Update on the PM-PEMS Measurement Allowance Program in the US

by

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Heavy-duty on-highway diesel engine manufacturers are required to demonstrate compliance with US EPA in-use not-to-exceed (NTE) regulated pollutants emissions limits using portable emissions measurement systems (PEMS). However, prior to enforcing such ruling, it was agreed that both EPA and the Engine Manufacturers Association (EMA) will investigate the performance of PEMS, and will establish an additional margin or measurement allowance (MA), if any, to the existing NTE threshold limit to account for PEMS inaccuracy in the field. In 2007, a program on gaseous PEMS was completed by SwRI, and the focus now is on particulate matter (PM) PEMS.

The objective of the PM-PEMS-MA project is to investigate the performance of several PM-PEMS with that of the filter-based laboratory method in order to determine a bias in PM emissions between the two methods using steady-state and NTE laboratory testing. In addition, the PM-PEMS will be subjected to changes in environmental conditions, shock and vibration profiles, and electromagnetic interferences in order to determine the error or bias associated with such changes.

Using many error surfaces that may influence the PM-PEMS brake-specific PM emissions calculation, a Monte Carlo simulation will be developed to establish the 5^{th}, 50^{th}, and 95^{th} percentile in the PM emissions bias from that of an ideal performance (no errors) at more than 200 reference NTEs. Such computer prediction, based on laboratory generated data, will be validated by conducting field testing with the PM-PEMS onboard trucks. If the computer prediction is validated, and if the 95^{th} percentile measurement error is positive at the NTE threshold of 0.03 g/hp-hr for the year 2010, and 0.02 g/hp-hr for the year 2011 and beyond, then the NTE limit will become the NTE threshold plus the error or the measurement allowance. However, if the error is negative or zero, no measurement allowance will be added to the NTE limit.

The PM-PEMS-MA is sponsored by EPA, EMA, and CARB. The PM-PEMS suppliers are Sensors, Horiba, and AVL.

The presentation includes more detail about this program along the methodologies that will be used to evaluate the various PM-PEMS. This program is currently underway in its early stages. It is projected to be completed by June, 2009, along with a final report due before the end of December, 2009.

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Background

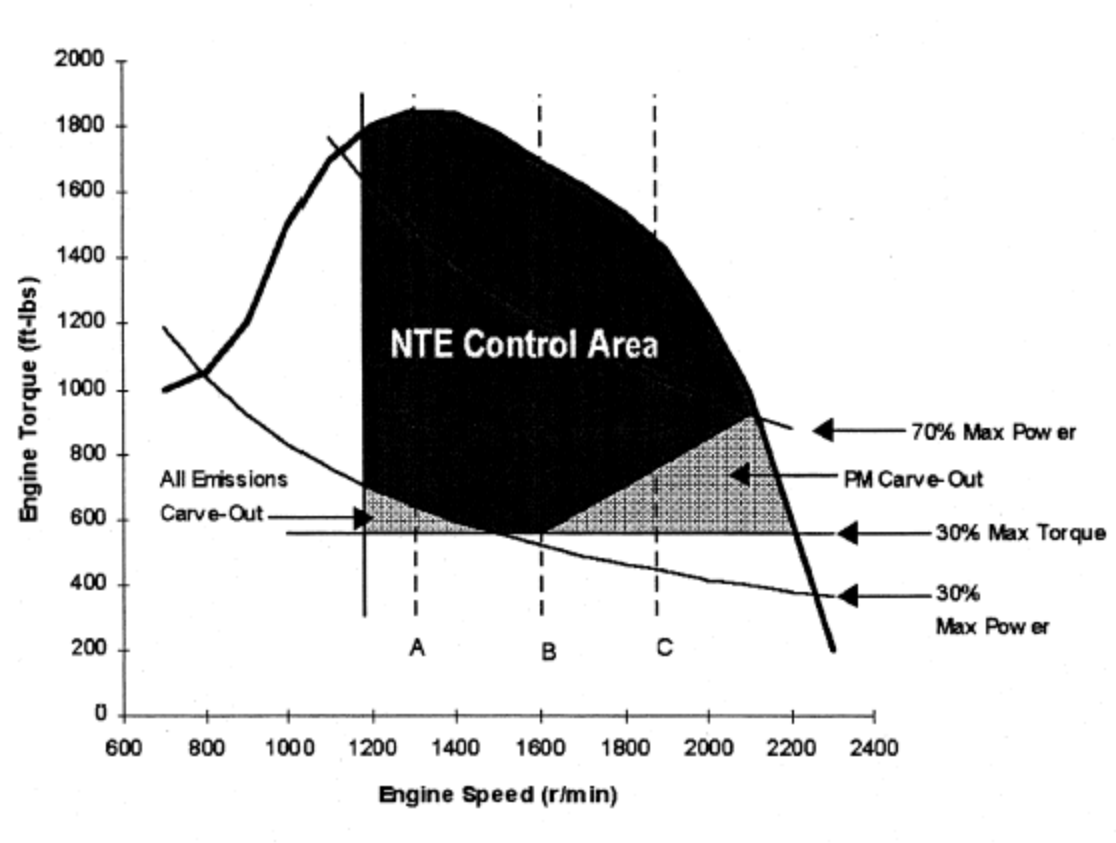
- The heavy-duty in-use (HDIU) regulation in the US requires the engine manufacturers to comply with:
  - In-use regulated emissions standard plus a measurement allowance in the "not to exceed" NTE zone
- EPA and EMA reached an agreement to develop a detailed data-driven process to establish a measurement allowance, before the regulation is enforced
- The gaseous measurement allowance was already established in 2007.
- The PM measurement allowance is currently underway

