Measurement of Real-World Emissions from Heavy-Duty Diesel Vehicles: The State-of-the-Art

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NATIONAL RESEARCH CENTER FOR ALTERNATIVE TRANSPORTATION FUELS, ENGINES AND EMISSIONS
Purpose of In-use Emissions Measurements

• Technology Development and/or Assessment
• Enforcement
• Compliance
• I/M
• Screening
• Inventory
Available Tools

- Engine Test Cells
  - Simulated Routes
  - FTP

- Chassis Dynamometers

- On-road, On-board Emissions Measurement Systems
  - AEI, Columbus, IN
  - Horiba, Ann Arbor, MI
  - Sensors, Saline, MI
Challenges to Measurement of On-board, On-road Diesel Emissions

- False positives; Error minimization
- Torque (or percent load) broadcast
- Exhaust flowrate measurement
- Fuel quality variability
- Emissions characteristics from current and future engines/exhaust aftertreatment systems (NO, NO₂, OC dominated PM emissions)
- Current definition of particulate matter.

- 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 collecting brake-specific emissions in the field (application dependent)

- Instrumentation
  - Advances in systems development have not been fast enough
  - Portability; Bulk
In-Use Emissions Work at WVU Related to Consent Decrees

• PHASE I: DEVELOPED MOBILE EMISSIONS MEASUREMENT SYSTEM FOR ON-BOARD, IN-USE HEAVY-DUTY VEHICLE APPLICATIONS

• PHASE II: DEVELOPED IN-USE EMISSIONS TESTING PROCEDURES, AND TEST ROUTES

• PHASE III: CONDUCTED EMISSIONS TESTING ON A VARIETY OF IN-SERVICE DIESEL ENGINES (≤ MY1998) 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: CONDUCTING ON-ROAD COMPLIANCE MONITORING OF HEAVY-DUTY DIESEL VEHICLES (≥MY2002) 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)

- Exhaust Sampling and Conditioning
- Exhaust Constituents (NOx & CO₂)
- Differential Pressure, Absolute Pressure, and Temperature
- Engine Speed, Vehicle Speed, & Torque
- Flow Meter
- Engine Interface
- Vehicle Speed & Location
- GPS
- Ambient Sensors
-Ambient Temperature, Pressure, & Humidity
Mobile Emissions Measurement System
NO\textsubscript{X} MASS EMISSION RATES ON SAB2SW ROUTE – MEMS AND LABORATORY: CUMMINS ISM 370

![Graph showing NO\textsubscript{X} mass emission rates on SAB2SW route.](image-url)
## Comparison of Brake Specific Emissions Results from the FTP Test Cell and MEMS

<table>
<thead>
<tr>
<th>FTP Cycle</th>
<th>CO₂ (g/bhp-hr)</th>
<th>NOx (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>
Exhaust Stack Measurements
Current Status and Future Direction

- **CO₂**
  - Solid State NDIR
    - Current “garage-grade” NDIR microbenches have served the purpose
    - **New Direction** – “Sensor-on-a-chip” (a hot-bolometer). *Silicon microbridge elements with photonic bandgap modified surfaces.*

- **CO**
  - Improvements are needed to current solid-state “garage-grade” NDIR’s ability to measure low levels of CO from diesel engines
Sensor-on-a-Chip (NDIR)

Source driver

Source temperature

Source emission

Dual wavelength source/detector

Detector response

Gas attenuation

Optical efficiency
Current Status and Future Direction

• NOx

  – Zirconium oxide sensors
    • Results are better with a NOx converter.
    • Avoid using the sensor in the raw exhaust stream
  – Current “garage-grade” NDUV may not fully account for noise attenuation, interferences, lamp decay
  – New Direction – UV Resonance Absorption Spectroscopy
UV-Resonance Absorption Spectroscopy

- Simple photometer technology
- Excellent agreement with other standard methods
- No critical components:
  - Hot measurement, no chiller
  - Direct measurement of NO₂, no converter
  - No ozone generator, no vacuum pumps etc.
- Calibration with long-term stable, gas-filled calibration cells
- Simultaneous measurement of up to 3 gas components NO, NO₂, NH₃
Current Status and Future Direction

