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Evaluation of Portable Emissions Measurement Systems that can be used for Emissions Inventory Development and Implementation of the Heavy-Duty Diesel Engine Not-To-Exceed Regulation

California Air Resources Board

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Outline

- Background
- Description of PEMS evaluation projects
- Results of the Project for Phase 1
  1. Back-up Generator
  2. Chassis Dynamometer
- Results of the Project for Phase 2
  – In-use or on the Road

Background - PEMS

- Portable emissions measurement systems (PEMS) have been around for more than a decade
- PEMS have been touted as a means of collecting 'real-world' emissions data under actual in-use operating conditions
- PEMS have undergone considerable development since their introduction, and can now measure PM as well as gases

Background - emissions inventory

- PEMS provide an alternative to engine and vehicle dynamometer testing for data collection for emission inventory development
- PEMS can be placed on actual in-use sources (both on-road and off-road engines) operating in the real world
- Emissions modeling can benefit from the use of on-board PEMS - particularly for off-road sources

Background - the NTE

- To ensure in-use compliance, the US EPA, ARB and EMA member companies agreed to a Not-To-Exceed (NTE) component of the 2007 regulation for heavy-duty diesel engines (HDDEs)
- HDDE manufacturers can perform NTE in-use compliance testing by using PEMS placed on in-use vehicles in over-the-road operation
- The HDDE in-use regulation provides a “Measurement Allowance” while conducting measurements on-road with PEMS to accommodate the variability associated with measuring on-road with PEMS compared to certification grade instruments in a laboratory environment

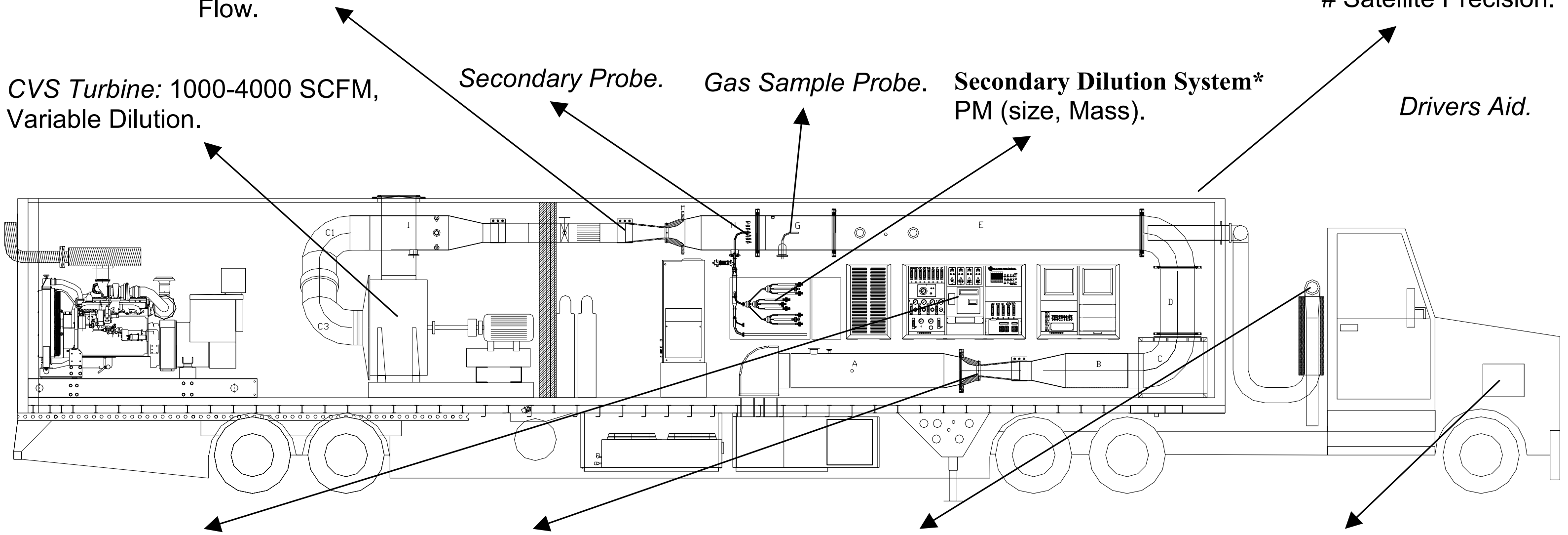
Project Description

- Program consisted of two phases designed to evaluate the PEMS under conditions with increased levels of complexity in measurement and potential variability in operation.
- For each task, PEMS directly compared with CE-CERT's Mobile Emissions Laboratory (MEL), which is fully compliant with the regulatory methods.
- Phase 1
  - The PEMS were evaluated with a backup generator (BUG) at a series of steady state load points.
  - The PEMS were evaluated using a series of chassis dynamometer test cycles, including transient operation.
- Phase 2 – The PEMS were evaluated over-the-road under varying ambient conditions, test cycles and other conditions.

Test Equipment – Gaseous Emissions

- All PEMS were tested against CE-CERT Mobile Emissions Laboratory (MEL) which serves as a reference method.
- Four primary gaseous PEMS were tested in Phase 1.
  - Semtech D
  - Horiba 1300 and 2200 (early prototype)
  - Ride-along Vehicle Emissions Measurement system (RAVEM) from Engine, Fuels, and Emissions Engineering, Inc.
  - Clean Air Technology Incorporated (CATI) Montana system
- The Semtech DS was the only gaseous PEMS used in the Phase 2 over-the-road testing.
- All Gaseous PEMS measured exhaust flow to provide total mass emissions

The CE-CERT MEL




cleanAIR


HORIBA
FILTER
SAMPLE


SEMTECH-D
sensors, inc.
WIRELESS COMMUNICATIONS MODULE
SPAN
ZERO
LINE FILTER
HEATED LINE
WARM UP
FID FLAME
SYS STATUS
ZERO
CPU STATUS
DATA LOG
ON/OFF
AUX-1
AUX-2
GPS
ANALOG OUTPUT
ETHERNET COMP HUB
VEHICLE INTERFACE
TEMP RH
AUX TEMP
HEATED LINE
DATA CARD
12VDC

r

Test Equipment PM

- The RAVEM and CATI systems provided PM measurements for the Phase 1 BUG testing
- Four PEMS with PM measurement capability were tested in the Phase 1 chassis dynamometer testing.
  - RAVEM (also measurement gaseous emissions)
  - Atrium Laser Induced Incandescence (LII)
  - AVL Photoacoustic Microsoot Sensor
  - TSI Dustrak
- Only the CATI and RAVEM can measure exhaust flow and provide total mass emissions in the exhaust.

