right to initiate calculations
- View button in left toolbar:
    - The four tabs show different trip stats
- To output a report: Report button in left toolbar -> Horiba (circle) logo -> Emission Report
    - Select Emission_NTE_Eng, then select "OK" button
    - Under "File", select "PDF Export" to save the summary report to a PDF
- Navigator button in left toolbar:
    - Horiba button -> File export (don't use convert, which merely exports the raw binary into a CSV)

    - Select group “EmissionResult_1”
    - Export the csv
    - Exports to C:\Horiba\OBS-PP\Data\ExportData
- To export binary data, go under HoribaDMC main software, select “results” under test menu, then select the file you want to export and export to the desired location…
- CRITICAL: To exit post processor, File –> Exit. ALWAYS select Exit and do not Save. ALWAYS select No when it asks to save.

GlobalMRV Test Checklist v1.6 **Date:_____________**

ERG Test Personnel: ________________ **Test No:______________**

- Ballast vehicle with 175-185 lbs if no passenger will be present (on-road tests only). Make sure no other ballast weights are present
- Check vehicle tire pressures, set to 33 ± 1 psi
- Make sure dash fuel economy readout has been reset
- Connect voltmeter, chiller, and Axion power wire to battery
- Power on system using button at lower left. Start control software by clocking on the small globe icon (not the larger Windows globe icon) in the taskbar. After starting the equipment, allow it to warm up for 45 mins (however the leak check can begin during this time)
    - Note time on:

      ____________________________ ⇦

- Make the various connections during the warmup procedure: Do not yet connect zero or span lines, and do not connect the marman exhaust flange as the probe tips will be needed during the leak check.
    - Install sample and drain lines
    - Install weather station plug at front of Unit
    - Install OBD and and GPS plugs at rear of unit
    - Connect all 6 exhaust lines
    - Prepare both gas and PM sample lines to rear of unit. Gas input uses filter bowl which connects both the dry and wet side. PM sample hose connects into chiller, then chiller PM sample output line connects to PM Dry, and the clear plastic tubing from the chiller connects to PM wet. Can leave off PM sample line as that will be plugged into GA input during leak check.
- Check and update test configuration (Edit test configuration to update vehicle info, engine, fuel info) as needed. Generally, there will be no changes, we will only list changes from standard test configuration. Ensure you save your changes and verify them after test edit configuration is closed.
- Check "data acquisition hardware" window to ensure we're acquiring all the parameters we need. Check time delay alignments, LD ECU (listener or controller), GPS, weather station, PM Analyzer, both gas analyzers. If changes are needed, edit data acquisition hardware with "Edit DAQ Config" button.
- Press Start Test, Note time:

  ____________________________ ⇦

- Data Collection Tab:
    - Perform Leak Tests. (Need to remove the downstream marmon-flanged sample pipe from exhaust). Identify the gaseous line (GA Dry Input) by removing that line from the back of the unit and determining which probe no longer has suction. Reconnect the line. Under Summary Menu, enter Gas Analyzers and press Leak Test. Cap the probe with the red cap. Press Proceed under Leak Test Window for Gas Analyzer 1. After line 1 leak test, switch second line (PM line) to GA Dry Input and leak test. Remove red cap after second "Passed" screen. After completion, press cancel and then return PM line to PM sampling port in chiller and reconnect the GA line
- Connect PM Line, adjust rotameter on rear of unit to stabilize at 4 L/min. Per GMRV recommendation, center the rotameter ball on 4.
- Mount probes to tailpipe and make sure both hoses are connected to tailpipe probes
- Connect Chiller to power and turn on chiller switch approximately 15 mins before test (single toggle switch). Ensure it drops to 5 degrees C.
- Perform Zero/Span (bottles started 275 psi)
    - Under Data Collection, Press Span
    - Verify system has been running for at least 45 mins, press Proceed
    - Connect zero bottle to zero port, span bottle to span port. Open tank valves and set regulators to 5 psi at zero flow condition (approach 5 slowly as valve must be closed completely to decrease the pressure. Turn counterclockwise to decrease, clockwise to increase
    - Enter gas concentrations from bottle in next dialog, press Proceed with Gas Analyzer 1 Selected. Allow span process to continue (Can identify the 2 exhaust lines by those that have flow during the zero- vent these two outside if indoors – note the 2 exhaust lines change for the z/s of the 2nd analyzer)
    - Select Gas Analyzer 2. Verify that gas concentrations match bottles after making this switch and adjust the values if necessary. Press Proceed with Gas Analyzer 2 Selected and allow process to continue. Press cancel after second analyzer span.
    - Pres proceed at maintenance completed window. Do not check any boxes.
    - After span completes, turn off valves on both tanks, drop regulator pressures by turning counterclockwise, and disconnect hoses from PEMS
- If desired, connect tablet to Global MRV (as master) using TeamViewer. On tablet, select TeamViewer Icon. Open TeamViewer12 on analyzer unit, then note ID. Enter the ID on the tablet (should autopopulate). Once connected, enter the password on the MRV display. Minimize the TeamViewer Popup using the right facing arrow. Note it very easily to accidentally close the software using the tablet by accidentally pressing the red X. The finger icon at the bottom of the tablet allows it to go into Mouse Interactions mode, which makes this less likely.
- Move vehicle to dynamometer and connect transfer pipe, or outside for road test
- Connect GlobalMRV OBD plug into dash
- Do a pre-test audit through the GA sample inlet:

  - Use the secondary GA input manifold (with the balloon) plugged directly into GA dry input.
  - Data Collection Tab, Choose Bags from Menu Button at Upper Left, press start bag
  - Allow background air to flow into unit, then crack open span gas bottle and gently move hose to the secondary manifold. Control pressure to slightly pressurize balloon. Hold for 5-10 seconds
  - Turn off gas flow with regulator and concurrently remove span gas tubing
  - Press stop bag
- Remove secondary manifold, ensure that the GA sample line and filter are properly mounted, and that PM line travels through chiller and both the dry and wet PM lines are connected
- Disconnect shore power and connect battery power
- Data Collection Tab, Choose Bags from Menu Button at Upper Left
- Press Start Bag, wait approx. 10 seconds until data appears in Bag 1 column then follow engine/test start procedures.
- Once cycle is complete, press Stop Bag
- Note then reset in-vehicle fuel economy log
  - Note vehicle-logged fuel economy: ______________________mpg
  - Use page scroll button on steering wheel to find range, Return button to reset
- Do a post-test audit through the GA sample inlet:
  - Use the secondary GA input manifold (with the balloon) plugged directly into GA dry input.
  - Data Collection Tab, Choose Bags from Menu Button at Upper Left, press start bag
  - Allow background air to flow into unit, then crack open span gas bottle and gently move hose to the secondary manifold. Control pressure to slightly pressurize balloon. Hold for 5-10 seconds
  - Turn off gas flow with regulator and concurrently remove span gas tubing
  - Press stop bag
- Test configuration Tab: Press Stop Test. Note end time:

  ____

- If on-road test, record ambient conditions, either from lab or from weather site source
  - Temperature: ______________
  - Pressure: ______________ (circle: uncorrected or corrected)
  - Humidity: ______________
- Allow system to purge while sampling clean air for ~30 mins
- Turn chiller off
- Blow out sample lines, probes, and exhaust lines. Disassemble GA filter and allow to dry
- Close Program using Red X (Do not run program while moving files)
- Open Axion Save Files directory, copy files off system folder
- Shut Down Windows, then press the blue button to completely power off the unit
- Make sure chiller and Axion are off, then remove Li-ion battery from vehicle to charge

GlobalMRV Test Checklist V2.0-Track **Date:____________**

ERG Test Personnel: _______________ **Test No:_____________**

- Check vehicle tire pressures, set to 33 ± 1 psi
- Make sure dash fuel economy readout has been reset
- Connect voltmeter, chiller, and Axion power wire to battery
- Power on system using button at lower left-using shore power. Start control software by clocking on the small globe icon (not the larger Windows globe icon) in the taskbar. After starting the equipment, allow it to warm up for 45 mins (however the leak check can begin during this time)
  - Note time on:

    ___________________________ ⇦

- Make the various connections during the warmup procedure: Do not yet connect zero or span lines, and do not connect the marman exhaust flange as the probe tips will be needed during the leak check.
  - Install sample and drain lines
  - Install weather station plug at front of Unit
  - Install OBD and and GPS plugs at rear of unit
  - Connect all 6 exhaust lines
  - Prepare both gas and PM sample lines to rear of unit. Gas input uses filter bowl which connects both the dry and wet side. PM sample hose connects into chiller, then chiller PM sample output line connects to PM Dry, and the clear plastic tubing from the chiller connects to PM wet. Can leave off PM sample line as that will be plugged into GA input during leak check.
- Check and update test configuration (Edit test configuration to update vehicle info, engine, fuel info) as needed. Generally, there will be no changes, we will only list changes from standard test configuration. Ensure you save your changes and verify them after test edit configuration is closed.
- Check “data acquisition hardware” window to ensure we’re acquiring all the parameters we need. Check time delay alignments, LD ECU (listener or controller), GPS, weather station, PM Analyzer, both gas analyzers. If changes are needed, edit data acquisition hardware with “Edit DAQ Config” button.
- Press Start Test, Note time:

  ___________________________ ⇦

- Data Collection Tab:
  - Perform Leak Tests. (Need to remove the downstream marmon-flanged sample pipe from exhaust). Identify the gaseous line (GA Dry Input) by removing that line from the back of the unit and determining which probe no longer has suction. Reconnect the line. Under Summary Menu, enter Gas Analyzers and press Leak Test. Cap the probe with the red cap. Press Proceed under Leak Test Window for Gas Analyzer 1. After line 1 leak test, switch second line (PM line) to GA Dry Input and leak test. Remove red cap after second "Passed" screen. After completion, press cancel and then return PM line to PM sampling port in chiller and reconnect the GA line
- Connect PM Line, adjust rotameter on rear of unit to stabilize at 4 L/min. Per GMRV recommendation, center the rotameter ball on 4.
- Mount probes to tailpipe and make sure both hoses are connected to tailpipe probes
- Connect Chiller to power and turn on chiller switch approximately 15 mins before test (single toggle switch). Ensure it drops to 5 degrees C.
- Perform Zero/Span (bottles started 275 psi)
  - Under Data Collection, Press Span
  - Verify system has been running for at least 45 mins, press Proceed
  - Connect zero bottle to zero port, span bottle to span port. Open tank valves and set regulators to 5 psi at zero flow condition (approach 5 slowly as valve must be closed completely to decrease the pressure. Turn counterclockwise to decrease, clockwise to increase
  - Enter gas concentrations from bottle in next dialog, press Proceed with Gas Analyzer 1 Selected. Allow span process to continue (Can identify the 2 exhaust lines by those that have flow during the zero- vent these two outside if indoors – note the 2 exhaust lines change for the z/s of the 2nd analyzer)
  - Select Gas Analyzer 2. Verify that gas concentrations match bottles after making this switch and adjust the values if necessary. Press Proceed with Gas Analyzer 2 Selected and allow process to continue. Press cancel after second analyzer span.
  - Pres proceed at maintenance completed window. Do not check any boxes.
  - After span completes, turn off valves on both tanks, drop regulator pressures by turning counterclockwise, and disconnect hoses from PEMS
- If desired, connect tablet to Global MRV (as master) using TeamViewer. On tablet, select TeamViewer Icon. Open TeamViewer12 on analyzer unit, then note ID. Enter the ID on the tablet (should autopopulate). Once connected, enter the password on the MRV display. Minimize the TeamViewer Popup using the right facing arrow. Note it very easily to accidentally close the software using the tablet by accidentally pressing the red X. The finger icon at the bottom of the tablet allows it to go into Mouse Interactions mode, which makes this less likely.
- Disconnect shore power and connect battery power
- Move vehicle to track
- Connect GlobalMRV OBD plug into dash, verify obd signal in GMRV and driver trace
- Do a pre-test audit through the GA sample inlet:

    - Use the secondary GA input manifold (with the balloon) plugged directly into GA dry input.
    - Data Collection Tab, Choose Bags from Menu Button at Upper Left, press start bag
    - Allow background air to flow into unit, then crack open span gas bottle and gently move hose to the secondary manifold. Control pressure to slightly pressurize balloon. Hold for ~10 seconds
    - Turn off gas flow with regulator and concurrently remove span gas tubing
    - Press stop bag
- Remove secondary manifold, ensure that the GA sample line and filter are properly mounted, and that PM line travels through chiller and both the dry and wet PM lines are connected
- Open driver trace, select cycle, enter date and test number in logging window, press start log, then press crank
- Data Collection Tab, Choose Bags from Menu Button at Upper Left
- Press Start Bag, wait approx. 10 seconds until data appears in Bag 1 column then follow engine/test start procedures.
- Engine start procedure:
    - Begin recording for accelerometer
    - Key on for 5 seconds first
    - Press start on driver trace
    - Start engine
    - Accelerometer: bump to dash at engine start
- Once cycle is complete, press Stop Bag
- Note then reset in-vehicle fuel economy log
    - Note vehicle-logged fuel economy: _______________________mpg ⇦
    - Use page scroll button on steering wheel to find range, Return button to reset
- Do a post-test audit through the GA sample inlet:
    - Use the secondary GA input manifold (with the balloon) plugged directly into GA dry input.
    - Data Collection Tab, Choose Bags from Menu Button at Upper Left, press start bag
    - Allow background air to flow into unit, then crack open span gas bottle and gently move hose to the secondary manifold. Control pressure to slightly pressurize balloon. Hold for 5-10 seconds
    - Turn off gas flow with regulator and concurrently remove span gas tubing
    - Press stop bag
- Test configuration Tab: Press Stop Test. Note end time:

