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

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Presented By:

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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)
  – 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

*Secondary Dilution System*

**Gas Sample Probe:**
- Temperature, Absolute Pressure, Throat $\Delta P$, Flow.

**Secondary Probe:**
- Temperature, Absolute Pressure, Throat $\Delta P$, Flow.

**CVS Turbine:** 1000-4000 SCFM, Variable Dilution.

**Diluted Exhaust:**
- Temperature, Absolute Pressure, Throat $\Delta P$, Flow.

**Dilution Air:**
- Temperature, Absolute Pressure, Throat $\Delta P$, Baro (Ambient), Flow, Dew Point (Ambient).

**Exhaust:**
- Temperature, $\Delta P$ (Exhaust-Ambient), Flow.

**Engine Broadcast:**
- Intake Temperature, Coolant Temperature, Boost Pressure, Baro Pressure, Vehicle Speed (mph), Engine Speed (rpm), Throttle Position, Load (% of rated).

**GPS:**
- Pat, Long, Elevation, # Satellite Precision.

**Other Sensor:**
- Dew Point, Ambient Temperature, Control room temperature, Ambient Baro, Trailer Speed (rpm), CVS Inlet Temperature.

**Gas Measurements:**
- $\text{CO}_2$ %, $\text{O}_2$ %, CO ppm, $\text{NO}_x$ ppm, THC ppm, $\text{CH}_4$ ppm.

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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.
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

Difference in Flow Rate Between FRM Method & PEMs

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BUG CO₂ emissions

CO₂ Emission Rates: PEMS Relative to FRM

-60 %  -50 %  -40 %  -30 %  -20 %  -10 %  0 %  5%  25%  65%  100%

PEMS1  PEM S2  PEMS3  PEMS4

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BUG NO$_x$ emissions

NO$_x$ Emission Rates: PEMS Relative to FRM

- PEMS 1: 12.5 g/hp-hr
- PEMS 2: 7.1 g/hp-hr
- PEMS 3: 6.7 g/hp-hr
- PEMS 4: 5.7 g/hp-hr

Load:
- 5%
- 25%
- 65%
- 100%
BUG PM emissions

PM Emission Rates: PEMS Relative to FRM

<table>
<thead>
<tr>
<th>Load</th>
<th>5%</th>
<th>25%</th>
<th>65%</th>
<th>100%</th>
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<tr>
<td>0.18 g/hp-hr</td>
<td>-100%</td>
<td>-90%</td>
<td>-80%</td>
<td>-70%</td>
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<td>0.12 g/hp-hr</td>
<td>-60%</td>
<td>-50%</td>
<td>-40%</td>
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<td>0.1 g/hp-hr</td>
<td>-20%</td>
<td>-10%</td>
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<td>5%</td>
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<td>1.2 g/hp-hr</td>
<td>5%</td>
<td>25%</td>
<td>65%</td>
<td>100%</td>
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</tbody>
</table>

PEMS1

PEMS3
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

![Torque vs. Engine Speed Graph]

NTE Control Area

![Power vs. Engine Speed Graph]

NTE Control Area

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NTE Cycles

NTE Steady State Cycle - 1770 RPM Run #1

- Vehicle Speed
- Torque J1939
- RPM

Time (sec)

Vehicle Speed (mph) and % Engine Load

Engine Speed (rpm)
Caterpillar HDT being tested
Chassis Exhaust Flow measurements

Exhaust Flow Rates - Integrated Cycles

- FRM
- PEMS1
- PEMS2
- PEMS4

Exhaust Flow (scfm)

0 100 200 300 400 500 600 700 800 900 1000

UDDS 50 MPH Cruise NTE 1290 NTE 1500 NTE 1770 NTE stepped

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Chassis CO$_2$ emissions

CO$_2$ Emissions

- FRM
- PEMS1
- PEMS2
- PEMS3
- PEMS4

Emissions (g/cycle)

- UDDS
- 50 MPH Cruise
- NTE 1290
- NTE 1500
- NTE 1770
- NTE stepped

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CO$_2$ Emissions Correlations

- $y = 1.0289x - 102.49$, $R^2 = 0.9991$
- $y = 1.1959x - 571.54$, $R^2 = 0.9949$
- $y = 1.1341x - 309.48$, $R^2 = 0.998$
- $y = 0.9128x - 1214.6$, $R^2 = 0.9274$

![Graph with four lines representing different PEMS emissions data points and their corresponding linear regression equations. Each line has a different $R^2$ value indicating the goodness of fit.](www.cert.ucr.edu)
Chassis NO$_x$ emissions

