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

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)

Exhaust Constituents NOx & CO_2

Exhaust Sampling and Conditioning

Differential Pressure, Absolute Pressure, and Temperature

Engine Speed, Vehicle Speed, & Torque

Flow Meter

Ambient Temperature, Pressure, & Humidity

Vehicle Speed & Location

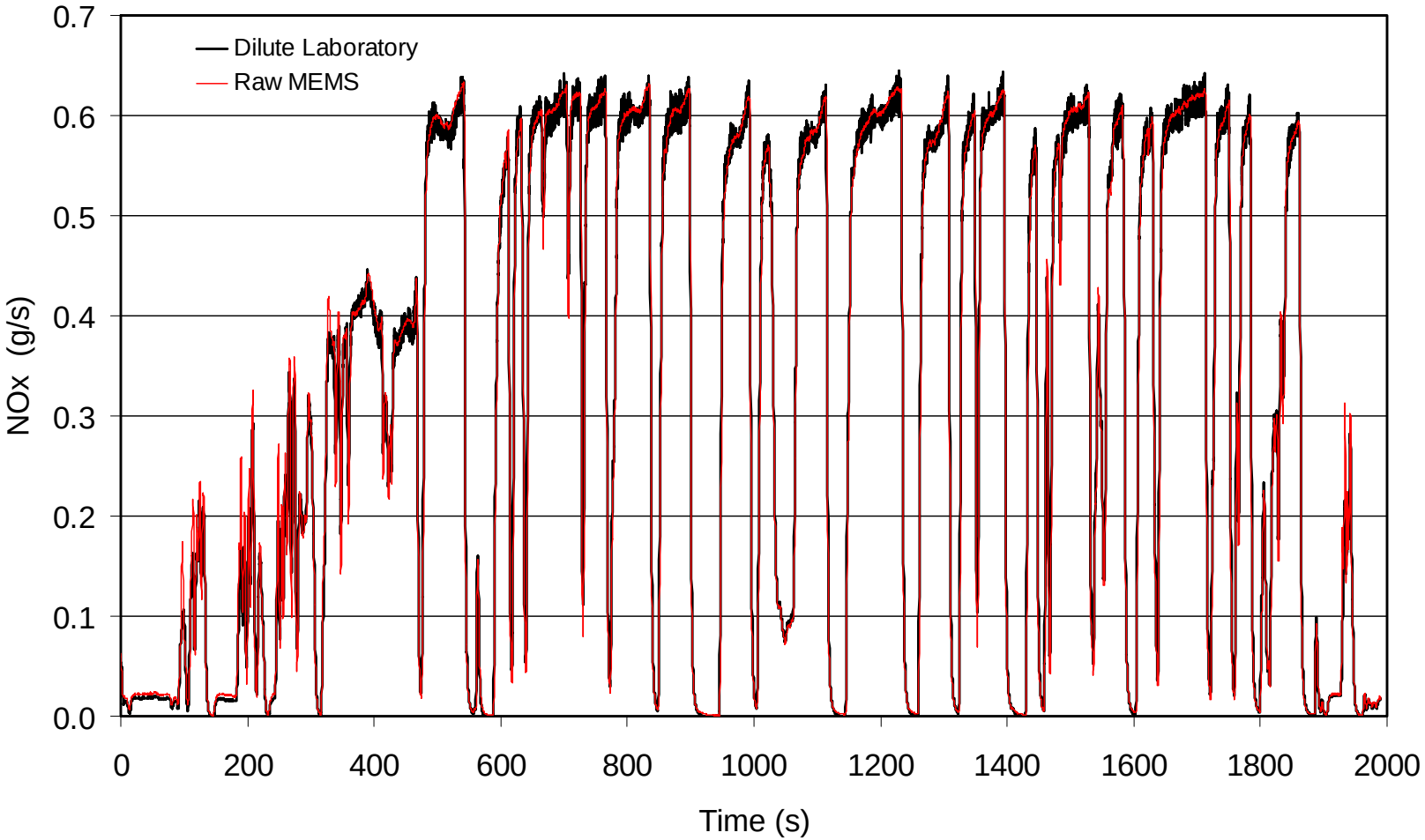
Engine Interface

Ambient Sensors

GPS