  ____________________________ ⇦

- Move vehicle to other track
- Perform Zero/Span (bottles started 275 psi)- do this in garage?
    - Under Data Collection, Press Span
    - Verify system has been running for at least 45 mins, press Proceed

  - Connect zero bottle to zero port, span bottle to span port. Open tank valves and set regulators to 5 psi at zero flow condition (approach 5 slowly as valve must be closed completely to decrease the pressure. Turn counterclockwise to decrease, clockwise to increase
  - Enter gas concentrations from bottle in next dialog, press Proceed with Gas Analyzer 1 Selected. Allow span process to continue (Can identify the 2 exhaust lines by those that have flow during the zero- vent these two outside if indoors – note the 2 exhaust lines change for the z/s of the 2nd analyzer)
  - Select Gas Analyzer 2. Verify that gas concentrations match bottles after making this switch and adjust the values if necessary. Press Proceed with Gas Analyzer 2 Selected and allow process to continue. Press cancel after second analyzer span.
  - Pres proceed at maintenance completed window. Do not check any boxes.
  - After span completes, turn off valves on both tanks, drop regulator pressures by turning counterclockwise, and disconnect hoses from PEMS
- Move vehicle to track
- Allow engine to idle for 10 minutes
- Do a pre-test audit through the GA sample inlet:
  - Use the secondary GA input manifold (with the balloon) plugged directly into GA dry input.
  - Data Collection Tab, Choose Bags from Menu Button at Upper Left, press start bag
  - Allow background air to flow into unit, then crack open span gas bottle and gently move hose to the secondary manifold. Control pressure to slightly pressurize balloon. Hold for 5-10 seconds
  - Turn off gas flow with regulator and concurrently remove span gas tubing
  - Press stop bag
- Remove secondary manifold, ensure that the GA sample line and filter are properly mounted, and that PM line travels through chiller and both the dry and wet PM lines are connected
- Open driver trace, select cycle, enter date and test number in logging window, press start log, then press crank
- Data Collection Tab, Choose Bags from Menu Button at Upper Left
- Running start for test
  - Begin recording for accelerometer
  - Press start bag 10 seconds before ready to start the test
  - Reset dash fuel economy
  - Accelerometer: bump to dash at test start
  - Press start on driver trace
- Once cycle is complete, press Stop Bag
- Note then reset in-vehicle fuel economy log
  - Note vehicle-logged fuel economy: ________________________mpg
  - Use page scroll button on steering wheel to find range, Return button to reset
- Do a post-test audit through the GA sample inlet:

  - Use the secondary GA input manifold (with the balloon) plugged directly into GA dry input.
  - Data Collection Tab, Choose Bags from Menu Button at Upper Left, press start bag
  - Allow background air to flow into unit, then crack open span gas bottle and gently move hose to the secondary manifold. Control pressure to slightly pressurize balloon. Hold for 5-10 seconds
  - Turn off gas flow with regulator and concurrently remove span gas tubing
  - Press stop bag
- Test configuration Tab: Press Stop Test. Note end time:

  ____________________________ ⇦

- Allow system to purge while sampling clean air for ~30 mins
- If on-road test, record ambient conditions, either from lab or from weather site source
  - Temperature: _______________
  - Pressure: _______________ (circle: uncorrected or corrected) ⇦
  - Humidity: _______________
- Turn chiller off
- Blow out sample lines, probes, and exhaust lines. Disassemble GA filter and allow to dry
- Close Program using Red X (Do not run program while moving files)
- Open Axion Save Files directory, copy files off system folder
- Shut Down Windows
- After windows has shut down, press the blue button to completely power off the unit-
- Make sure chiller and Axion are off, then remove Li-ion battery from vehicle to charge
- Add fuel to test vehicle, ~2 gallons

GlobalMRV Data

- Will probably need 3 files of the 6 to process the data
- Use AxionBags to determine the time of the start and end of test
- UseAxionEng as the source of the customized OBD variable list data
- Use Axion file as the source of emissions data
- Can use AxionGA file for detailed gas analyzer
  - Cols B-F are automatic average of the two analyzers, or one analyzer if the other is down
  - Cols G-P are gas analyzer 1 status and readings
  - Cols Q- Z are gas analyzer 2 status and readings
  - Span data is shown only in this file. Span does not show up in automatic average columns; only in the individual analyzer columns
  -

3DATX Test Checklist v1.6 **Date:______________**

ERG Test Personnel: __________________ **Test No:_______________**

Day before test

- Make sure cold packs, grey box, and brass traps are stored in freezer
- Charge batteries in ParSYNC overnight (4-5 hrs or overnight). Plug both chargers into both heater and pump battery connections
- Charge tablet

Test Day

- Place ParSYNC in heated pack and turn on the heat blanket. Set blanket using + button to max temp (171 F or 77C), and allow it to warm up the unit for 1.5 hrs. (Blanket has a 1 hr timer before turning off)
- Ballast vehicle with extra 30 lb weight, plus 170-180 lbs if no passenger will be present (on-road tests only)
- Check vehicle tire pressures, set to 33 ± 1 psi
- Make sure dash fuel economy readout has been reset
- Keep tablet on shore power until start of test
- Turn on heater power (Power button on grey panel of ParSYNC); temperature should be set to 55 degrees C.
- Turn on ParSYNC pump and analyzer using Silver Button
- On 3DATX computer, run ParSYNC shortcut from desktop
- Press Config Load to load the test configuration
    - Config location is C\ParSYNC\Config Files\
    - Choose most recent accepted configuration
    - Press Configure to write the configuration for the next data file
- Zero analyzers:
    - Press ZERO tab
    - Ensure inlet is sampling ambient air through chiller and press Zero Start, then allow to complete (~30 seconds)
- Check and record a zero span
    - Evacuate tedlar bag and then add audit gas (fill until bag opens 1-1.5" at valve)
    - Press Start
    - Allow system to sample ambient air through the chiller for 30 s then draw span gas from bag through chiller for 30 s (or until CO_2 stabilizes)
    - Press Pause
    - Increment bag number to indicate span vs test in data file
    - Note Span gas concentration values from bottle label:

CO_2___________________NO: ___________________

- As necessary, review datafiles and update configuration voltages
    - Stop recording
    - Review datafile and find voltage settings for the zero and span values
    - Restart program and enter the zero and span voltages (update concentrations if necessary) in the configuration tab, save the configuration with a new name, which then becomes the configuration to be loaded during the next test. (Note that, top to bottom, the cells are span voltage, zero voltage, span concentration, zero concentration)
    - Press configure on Config tab
- Zero analyzers:
    - Press ZERO tab
    - Ensure inlet is sampling ambient air through chiller and press Zero Start, then allow to complete (~30 seconds)
- If configuration has changed, record the new zero span
    - Press Start if data collection was stopped or paused
    - Allow system to sample ambient air through the chiller for 30 s then draw span gas from bag through chiller for 30 s (or until CO_2 stabilizes)
    - Press Pause
    - Increment bag number to indicate span vs test in data file
- Install both water traps with cold packs into grey box and install it (oriented vertically so water can collect at the bottom of each tee) into the vehicle. (Do this approx. 20 mins before test)
- Install ParSYNC into vehicle; route sample and exhaust lines. Avoid significant low spots in sample line between window and chiller box that could collect condensation
- Install HEMData logger into vehicle (will drain battery if plugged in overnight). Make sure HEMdata flashes blue and not red when installed (miniSD card must be inserted exactly the right distance into the logger to prevent it from flashing red- insert so that exactly 2 of the legs of the "m" in microSD are visible)
- Move vehicle to dynamometer or outside driveway
- Do one more zero procedure, sampling through the exhaust sample line
- Take a screen capture showing the configuration values for NO_2, NO, and CO_2.
    - Return to Config tab, Press print screen
    - Open windows Paint and paste the screen capture
    - Save the file as <date.jpg> in the c:\ParSYNC\Print Screen directory and close Paint
- When ready to begin, press Start
- Follow engine/test start procedures and conduct cycle
- After cycle is complete, turn off engine then press pause to stop data collection
- Note then reset in-vehicle fuel economy log
    - Note vehicle-logged fuel economy: _______________________mpg
    - Use page scroll button on steering wheel to find range, Return button to reset
- Check and record a zero span
    - Increment bag number to indicate span vs test in data file then re-start sampling
    - Allow system to sample ambient air for 30 s then flow span gas for 30 s

- To stop the data logging, press the small red button in the upper left of the screen (or press Stop in the Config tab)
- Record ambient conditions, either from lab or from weather site source
    - Temperature: _______________
    - Pressure: _______________ (circle: uncorrected or corrected)
    - Humidity: _______________
- Close program with the X in upper right
- Disconnect sample lines and drain water traps. Leave system pump on to purge approximately 30 minutes. Store water traps at room temperature
- Turn off ParSYNC with both buttons: Turn off heater on grey panel, turn off pump using silver button
- Remove HEMData logger from vehicle (do not leave plugged in overnight) and copy data from logger
- Store cold packs and grey box in freezer
- Charge batteries in ParSYNC overnight (4-5 hrs or overnight). Plug both chargers into both heater and pump battery connections
- Charge tablet

Post Processing

- Data is written as a csv. Follow shortcut to ParSYNC Data directory

Flow Rates per flow test: 2L /min

3DATX Test Checklist   v2.1-Track **Date:_____________**

ERG Test Personnel: ________________ **Test No:______________**

Day before test

- Make sure cold packs, grey box, and brass traps are stored in freezer
- Take ParSYNC to hotel and charge batteries in ParSYNC overnight (4-5 hrs or overnight). Plug both chargers into both heater and pump battery connections.
- Charge tablet
- Turn on ParSYNC heat when leaving hotel; temperature should be set to 55 degrees C.

Test Day

- Place ParSYNC in heated pack and turn on the heat blanket. Set blanket using + button to max temp (171 F or 77C), and allow it to warm up the unit for 1.5 hrs. (Blanket has a 1 hr timer before turning off). Time on:__________
- Ballast vehicle with extra 30 lb weight for difference w/ MRV
- Check vehicle tire pressures, set to 33 ± 1 psi
- Make sure dash fuel economy readout has been reset
- Keep tablet on shore power until start of test
- Turn on heater power (Power button on grey panel of ParSYNC); temperature should be set to 55 degrees C.
- Turn on ParSYNC pump and analyzer using Silver Button
- On 3DATX computer, run ParSYNC shortcut from desktop
- Press Config Load to load the test configuration
    - Config location is C\ParSYNC\Config Files\
    - Choose most recent accepted configuration
    - Press Configure to write the configuration for the next data file
- Zero analyzers:
    - Press ZERO tab
    - Ensure inlet is sampling ambient air through chiller and press Zero Start, then allow to complete (~30 seconds)
- Check and record a zero span
    - Evacuate tedlar bag and then add audit gas (fill until bag opens 1-1.5” at valve)
    - Press Start
    - Allow system to sample ambient air through the chiller for 30 s then draw span gas from bag through chiller for 30 s (or until CO2 stabilizes)
    - Press Pause
    - Increment bag number to indicate span vs test in data file
    - Note Span gas concentration values from bottle label:

CO2_________________NO: _________________

- As necessary, review datafiles and update configuration voltages
    - Stop recording
    - Review datafile and find voltage settings for the zero and span values
    - Restart program and enter the zero and span voltages (update concentrations if necessary) in the configuration tab, save the configuration with a new name, which then becomes the configuration to be loaded during the next test. (Note that, top to bottom, the cells are span voltage, zero voltage, span concentration, zero concentration)
    - Press configure on Config tab
- Zero analyzers:
    - Press ZERO tab
    - Ensure inlet is sampling ambient air through chiller and press Zero Start, then allow to complete (~30 seconds)
- If configuration has changed, record the new zero span
    - Press Start if data collection was stopped or paused
    - Allow system to sample ambient air through the chiller for 30 s then draw span gas from bag through chiller for 30 s (or until CO2 stabilizes)
    - Press Pause
    - Increment bag number to indicate span vs test in data file
- Install both water traps with cold packs into grey box and install it (oriented vertically so water can collect at the bottom of each tee) into the vehicle. (Do this approx. 20 mins before test)
- Install ParSYNC into vehicle; route sample and exhaust lines. Avoid significant low spots in sample line between window and chiller box that could collect condensation
- Install HEMData logger into vehicle (will drain battery if plugged in overnight). Make sure HEMdata flashes blue and not red when installed (miniSD card must be inserted exactly the right distance into the logger to prevent it from flashing red- insert so that exactly 2 of the legs of the “m” in microSD are visible)
- Tow or push vehicle to test track
- Do one more zero procedure, sampling through the exhaust sample line
- Take a screen capture showing the configuration values for NO2, NO, and CO2.
    - Return to Config tab, Press print screen
    - Open windows Paint and paste the screen capture
    - Save the file as <date.jpg> in the c:\ParSYNC\Print Screen directory and close Paint
- When ready to begin, press Start
- Engine start procedure:
    - Begin recording for accelerometer
    - Key on for 5 seconds first
    - Press start on driver trace
    - Start engine
    - Accelerometer: bump to dash at engine start
- After cycle is complete, turn off engine then press pause to stop data collection

- Note fuel economy log:
  - Note vehicle-logged fuel economy: _______________________mpg
  - Use page scroll button on steering wheel to find range, Return button to reset
- Move vehicle to shop
- Check and record a zero span
  - Increment bag number to indicate span vs test in data file then re-start sampling
  - Allow system to sample ambient air for 30 s then flow span gas for 30 s
  - Pause and then increment bag
- Drain chiller water dropouts
- Move vehicle to other track; allow to idle for 10 minutes
- Running start for test
  - Begin recording for accelerometer
  - Press Start to begin data logging
  - Reset dash fuel economy
  - Accelerometer: bump to dash at test start
  - Press start on driver trace
- After cycle is complete, turn off engine then press pause to stop data collection
- Note fuel economy log:
  - Note vehicle-logged fuel economy: _______________________mpg
  - Use page scroll button on steering wheel to find range, Return button to reset
- Check and record a zero span
  - Increment bag number to indicate span vs test in data file then re-start sampling
  - Allow system to sample ambient air for 30 s then flow span gas for 30 s
- To stop the data logging, press the small red button in the upper left of the screen (or press Stop in the Config tab)
- Record ambient conditions, either from lab or from weather site source
  - Temperature: _______________
  - Pressure: _______________ (circle: uncorrected or corrected)
  - Humidity: _______________
- Close program with the X in upper right
- Disconnect sample lines and drain water traps. Leave system pump on to purge approximately 30 minutes. Store water traps at room temperature
- Turn off ParSYNC with both buttons: Turn off heater on grey panel, turn off pump using silver button
- Remove HEMData logger from vehicle (do not leave plugged in overnight) and copy data from logger
- Store cold packs and grey box in freezer
- Charge batteries in ParSYNC overnight (4-5 hrs or overnight). Plug both chargers into both heater and pump battery connections
- Charge tablet
- Add fuel to test vehicle (~2 gallons)

Post Processing

- Data is written as a csv. Follow shortcut to ParSYNC Data directory

Flow Rates per flow test: 2L /min

Appendix E

Individual Fuel Economy and Emission Mass Results

This appendix includes the emission mass results for all of the individual tests from which plots were presented in Section 6. Results are presented for the lab modal system, the lab CVS dilute system, and each PEMS where appropriate for the emission type and test type. The blinding index labels for each of the three PEMS are consistent in this section with those presented in Section 6. Table E-1 presents the results for fuel economy and CO_2 total mass emissions for dynamometer, road, cold-start smooth and rough track, and hot-running smooth and rough track tests. The successive tables present similar results for NO/NOx, CO, HC, and PM for all test types.