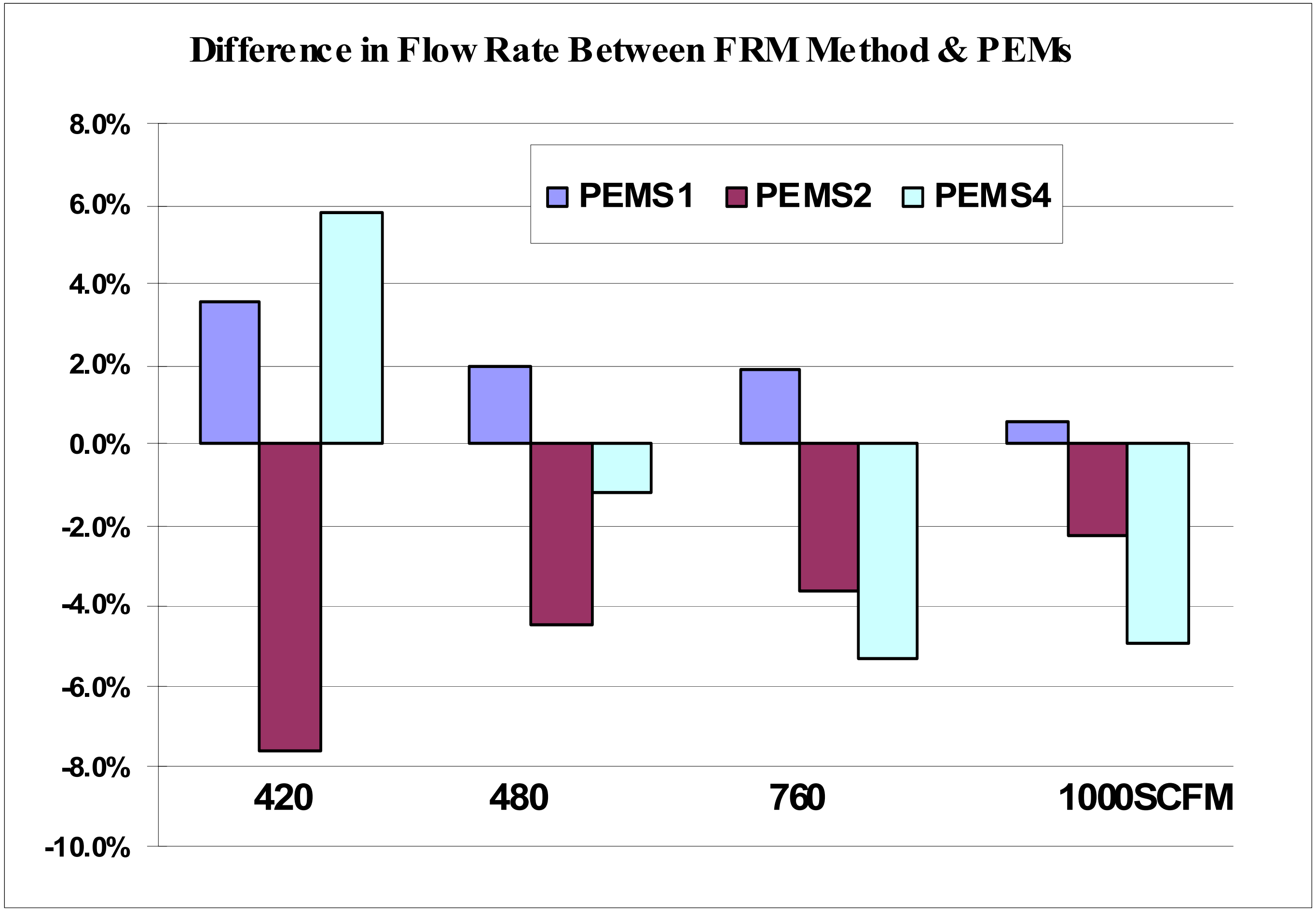

AVL
AVL MICRO SOOT SENSOR MEASURING UNIT


DUSTTRAK
TSI

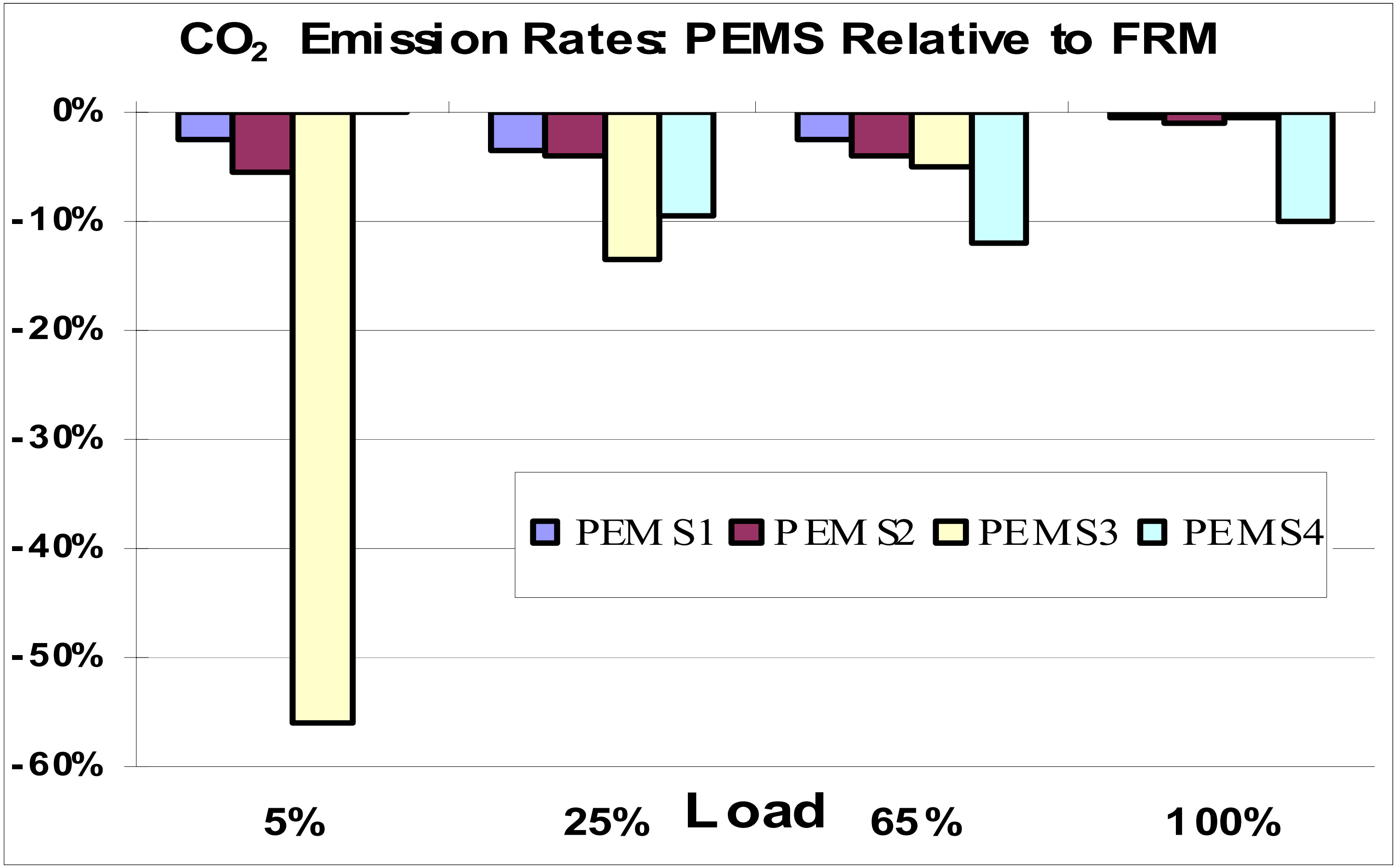
Description of BUG Testing

- Conducted at CE-CERT using a 2000 model year Caterpillar 3406C engine
- Engine was operated at four load points (5, 25, 67 and 100 percent of rated power)
- Seven repetitions were conducted at each of the four load points
- CATI, Semtech, RAVEM, and Horiba

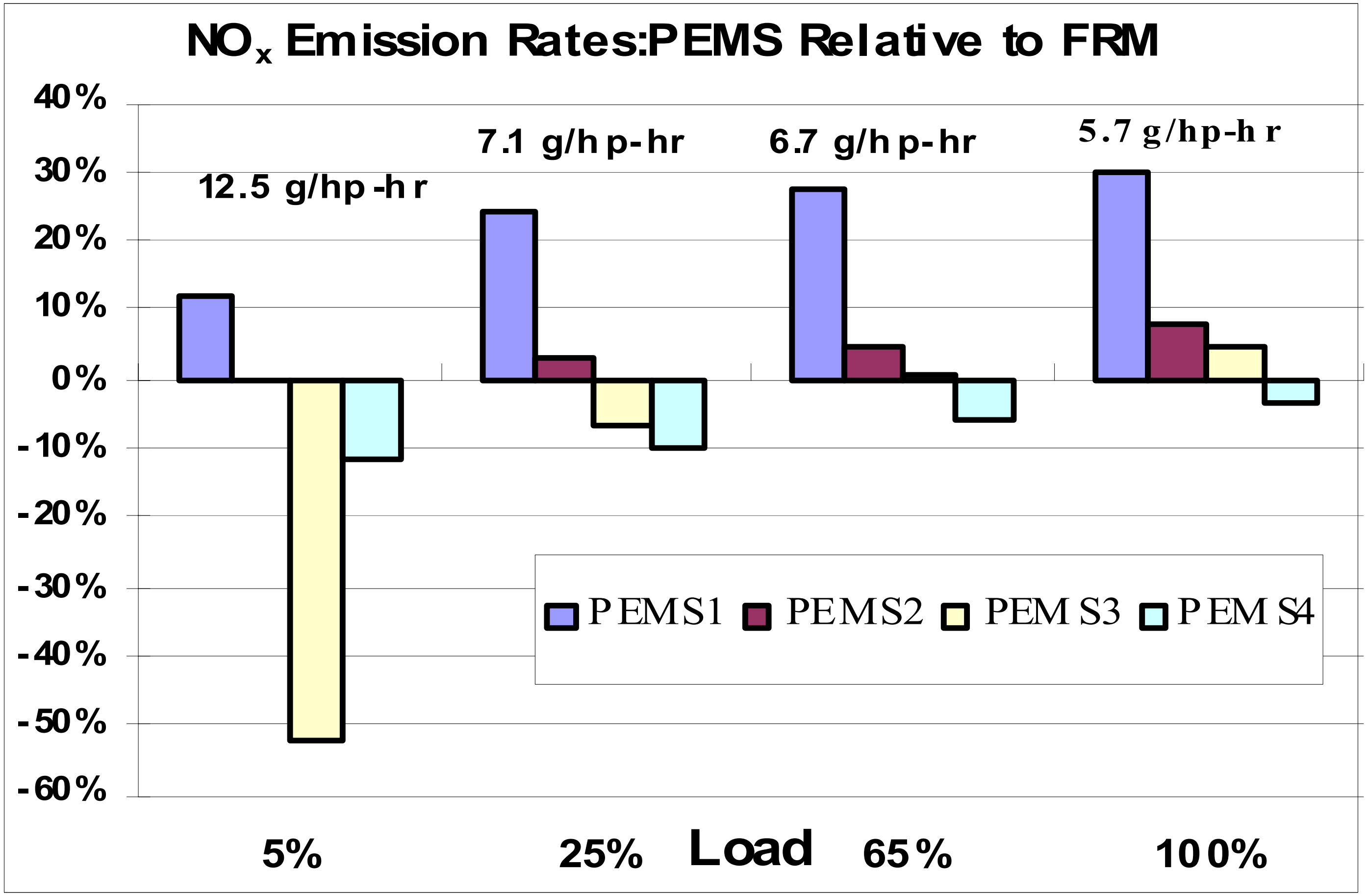
BUGs Exhaust Flow



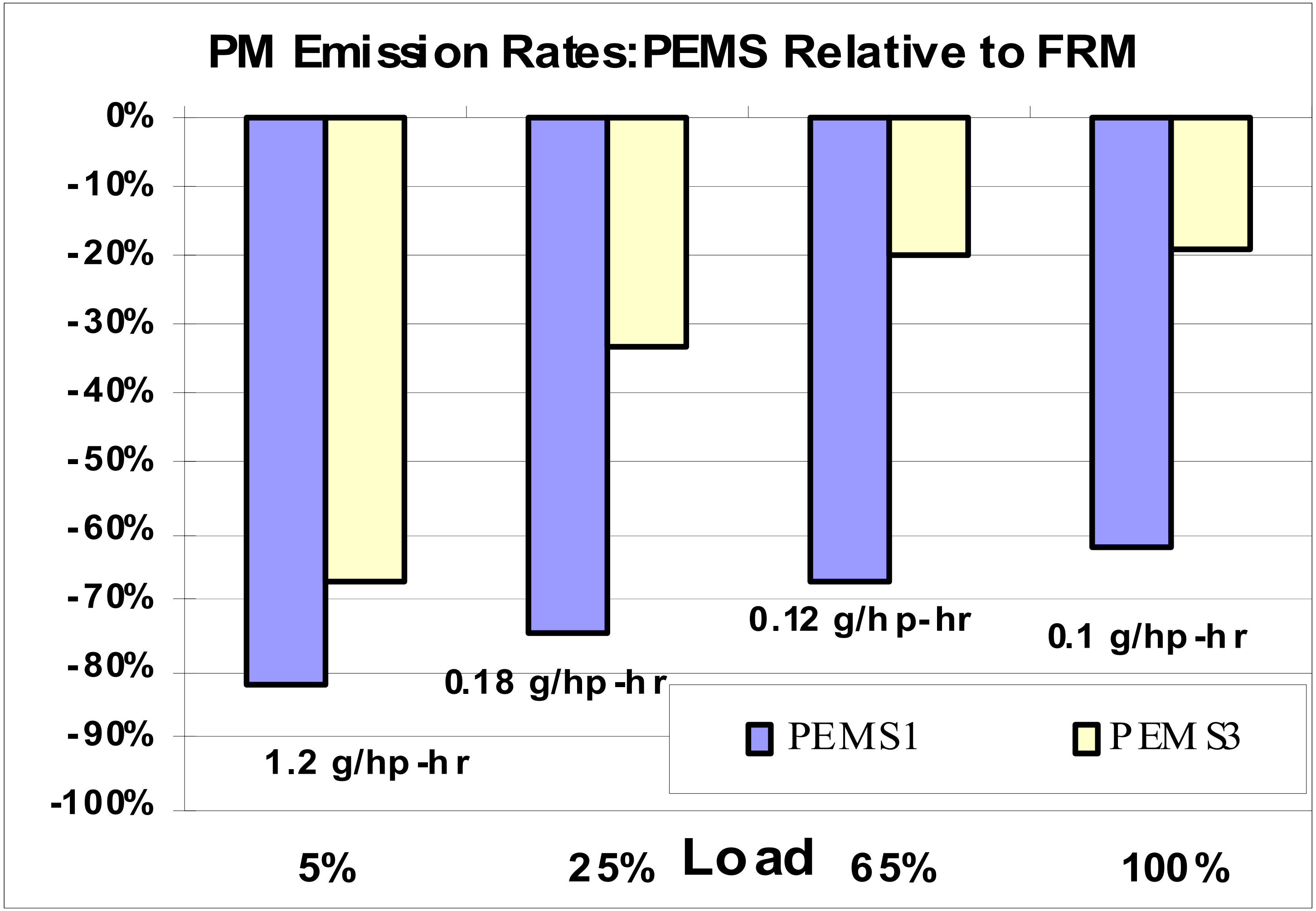
BUG CO_2 emissions



BUG NO_x emissions



BUG PM emissions



Context of Chassis Dynamometer Testing

- Initial focus of program was more research based
- With upcoming NTE regulation, chassis dynamometer study became a 'pre-pilot' for the measurement allowance program
- Original project scope modified for chassis dynamometer testing to include:
  - Engine operation in NTE zone, with a focus on gaseous emissions
  - Emissions inventory cycles with both gaseous and PM emissions

