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

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West Virginia University
Fuels, Engines, and Emissions Research

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, NO_2, 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

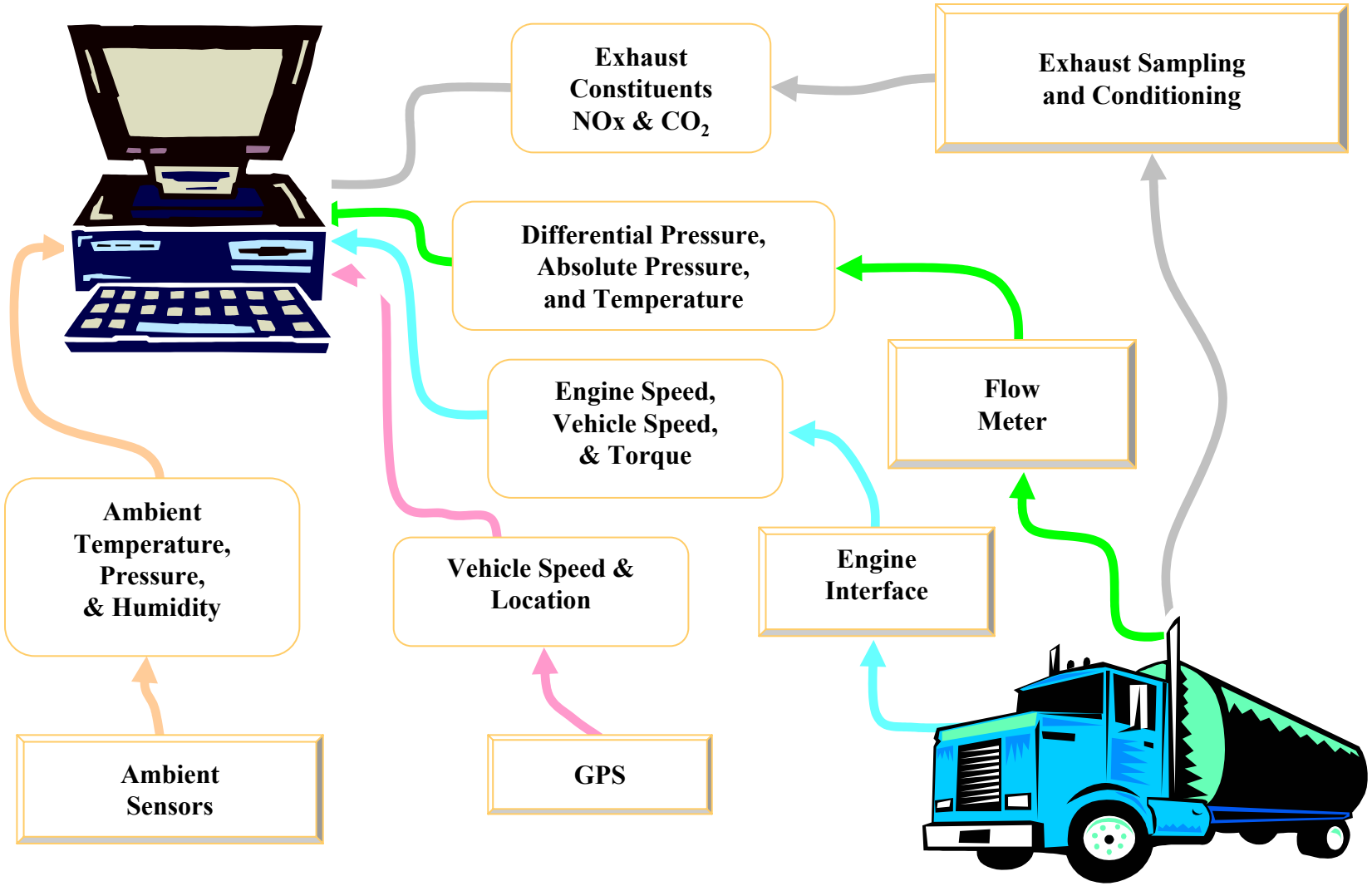
- **PHASE I: DEVELOPED MOBILE EMISSIONS MEASUREMENT SYSTEM FOR ON-BOARD, IN-USE HEAVY-DUTY VEHICLE APPLICATIONS**
- **PHASE II: DEVELOPED IN-USE EMISSIONS TESTING PROCEDURES, AND TEST ROUTES**
- **PHASE III: CONDUCTED EMISSIONS TESTING ON A VARIETY OF IN-SERVICE DIESEL ENGINES (≤MY1998) USING THE *WVU 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.**