What is an NTE Zone?

- The NTE zone is a series of engine and environmental conditions defined for NTE emissions compliance:
  - Engine speed > 15 % > nlo +0.15(nhi-nlo)
  - Engine Torque > 30 % of peak engine torque
  - Engine Power > 30 % of engine rated power
  - Vehicle altitude < 1676 m
  - Ambient temperature < T(°F) = 100 - 0.00254xAltitude(feet) (38°C at Sea Level, 30°C at 1676 meters)
  - Coolant Temperature: T(°F) > (IMP+9.8889) ÷ 0.0778, Intake manifold pressure (IMP) in bar
  - For EGR engines only, IMT : **T(°F) > (IMP+7.75) ÷ 0.0875**
  - Exhaust Temperature > 250 °C, 12 inch downstream of DPF

  - <u>NTE event has to last for a period ≥ 30 seconds satisfying all above conditions to be valid.</u>

Engine Torque Map Example of an NTE area



Laboratory Limit = 0.01 g/hp-hr

NTE PM Limit = 0.03 g/hp-hr,

After 2011,

NTE PM Limit will be reduced to

0.02 g/hp-hr

What is the Measurement Allowance (MA)?

- Performance of a PM-PEMS are expected to be different than that of a laboratory system due to the difference in space requirements and applications
- The MA is a positive additive factor to the in-use emissions limit, or zero in case it is zero or negative
- The MA is derived based on a series of experimentally generated error surfaces using:
  - Steady-state and transient engine experiments
  - Shock and vibration
  - Electromagnetic interference (EMI) and radio frequency interference (RFI)
  - Temperature and Humidity Effects
  - Pressure Effects
- Experimental error surfaces are used in a Monte-Carlo simulation to determine the 5^{th}, 50^{th}, and 95^{th} percentile of the PM measurement allowance, which is defined as the ideal PM plus the sum of errors associated with different error surfaces
- Model to be validated by conducting a series of in-use testing experiments

PM-PEMS Requirement

- PM-PEMS are required to be independent systems capable of determining brake specific PM emissions from onboard on-highway heavy-duty trucks. Some of the basic requirements include:
  - Gravitational or inertial PM Mass measurement principles
  - Measurement of PM for valid NTE larger or equal to 30 seconds
  - Communication with engine control module (ECM) to determine an NTE zone by logging engine speed and torque
  - Exhaust flow measurement
  - Post Processing of data to determine brake specific emissions in valid NTE windows

