In-Use, On-Road Emissions Testing of Heavy-Duty Diesel Vehicles: Challenges and Opportunities

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NATIONAL RESEARCH CENTER FOR ALTERNATIVE TRANSPORTATION FUELS, ENGINES AND EMISSIONS
MOBILE EMISSIONS MEASUREMENT SYSTEM

Mack Truck
Purpose Of In-use Emissions Measurements

• COMPLIANCE
• I/M
• SCREENING
• INVENTORY
• TECHNOLOGY DEVELOPMENT AND/OR ASSESSMENT
Available Tools

- Engine Test Cells (Engine Recalls)
- Chassis Dynamometers
  - Fixed and Transportable Chassis Dynamometers
- On-road, On-board Emission Measurement Systems
Testing An Urban Transit Bus

(WVU Transportable Heavy-duty Vehicle Emissions Testing Laboratory)
Need For On-board Emissions Measurement Systems

- Real-world, on-road emissions are very different from in-laboratory emissions
- Engine certification cycles are not representative of in-use, on-road operation
  - Federal Test Procedure (FTP)
  - Urban Dynamometer Driving Schedule (UDDS)
- FTP and UDDS were developed by studying traffic patterns in New York and Los Angeles during the 1970s
- Traffic patterns have changed over the years.
- Different chassis dynamometer cycles yield very different emissions results
Challenges to Measurement of On-board, On-road Diesel Emissions

- Torque (or percent load) broadcast
- Instrumentation
  - Portability; Bulk
- Obsession with brake-specific emissions
  - It is recognized that the FTP (brake-specific emissions) is essential
  - However, In-use fuel-specific emissions would eliminate majority of challenges associated with brake-specific emissions measurements
Prior Art in Portable In-field Measurements

- Caterpillar (Englund, 1982)
- SwRI (Human and Ullman, 1992)
- General Motors (Kelly and Groblicki, 1993)
- Ford Motor Company, 1994
- U.S. Coast Guard, 1997
- Flemish Institute for Technology Research, VITO, (Since 1991; de Vlieger, 1997)
In-Use Emissions Work at WVU Related to Consent Decrees

- **PHASE I:** DEVELOPMENT OF A STATE-OF-THE-ART MOBILE EMISSIONS MEASUREMENT SYSTEM FOR ON-BOARD, IN-USE HEAVY-DUTY VEHICLE APPLICATIONS
- **PHASE II:** DEVELOPMENT OF IN-USE EMISSIONS TESTING PROCEDURES, AND TEST ROUTES
- **PHASE III:** CONDUCT EMISSIONS TESTING ON A VARIETY OF IN-SERVICE DIESEL ENGINES USING THE WVU MOBILE EMISSIONS MEASUREMENT SYSTEM (MEMS) TO CHARACTERIZE REAL-WORLD EMISSIONS FROM SUCH ENGINES
In-Use Emissions Work at WVU
Related to Consent Decrees (…Cont’d)

• PHASE IV: CONDUCT ON-ROAD COMPLIANCE MONITORING OF HEAVY-DUTY DIESEL VEHICLES USING THE MONITORING TECHNOLOGY, AND PREVIOUSLY DEFINED TESTING PROCEDURES (AND DRIVING ROUTES) DEVELOPED BY WVU, AND APPROVED BY THE US EPA.
Mobile Emissions Measurement System
(MEMS)
MEMS Sampling and Emissions Analysis System
Mobile Emissions Measurement System

Flow
- Annubar
- Differential Pressure Transducer
- Absolute Pressure Transducer
- Thermocouples

Emissions
- Solid State NDIR for CO₂
- Zirconium Oxide Sensor for NOx
- NO₂ Converter
- Thermoelectric Chiller
- Heated Sampling System

Engine Power
- ECU Protocol Adaptor
- Serial Interface to DAS
Mobile Emissions Measurement System

GPS
  Differential
  Serial or Analog Interface to DAS

Ambient Sensors
  Absolute Pressure Transducer
  Relative Humidity
  Thermocouple

System Integration
  National Instruments PXI-1025 Chassis; PC-104 Serial Interface Card
  64 Analog Channels
  Expandable to 256+ Analog Channels
  Visual Basic Interface Environment
V-Cone®