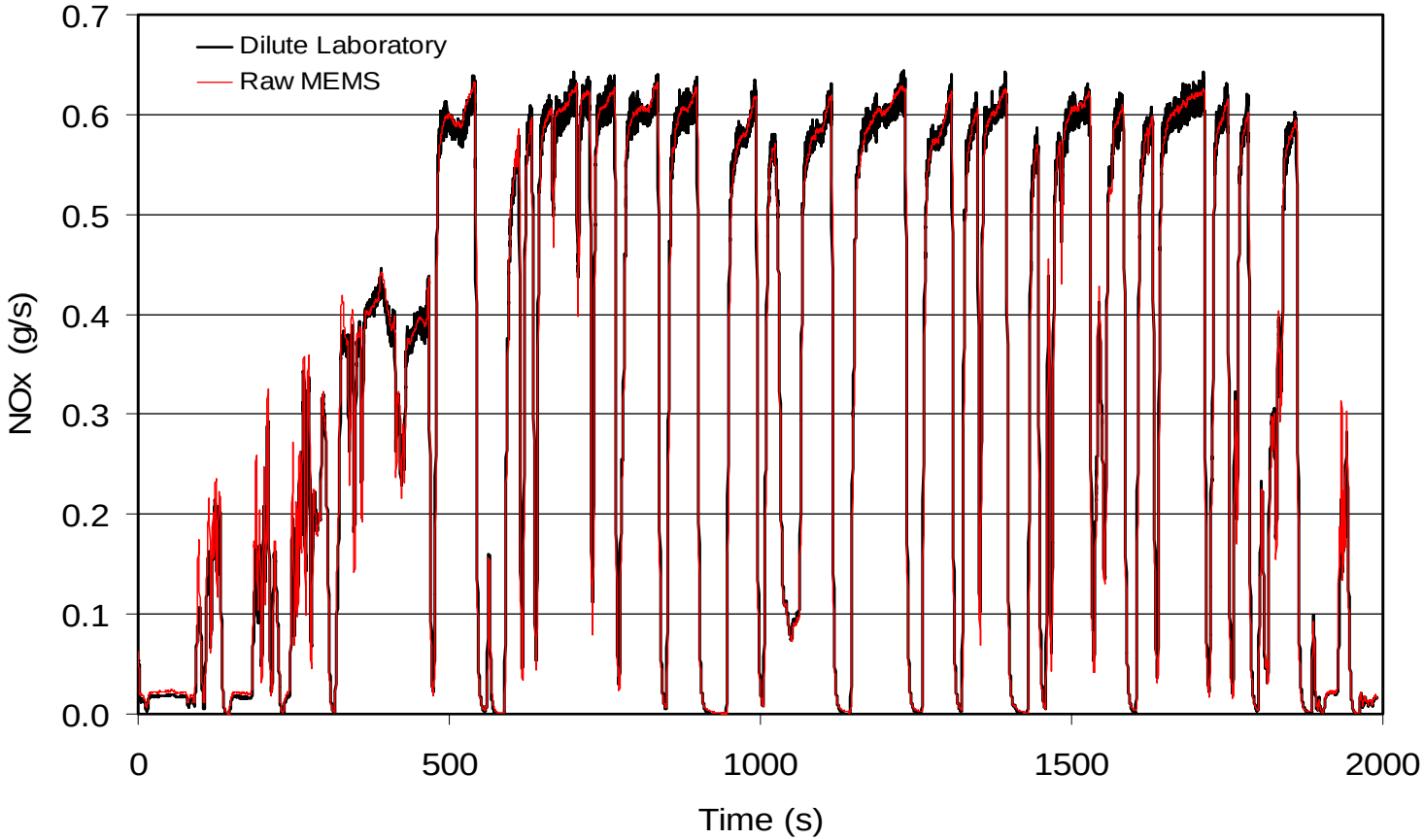
Mobile Emissions Measurement System

(MEMS)



Mobile Emissions Measurement System

NO_X MASS EMISSION RATES ON SAB2SW ROUTE – MEMS AND LABORATORY: CUMMINS ISM 370



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COMPARISON OF BRAKE SPECIFIC EMISSIONS RESULTS FROM THE FTP TEST CELL AND MEMS

FTP Cycle	CO_2 (g/bhp-hr)	NOx (g/bhp-hr)
Laboratory	548.0	4.397
MEMS	524.0	4.389
Percent Difference	-4.39%	-0.18%