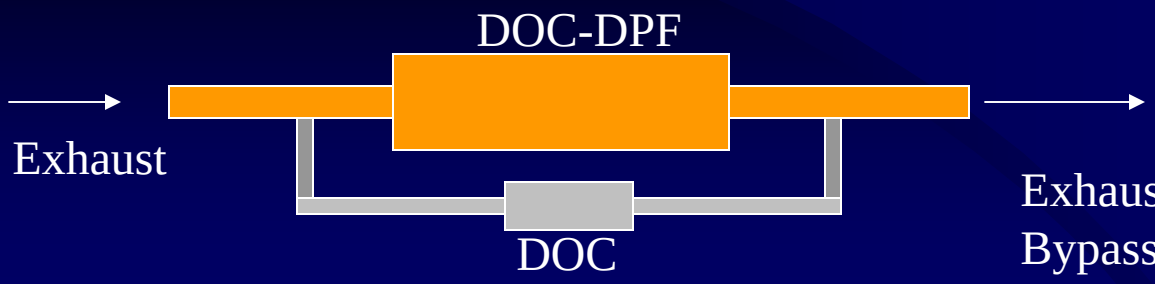
PM-PEMS Accepted for the MA program

- Horiba OBS-PM in conjunction with OBS-2200
  - Partial flow sampling system with a filter collection. (Integrated Sample)
  - TSI electrical aerosol detector (EAD). (second by second measurement)
  - Correlate EAD with filter measurement to determine PM concentration in NTE
  - If successful in the MA program, the system will require additional EPA approval before it can be used for in-use testing compliance. This system does not satisfy EPA fundamental requirement for measuring PM mass.
- Sensors PPMD in conjunction with Semtech-DS
  - Partial flow sampling system with a series of 8 quartz crystals microbalances. (Integrated Sample in NTE)
  - If successful in the MA, the system does not require additional EPA approval for in-use testing compliance because it meets the EPA fundamental requirement for measuring PM mass.
- AVL MSS in conjunction in with the Sensors Semtech-DS
  - MSS will be used in the program but will not be utilized in the MA
  - It requires an EPA approval to be used for in-use testing compliance in the US. This system does not meet the fundamental PM mass measurement requirement. In addition, it only measures the elemental carbon “soot” portion of PM

Engine Test Cell Along with the PM-PEMS

Engines and Exhaust Configuration

- Engines
  - 07 International 6.4 liter engine
    - Turbocharged
    - High-Pressure Loop, water cooled EGR
    - Active regeneration with post injection
  - 07 Volvo 11 liter engine
    - Turbocharged
    - High-Pressure Loop, water cooled EGR
    - Active regeneration with exhaust injection
- Exhaust Configurations
  - DPF out
  - DPF out plus bypass with DOC targeting 0.02 g/hp-hr in NTE zone
  - DPF out plus bypass with DOC targeting 0.03 g/hp-hr in NTE zone



Brake Specific Emissions Calculation Methods

- Method 1
  - BSPM = f(PM, $torque_{ECM}$, $speed_{ECM}$, exhaust flow)

$$e_{PM}\left(g/kW\cdot hr\right)=\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\sum_{i=1}^{N}\left[\frac{Speed_i\left(rpm\right)*T_i\left(N\cdot m\right)*2*3.14159*\Delta t}{60*1000*3600}\right]}$$

- Method 2, Method 3 (only applies to AVL)
  - BSPM = f(PM, exhaust flow, fuel-$flow_{ECM}$, gas-based fuel flow)