Table E-1. Individual Test Fuel Economy and CO_2 Mass Emissions

	Fuel Economy (mpg)									CO2 Emission Mass (g)								
	PEMS A			PEMS B			PEMS C			PEMS A			PEMS B			PEMS C		
Test	CVS Dilute	PEMS	Dash	CVS Dilute	PEMS	Dash	CVS Dilute	PEMS	Dash	Lab Modal	CVS Dilute	PEMS	Lab Modal	CVS Dilute	PEMS	Lab Modal	CVS Dilute	PEMS
Dyno 1	30.20	34.19	30.1	29.98	31.55	31.1	30.07	39.29	31.0	7813	7843	6803	7490	7885	7378	7915	7862	6036
Dyno 2	30.82	35.34	31.2	29.98	32.27	30.8	27.48	38.27	28.3	7642	7692	6582	7766	7879	7192	8486	8632	6205
Dyno 3	30.18	35.19	31.1	30.09	32.48	31.3	29.98	40.31	31.2	7633	7845	6610	8113	7876	7166	7807	7901	5887
Dyno 4	30.19	35.33	30.7	30.35	32.79	31.3	30.61	45.91	31.9	7738	7854	6595	8114	7798	7089	7599	7734	5163
Dyno 5	31.24	34.50	31.7	29.98	31.96	31.2	30.40	45.24	31.3	7953	7577	6731	8161	7911	7261	7763	7780	5238
Road 1	NA	30.26	26.4	NA	28.35	26.2	NA	NA	27.6	NA	NA	7622	NA	NA	8184	NA	NA	NA
Road 2	NA	31.37	28.6	NA	30.11	28.1	NA	34.80	28.9	NA	NA	7370	NA	NA	7690	NA	NA	6777
Road 3	NA	30.45	26.4	NA	30.31	28.6	NA	32.60	28.5	NA	NA	7592	NA	NA	7659	NA	NA	7240
Road 4	NA	32.26	29.5	NA	29.38	27.9	NA	33.98	28.5	NA	NA	7164	NA	NA	7916	NA	NA	6942
Road 5	NA	31.23	28.4	NA	29.80	28.6	NA	39.12	30.0	NA	NA	7410	NA	NA	7794	NA	NA	6043
Smooth Track 1	NA	29.16	26.2	NA	27.42	26.4	NA	34.19	26.8	NA	NA	7933	NA	NA	8401	NA	NA	6898
Smooth Track 2	NA	29.91	26.8	NA	27.84	26.8	NA	34.29	26.9	NA	NA	7671	NA	NA	8302	NA	NA	6883
Smooth Track 3	NA	29.36	26.4	NA	28.35	26.6	NA	34.04	26.0	NA	NA	7861	NA	NA	8195	NA	NA	6939
Rough Track 1	NA	29.96	26.9	NA	25.98	25.7	NA	33.96	26.8	NA	NA	7704	NA	NA	8806	NA	NA	6920
Rough Track 2	NA	29.69	26.8	NA	26.70	26.2	NA	34.15	27.0	NA	NA	7768	NA	NA	8640	NA	NA	6903
Rough Track 3	NA	29.76	27.0	NA	27.42	26.7	NA	34.70	26.7	NA	NA	7764	NA	NA	8370	NA	NA	6805
Hot Running Smooth Track 1	NA	30.53	27.0	NA	27.12	26.4	NA	35.56	28.0	NA	NA	7582	NA	NA	8546	NA	NA	6614
Hot Running Smooth Track 2	NA	30.78	27.5	NA	28.66	27.5	NA	36.46	28.0	NA	NA	7511	NA	NA	7936	NA	NA	6476
Hot Running Smooth Track 3	NA	30.85	27.4	NA	28.87	26.8	NA	35.25	27.1	NA	NA	7493	NA	NA	8111	NA	NA	6693
Hot Running Rough Track 1	NA	30.46	27.0	NA	28.87	27.2	NA	34.29	27.4	NA	NA	7586	NA	NA	7981	NA	NA	6880
Hot Running Rough Track 2	NA	30.87	27.6	NA	28.87	27.1	NA	34.84	27.0	NA	NA	7472	NA	NA	7995	NA	NA	6777
Hot Running Rough Track 3	NA	30.63	27.3	NA	28.15	26.9	NA	35.67	27.3	NA	NA	7531	NA	NA	8140	NA	NA	6636

Table E-2. Individual Test NO/NOx Mass Emissions

	NO/NOx Emission Mass (g)								
	PEMS D			PEMS E			PEMS F		
Test	Lab Modal	CVS Dilute	PEMS	Lab Modal	CVS Dilute	PEMS	Lab Modal	CVS Dilute	PEMS
Dyno 1	0.355	0.483	0.257	0.321	0.501	0.548	0.371	0.606	0.423
Dyno 2	0.328	0.555	0.288	0.580	0.625	0.706	0.322	0.550	0.303
Dyno 3	0.370	0.561	0.276	0.405	0.530	0.274	0.419	0.606	0.472
Dyno 4	0.363	0.580	0.237	0.299	0.525	0.432	0.383	0.564	0.413
Dyno 5	0.418	0.540	0.239	0.344	0.523	0.395	0.360	0.541	0.404
Road 1	NA	NA	0.264	NA	NA	NA	NA	NA	0.738
Road 2	NA	NA	0.316	NA	NA	0.638	NA	NA	0.159
Road 3	NA	NA	0.254	NA	NA	0.287	NA	NA	0.159
Road 4	NA	NA	0.258	NA	NA	0.437	NA	NA	0.293
Road 5	NA	NA	0.182	NA	NA	0.793	NA	NA	0.221
Smooth Track 1	NA	NA	0.200	NA	NA	0.504	NA	NA	0.257
Smooth Track 2	NA	NA	0.777	NA	NA	1.164	NA	NA	0.291
Smooth Track 3	NA	NA	0.268	NA	NA	0.715	NA	NA	0.290
Rough Track 1	NA	NA	0.762	NA	NA	0.614	NA	NA	0.383
Rough Track 2	NA	NA	0.298	NA	NA	0.544	NA	NA	0.290
Rough Track 3	NA	NA	0.239	NA	NA	1.075	NA	NA	0.208

Table E-3. Individual Test CO Mass Emissions

	CO Emission Mass (g)					
	PEMS G			PEMS H		
Test	Lab Modal	CVS Dilute	PEMS	Lab Modal	CVS Dilute	PEMS
Dyno 1	5.005	5.707	4.709	3.361	3.645	3.509
Dyno 2	3.976	4.392	3.505	3.238	3.574	4.360
Dyno 3	4.434	4.296	3.374	5.694	6.183	5.859
Dyno 4	10.118	12.438	7.561	3.746	3.992	2.895
Dyno 5	4.571	4.732	3.963	5.510	5.065	6.542
Road 1	NA	NA	5.883	NA	NA	10.259
Road 2	NA	NA	4.906	NA	NA	8.209
Road 3	NA	NA	4.034	NA	NA	8.255
Road 4	NA	NA	4.747	NA	NA	8.022
Road 5	NA	NA	3.640	NA	NA	8.344
Smooth Track 1	NA	NA	2.968	NA	NA	6.827
Smooth Track 2	NA	NA	3.337	NA	NA	9.503
Smooth Track 3	NA	NA	4.164	NA	NA	5.422
Rough Track 1	NA	NA	5.971	NA	NA	10.142
Rough Track 2	NA	NA	5.157	NA	NA	7.614
Rough Track 3	NA	NA	4.612	NA	NA	6.798

Table E-4. Individual Test HC Mass Emissions

	HC Emission Mass (g)					
	PEMS I			PEMS J		
Test	Lab Modal	CVS Dilute	PEMS	Lab Modal	CVS Dilute	PEMS
Dyno 1	0.685	0.724	0.429	1.051	1.163	0.890
Dyno 2	0.861	0.855	0.529	0.967	1.074	0.804
Dyno 3	1.111	1.092	0.591	0.884	0.921	0.736
Dyno 4	0.926	1.094	0.538	0.928	1.009	0.749
Dyno 5	0.868	1.209	0.538	0.951	0.910	0.753
Road 1	NA	NA	0.637	NA	NA	0.670
Road 2	NA	NA	0.931	NA	NA	0.974
Road 3	NA	NA	0.836	NA	NA	0.447
Road 4	NA	NA	0.668	NA	NA	0.521
Road 5	NA	NA	0.439	NA	NA	0.399
Smooth Track 1	NA	NA	0.292	NA	NA	0.403
Smooth Track 2	NA	NA	1.175	NA	NA	0.484
Smooth Track 3	NA	NA	0.391	NA	NA	0.603
Rough Track 1	NA	NA	1.200	NA	NA	0.404
Rough Track 2	NA	NA	0.650	NA	NA	0.452
Rough Track 3	NA	NA	0.470	NA	NA	0.485

Table E-5. Individual Test PM Mass Emissions

	PM Emission Mass (g)					
	PEMS K			PEMS L		
PEMS	Lab Modal	CVS Dilute	PEMS	Lab Modal	CVS Dilute	PEMS
Dyno 1	0.095	0.152	0.108	0.093	0.137	0.041
Dyno 2	0.101	0.142	0.135	0.086	0.135	0.040
Dyno 3	0.106	0.175	0.135	0.086	0.141	NA
Dyno 4	0.098	0.227	0.252	0.086	0.137	0.045
Dyno 5	0.116	0.160	0.125	0.109	0.182	0.073
Road 1	NA	NA	0.106	NA	NA	0.052
Road 2	NA	NA	0.135	NA	NA	0.045
Road 3	NA	NA	0.101	NA	NA	0.040
Road 4	NA	NA	0.077	NA	NA	0.043
Road 5	NA	NA	0.133	NA	NA	0.027
Smooth Track 1	NA	NA	0.093	NA	NA	0.027
Smooth Track 2	NA	NA	0.071	NA	NA	0.032
Smooth Track 3	NA	NA	0.181	NA	NA	0.035
Rough Track 1	NA	NA	0.153	NA	NA	0.036
Rough Track 2	NA	NA	0.096	NA	NA	0.036
Rough Track 3	NA	NA	0.049	NA	NA	0.023

The next group of tables present the individual emission mass results for the hot-running tests at the test track. Both smooth track and rough track results are presented in the tables.

Table E-6. Individual Test NO/NOx Mass Emissions for Hot Running Track Tests

	NO/NOx Emission Mass (g)		
PEMS	PEMS M	PEMS N	PEMS O
Hot Running Smooth Track 1	0.701	0.158	0.176
Hot Running Smooth Track 2	0.635	0.377	0.193
Hot Running Smooth Track 3	1.033	0.247	0.220
Hot Running Rough Track 1	1.342	0.376	0.163
Hot Running Rough Track 2	0.778	0.217	0.180
Hot Running Rough Track 3	0.817	0.169	0.140

Table E-7. Individual Test CO Mass Emissions for Hot Running Track Tests

	CO Emission Mass (g)	
PEMS	PEMS P	PEMS Q
Hot Running Smooth Track 1	8.309	5.560
Hot Running Smooth Track 2	6.444	2.117
Hot Running Smooth Track 3	6.095	3.219
Hot Running Rough Track 1	6.658	7.143
Hot Running Rough Track 2	8.178	3.206
Hot Running Rough Track 3	6.012	3.170

Table E-8. Individual Test HC Mass Emissions for Hot Running Track Tests

	HC Emission Mass (g)	
PEMS	PEMS R	PEMS S
Hot Running Smooth Track 1	0.150	0.433
Hot Running Smooth Track 2	0.119	0.584
Hot Running Smooth Track 3	0.136	0.399
Hot Running Rough Track 1	0.125	0.296
Hot Running Rough Track 2	0.101	0.509
Hot Running Rough Track 3	0.098	0.309

Table E-9. Individual Test PM Mass Emissions for Hot Running Track Tests

	PM Emission Mass (g)	
PEMS	PEMS T	PEMS U
Hot Running Smooth Track 1	0.013	0.060
Hot Running Smooth Track 2	0.014	0.048
Hot Running Smooth Track 3	0.012	0.044
Hot Running Rough Track 1	0.012	0.060
Hot Running Rough Track 2	0.012	0.054
Hot Running Rough Track 3	0.011	0.008

Table E-10 presents the individual test results of the single PEMS that was included in additional unballasted testing on the dynamometer and on-road.