• **Total Hydrocarbons**
  – NDIR detectors are not recommended for diesel exhaust
  – Heated Flame Ionization Detectors serve well
  – *New Direction – Reduce the size and complexity of the FIDs. Systems are available, but prone to breakdowns*

• **Exhaust Flowrate**
  – Considering the system accuracy, turn-down ratio, meter drift, measurement frequency, response time, size and weight, robustness (including operation in harsh environments), low backpressure on the engine, etc.
    • Averaging pitot tubes (e.g. Annubar), the AEI system
    • Others:
      – Ultrasonic flowmeters (size/temperature limitations),
      – Hot-wires (response time limitations),
      – ECU based value (calculated value),
      – Intake measurements (system leaks, time delays, secondary air pump during cold start, positioning in the intake system)
Current Status and Future Direction

• Torque and Engine Speed
  – Engine Speed is an Accurate Measurement
  – Inference of Engine Power is Possible via Publicly Broadcast ECU Information
  – Engine Torque/Power Can Be Inferred to Within ±10% of Laboratory Measurements
    • Engine Maintenance History
    • Lug Curve
    • Accessory Loading
    • Ambient Conditions Limitation
    • Operate Within the NTE Zone
    • Use Good Engineering Judgment
Current Status and Future Direction

• Uncertainties associated with **Exhaust Flowrate** and **Torque** measurements can be avoided by **Fuel Specific Measurements**

• Only concentration measurements will be required
Brake Specific Emissions

\[
\frac{\text{NO}_x}{\text{CO}_2} = \frac{(\text{g/bhp-hr})_{\text{NO}_x}}{(\text{g/bhp-hr})_{\text{CO}_2}}
\]

\[
= \frac{(\text{Density}) \times (\text{Exhaust Mass Flow Rate}) \times (\text{Concentration})_{\text{NO}_x}}{\text{bhp-hr}}
\]

\[
= \frac{(\text{Density}) \times (\text{Exhaust Mass Flow Rate}) \times (\text{Concentration})_{\text{CO}_2}}{\text{bhp-hr}}
\]
**NOX Index**
*(Fuel Specific Emissions)*

grams of NOx / kg of Fuel

- NOx concentration
- CO₂ concentration
- Fuel H:C ratio

\[
\frac{(\text{Concentration of NOx}) \times (\text{Exhaust flow rate}) \times M_{\text{NOx}}}{(\text{Concentration of CO}_2) \times (\text{Exhaust flow rate}) \times (12.011 + 1.008 \times (\text{H:C}))}
\]
Engine Operation Over an On-road Route
NTE Zone: Engine Operation and Brake Specific NOx as a function of Engine Speed and Engine Load
3-D plot of Brake Specific NOx as a function of Engine Speed and Engine Load
Errors in Torque Broadcast
(Simulated SAB-to-BM Route)

[Graph showing engine load (ft-lb) over time (s) with various lines indicating different torques and % difference.]
Simulated SAB-to-BM Route – NTE Zone
Ratio of bsNOx/bsCO2 vs. Time

- Ratio from on-road data
- Ratio from FTP cycle

**Graph Details:**
- X-axis: Time (s)
- Y-axis: Ratio of bsNOx/bsCO2
- Data points and trend lines indicate variations in ratio over time.
Ratio of bsNOx/bsCO2 vs. Power

- Ratio on road
- Ratio from FTP cycle
- bsNOx
- Standard bsNOx

Power (hp) vs. Ratio (NOx/CO2) with data points indicating different power levels and ratio values.
In-use Particulate Matter Emissions

Major Challenge:

• Definition of particulate matter
• Current definition of particulate matter emissions is valid in a multi-million dollar brick-and-mortar engine/chassis dynamometer test cell
• EPA is hoping to demonstrate “equivalency” between portable PM instruments and test cell methods.
  – On integrated PM measurements
• Several years down the road unless definition of PM is modified.
Real-Time Particulate Mass Monitor (Quartz Crystal Microbalance)