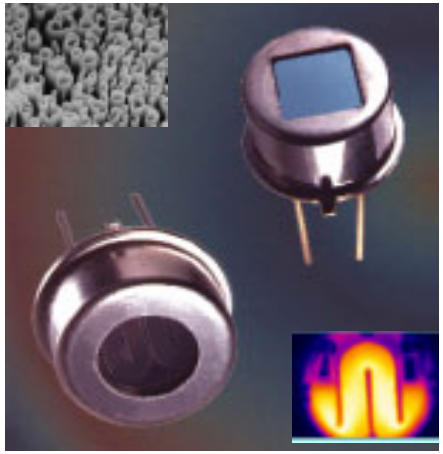
Exhaust Stack Measurements

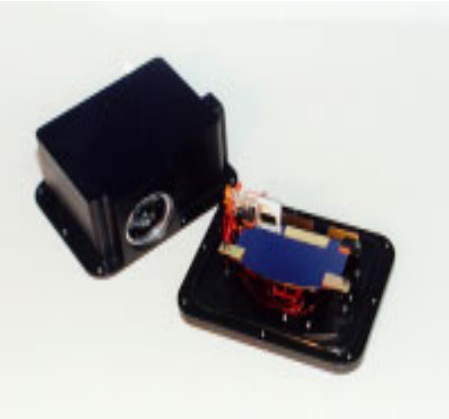
Current Status and Future Direction

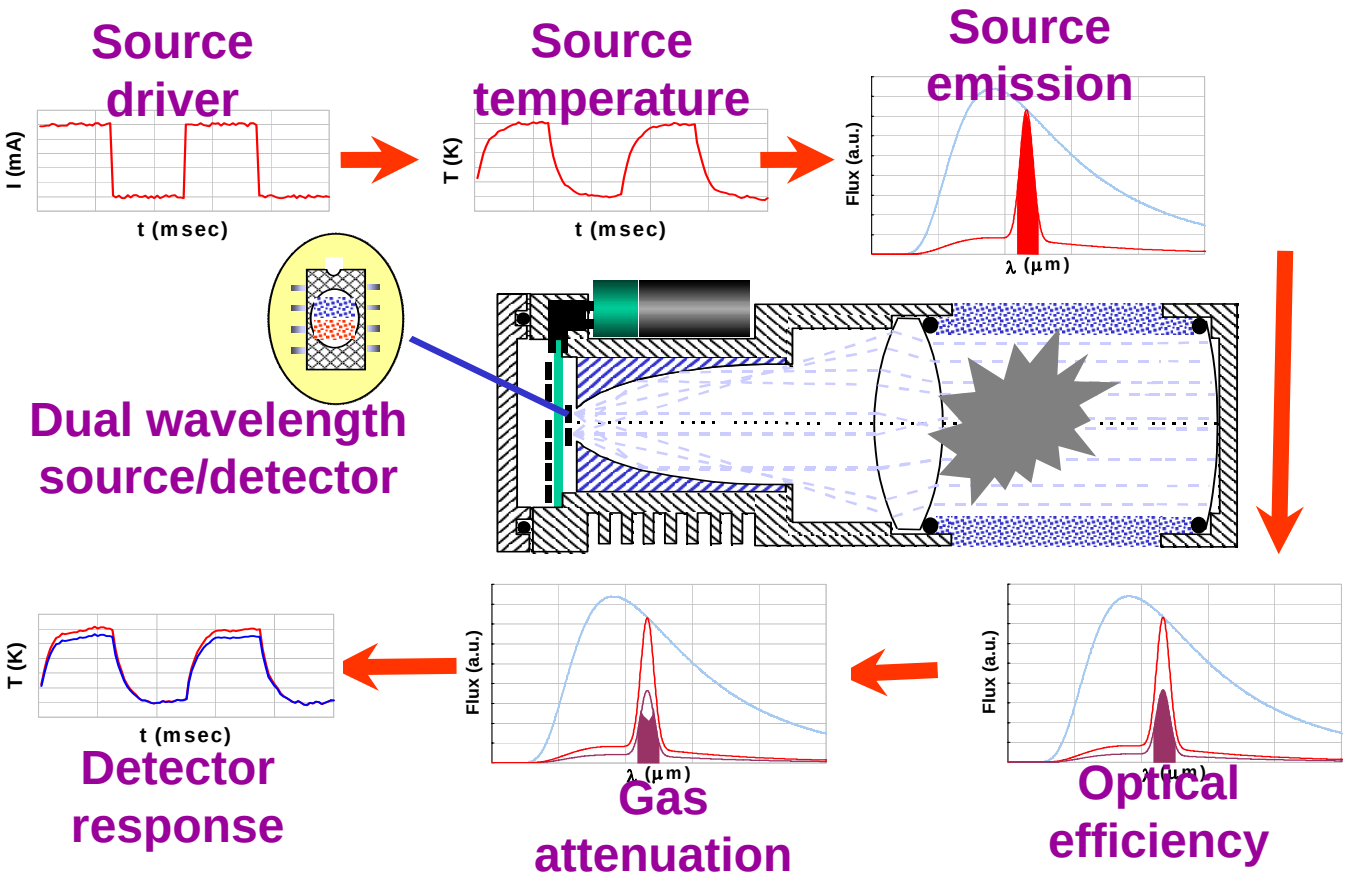
- **CO_2**
  - Solid State NDIR
    - Current "garage-grade" NDIR microbenches have served the purpose
  - ***New Direction – "Sensor-on-a-chip" (a hot-bolometer). Silicon microbridge elements with photonic bandgap modified surfaces.***

- **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)





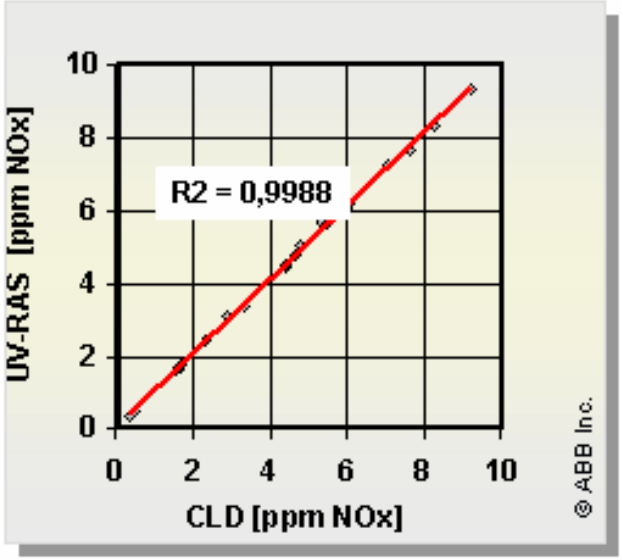


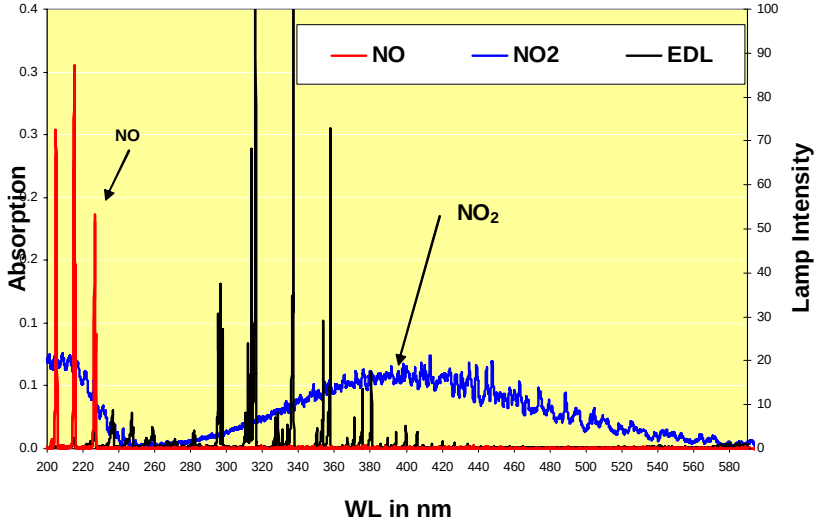
Current Status and Future Direction

- **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 NO_2 , **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, NO_2, NH_3





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

$$\frac{NOx}{CO_2} = \frac{(g/bhp\text{-}hr)_{NOx}}{(g/bhp\text{-}hr)_{CO2}}$$

$$= \frac{\dfrac{(Density)*(Exhaust\ Mass\ Flow\ Rate)*(Concentration)_{NOx}}{bhp\text{-}hr}}{\dfrac{(Density)*(Exhaust\ Mass\ Flow\ Rate)*(Concentration)_{CO2}}{bhp\text{-}hr}}$$