Table E-10. Individual Test Results for the Additional Testing of a Single PEMS without Vehicle Ballast

	Fuel Econ (mpg)			CO2 Mass (g)			NOx Mass (g)			CO Mass (g)			HC Mass (g)			PM Mass (g)	
Test	**CVS Dilute**	**PEMS**	**Dash**	**Lab Modal**	**CVS Dilute**	**PEMS**	**Lab Modal**	**CVS Dilute**	**PEMS**	**Lab Modal**	**CVS Dilute**	**PEMS**	**Lab Modal**	**CVS Dilute**	**PEMS**	**CVS Dilute**	**PEMS**
Unballasted Dyno 1	32.63	36.21	32.7	7605	7244	6421	0.346	0.474	0.239	4.298	4.257	4.706	0.854	0.930	0.443	0.086	0.025
Unballasted Dyno 3	32.16	35.98	32.6	7604	7358	6460	0.311	0.417	0.180	5.104	4.602	5.467	0.727	0.795	0.471	0.121	0.036
Unballasted Road 1	NA	33.64	30.8	NA	NA	6880	NA	NA	0.183	NA	NA	7.221	NA	NA	0.571	NA	0.023
Unballasted Road 2	NA	33.97	31.0	NA	NA	6808	NA	NA	0.171	NA	NA	9.770	NA	NA	0.790	NA	0.028

Appendix F

Continuous Mass Emission Traces from On-Road and Cold-Start Track Tests

This appendix includes continuous mass emission traces for the on-road and cold-start track tests on the rough and smooth surfaces. The PEMS identifier labels are consistent with those used in Section 6. Dynamometer test result traces are presented in the main report as they allow for direct comparison between the PEMS and the lab modal measurements and an associated discussion. The on-road and track test results allow for no such comparisons, and so are included without discussion in this appendix.

Plots are organized by exhaust constituent, test type, then PEMS. Each plot contains the results for the given compound of the replicate tests within a given test type for each PEMS. For track tests, only cold-start results are presented, and each test is given either an "R" or "S" designation in the legend for rough track or smooth track, respectively. Results are presented for CO_2, NO/NOx, CO, HC, then PM.

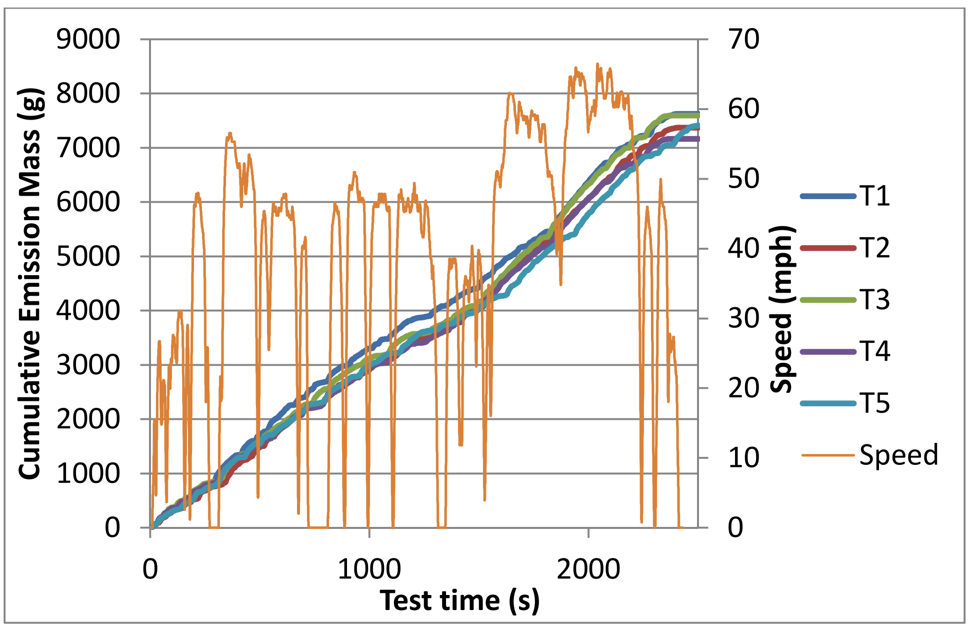

Figure F-1. Continuous CO_2 mass traces for the on-road tests with PEMS A.

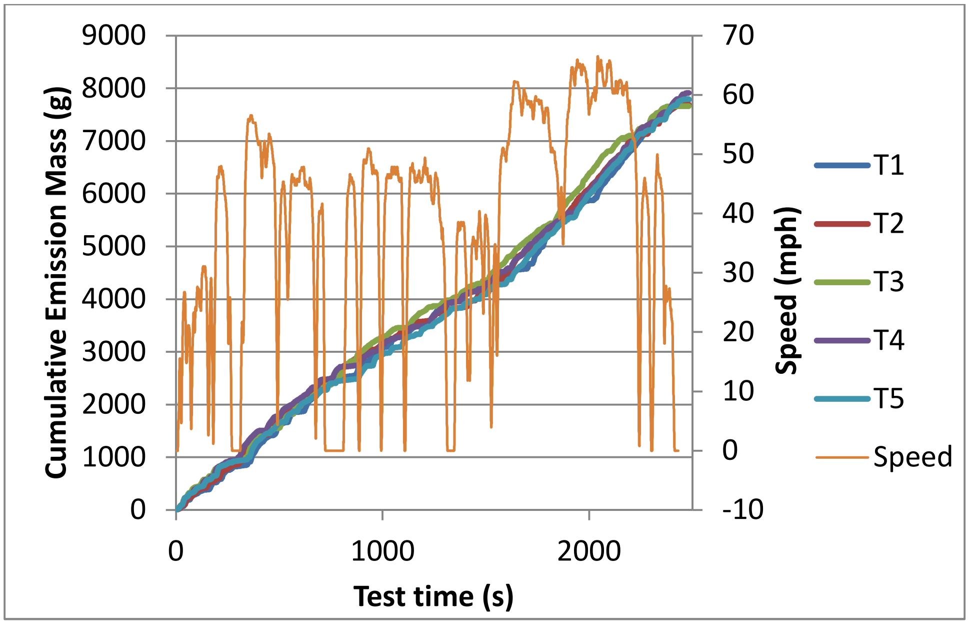

Figure F-2. Continuous CO_2 mass traces for the on-road tests with PEMS B.

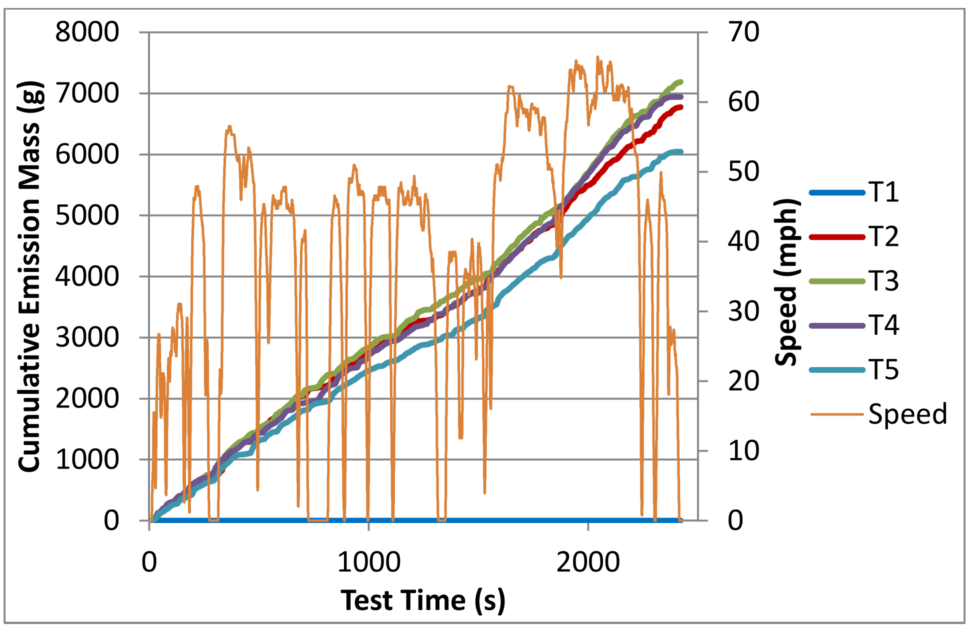

Figure F-3. Continuous CO_2 mass traces for the on-road tests with PEMS C.

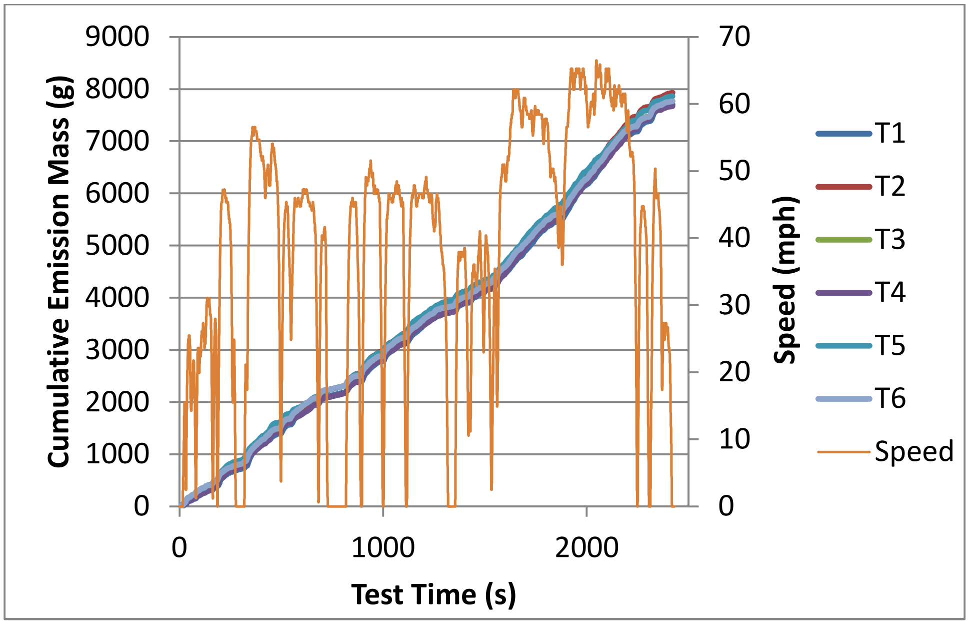

Figure F-4. Continuous CO_2 mass traces for the cold-start track tests with PEMS A.

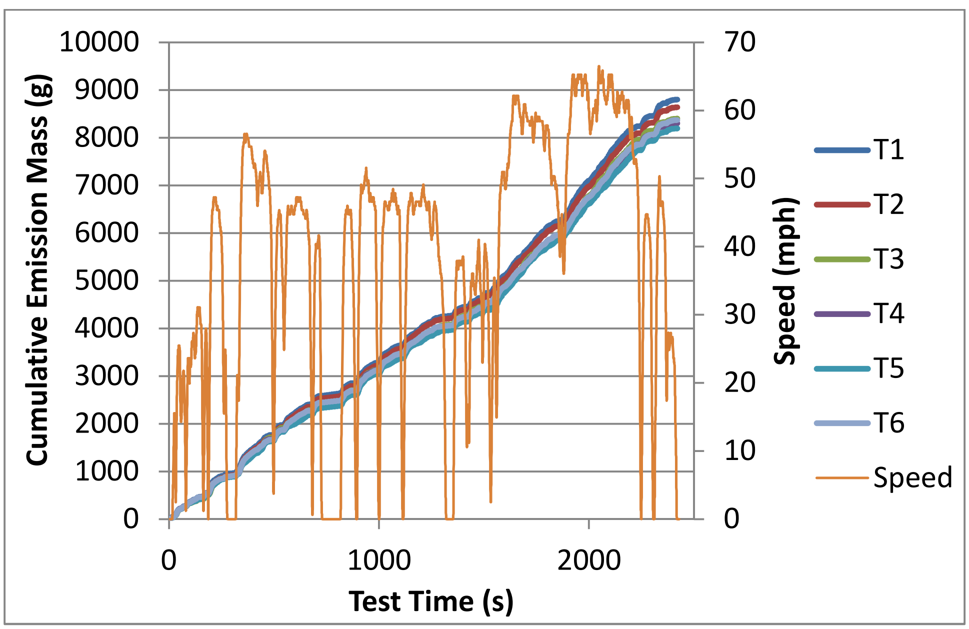

Figure F-5. Continuous CO_2 mass traces for the cold-start track tests with PEMS B.