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%

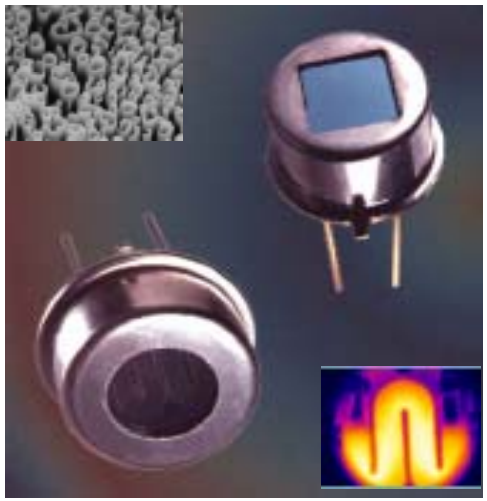
Exhaust Stack Measurements

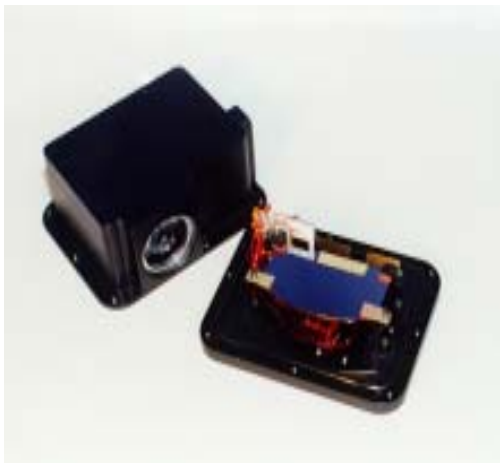
Current Status and Future Direction

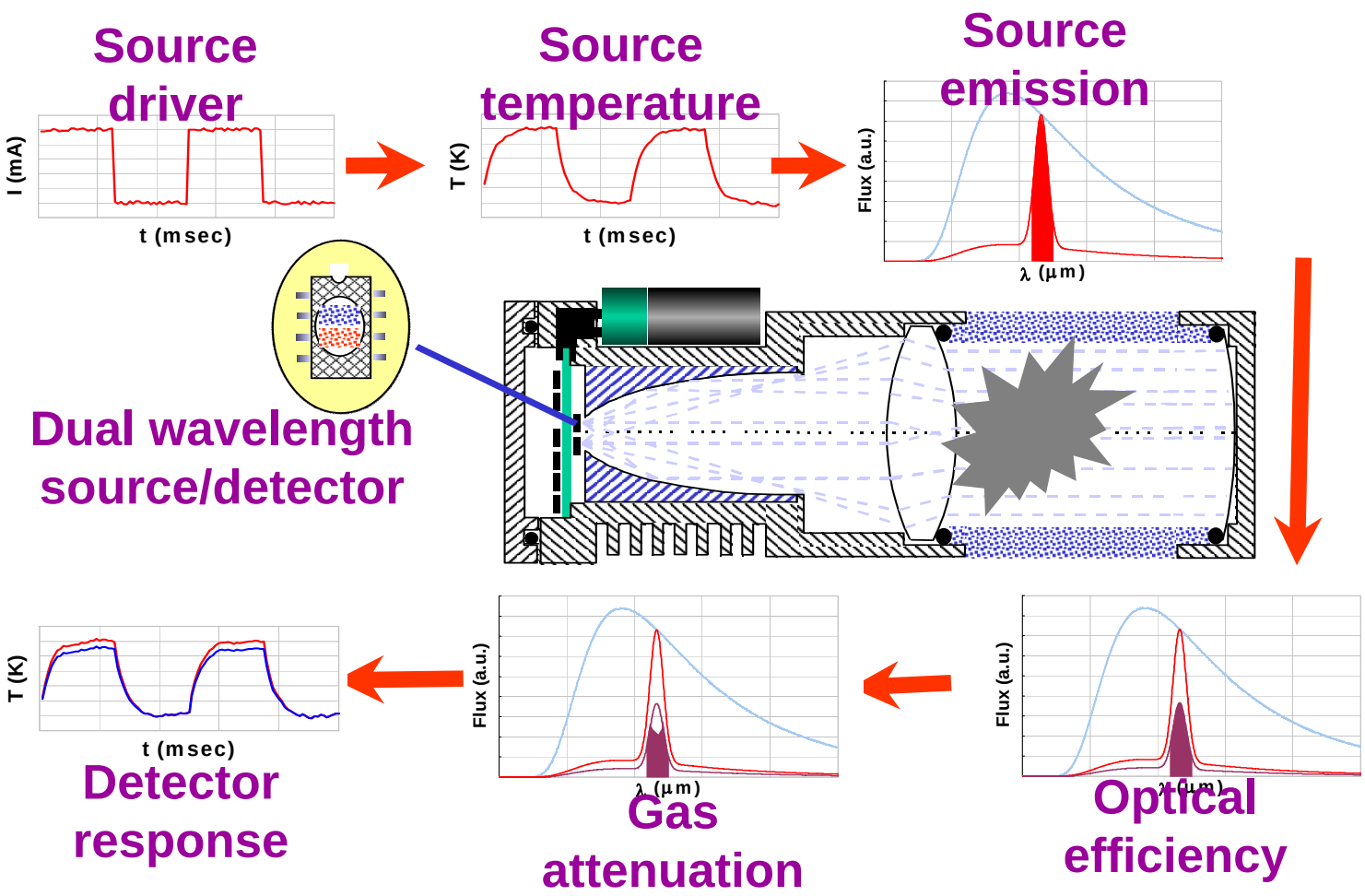
- **CO_2**
  - Solid State NDIR
    - Current “garage-grade” NDIR microbenches have served the purpose
  - ***New Direction – “Sensor-on-a-chip” (a hot-bolometer). Silicon microbridge elements with photonic bandgap modified surfaces.***