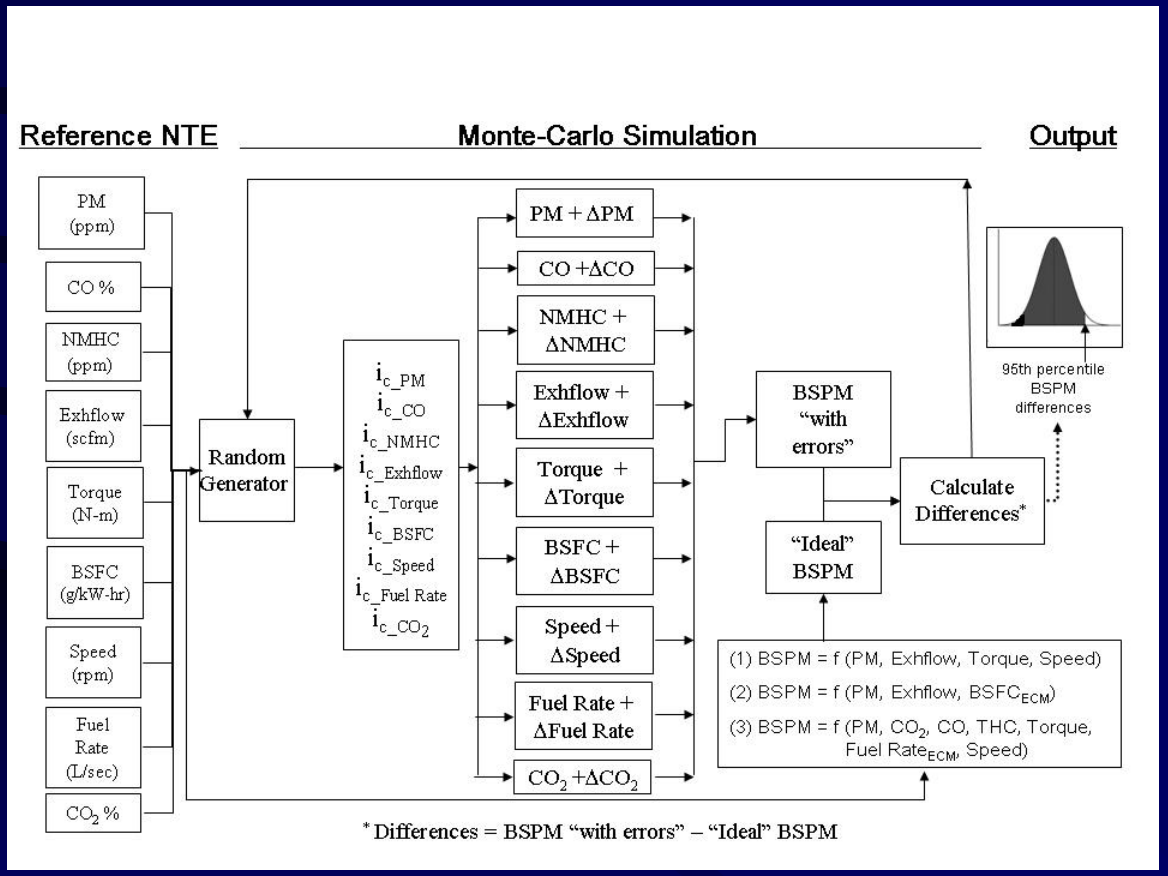
Method 2

$$e_{PM}\left(g/kW\cdot hr\right)=\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\frac{M_C}{w_{fuel}}*\sum_{i=1}^{N}\left[\frac{\dot{n}_i\left(\frac{mol}{s}\right)*\left[xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}\right]*\Delta t}{\left[\frac{\dot{m}_{fuel_i}\left(\frac{g}{s}\right)}{\frac{Speed_i\left(rpm\right)*T_i\left(N\cdot m\right)*2*3.14159}{60*1000*3600}}\right]}\right]}$$