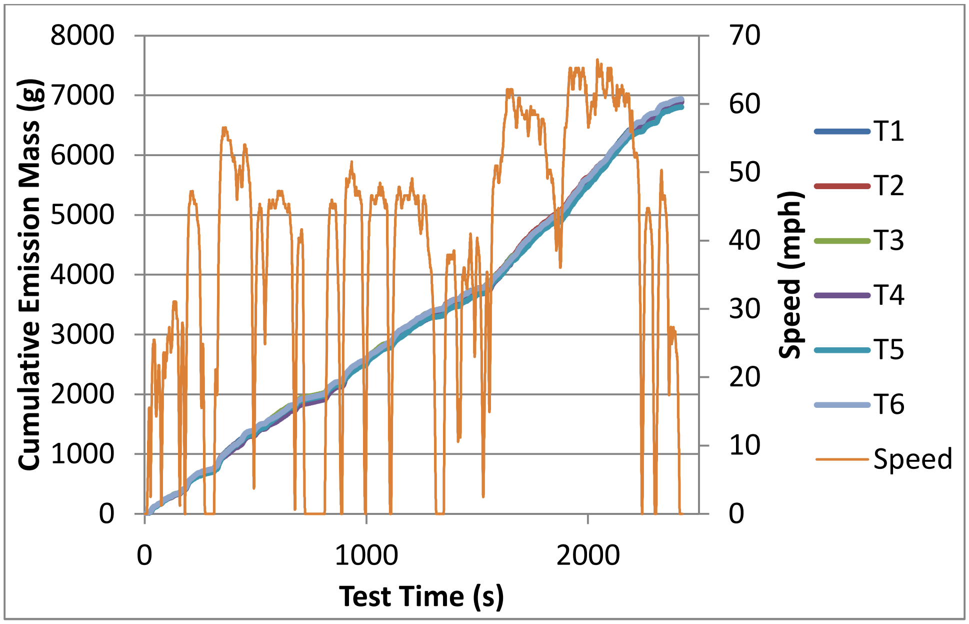

Figure F-6. Continuous CO_2 mass traces for the cold-start track tests with PEMS C.

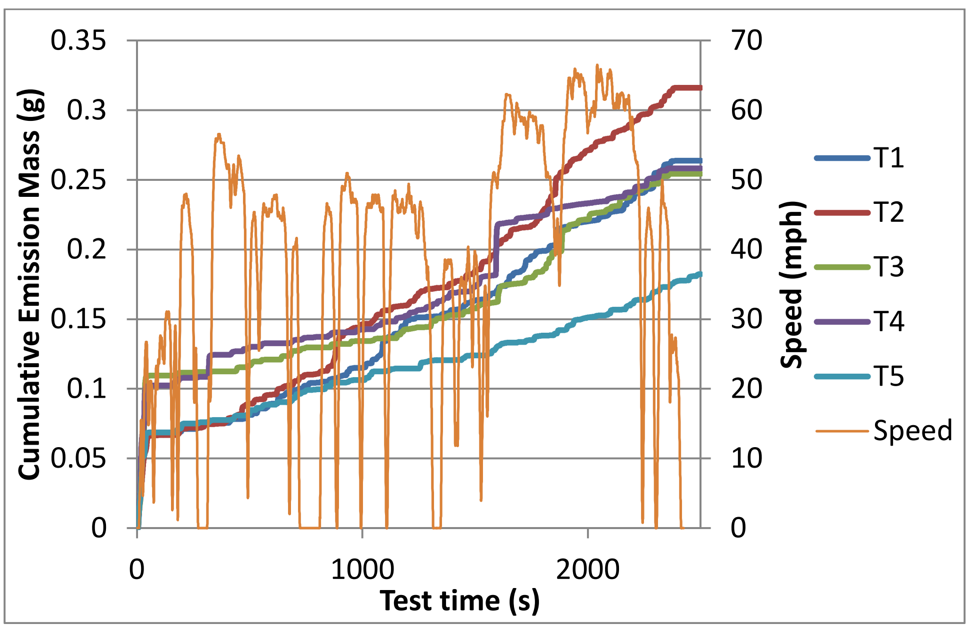

Figure F-7. Continuous NO/NOx mass traces for the on-road tests with PEMS D.

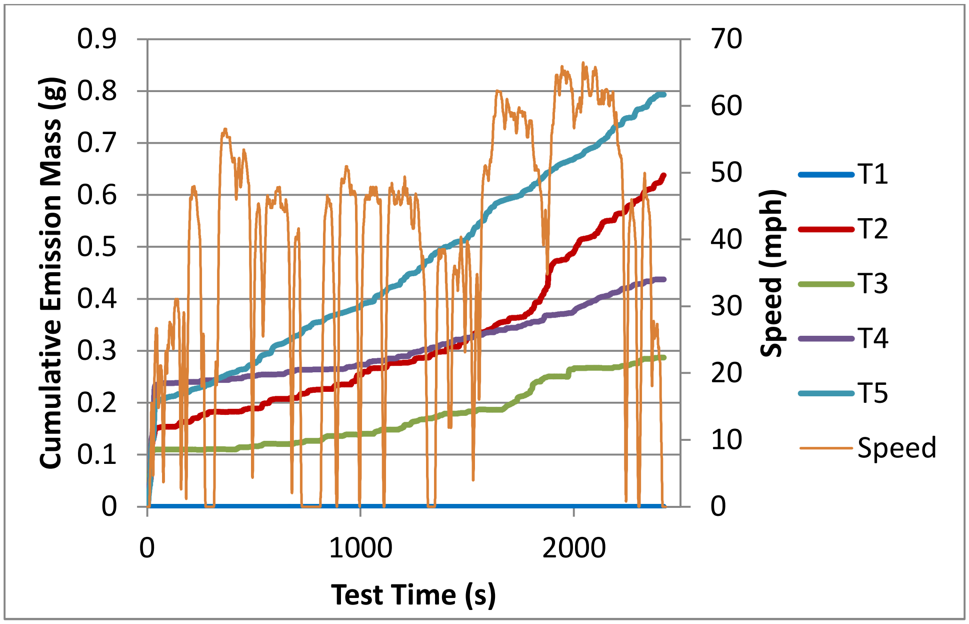

Figure F-8. Continuous NO/NOx mass traces for the on-road tests with PEMS E.

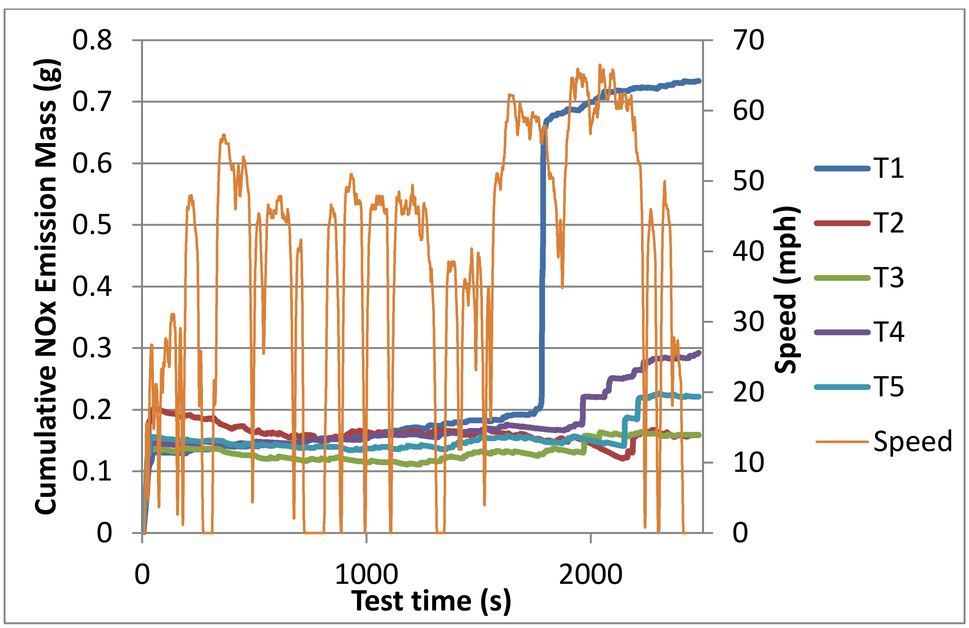

Figure F-9. Continuous NO/NOx mass traces for the on-road tests with PEMS F.

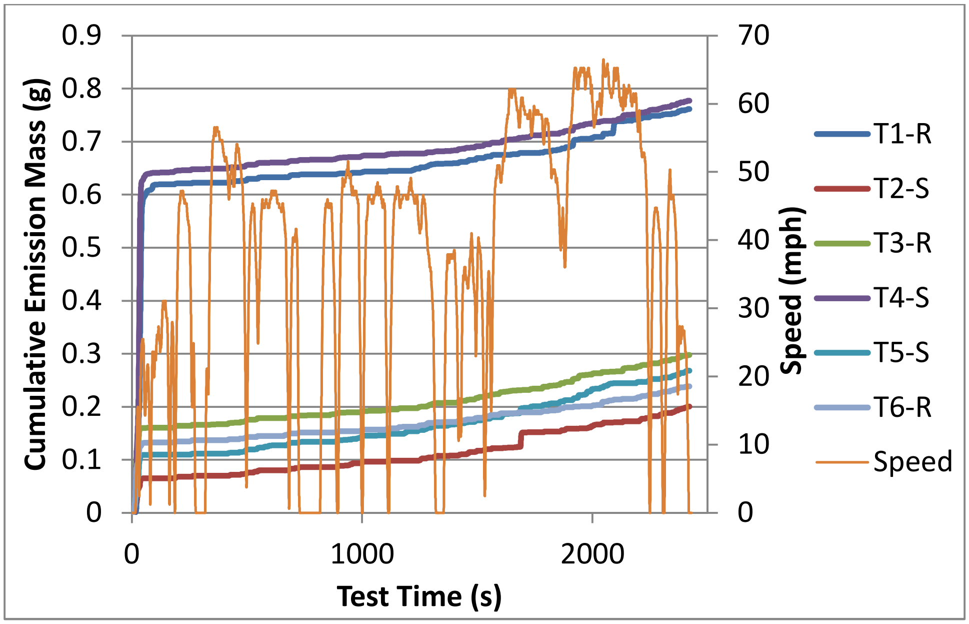

Figure F-10. Continuous NO/NOx mass traces for the cold-start track tests with PEMS D.

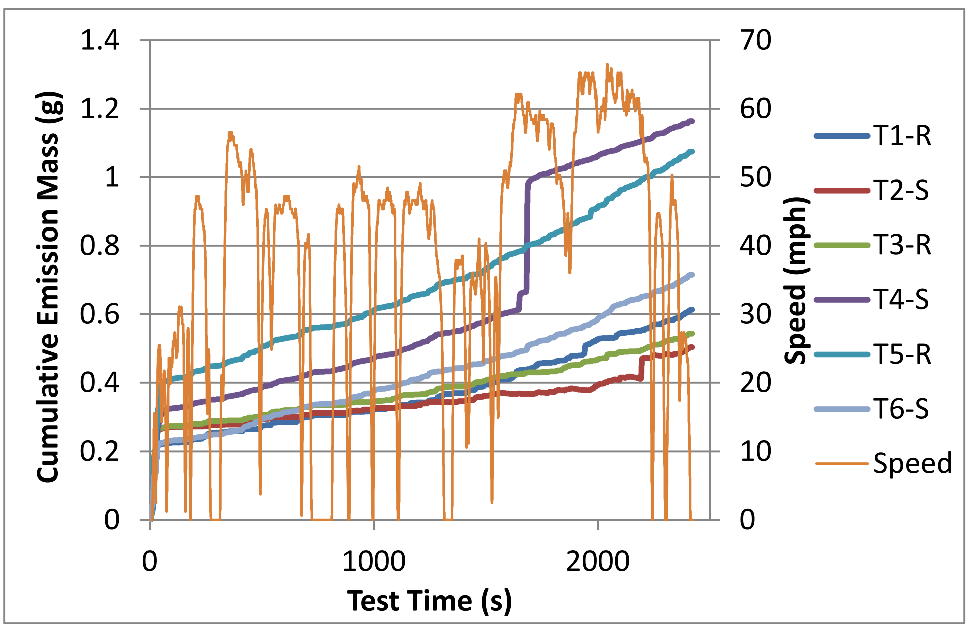

Figure F-11. Continuous NO/NOx mass traces for the cold-start track tests with PEMS E.

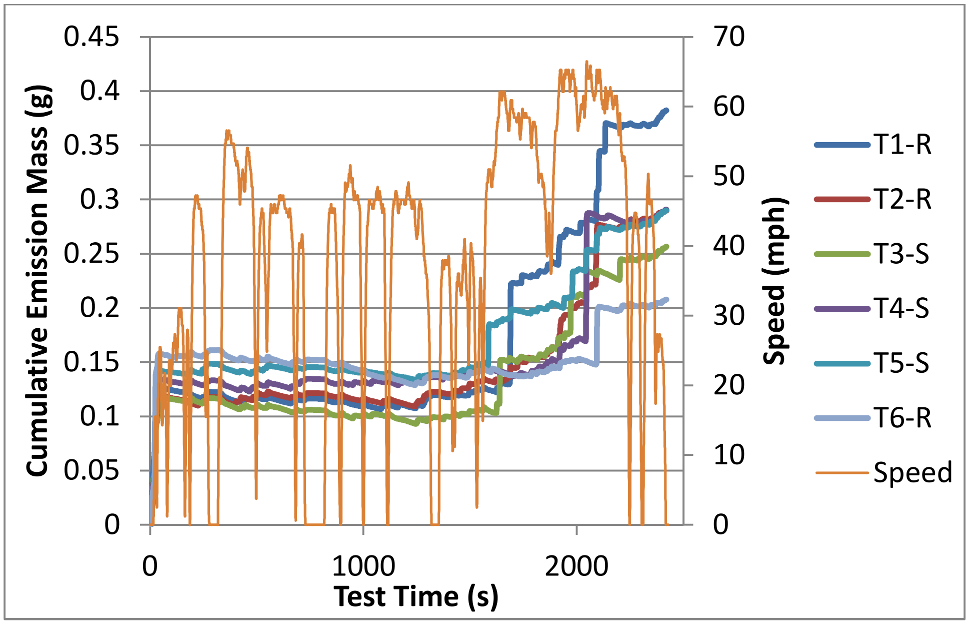

Figure F-12. Continuous NO/NOx mass traces for the cold-start track tests with PEMS F.