- **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)





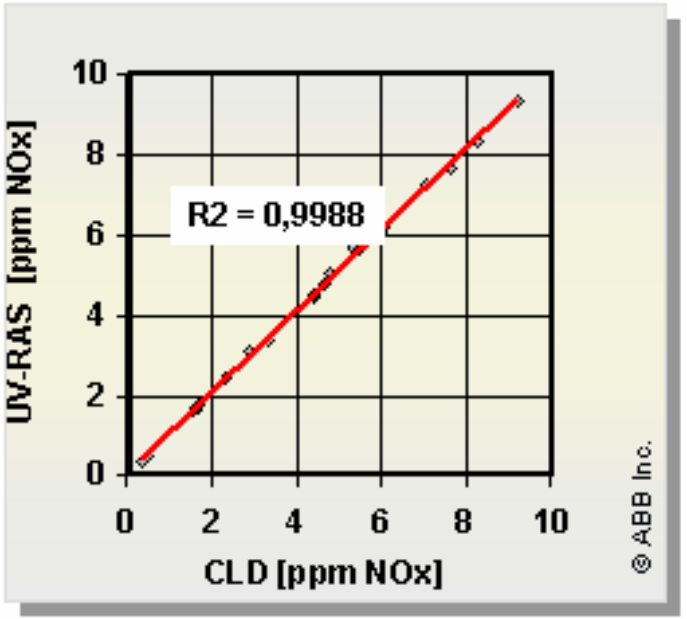


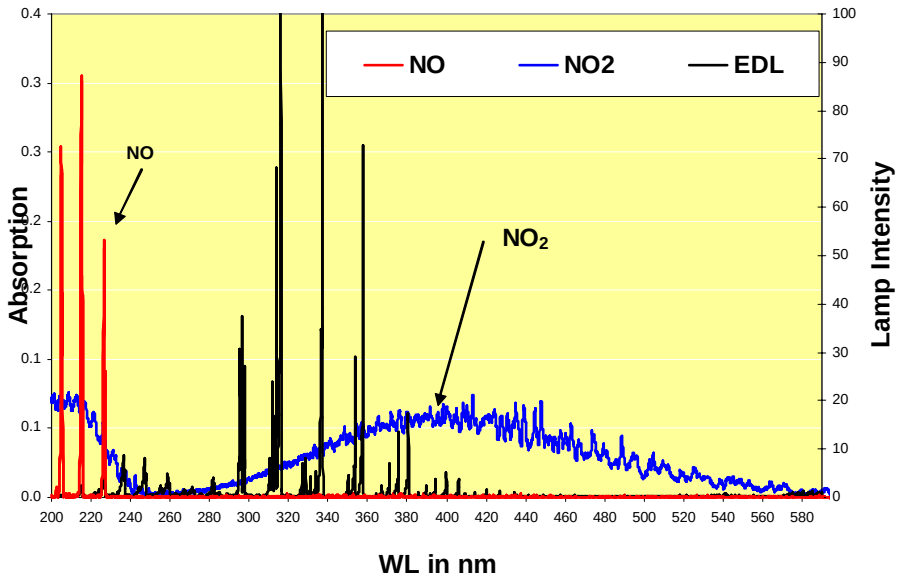
Current Status and Future Direction

- **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