Description of Chassis Dyno Testing

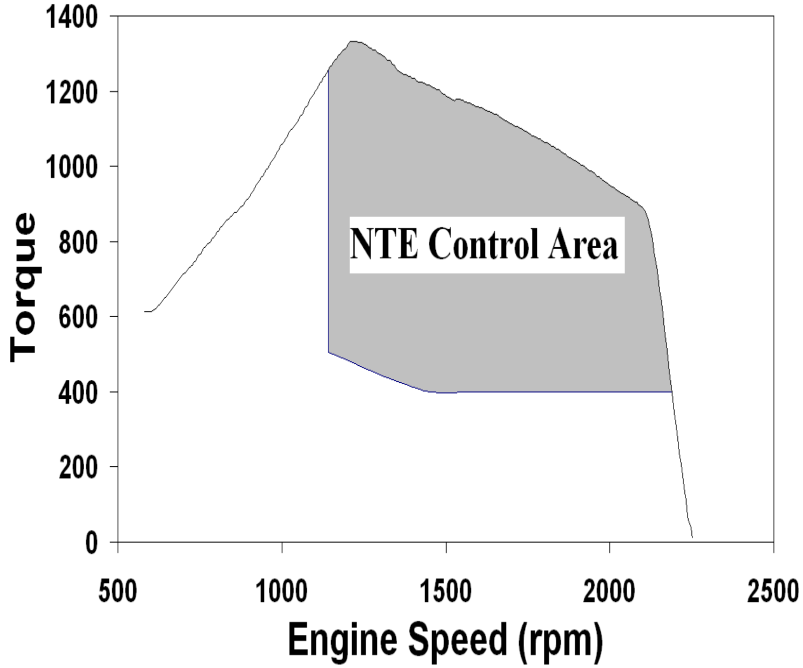
- Testing at the ARB HDV Lab in Los Angeles
- Test vehicle equipped with 2003 Caterpillar C-15 ACERT engine
- Test cycles - Six test cycles: 4 short "NTE-zone" cycles, plus the UDDS and ARB 50-mph cruise mode
- CATI, Semtech, RAVEM, and Horiba - gaseous
- AVL, Artium, DustTrak, RAVEM - PM

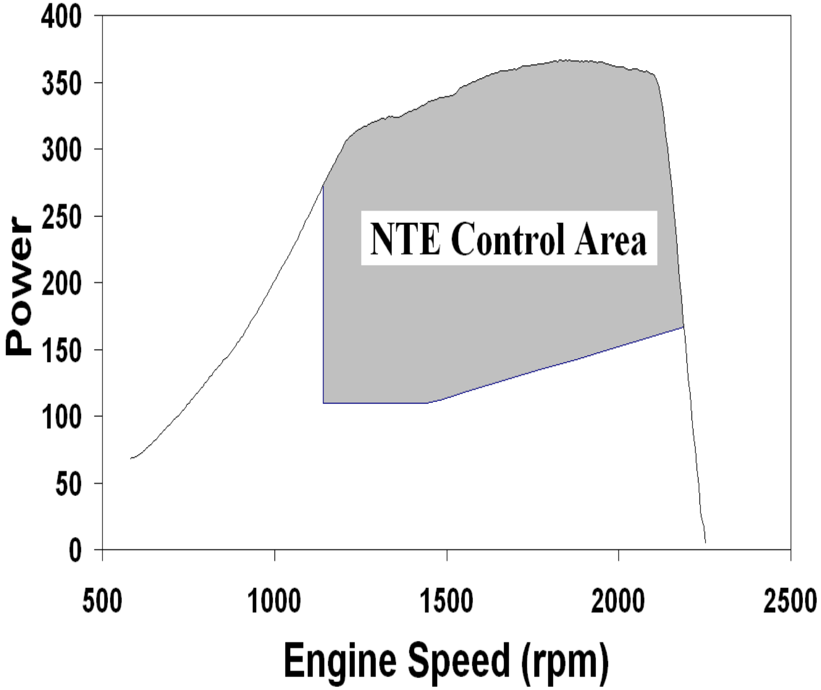
NTE Events and Cycles

- An NTE event is generated when the following conditions are met for at least 30 seconds
  1. Speed >15%(n_{hi}-n_{lo}) + n_{lo}
  2. Torque ≥ 30% max
  3. Power ≥ 30% max
  4. Altitude ≤ 5500 feet
  5. Amb temp ≤ 100°F sea level to 86°F at 5500 feet

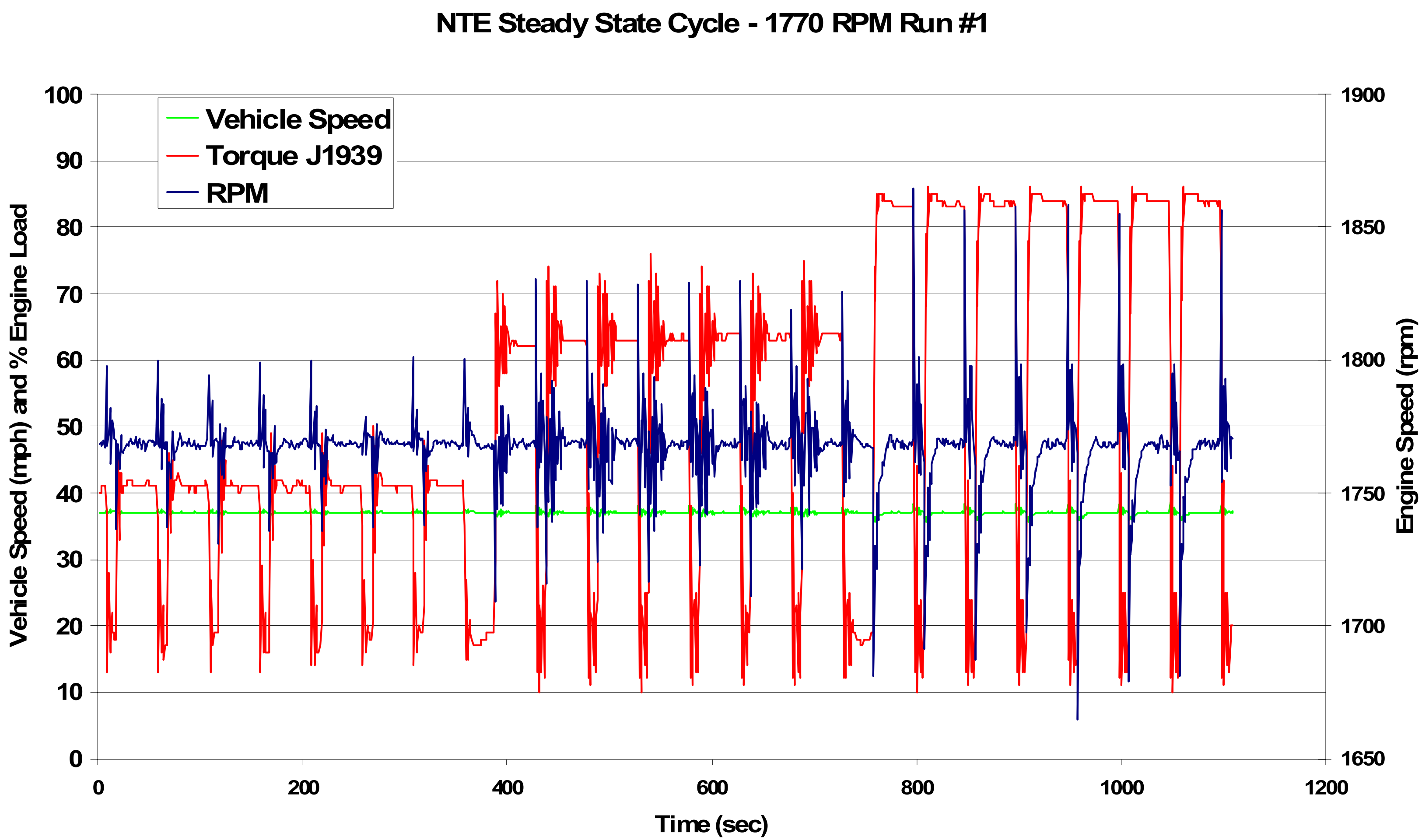
Other conditions cover variables such as BSFC, exclusions zones, manifold temperature, engine coolant temperature, and aftertreatment systems