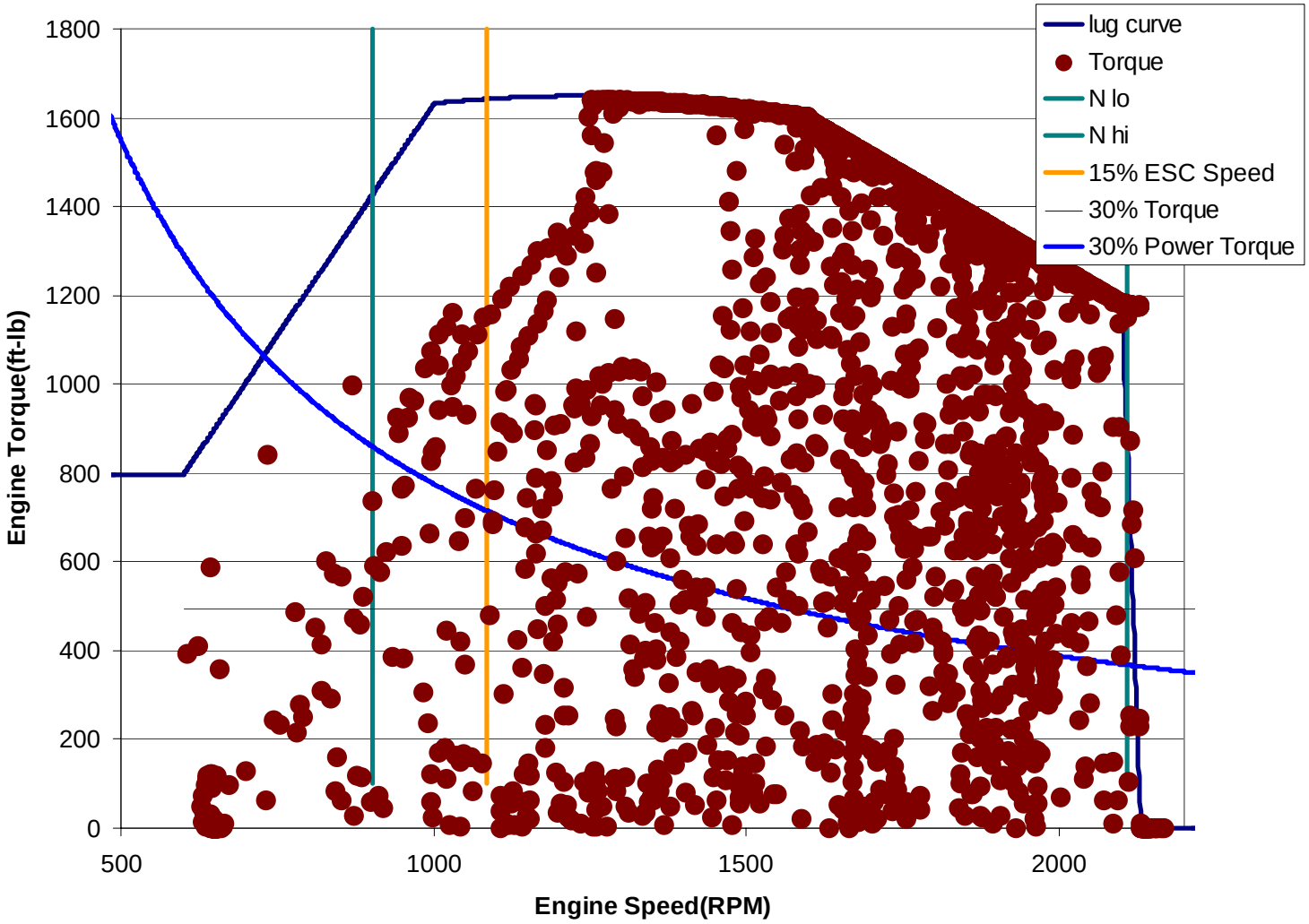
NO_X Index
(Fuel Specific Emissions)

grams of NOx / kg of Fuel

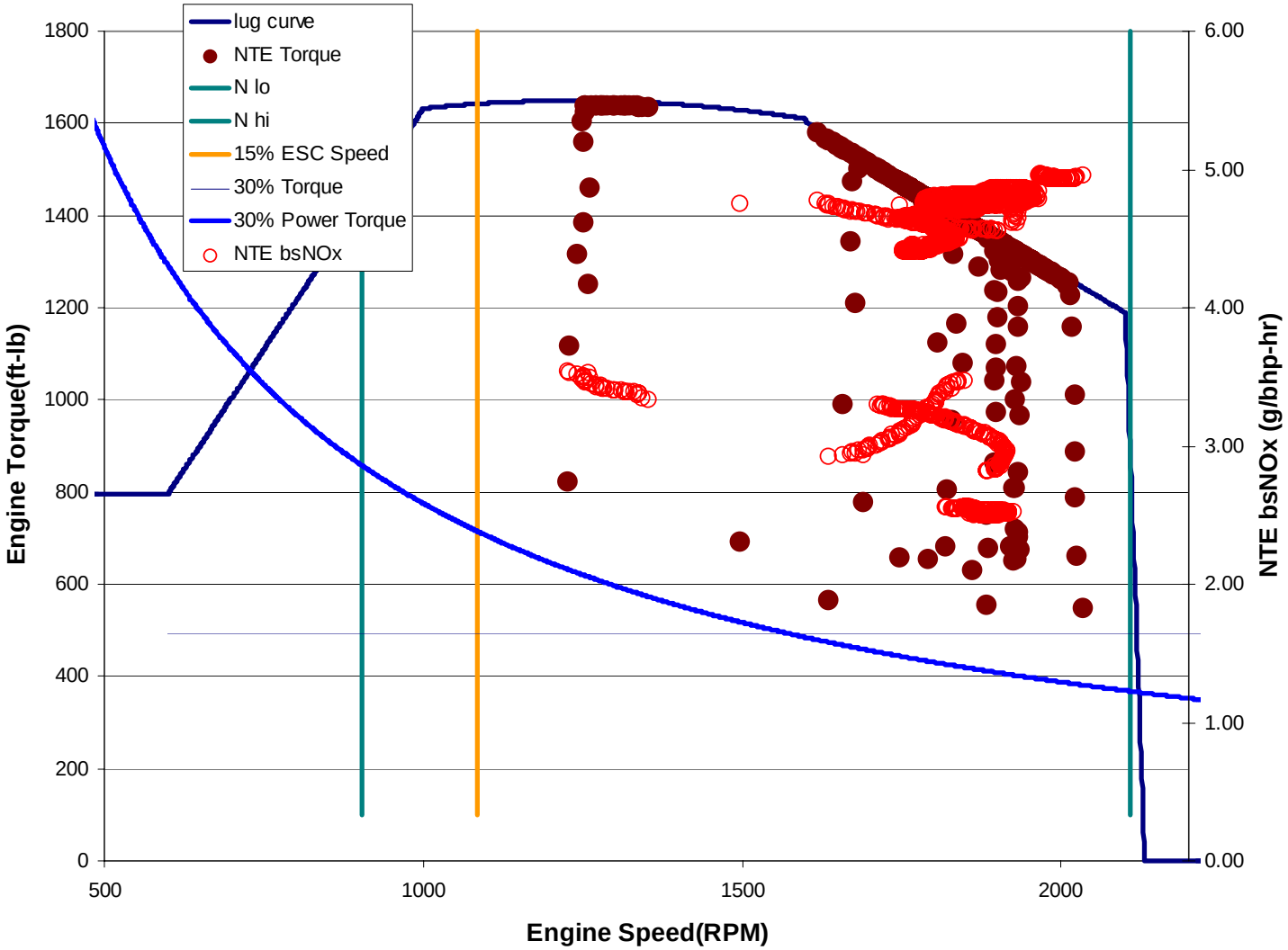
- NOx concentration
- CO_2 concentration
- Fuel H:C ratio