No straight pipe runs

“Pre-conditions” the flow

Accuracy to +/- 0.5%

Repeatability to 0.1%

Low headloss

Low maintenance

No recalibration
V-Cone®
CO$_2$ Mass Emission Rates Using V-Cone® and Annubar®

(DDC Series 60, MY2000)
Solid State NDIR Sensor - Response to SF₆

The signal to noise ratio for these deflections indicates a sensitivity limit of ~3 ppm for SF₆ when the system response time is 1 second. Averaging over 5-10 seconds should improve sensitivity to better than 1 ppm.

Source: Ion-Optics, Inc.
Percentage of NO₂ Reported by Zirconia Sensor

<table>
<thead>
<tr>
<th>NO₂ Concentration (ppm) before NOₓ Converter</th>
<th>Percent of NO₂ after Converter Reported by MEXA-120</th>
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<tbody>
<tr>
<td>62</td>
<td>-</td>
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<tr>
<td>124</td>
<td>70</td>
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<td>558</td>
<td>62</td>
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<tr>
<td>620</td>
<td>58</td>
</tr>
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</table>
Effect of Sampling Lines on NOx Measurements

- DD60 Series Engine
- Heated Stainless Steel Line
- Cold Teflon Line
- Heated Filter
- NOx Converter
- Dryer
- Fourier Transform Infrared Spectrometer Analyzer
Effect of Sampling Lines on NOx Measurements

A. Heated line
B. Heated line + Converter + Dryer + Heated line
C. Heated line + Converter + Dryer + Teflon line
D. Heated line + Converter + Teflon line
Comparison of Concentrations Reported by the 955 NO\textsubscript{x} Analyzer with Wet and Dry Exhaust Samples from a Mack E7-400 Engine

Cycle Integrated Percent Difference with Chiller: =8.5%
**NO\textsubscript{x} Index**

grams of NO\textsubscript{x} / kg of Fuel

- NO\textsubscript{x} concentration
- CO\textsubscript{2} concentration
- Fuel H:C ratio

\[
\frac{\text{Concentration of NO}\textsubscript{x}}{\text{Exhaust flow rate}} \times \text{MW}_{\text{NO}\textsubscript{x}}
\]

\[
\frac{\text{Concentration of CO}_2}{\text{Exhaust flow rate}} \times (12.011 + 1.008 \times (\text{H:C}))
\]
NO\textsubscript{x}/ NH\textsubscript{3} Zirconia Sensor

Exhaust gas

NO\textsubscript{x} = a (ppm)
NH\textsubscript{3} = b (ppm)

NH\textsubscript{3} Oxidation

Output: A (ppm)
A = a + b

NH\textsubscript{3} Sensor

NO\textsubscript{x} deNO\textsubscript{x}

Output: B (ppm)
B = a – b
(Here, a > b)

NO\textsubscript{x} Sensor

NO\textsubscript{x} = (A+B)/2
NH\textsubscript{3} = (A-B)/2

Sensor-on-a-Chip

Source driver

Source temperature

Source emission

Dual wavelength source/detector

Detector response

Gas attenuation

Optical efficiency

Source: Ion-Optics, Inc.
Real-Time Particulate Mass Monitor

*MARI* Model RPM 100®

Sample Conditioning System and a Microbalance

Dilution Ratios – 1:12 to 1:2000
Crystal Surfaces
Continuous TPM Measured with *MARI MODEL RPM 100®*

TPM Trace vs. Power: FTP Cycle
TPM Trace over the Transient Portion (Sinusoidally Varying) of a Customized Engine Cycle
ECU Derived Engine Torque

Function of: Lug Curve
Friction Torque (Zero Fueling Curve or Zero Flywheel (Zero Output Shaft Load) Percent Load Curve

WVU Approach:

Measure the no-load percent load through the speed domain at the curb and employ the lug curve obtained through laboratory testing or from manufacturer-supplied data.