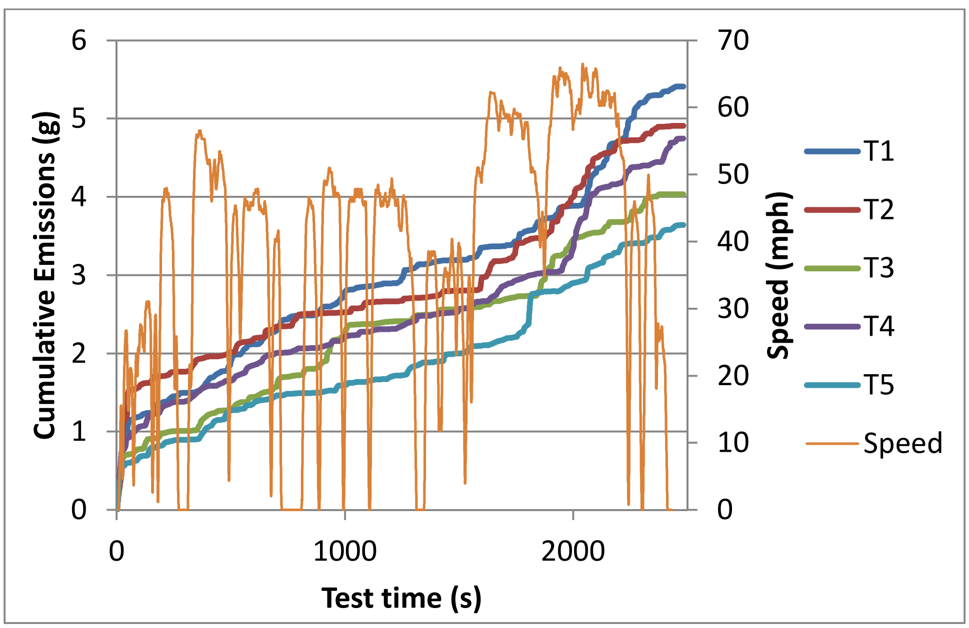

Figure F-13. Continuous CO mass traces for the on-road tests with PEMS G.

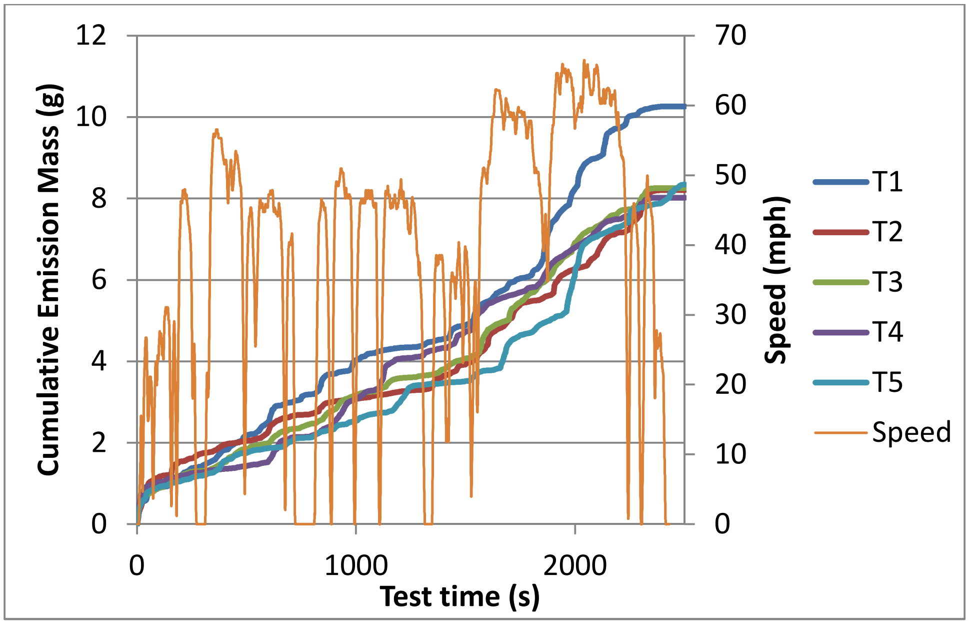

Figure F-14. Continuous CO mass traces for the on-road tests with PEMS H.

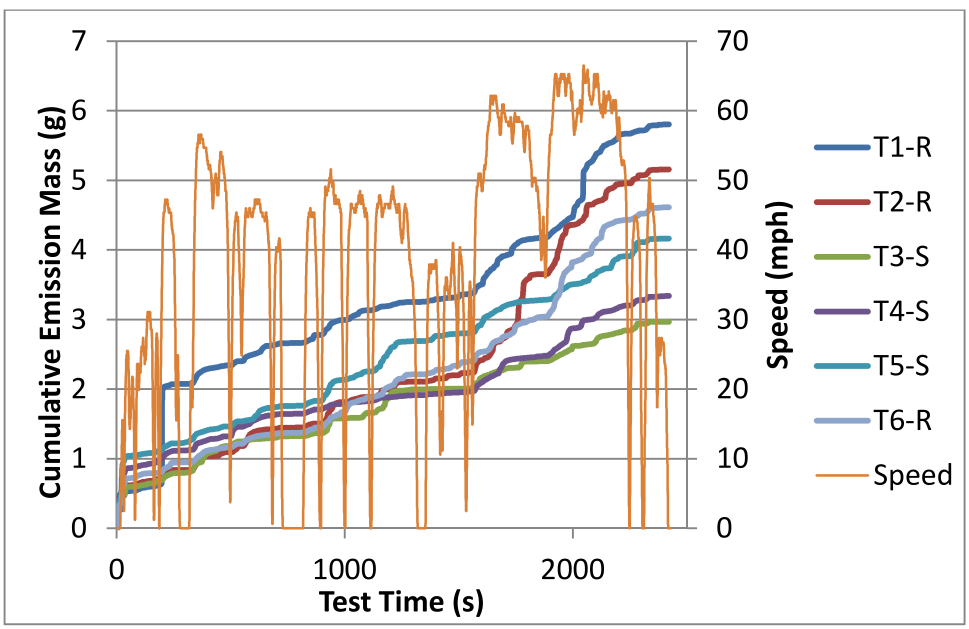

Figure F-15. Continuous CO mass traces for the cold-start track tests with PEMS G.

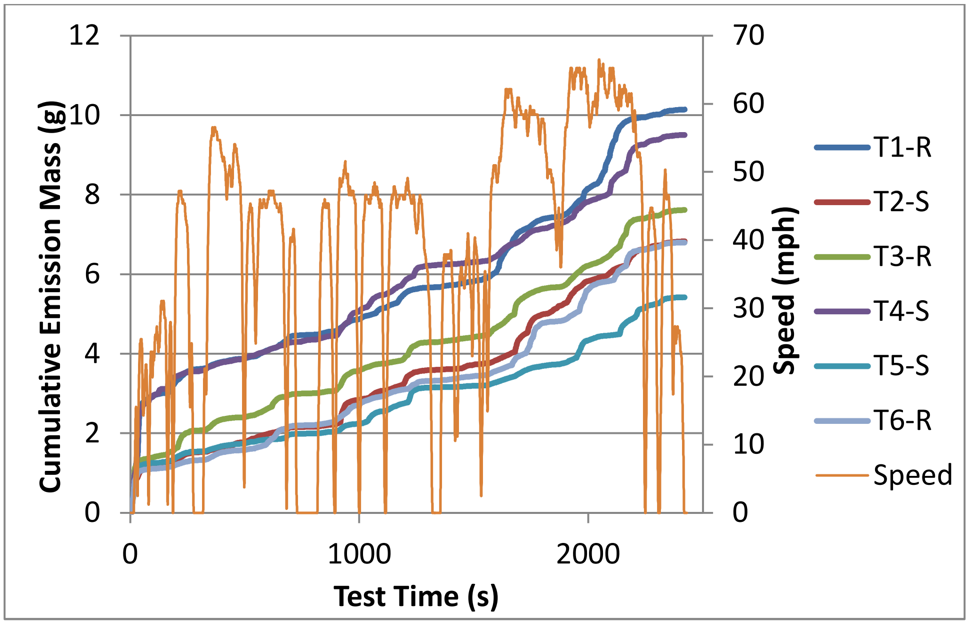

Figure F-16. Continuous CO mass traces for the cold-start track tests with PEMS H.

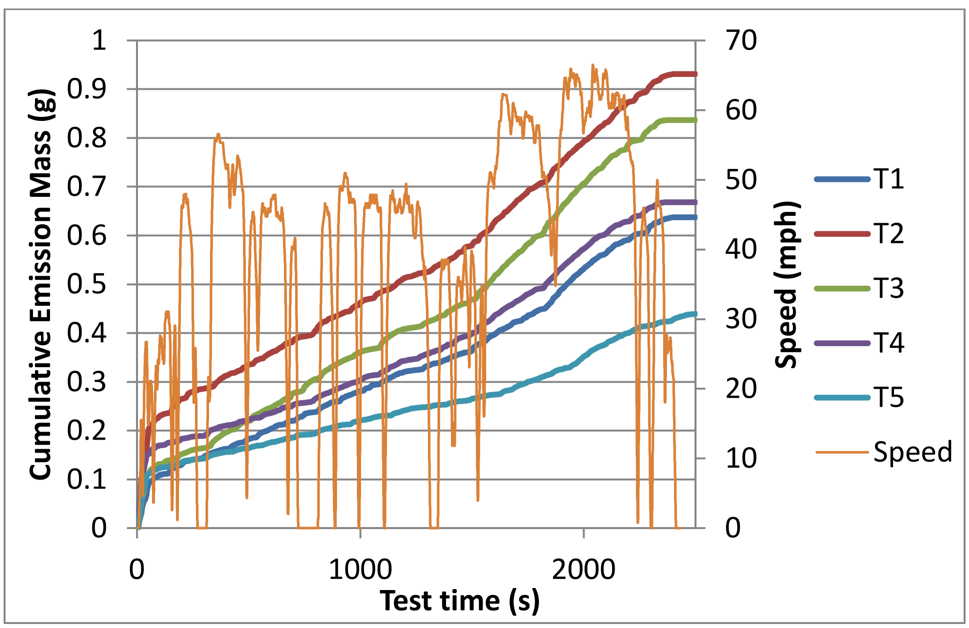

Figure F-17. Continuous HC mass traces for the on-road tests with PEMS I.

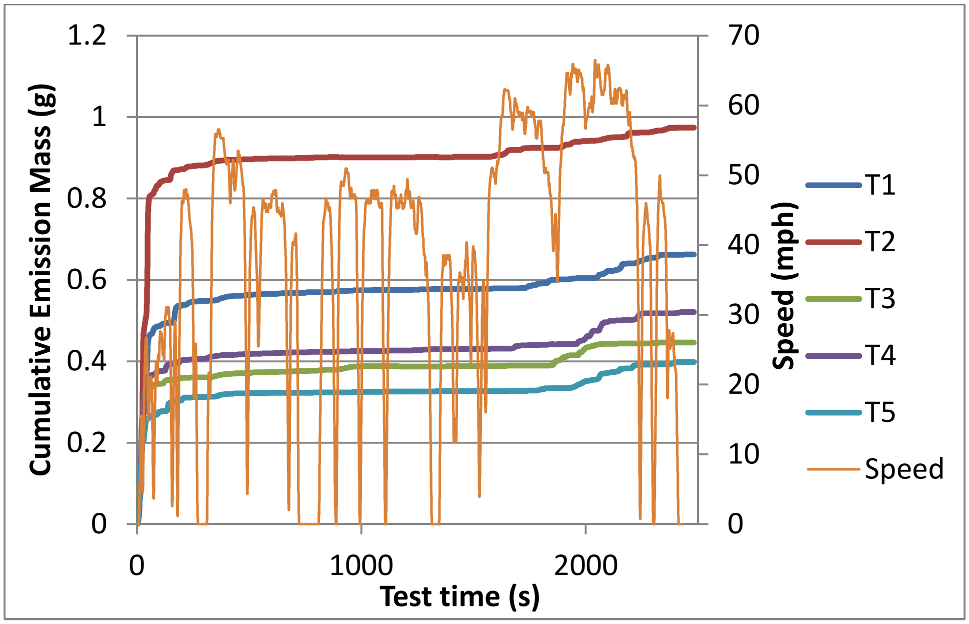

Figure F-18. Continuous HC mass traces for the on-road tests with PEMS J.

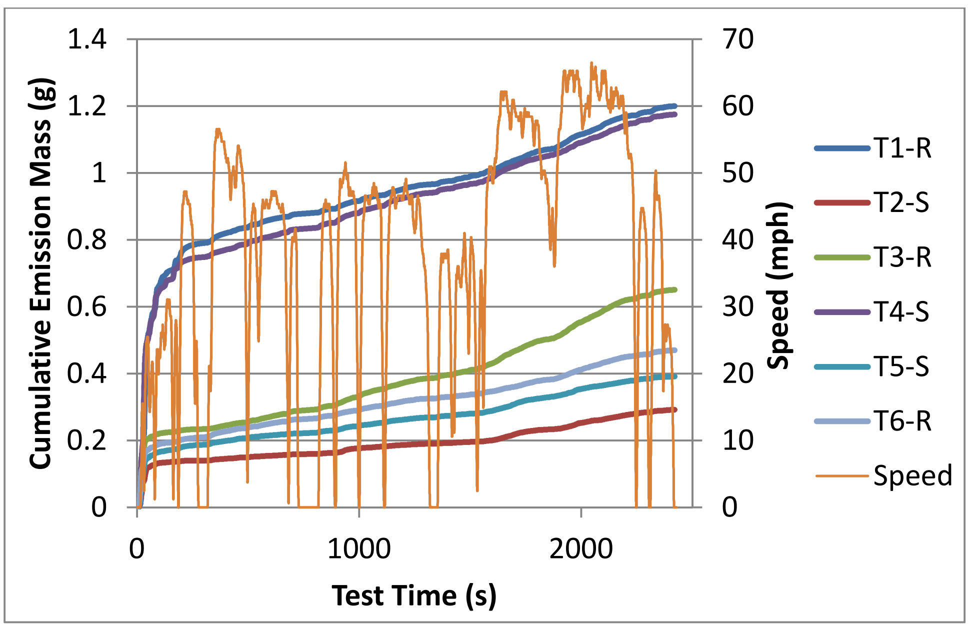

Figure F-19. Continuous HC mass traces for the cold-start track tests with PEMS I.