- In-use, On-board applications (capable of handling severe vibrations)
- Test cell applications
- Ultra-clean (US EPA 2007 Standards) engines
- Older “dirty” engines
- Sample Conditioning System provides accurate dilution up to 1:2000
- NOx, CO₂, CO, HC
- CAN network communication & RS232, GPS
Continuous TPM Measured with TPM Trace vs. Power: FTP Cycle
The RPM-100 (QCM) in a Backpack and on a Caterpillar D11 Dozer with a 3508 V-8
Gravimetric PM Comparisons Between the RPM-100 and the Full-flow Dilution Tunnel

<table>
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<tr>
<th></th>
<th>Test 01</th>
<th>Test 02</th>
<th>Test 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARI RPM 100 Integrated PM Mass</td>
<td>0.74</td>
<td>1.97</td>
<td>1.73</td>
</tr>
<tr>
<td>Full-Flow Dilution Tunnel Gravimetric Integrated PM Mass</td>
<td>0.71</td>
<td>1.75</td>
<td>1.79</td>
</tr>
<tr>
<td>Percent Difference</td>
<td>4.2%</td>
<td>12.6%</td>
<td>-3.4%</td>
</tr>
</tbody>
</table>

Note: The RPM-100 sampled from the raw exhaust stream. The resultant error includes all sources of errors in the emissions measurement systems (exhaust flow rate; concentration; data acquisition; etc.)
Conclusions

• Re-visit the definition of particulate matter
• Give serious consideration to fuel-specific emissions measurements
• Move all on-board emissions measurement systems out of the truck cab and onto the exhaust stack – make accurate and precise measurements more vehicle driver/owner friendly.
• New, accurate sensors are available
• Need to focus on measurement of emissions (species and concentrations), which will be encountered in 2007.
The End

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Engine Speed Histogram for the Candidate Routes
Mack CH Tractor and Trailer
With a Nominal 60,000 lbs GVW

<table>
<thead>
<tr>
<th>Route</th>
<th>Percentage of Time (%)</th>
</tr>
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<tbody>
<tr>
<td>SAB2SAB</td>
<td>16.22 1.69 1.49 3.42 12.86 24.30 31.43 8.59</td>
</tr>
<tr>
<td>SAB2SW</td>
<td>9.99 1.23 1.80 1.14 5.81 21.95 43.17 14.90</td>
</tr>
<tr>
<td>SW2SAB</td>
<td>10.50 1.97 3.34 2.20 7.19 14.42 45.40 14.98</td>
</tr>
<tr>
<td>SAB2BM</td>
<td>9.81 0.53 1.96 1.69 8.68 16.77 45.31 15.27</td>
</tr>
<tr>
<td>BM2SAB</td>
<td>10.86 1.83 1.51 2.20 10.31 18.48 32.86 21.93</td>
</tr>
<tr>
<td>WASHSPA1</td>
<td>17.04 1.87 2.12 3.79 12.35 28.13 25.14 9.57</td>
</tr>
<tr>
<td>WASHSPA2</td>
<td>20.46 2.87 3.40 4.14 10.79 30.78 19.10 8.45</td>
</tr>
<tr>
<td>WASHSPA3</td>
<td>4.36 0.56 0.89 0.87 7.84 35.04 45.44 4.99</td>
</tr>
</tbody>
</table>
ECU-Derived Engine Power Histogram for the Candidate Routes Mack CH Tractor and Trailer With a Nominal 60,000 lbs GVW
Inference of Engine Power

![Engine Performance Graph](image-url)

- **Shaft Torque (ft-lb)**
- **Engine Speed (rpm)**
- **ECU Percent Load (%)**

- **Lug Curve**
- **Percent Load**
- **Curb Idle Load**
- **Curb Idle Percent Load**
Results – Steady State Instantaneous Engine Speed and Torque

- Constant 1500 rpm
- 10 Second Period
- Torque Varied From 325 ft-lb to Maximum