$$\frac{(\text{Concentration of NOx}) \times (\text{Exhaust flow rate}) \times MW_{NOx}}{(\text{Concentration of } CO_2) \times (\text{Exhaust flow rate}) \times (12.011+1.008*(H:C))}$$

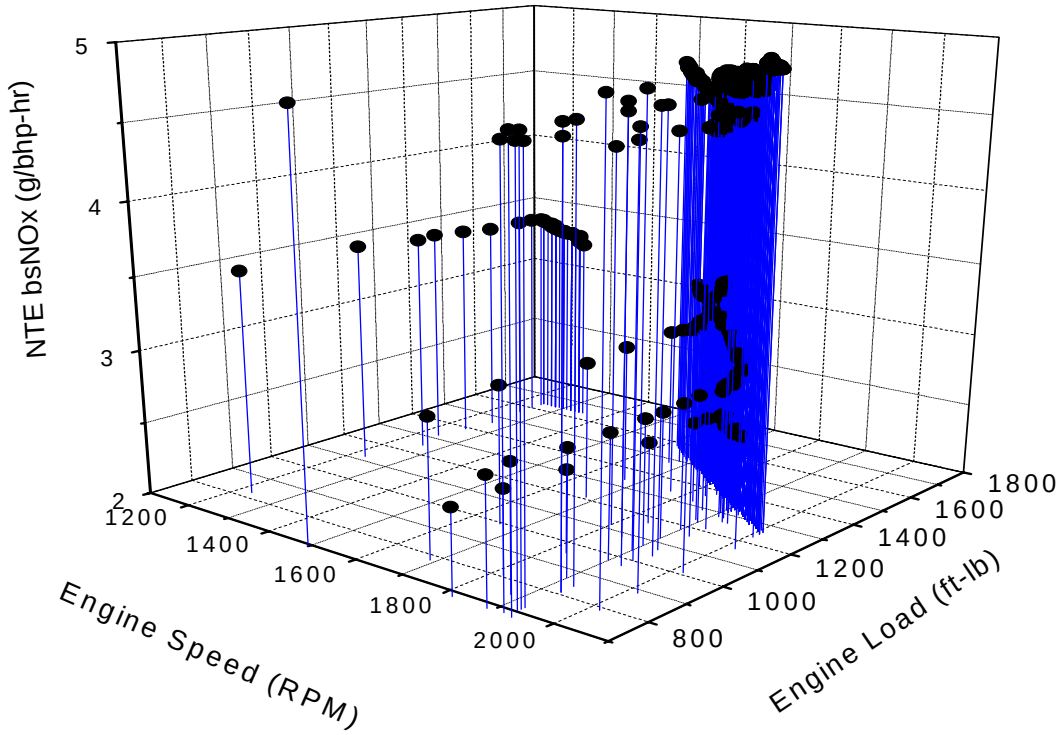
Engine Operation Over an On-road Route