NTE Control Zone

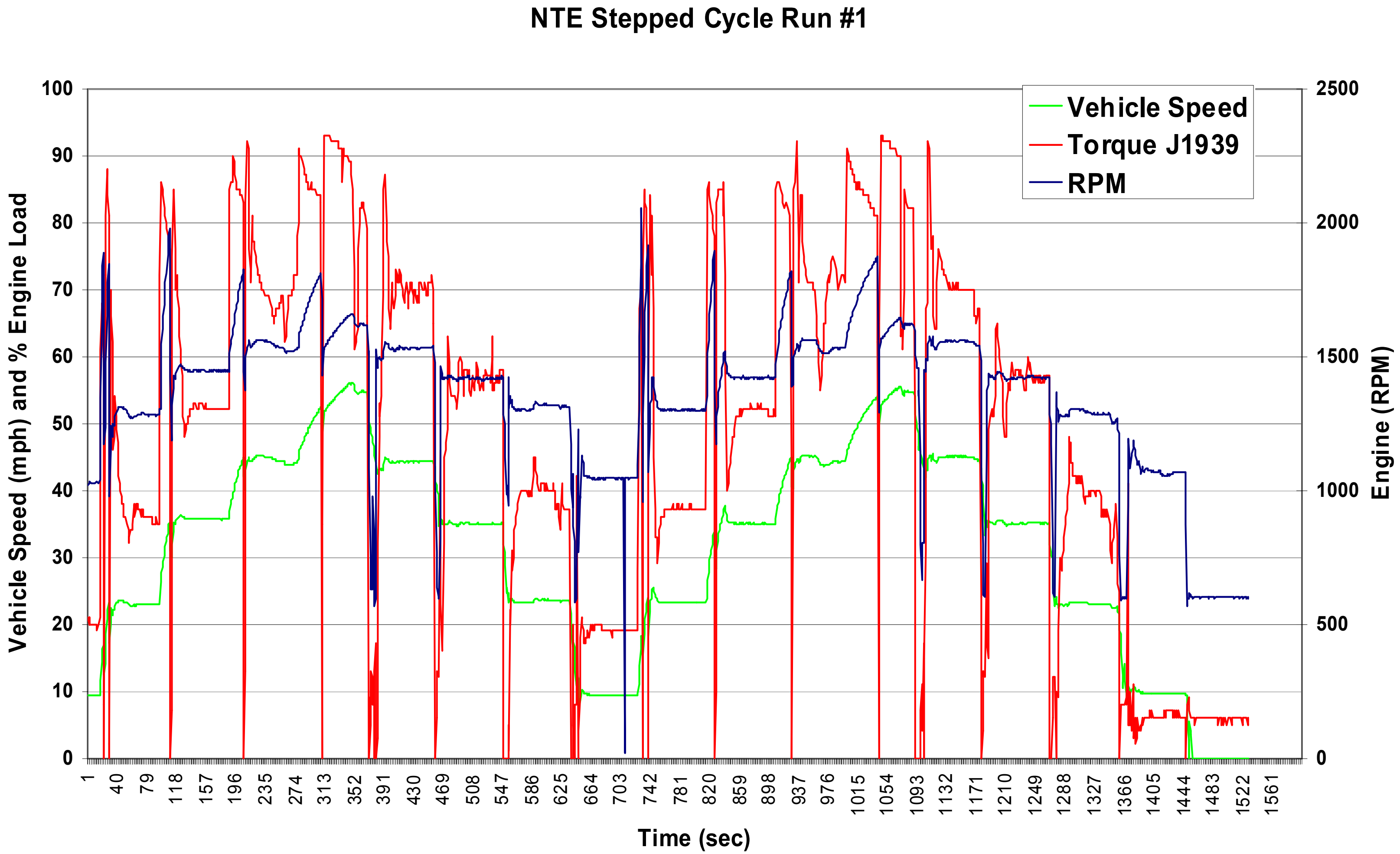




NTE Cycles


NTE Steady State Cycle - 1770 RPM Run #1
Vehicle Speed
Torque J1939
RPM
Vehicle Speed (mph) and % Engine Load
Engine Speed (rpm)
Time (sec)
100
90
80
70
60
50
40
30
20
10
0
1900
1850
1800
1750
1700
1650
0
200
400
600
800
1000
1200

NTE Cycles


NTE Stepped Cycle Run #1
Vehicle Speed
Torque J1939
RPM
Vehicle Speed (mph) and % Engine Load
Engine (RPM)
Time (sec)
100
90
80
70
60
50
40
30
20
10
0
2500
2000
1500
1000
500
0
1
40
79
118
157
196
235
274
313
352
391
430
469
508
547
586
625
664
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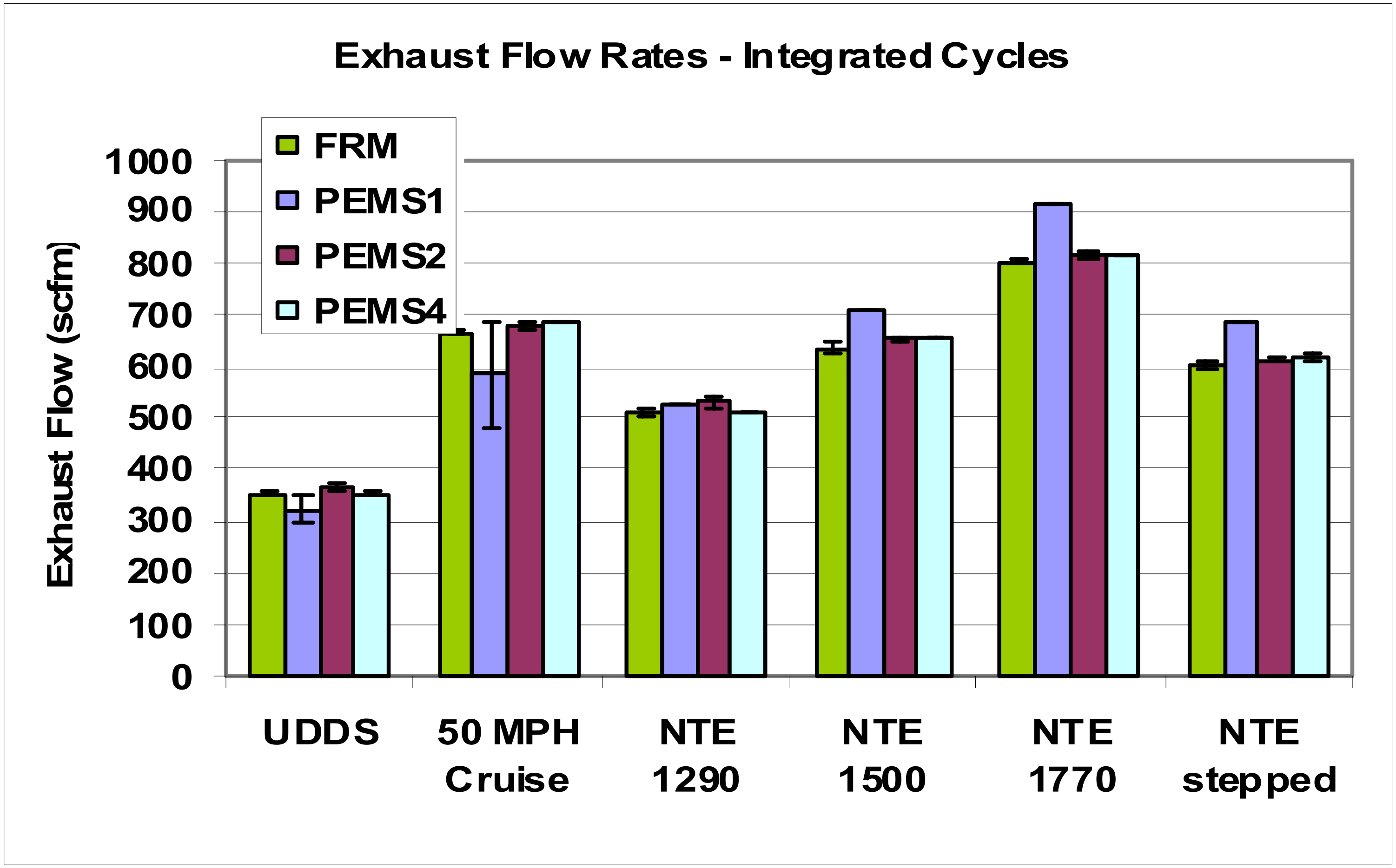
1522
1561