\[ T^{rpm}(t) = \left( \frac{ECU^{rpm}\% - ECU^{rpm\% \text{ no load}}}{ECU^{rpm\% \text{ max}} - ECU^{rpm\% \text{ no load}}} \right) \times T^{rpm}_{\text{max}} \]
Shaft Torque and ECU Percent Load Variation for a Modern Electronically Controlled Engine

![Graph showing shaft torque and ECU percent load variation as a function of engine speed.](image-url)
Error in the Inferred Torque Due to an Error in Measured Percent Load

![Graph showing the relationship between Percent Load (%) and Error in Torque Value (%). The graph includes curves for different deviation levels: 14% Idle Point, -2% Deviation, -1% Deviation, 0% Deviation, 1% Deviation, and 2% Deviation. The x-axis represents Percent Load (%) ranging from 0 to 100, and the y-axis represents Error in Torque Value (%) ranging from -10 to 0. The curves show how the error in the inferred torque changes with different levels of deviation and percent load.]
Error in the Inferred Torque Due to an Error in No-Load ECU Load Reading

![Graph showing the relationship between percent load and error in torque value. The graph includes lines for 14% idle point and various deviations (-3%, -2%, -1%, 0%, 1%, 2%, 3%). The x-axis represents percent load, and the y-axis represents error in torque value. The graph visually illustrates how different load percentages affect the inferred torque with various deviation levels.]
Integrated 30 Second Brake Power Windows Between Laboratory and ECU Inferred Data for a Modern Diesel Engine Exercised Through the FTP Cycle (600 to 1000 Seconds)
Inferred Data for a Modern Diesel Engine Exercised through the FTP Cycle

Integrated 30 Second Brake Power Windows
Percent Difference Between Laboratory and ECU
TEST ENGINES

- **Mack E7-400**
  - 12 L, 400 hp, 1460 ft-lb torque

- **Cummins ISM-370**
  - 10.8 L, 370 hp, 1350 ft-lb torque

- **Navistar T444E**
  - 7.3 L, 210 hp, 520 ft-lb torque
NO\textsubscript{x} MASS EMISSION RATES ON FTP – REAL WORLD AND LABORATORY: CUMMINS ISM 370
## COMPARISON OF BRAKE SPECIFIC EMISSIONS
RESULTS FROM THE FTP TEST CELL AND MEMS

<table>
<thead>
<tr>
<th>FTP Cycle</th>
<th>CO$_2$ (g/bhp-hr)</th>
<th>NO$_x$ (g/bhp-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory</td>
<td>548.0</td>
<td>4.397</td>
</tr>
<tr>
<td>MEMS</td>
<td>524.0</td>
<td>4.389</td>
</tr>
<tr>
<td>Percent Difference</td>
<td>-4.39%</td>
<td>-0.18%</td>
</tr>
</tbody>
</table>
CHASSIS DYNAMOMETER TESTING

- Steady state testing was performed
- Vehicle speeds of 35, 45, and 55 mph
- Errors
  - MEMS CO$_2$ = -2.17%
  - MEMS MEXA-120 = -2.14%
ON-ROAD ROUTE DEVELOPMENT

- Four routes were developed to operate a heavy-duty Class 8 tractor throughout representative ranges of speed and load
  - **Morgantown Route**
    - Urban and highway operation
  - **Saltwell Route**
    - Highway operation
  - **Bruceton Mills Route**
    - Highway operation (mountainous terrain)
  - **Pittsburgh Route**
    - Urban and highway operation
CONCLUSIONS

• An on-board emissions measurement system is needed to measure brake specific emissions from vehicles during their in-use operation, since engine and chassis dynamometer cycles are not representative of real-world driving conditions.

• MEMS utilizes state-of-the-art technology to report emissions measurements.
  • Horiba BE-140 NDIR HC, CO, CO₂ analyzer; Horiba MEXA-120 NOx analyzer.
  • Horiba NOx converter, M&C Products thermoelectric chiller.

• MEMS is capable of reporting brake-specific emissions of CO₂ to within 3% and NOx to within 5% over an FTP cycle.

• WVU has developed routes have been developed to operate the engine of a heavy-duty vehicle through a wide range of speed and load combinations.

• It is anticipated that over the next couple of years in-use emissions measurement tools will be more compact, accurate, precise, rugged, and easy to use.