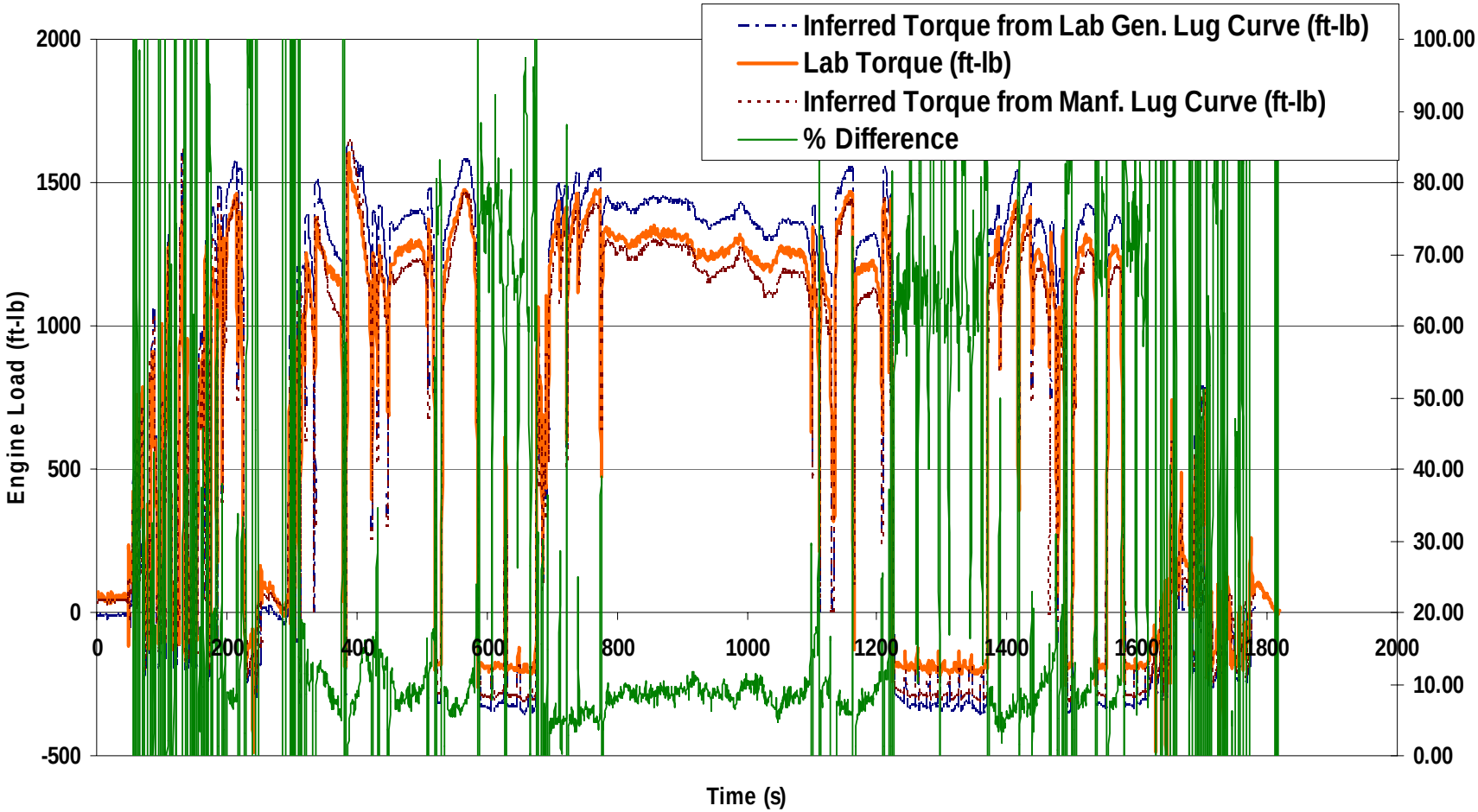
NTE Zone: Engine Operation and Brake Specific NOx as a function of Engine Speed and Engine Load



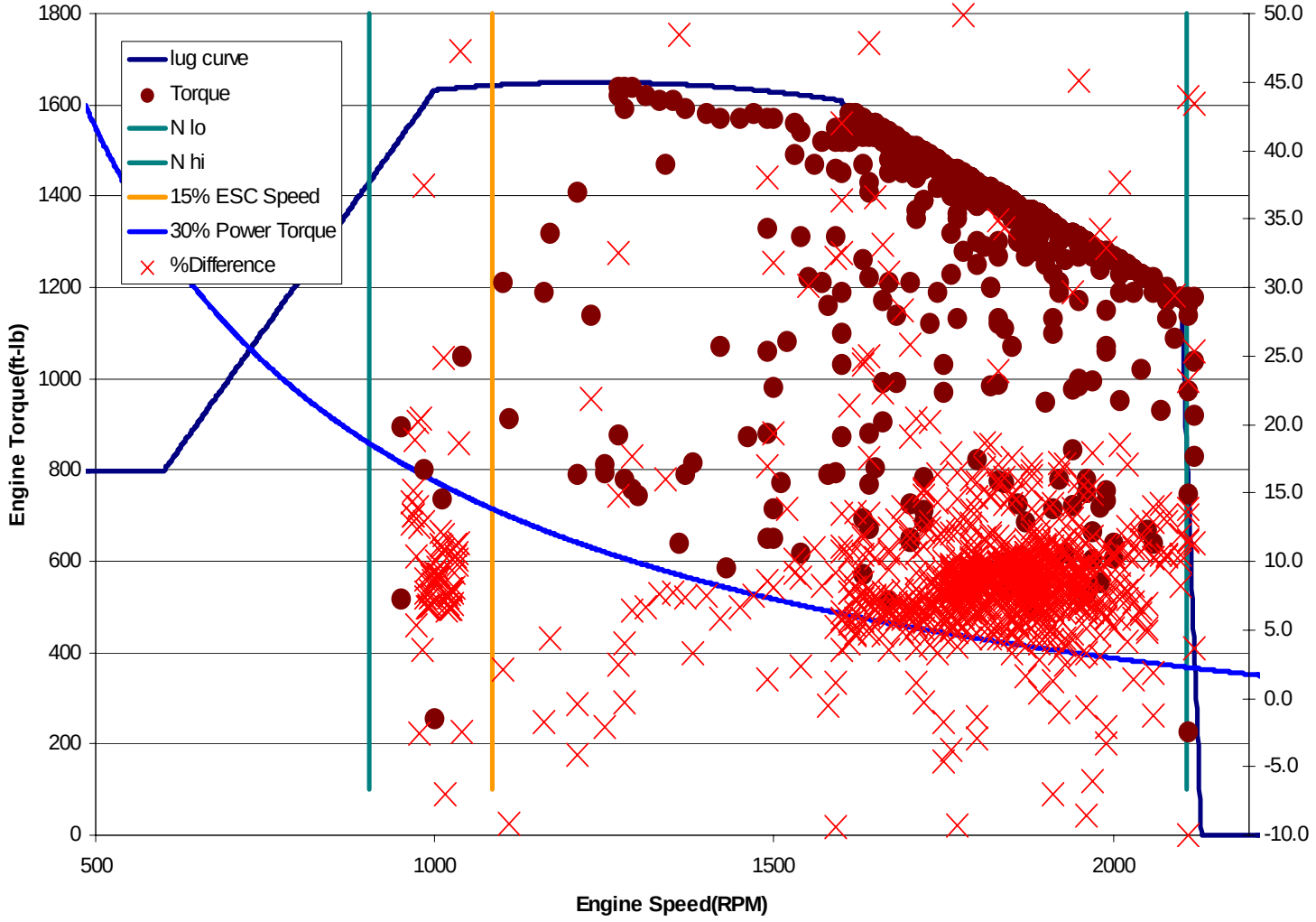
3-D plot of Brake Specific NOx as a function of Engine Speed and Engine Load