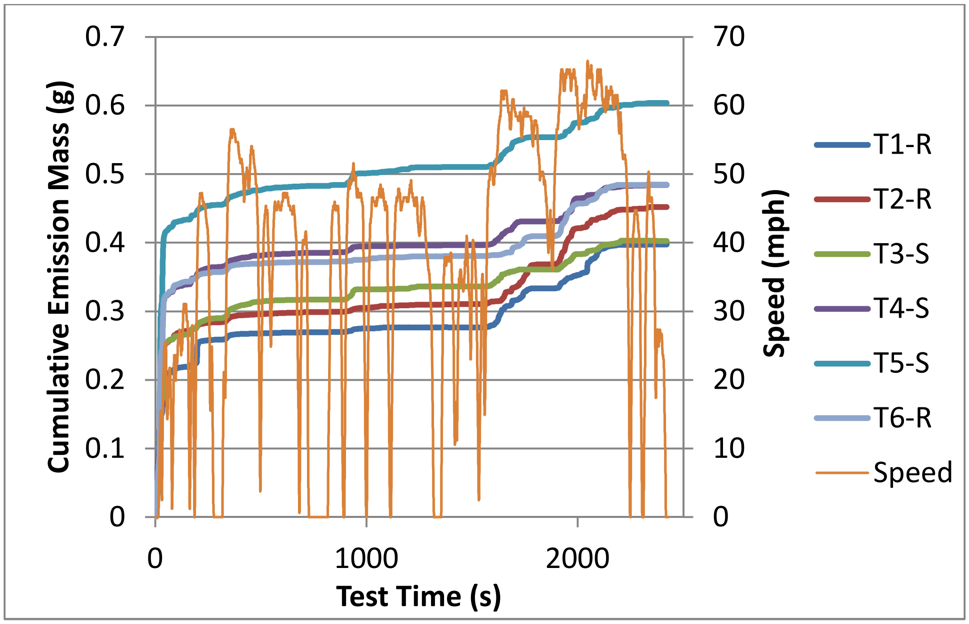

Figure F-20. Continuous HC mass traces for the cold-start track tests with PEMS J.

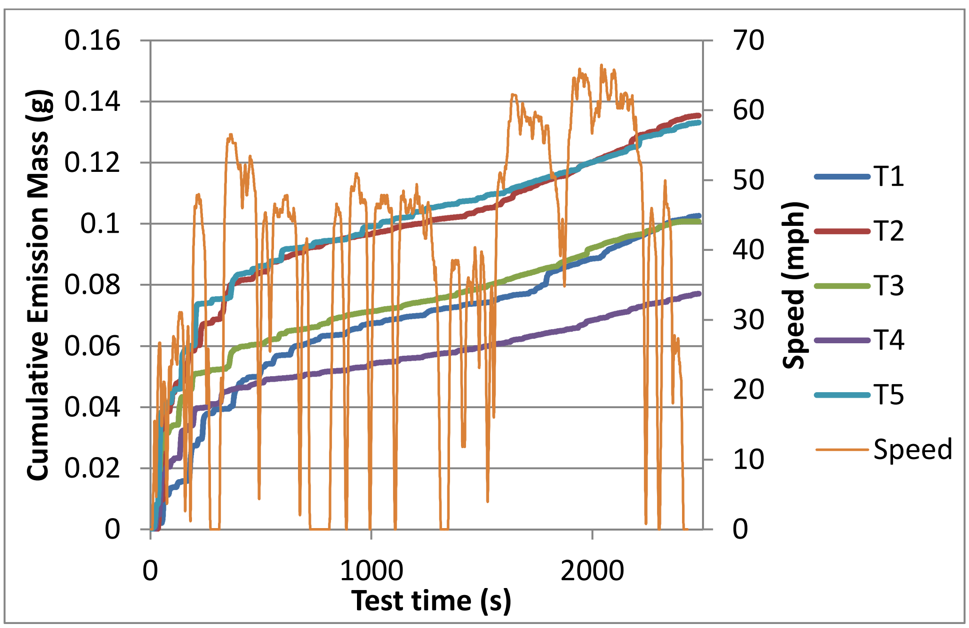

Figure F-21. Continuous PM mass traces for the on-road tests with PEMS K.

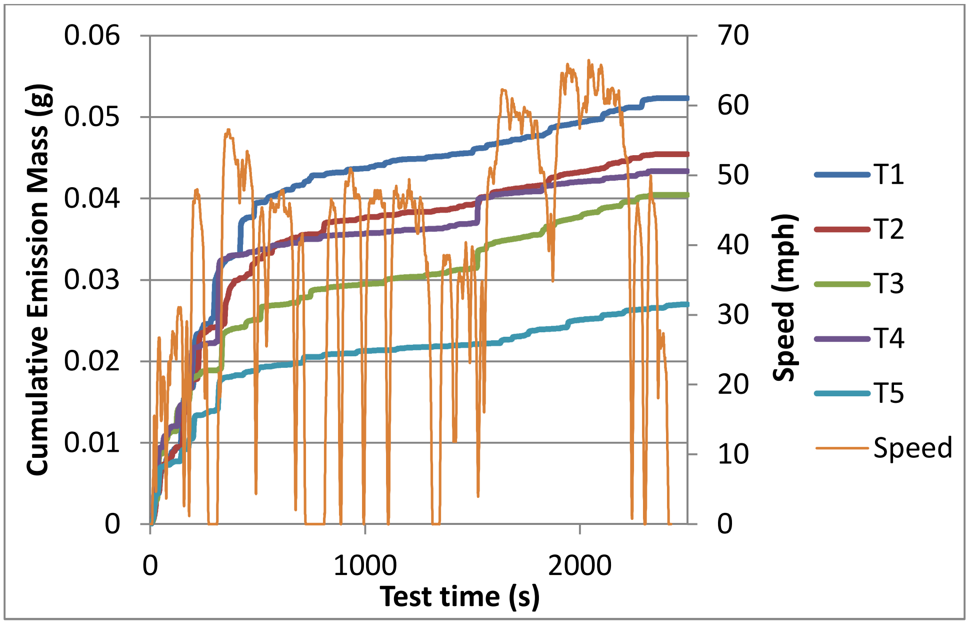

Figure F-22. Continuous PM mass traces for the on-road tests with PEMS L.

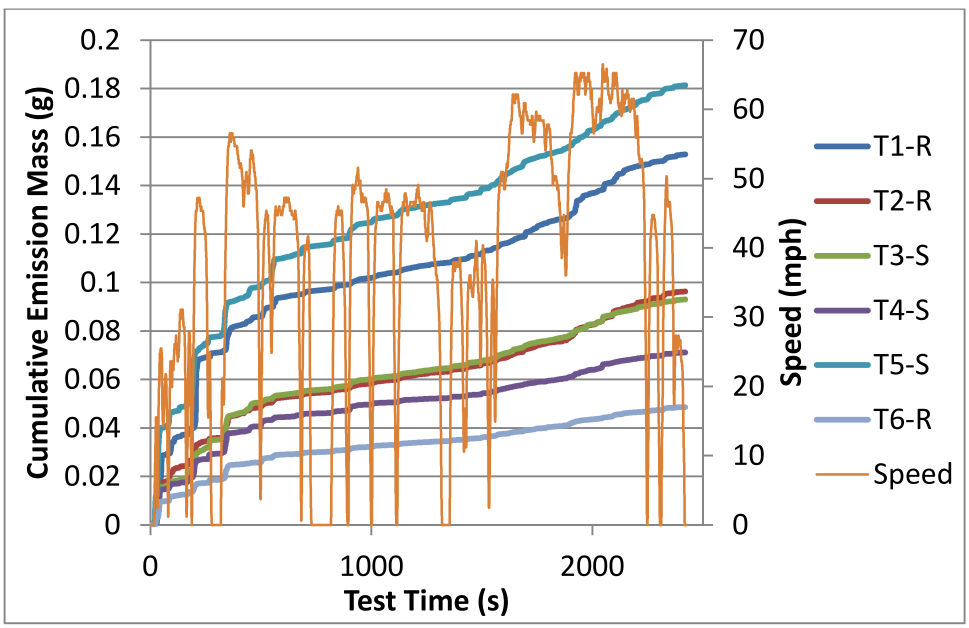

Figure F-23. Continuous PM mass traces for the cold-start track tests with PEMS K.

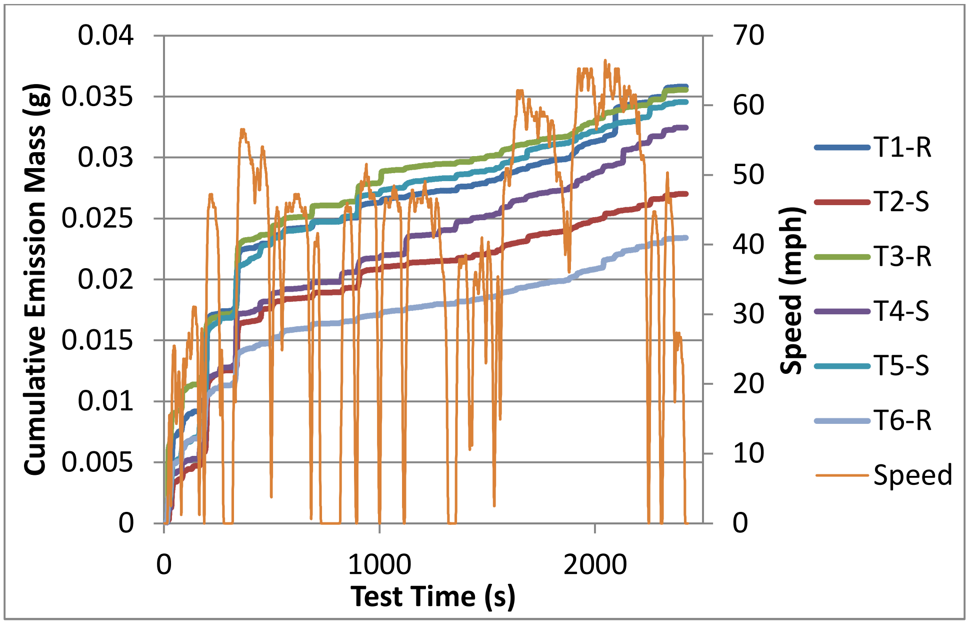

Figure F-24. Continuous PM mass traces for the cold-start track tests with PEMS L.

Appendix G

Unballasted Test Results

This appendix includes the emission mass results for the tests of the single PEMS for which additional tests were performed without ballast added to the vehicle. This testing is described in Section 6.7 of the report. The plots include the results for the original ballasted tests as well as the extra tests of the vehicle without ballast. The means of replicate tests are shown along with 95% confidence interval error bars. Note that each bar does not have the same number of tests. There were five dynamometer tests and five on-road tests performed for this PEMS with the vehicle in a ballasted condition, and two dynamometer tests and two on-road tests performed without ballast. The average NOx emission mass across these tests is presented in Figure G-1. The bars for the Lab CVS measurement in the dynamometer test includes the results of all 15 tests of all three PEMS, however the Lab CVS bar for the unballasted tests include only those two tests. For the unballasted tests, the mean NO/NOx levels are lower, however these differences are not likely to be statistically significant.