Caterpillar HDT being tested

Chassis Exhaust Flow measurements



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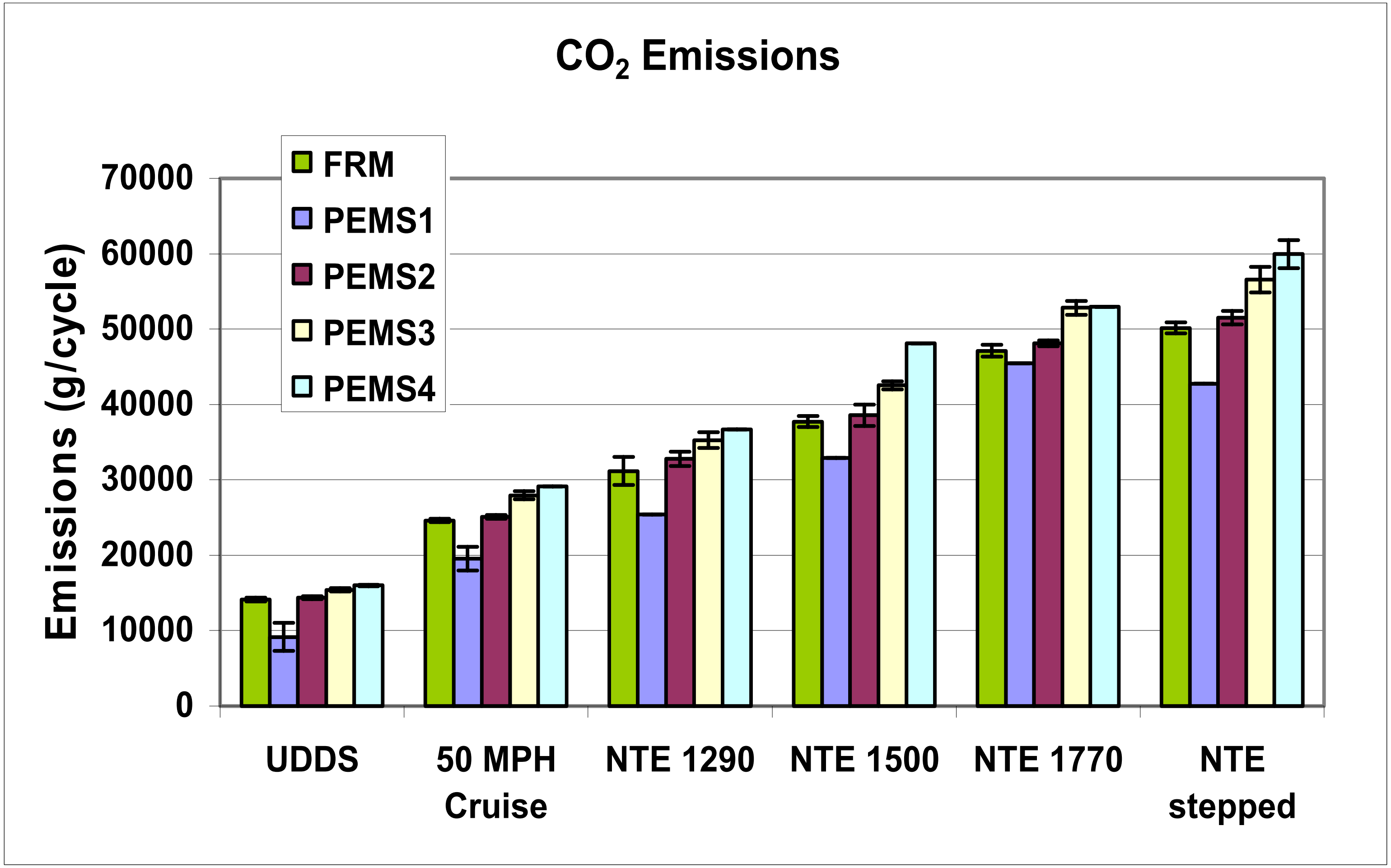
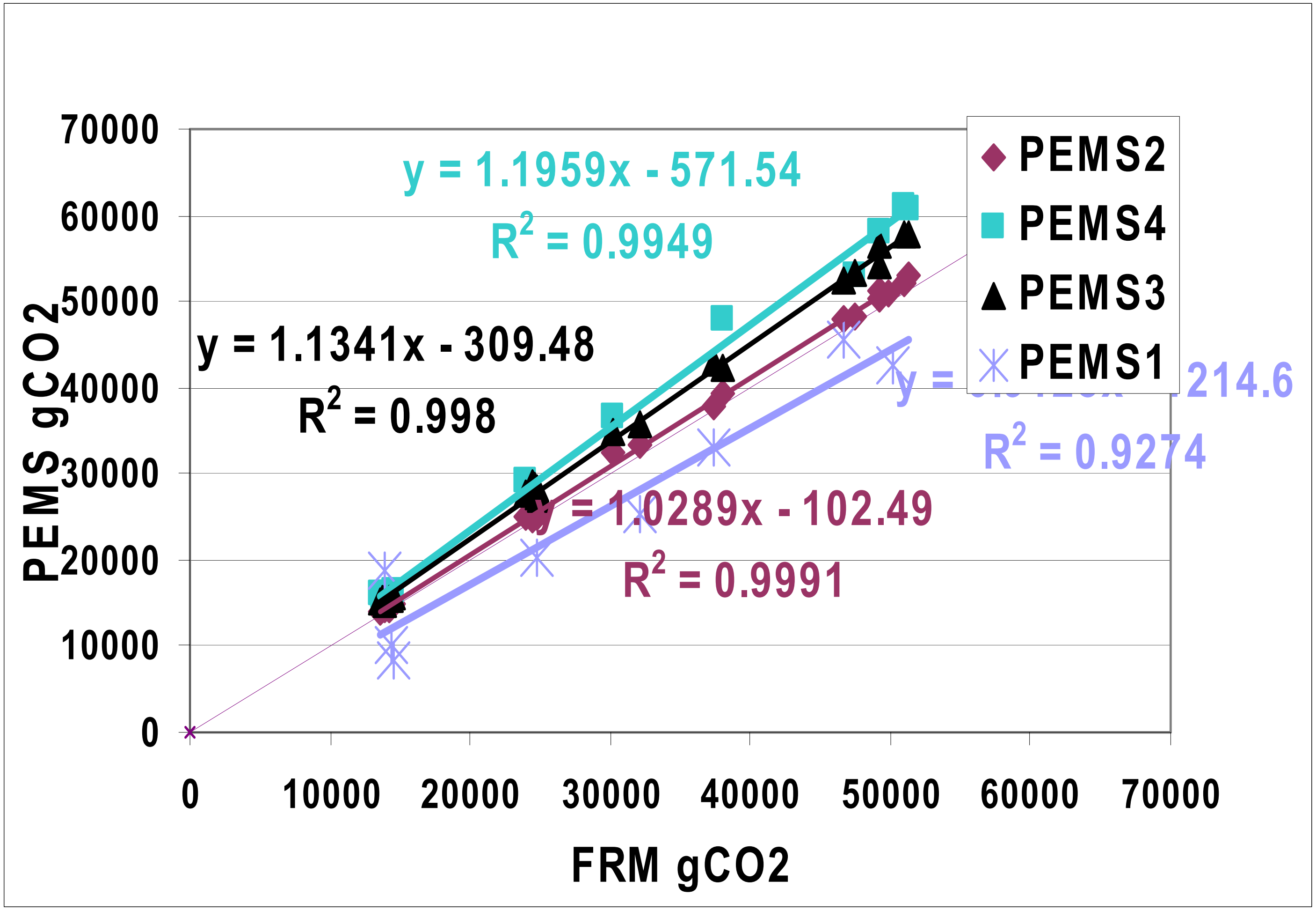
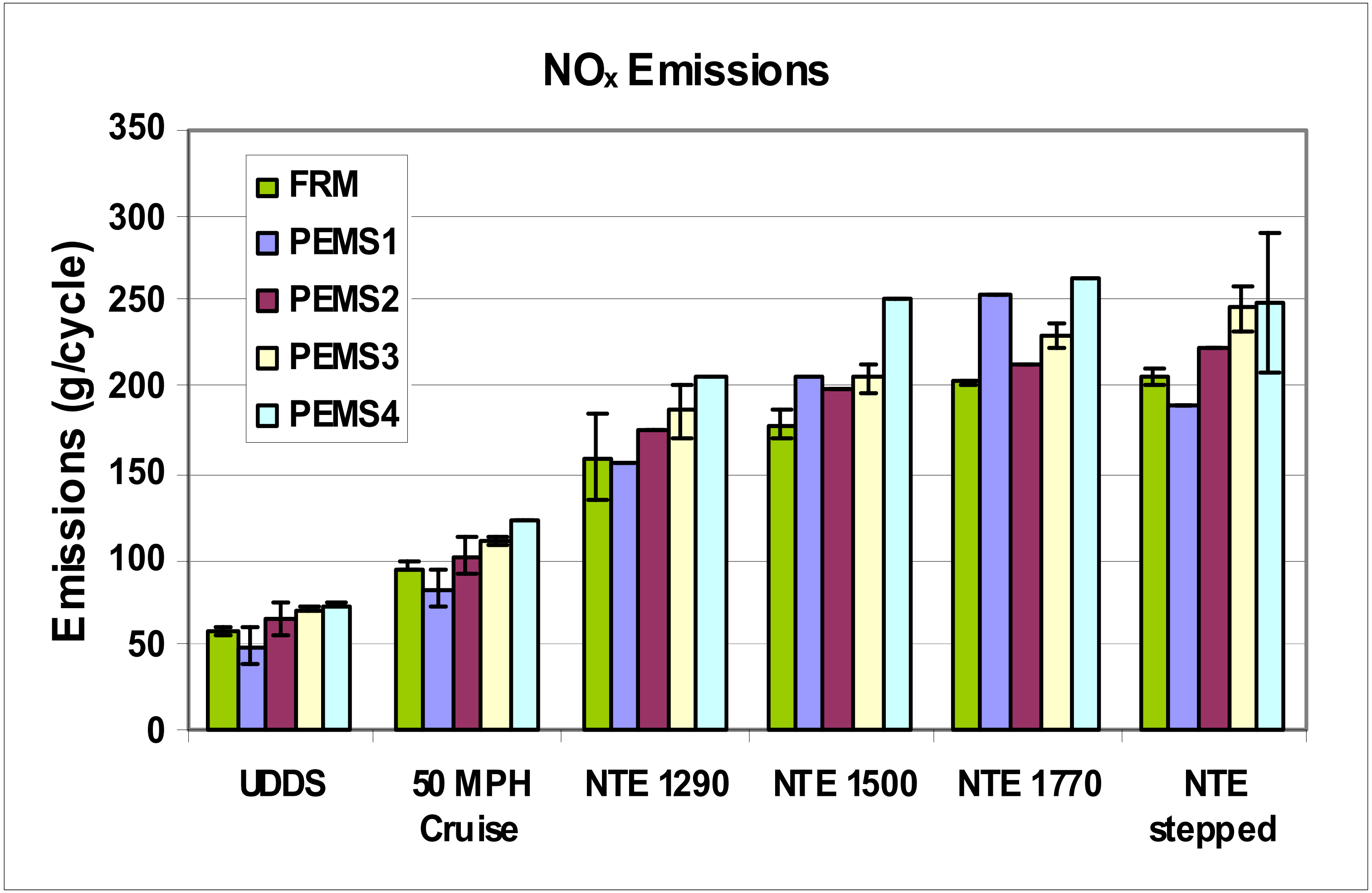
Chassis CO_2 emissions