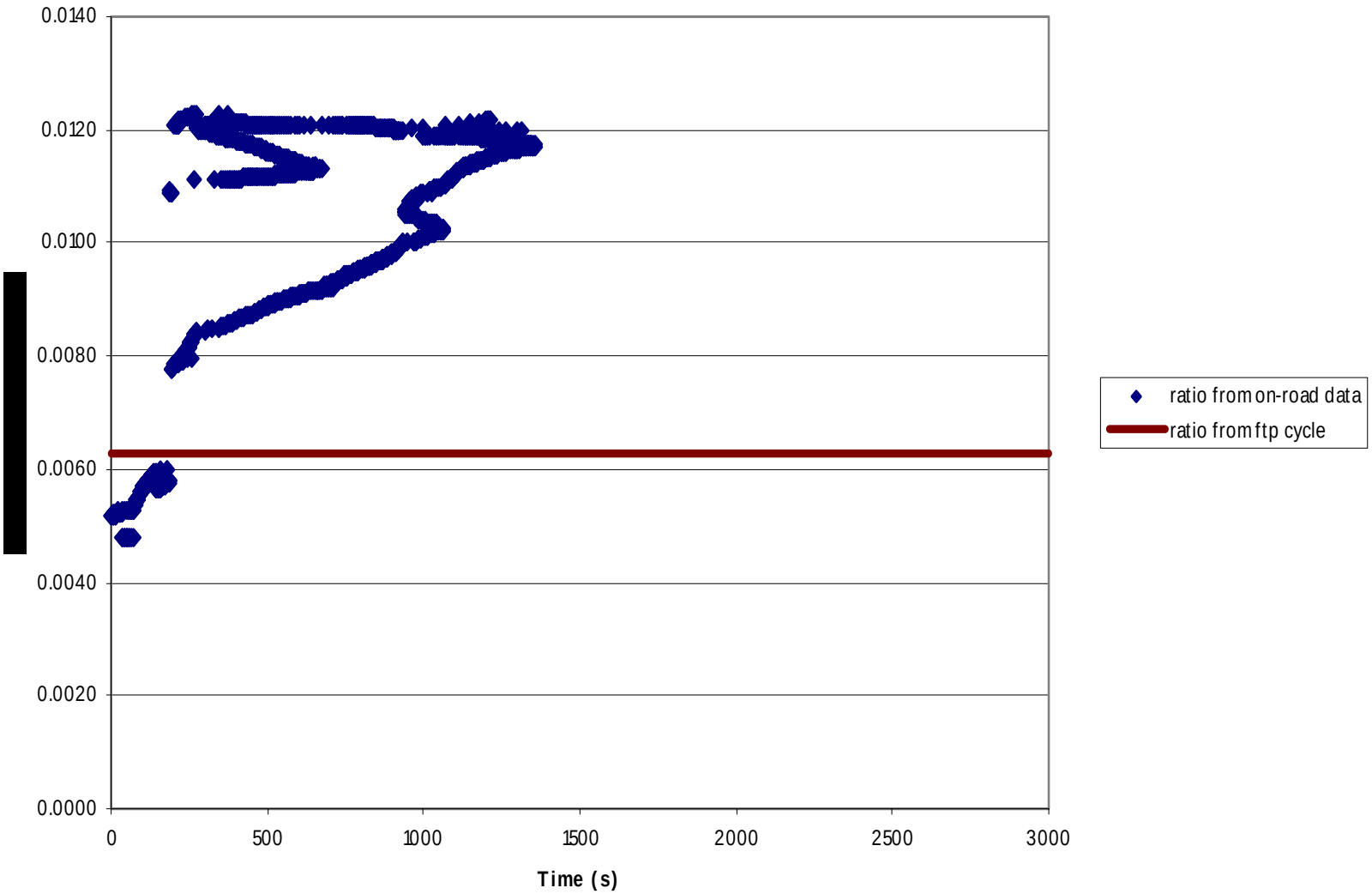
Errors in Torque Broadcast (Simulated SAB-to-BM Route)