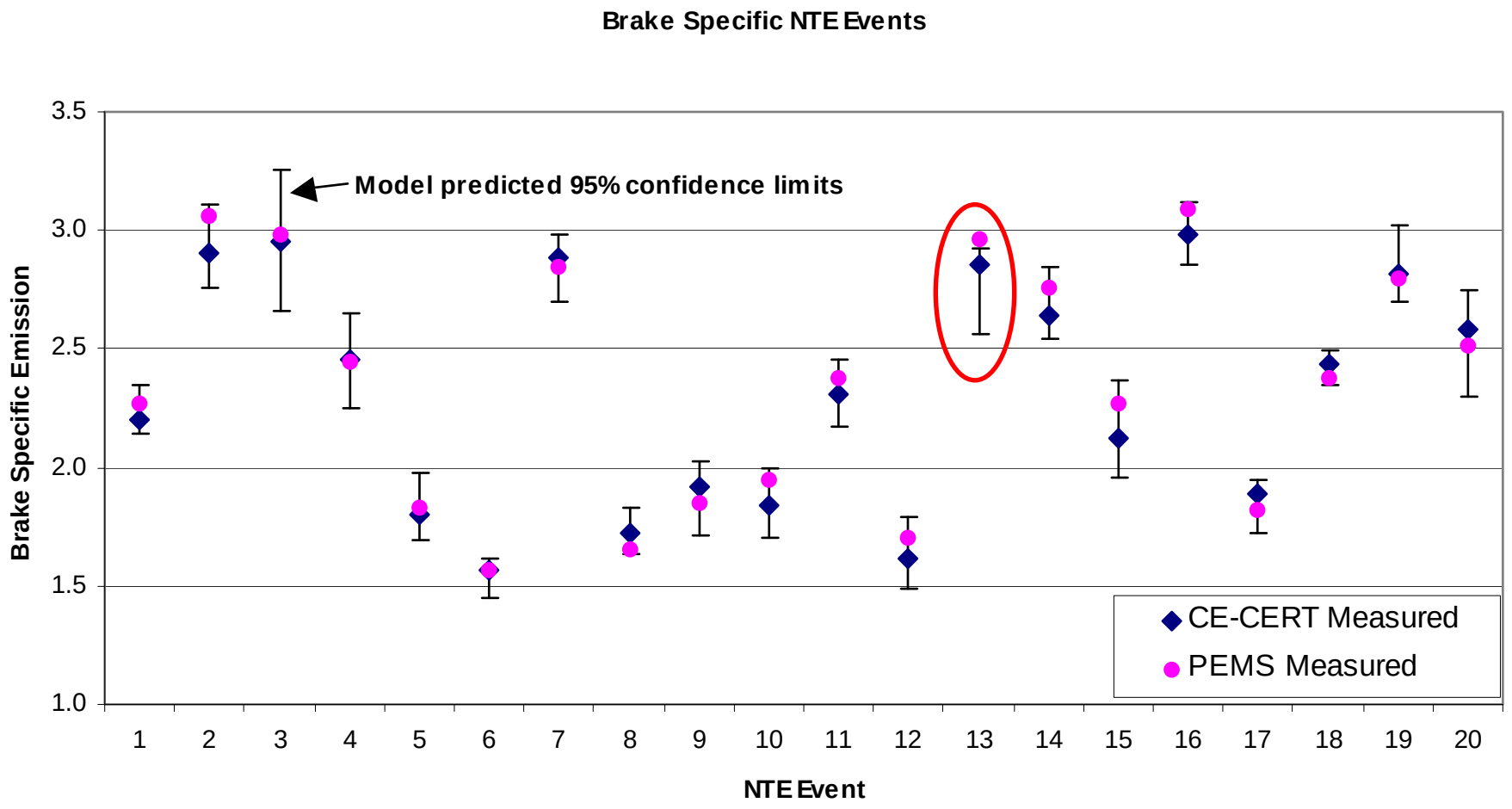
Method 3

$$e_{PM}\left(g/kW\cdot hr\right)=\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\frac{w_{fuel}}{M_C}*\sum_{i=1}^{N}\left[\frac{\dot{m}_{fuel}\left(\frac{g}{s}\right)}{xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}}*\Delta t\right]}{\sum_{i=1}^{N}\left[\frac{Speed_i\left(rpm\right)*T_i\left(N\cdot m\right)*2*3.14159*\Delta t}{60*1000*3600}\right]}$$

Example of a Monte-Carlo Simulation-Not All Surfaces Included



Example of Model Validation (Data not Real)



Timeline

- Engine Installation and PM-PEMS commissioning is currently underway
- Program is expected to be completed by late June, 2009.
- Final report is expected to be available before December 2009

Acknowledgements

- This work is supported by:
  - US Environmental Protection Agency (EPA)
  - California Air Resources Board (CARB)
  - Engine Manufacturers Association (EMA)

- A measurement allowance steering committee (MASC), representing EPA, CARB, and EMA meets on a monthly basis to discuss the progress of this project.