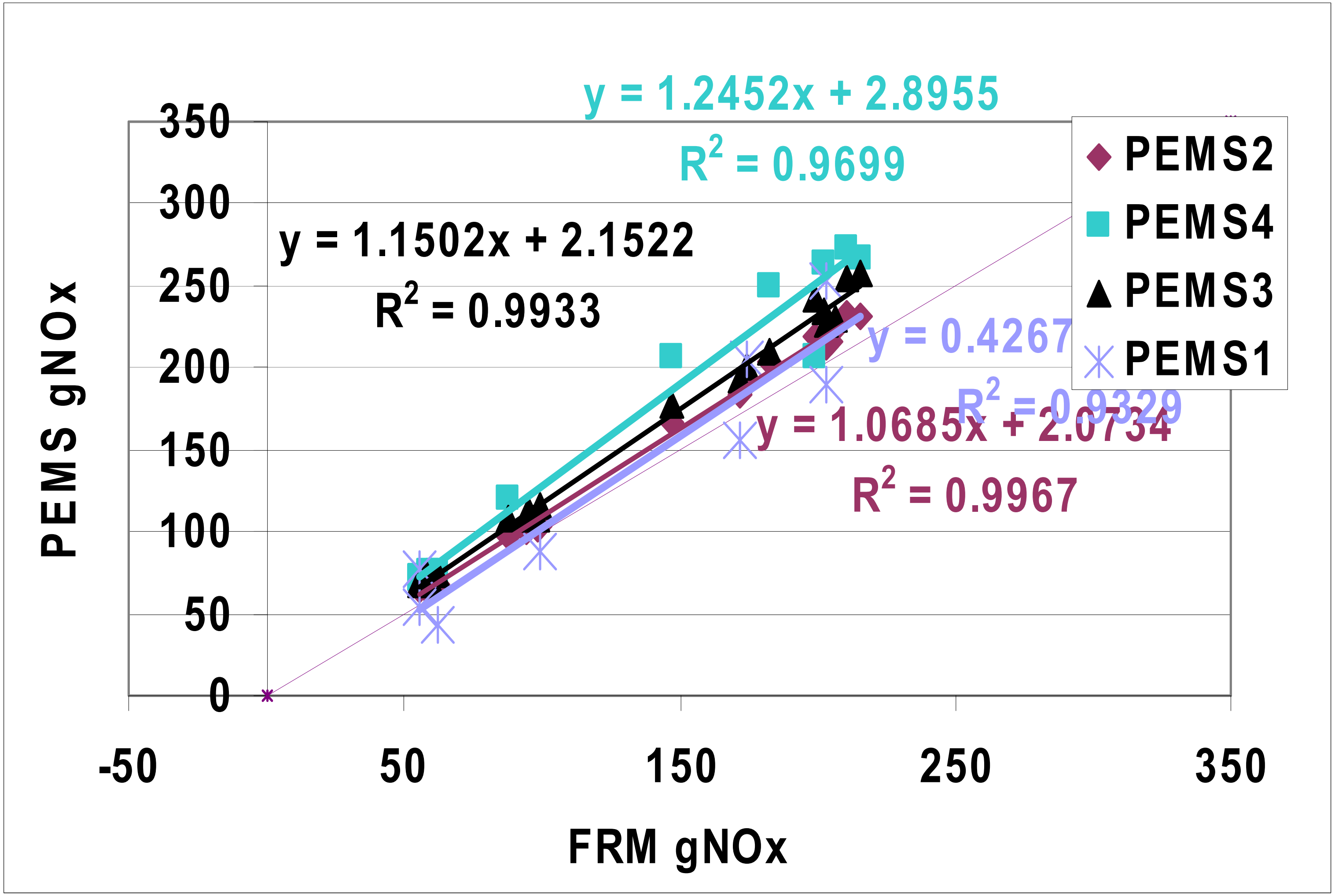
CO_2 Emissions Correlations



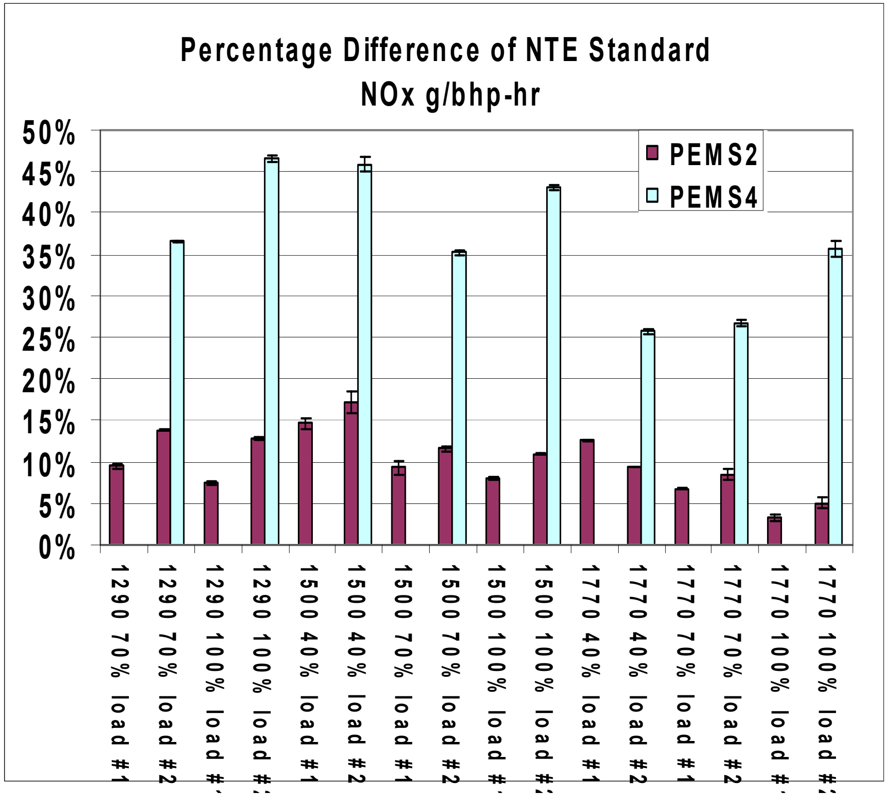
Chassis NO_x emissions

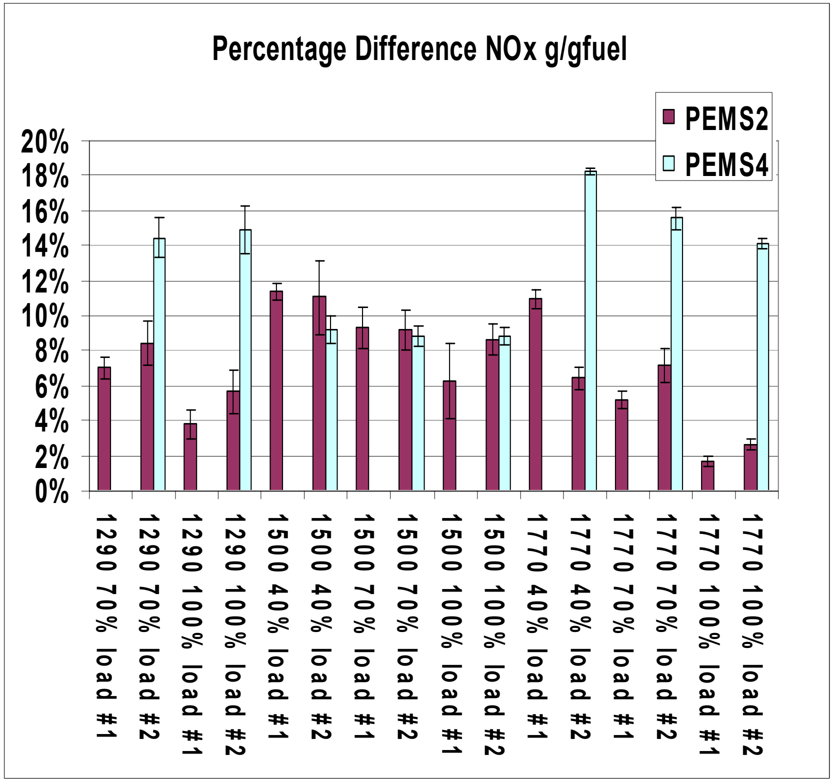


NO_x Emissions Correlation

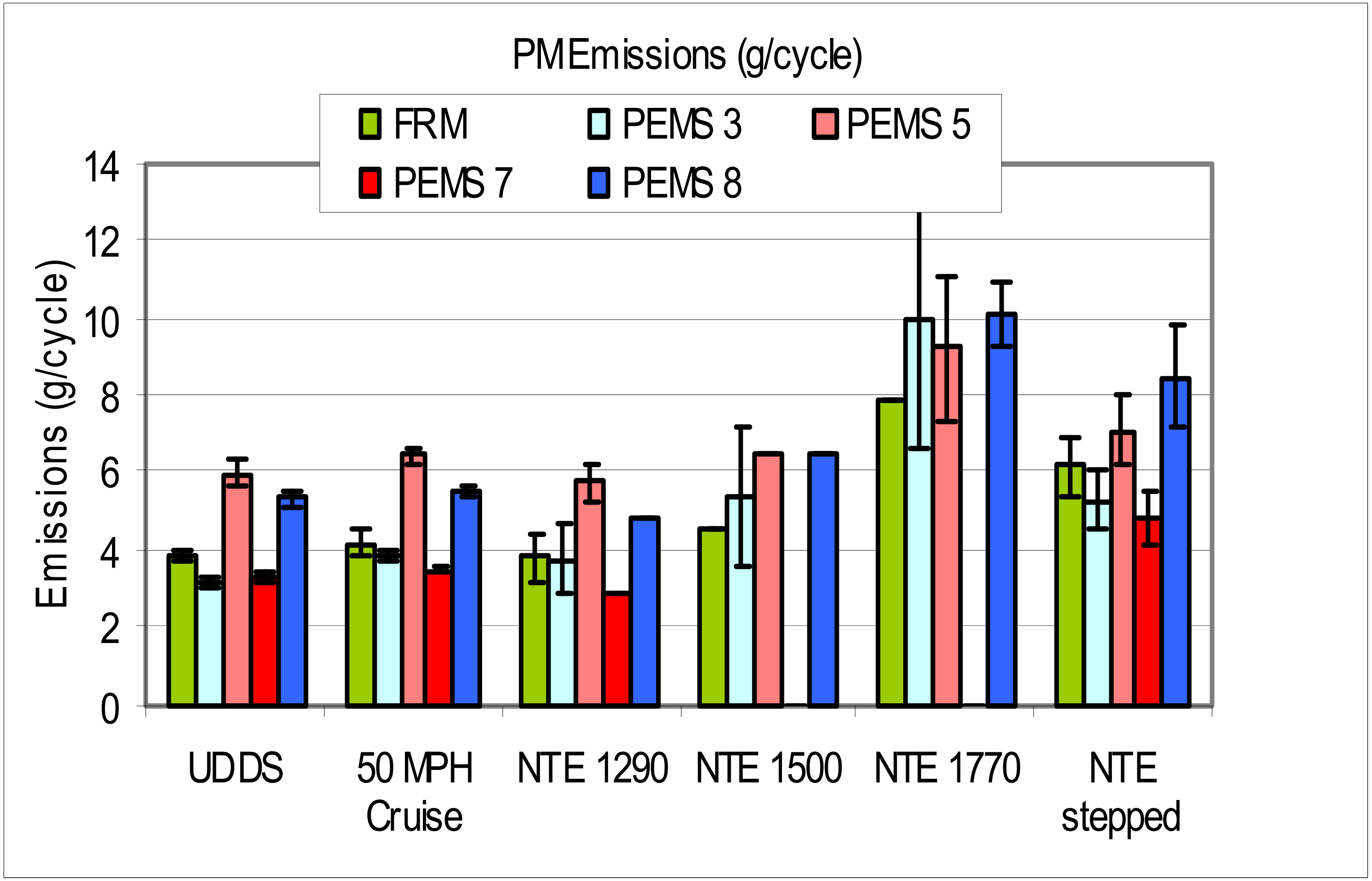


Chassis NTE NO_x emissions

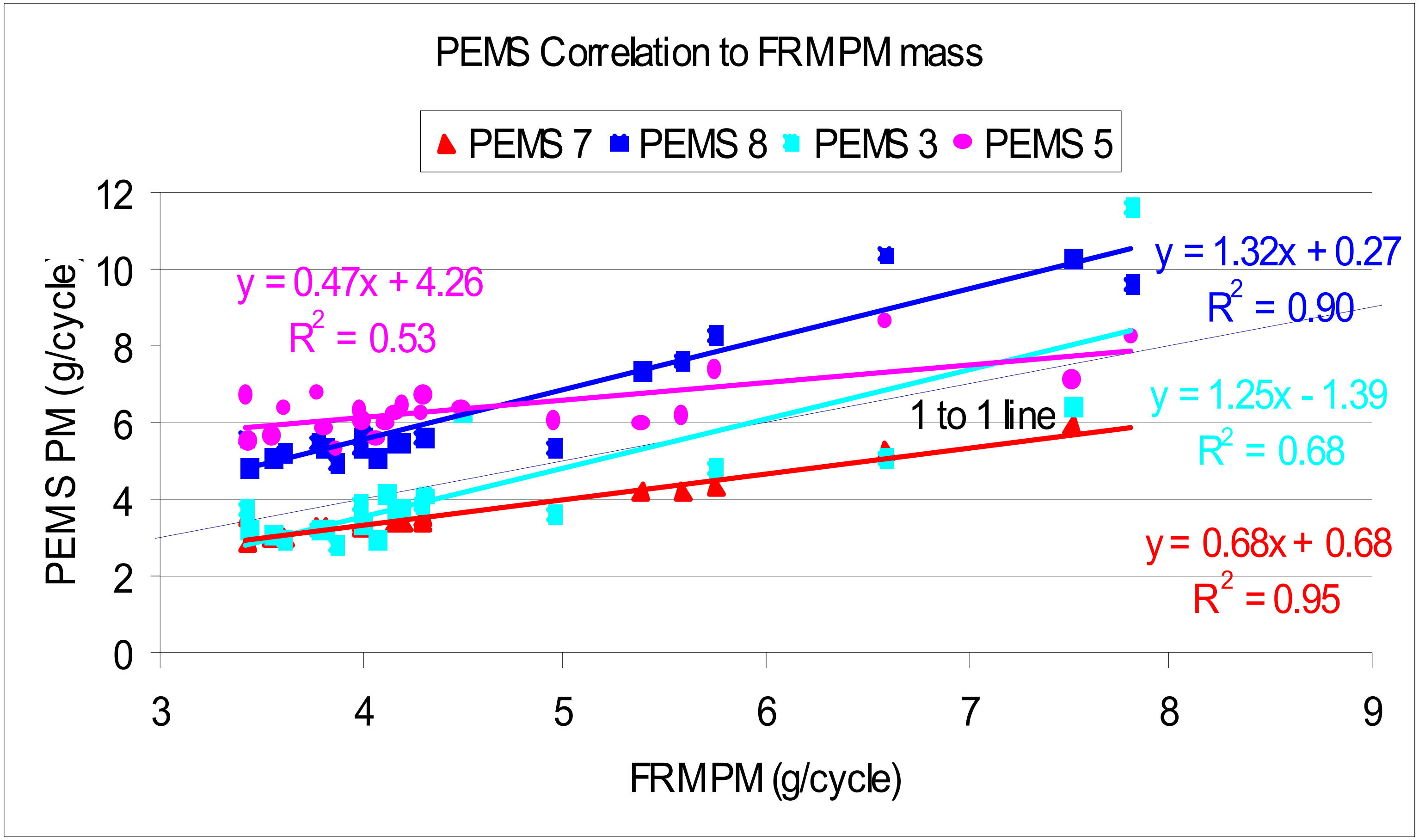




Chassis PM emissions



PM Emissions Correlation



Summary Phase 1 - gases

- NO_x emissions
  - The results differed significantly depending on the PEMS
  - BUGs – the best PEMS showed agreement within 10% of the MEL, with others showed much larger deviations
  - Chassis – the best PEMS was approximately 5-15% higher than the MEL. Larger deviations were PEMS over either the integrated cycles or NTE event data
- CO_2 emissions
  - The results differed significantly depending on the PEMS
  - BUGs/Chassis – the best PEMS showed agreement within ~5% of the MEL; others showed much larger deviations