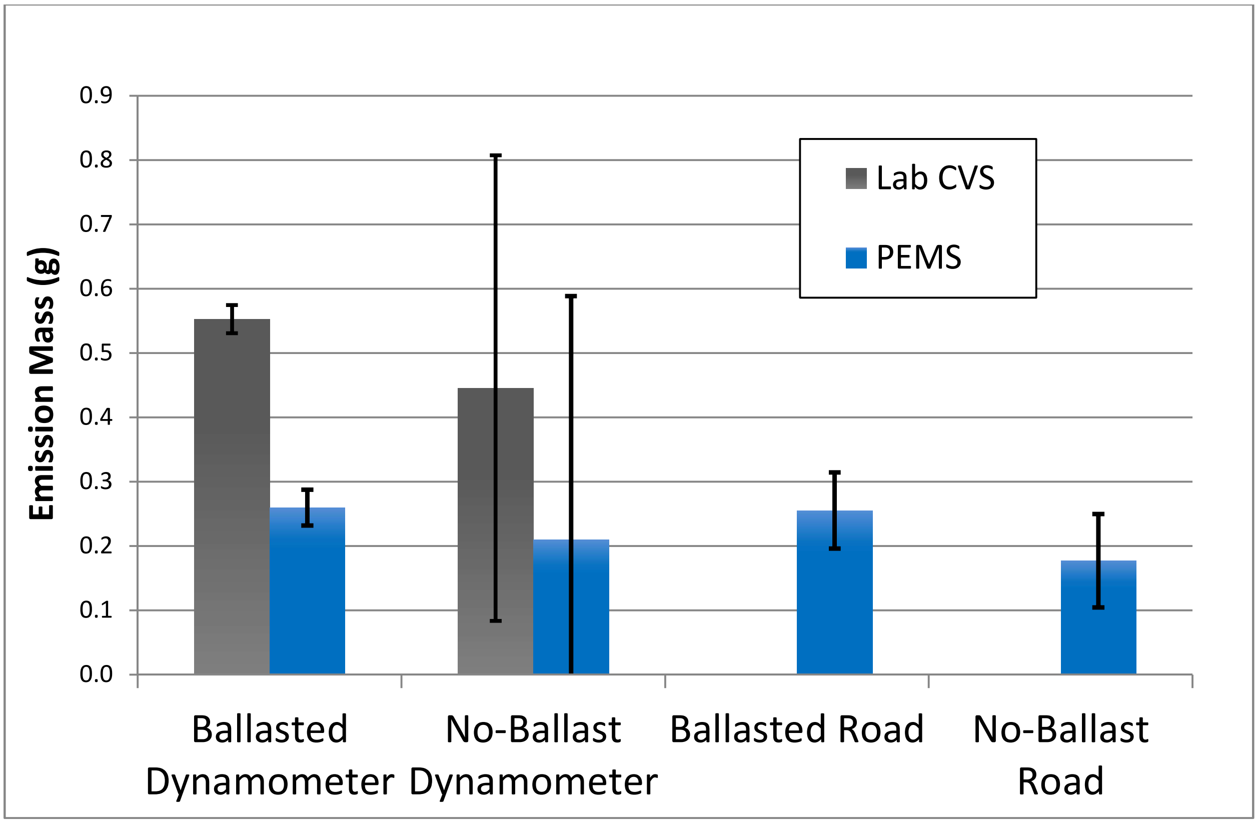

Figure G-1. Average NO/NOx mass emissions for the dynamometer and road tests with and without ballast.

Average mass emissions of CO for this testing are presented in Figure G-2. There is no apparent difference in CO mass emissions between any of the ballasted and unballasted tests, for either the Lab CVS or the PEMS.

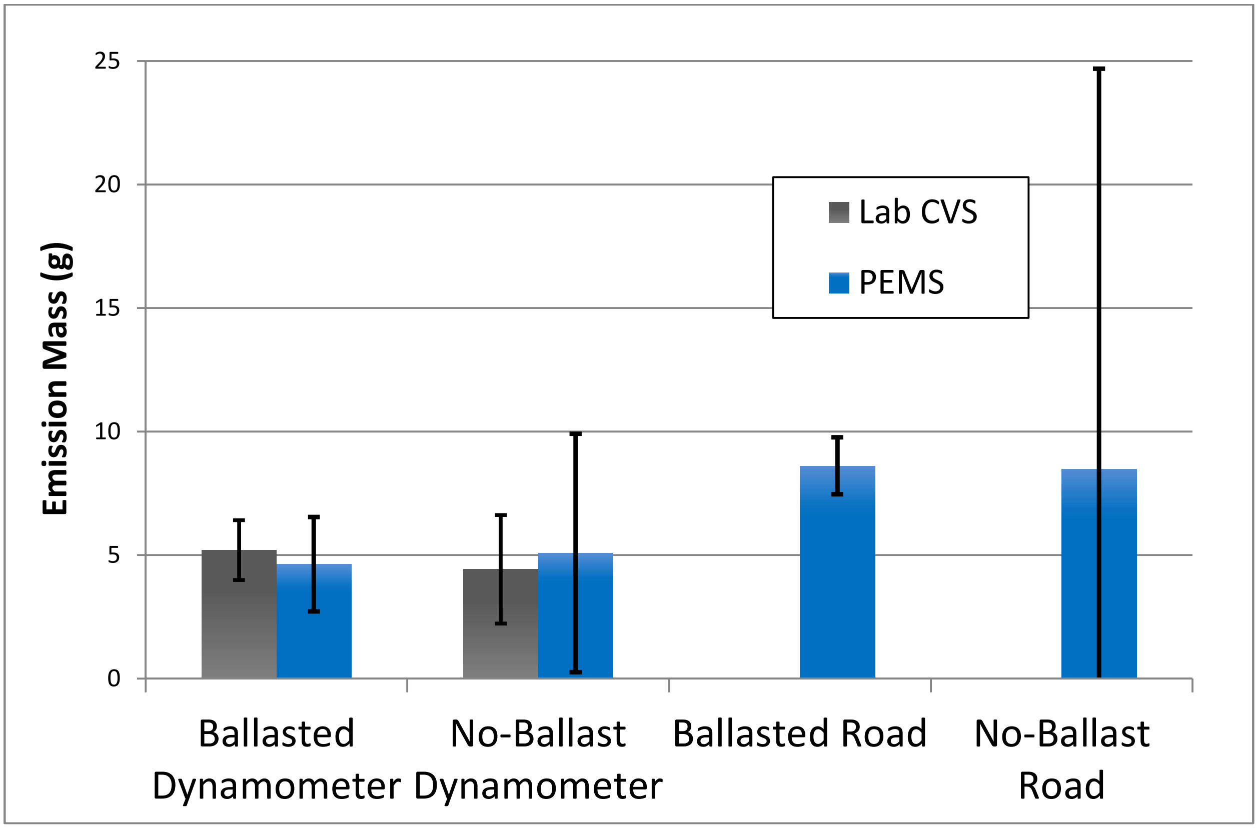

Figure G-2. Average CO mass emissions for the dynamometer and road tests with and without ballast.

Average mass emission results for HC are presented in G-3. As with CO, it is unlikely that there is any statistical significance between the ballasted and unballasted tests for these measurements.

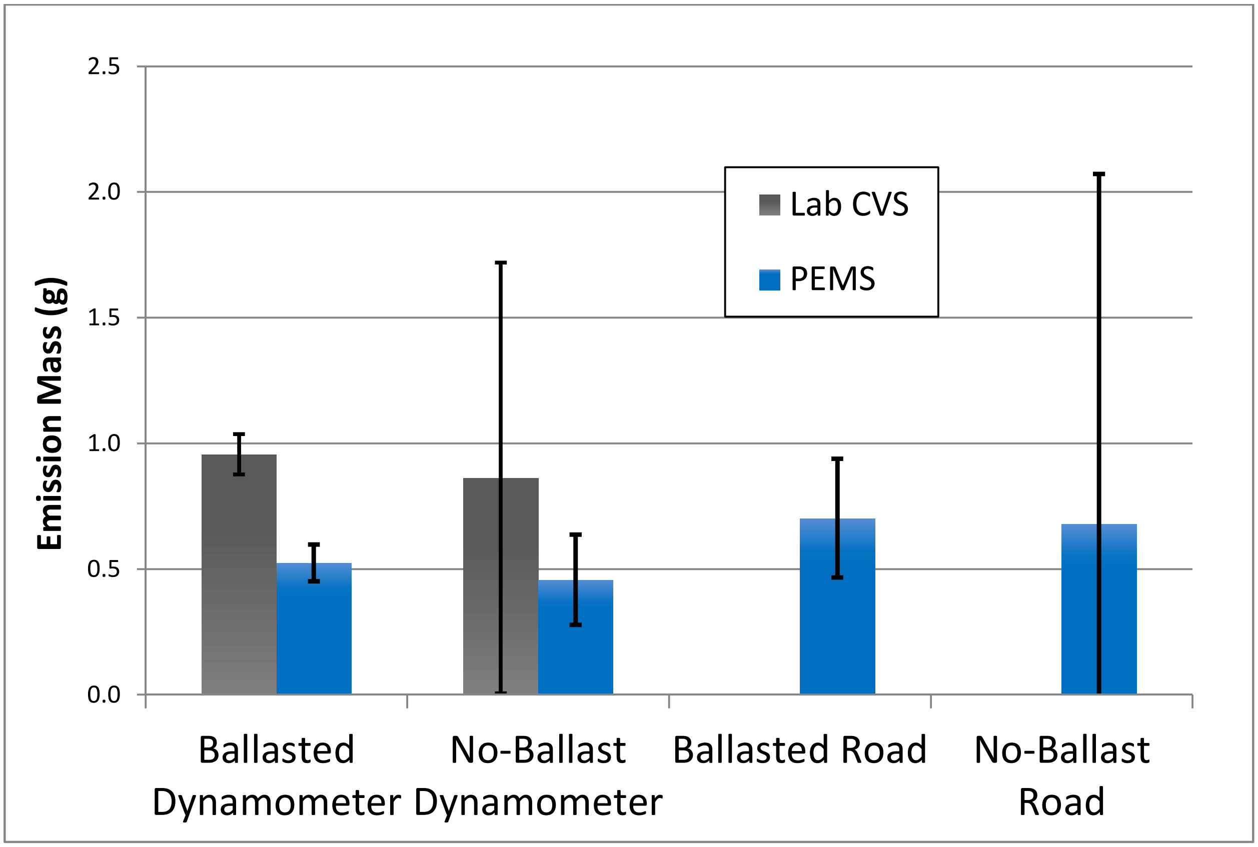

Figure G-3. Average HC mass emissions for the dynamometer and road tests with and without ballast.

Average mass results for PM are presented in G-4. The mean emission masses for the unballasted testing are lower for both the Lab CVS and PEMS systems, however the level of variability of the measurements in the no-ballast condition prevent determining that the differences is statistically significant.

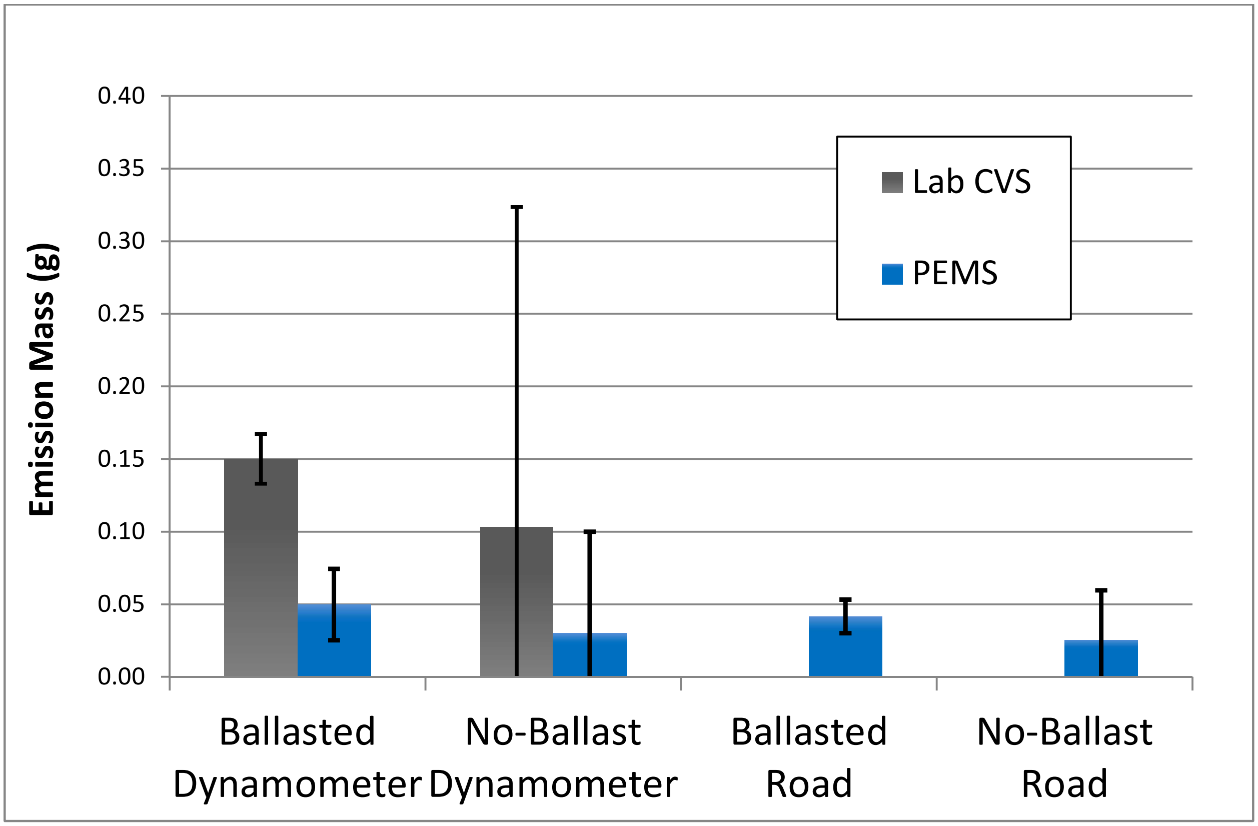

Figure G-4. Average PM mass emissions for the dynamometer and road tests with and without ballast.

Appendix H

Filter Blank Log

Blank # and Type	Date Taken	PEMS Filter Number	PEMS Filter Initial Weight	PEMS Filter Final Weight	PEMS Filter Weight Gain (mg)	Estimated Equivalent Test Mass to WG (g)	Percentage of Blank Equivalent Test Weight to Average Test Mass
#1 Field Blank	7/24/17	104720	140.6938	140.6977	0.0039	0.0231	19.9%
#2 System Blank	7/31/17	105006	141.167	141.1688	0.0018	0.0107	9.2%
#3 System Blank	8/3/17	105011	138.5457	138.5474	0.0017	0.0101	8.7%
#4 System Blank	8/11/17	105066	136.2122	136.2142	0.0020	0.0118	10.2%
#5 System Blank	8/14/17	105021	140.7799	140.7808	0.0009	0.0053	4.6%
#6 Field Blank	8/15/17	105017	140.092	140.0952	0.0032	0.0189	16.3%
						Average of All:	**11.5%**
						Average of System Blanks:	**8.2%**