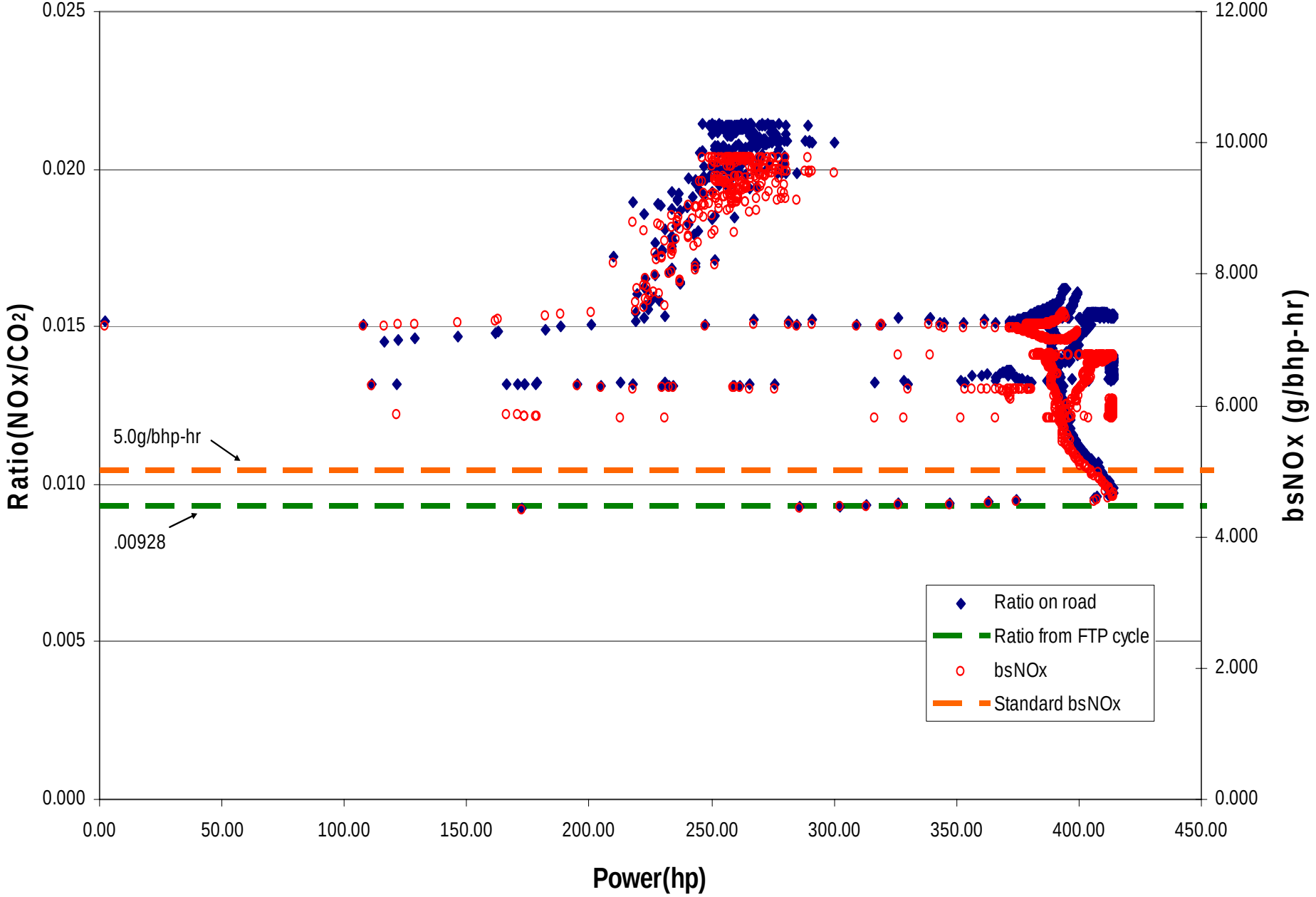
Simulated SAB-to-BM Route – NTE Zone



Ratio of bsNOx/bsCO2 vs. Time



Ratio of bsNOx/bsCO2 vs. Power



In-use Particulate Matter Emissions

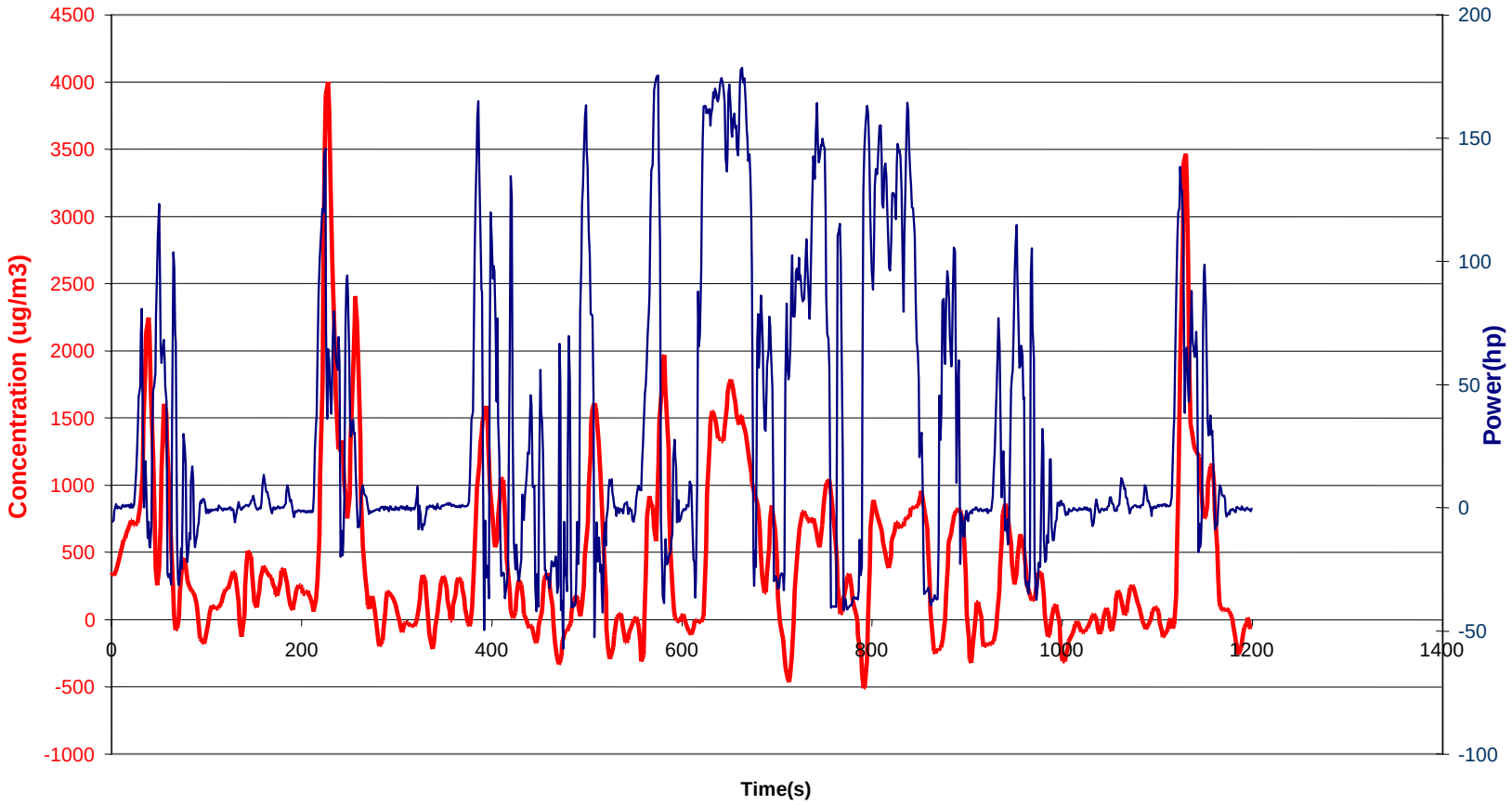
Major Challenge:

- **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, CO_2, 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

	Test 01	Test 02	Test 03
MARI RPM 100 Integrated PM Mass	0.74	1.97	1.73
Full-Flow Dilution Tunnel Gravimetric Integrated PM Mass	0.71	1.75	1.79
Percent Difference	4.2%	12.6%	-3.4%

***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.