Summary Phase 1 – gases – continued

- CO and THC emissions
  - CO and THC emissions were relatively low for both BUG and chassis testing compared to the applicable emissions standard
  - On a relative basis, the CO and THC showed larger deviations from the MEL than NO_x or CO_2
  - For the BUG testing, the HC deviations were ~15% for the best performing PEMS, and in the range of 40-160% for the other PEMS in comparison with the NTE standard
  - For the BUG testing, the THC deviations were generally less than 5% for the best performing PEMS
- Some gaseous measurements are in reasonable agreement, while others still need work

Summary Phase 1 - PM

- The results for PM are more ambiguous, complicated by the fact that PM is operationally defined, and its composition changes as a function of engine load
- For the BUG PM measurements, both instruments were biased low vs. MEL, with the best measurements ~20% lower.
- For the chassis testing, two instruments showed either a high or low bias vs. MEL but good $R^2>0.9$
- For the chassis testing, the correlations for the other instruments were lower $R^2 > 0.52$ and 0.68, with one showing a high bias and the other showing no bias

Summary Phase 1 – PM continued

- This assumes that the reference method provides an accurate quantification of ICE combustion PM (?)
- For 2007+, changes in PM mass and composition will further complicate matters
- The results from this project (and others, e.g., E-66) suggest that more research and coordination is needed to more systematically define and specify important PM measurement parameters

Phase 2 – Measurement Allowance On-Road Validation - Background

- Need an allowance on regulated emission measurement uncertainty
- Measurement Allowance is defined from

  "The difference between a federal reference method (such as SwRi and/or CE-CERT) and a portable emissions measurement system (PEMs) over all operating conditions."
- NO_x measurements drove the allowance program.
- 2007 NO_x certification standard is 0.2 g/bhp-hr
  - Phase in allowance ~ 50% of sales by 2007 and 100% by 2010
  - In-Use allowance ~1.5 times standard
  - Age allowance ~0.2 g/bhp-hr
  - ***Measurement allowance ~x.x g/bhp-hr***

Phase 2 – Measurement Allowance On-Road Validation - Background

- Steering Committee was formed
- This committee had two main tasks
  - Develop a Monte Carlo Model to statically examine errors from:
    - Testing and Model Development done at SwRI
    - The Environment (temperature, pressure, vibration, electrical interference)
    - Transient NTE emission
    - Steady state NTE emission
    - And others (flow, ECM signals…)
  - Validate the model with CE-CERT's MEL

Project Description – Phase 2

- CE-CERT's unique laboratory uses reference methods, and is a mobile laboratory that will provide real word PEMs deviations to validate the model
- MEL had to pass certain Audit tests to be part of the program:
  - CFR 40 part 1065 Audit (New for 2007)
  - SwRI back to back correlation (9 tests each)
    - 3% NO_x and 3% CO_2 deviations on transient cycles
    - Just over 1% deviation on fuel specific NO_x
  - Audit cal gas over all routes to verify no reference deviations
- PEMS tested on-road over three routes that stressed the NTE zones and environmental limitations.
- Focus on only a single PEMS, Semtech DS