![Bar chart showing NO$_x$ emissions for different conditions and systems. The y-axis represents Emissions (g/cycle) ranging from 0 to 350, and the x-axis represents different test conditions and systems. The chart includes labels for UDDS, 50 MPH Cruise, NTE 1290, NTE 1500, NTE 1770, and NTE stepped. The chart also includes legend entries for FRM, PEMS1, PEMS2, PEMS3, and PEMS4.]
NO\textsubscript{x} Emissions Correlation

\begin{align*}
\text{FRM gNOx} & \quad \text{PEMS gNOx} \\
\cdot & \quad \bullet \quad \times \quad \triangle \quad \\
\text{PEMS1} & \quad \text{PEMS2} & \quad \text{PEMS3} & \quad \text{PEMS4}
\end{align*}

\begin{align*}
\text{y} &= 1.2452x + 2.8955 \\
R^2 &= 0.9699 \\
\text{y} &= 1.1502x + 2.1522 \\
R^2 &= 0.9933 \\
\text{y} &= 0.4267x - 13.049 \\
R^2 &= 0.9329 \\
\text{y} &= 1.0685x + 2.0734 \\
R^2 &= 0.9967
\end{align*}
Chassis NTE NO\textsubscript{x} emissions

Percentage Difference of NTE Standard NO\textsubscript{x} g/bhp-hr

Percentage Difference NO\textsubscript{x} g/gfuel
Chassis PM emissions

PM Emissions (g/cycle)

<table>
<thead>
<tr>
<th>Emissions (g/cycle)</th>
<th>FRM</th>
<th>PEMS 3</th>
<th>PEMS 5</th>
<th>PEMS 7</th>
<th>PEMS 8</th>
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<tbody>
<tr>
<td>0</td>
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<td>14</td>
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</table>

UDDS 50 MPH Cruise NTE 1290 NTE 1500 NTE 1770 NTE stepped
PM Emissions Correlation

PEMS Correlation to FRMPM mass

- \( y = 1.25x - 1.39 \) with \( R^2 = 0.68 \)
- \( y = 0.68x + 0.68 \) with \( R^2 = 0.95 \)
- \( y = 1.32x + 0.27 \) with \( R^2 = 0.90 \)
- \( y = 0.47x + 4.26 \) with \( R^2 = 0.53 \)
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\textsubscript{x} or CO\textsubscript{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

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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\textsubscript{x} measurements drove the allowance program.
- 2007 NO\textsubscript{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\textsubscript{x} and 3% CO\textsubscript{2} deviations on transient cycles
    • Just over 1% deviation on fuel specific NO\textsubscript{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 Routes

Riverside to San Diego  
Riverside to Mammoth
Emission Factor Calculation Methods

Brake Specific

Method 1 = \( \frac{\sum g}{\sum \text{Work}} \)

Fuel Specific

Method 2 = \( \frac{\sum g}{\sum \left[ \frac{\text{CO}_2 \text{fuel}}{\text{ECM fuel}} \times \text{Work} \right]} \)

Method 3 = \( \frac{\sum \left[ g \times \frac{\text{ECM fuel}}{\text{CO}_2 \text{fuel}} \right]}{\sum \text{Work}} \)

Work = (act_torq - fric_torq)*ref_torq

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Results NO$_x$ Deltas (FRM-PEMs)/Standard

Method 1, 2, & 3 Brake Specific kNO$_x$ PEMs vs MEL Deltas

- Meth1
- Meth2
- Meth3

NTE Event Number (#)

Deviation vs. Standard (%)
NO_x Correlation

MEL vs PEMs for bsNO_x

y = 0.968x + 0.34
R^2 = 0.862

y = 0.889x + 0.52
R^2 = 0.846

y = 0.88x + 0.54
R^2 = 0.844
NO\textsubscript{x} Absolute Deviations

Differences in bsNO\textsubscript{x} vs. MEL NO\textsubscript{x} Level
Final HDIUT Measurement Allowance Values by Model Year

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>2007 – 2009 Model Year</th>
<th>2010 and Subsequent Model Year</th>
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</thead>
<tbody>
<tr>
<td>NO(_x)</td>
<td>0.45</td>
<td>0.15</td>
</tr>
<tr>
<td>NMHC</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>CO</td>
<td>0.50</td>
<td>0.25</td>
</tr>
</tbody>
</table>

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+

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  – 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?