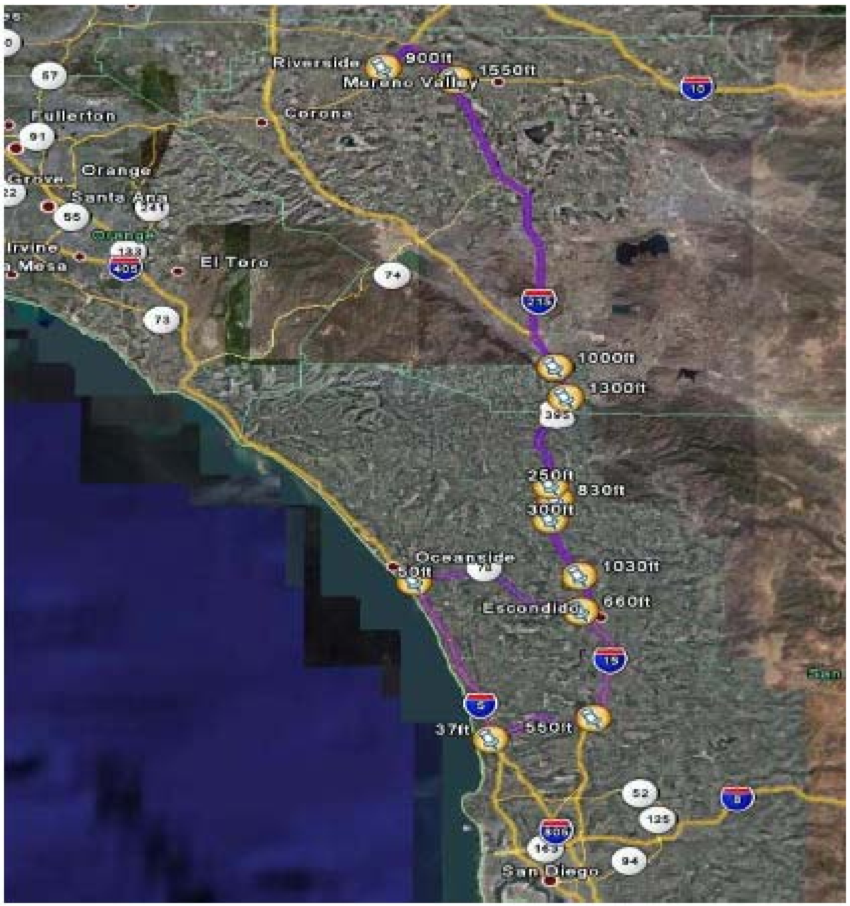
Test Set-up

Inside Cab

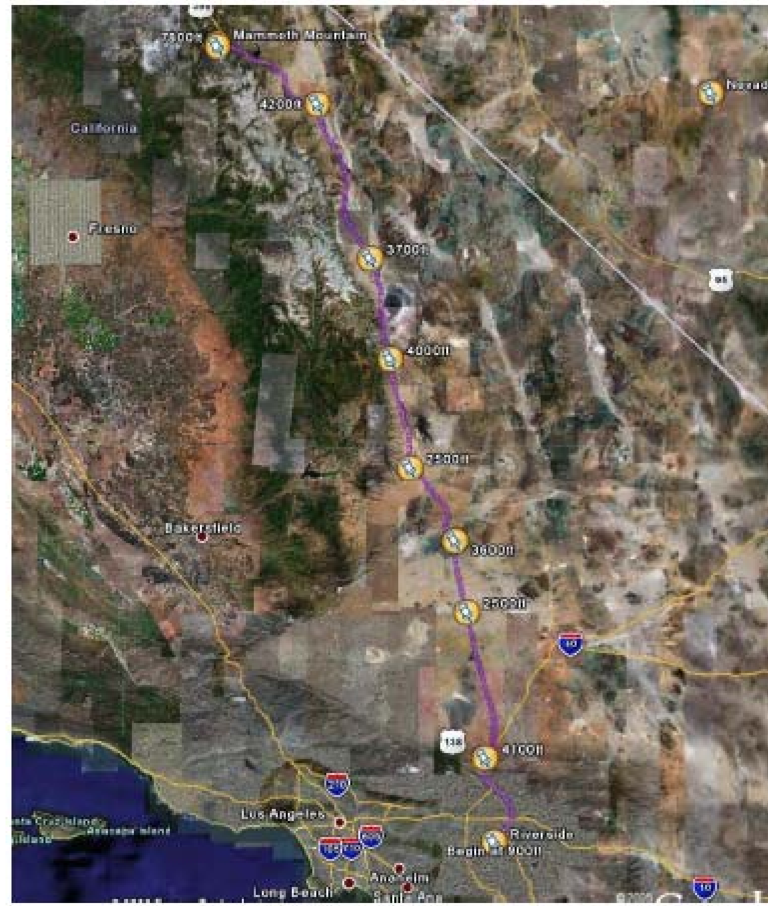
Outside Cab

Test Routes

Riverside to San Diego



Riverside to Mammoth



Emission Factor Calculation Methods

Brake Specific

$$Method\,1 = \frac{\sum g}{\sum Work}$$

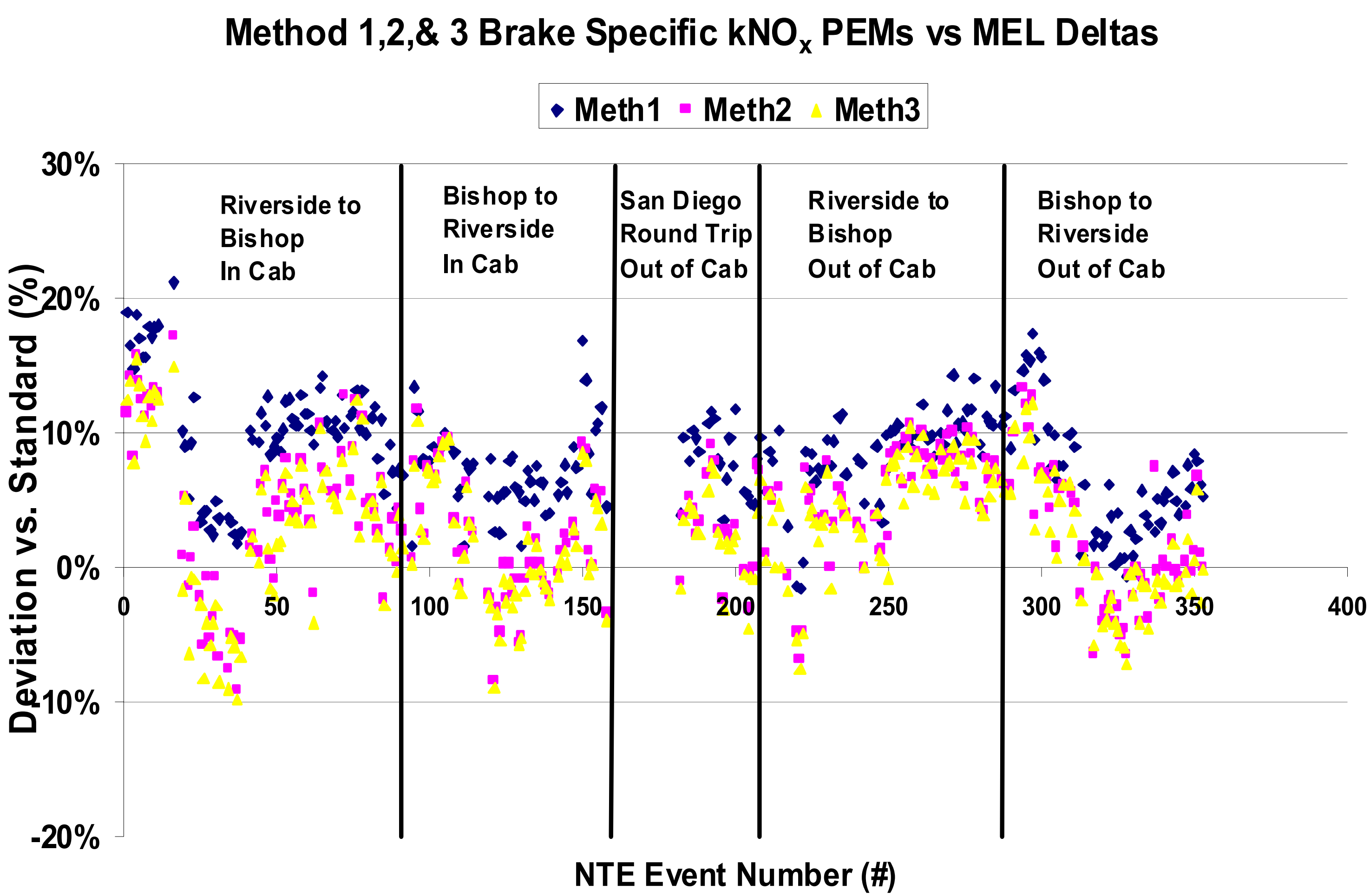
Fuel Specific

$$Method\,2 = \frac{\sum g}{\sum \left[\frac{CO_2\ fuel}{ECM\ fuel} \times Work \right]}$$

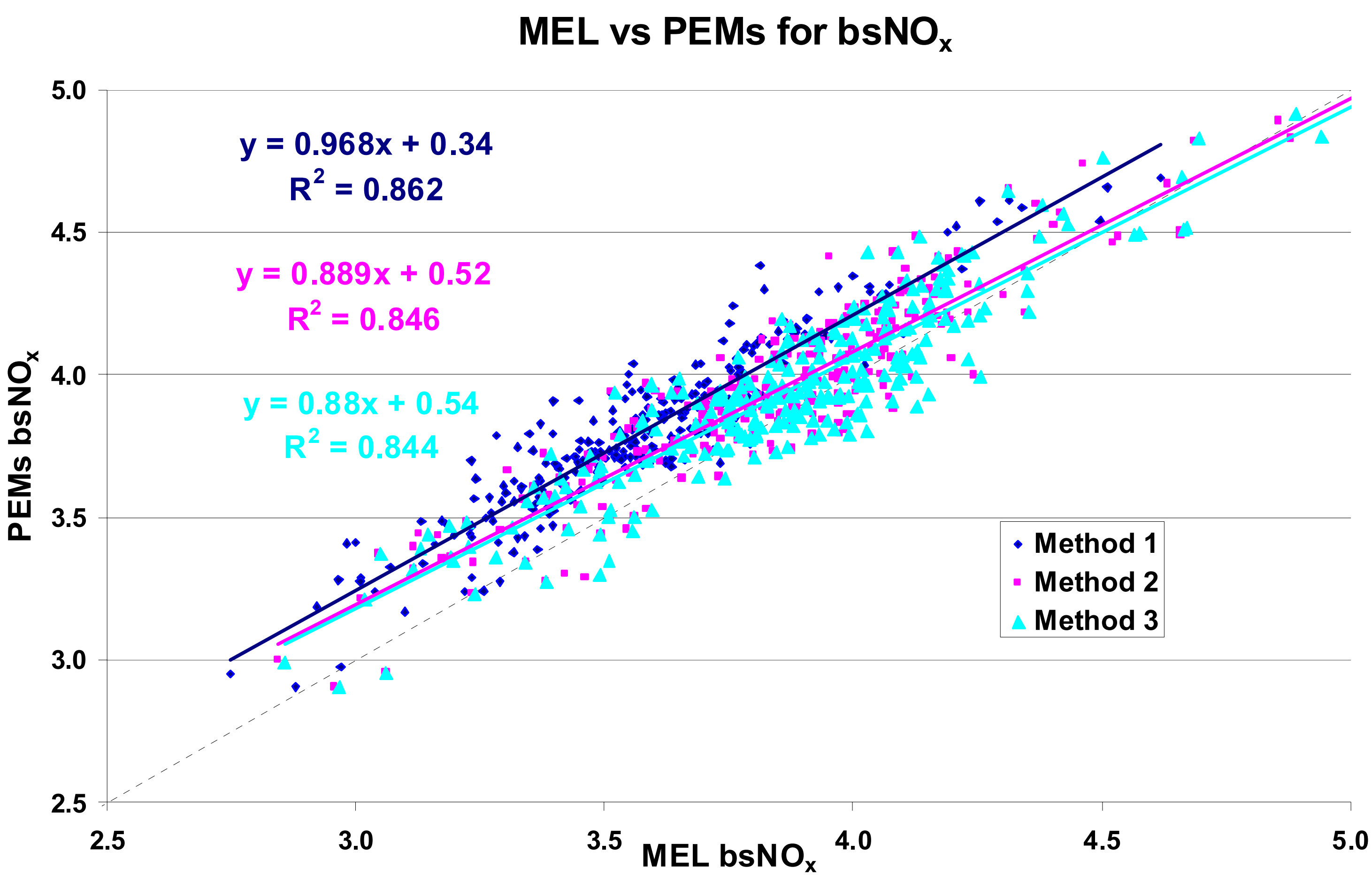
$$Method\,3 = \frac{\sum \left[g \times \frac{ECM\ fuel}{CO_2\ fuel} \right]}{\sum Work}$$

Work = (act_torq - fric_torq)*ref_torq

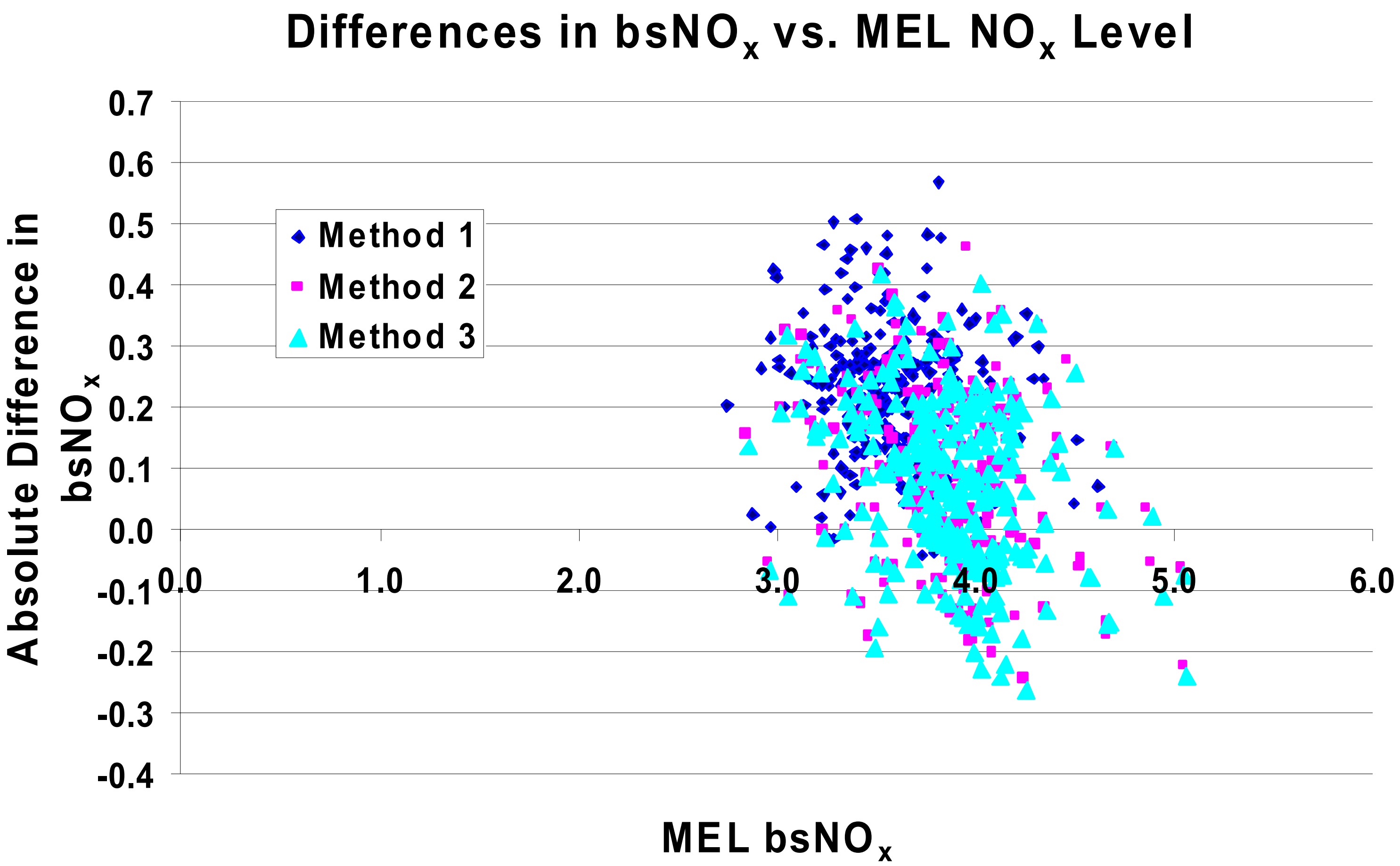
Results NO_x Deltas (FRM-PEMs)/Standard



NO_x Correlation



NO_x Absolute Deviations



Final HDIUT Measurement Allowance Values by Model Year

Pollutant	2007 – 2009 Model Year	2010 and Subsequent Model Year
NO_x	0.45	0.15
NMHC	0.02	0.01
CO	0.50	0.25

1. Grams per brake-horsepower-hour

- Values were established using engine testing, environmental testing, Monte Carlo Modeling and on-road data from this study
- Initially modeling validated for only Method 1 for NO_x
- EPA & CARB worked with SwRI on additional testing and modeling to validate the other two methods
- In discussions with EPA, CARB, and EMA it was agreed that
  - The initial values would be used for 2007 to 2009
  - The new more stringent values would be used for 2010+

Acknowledgements

- Funding by CARB (EPA and EMA for Phase 2)
- PEMS providers
  - Artium
  - AVL
  - Clean Air Technologies, Inc.
  - Engine, Fuels and Emissions Engineering
  - Horiba
  - Sensors, Inc.
- Caterpillar Engine Company – truck loan
- ARB Heavy-Duty Vehicle Laboratory
- Measurement Allowance Steering Committee

Thank You & Questions?