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

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

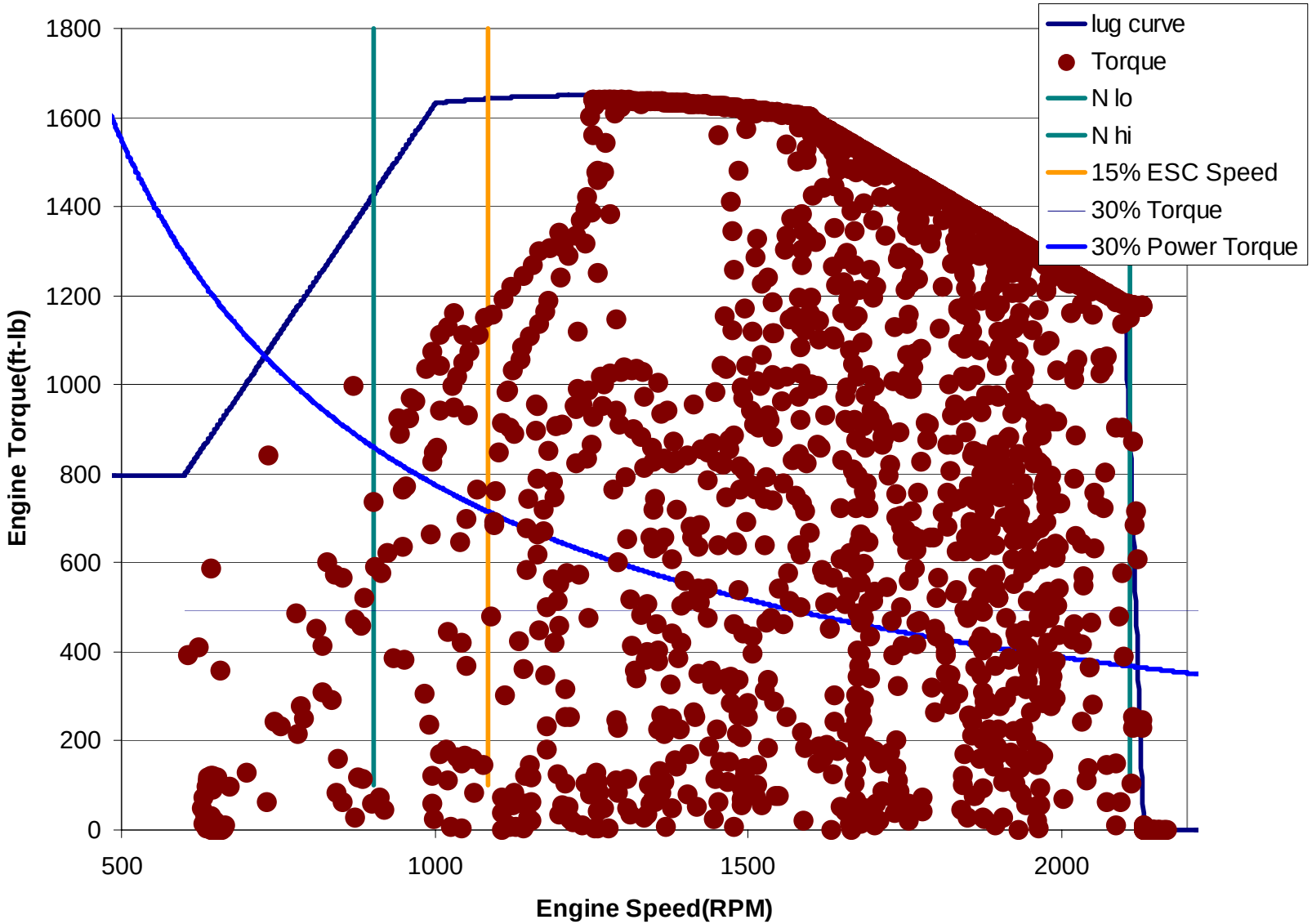
NO_X Index
(Fuel Specific Emissions)

grams of NOx / kg of Fuel

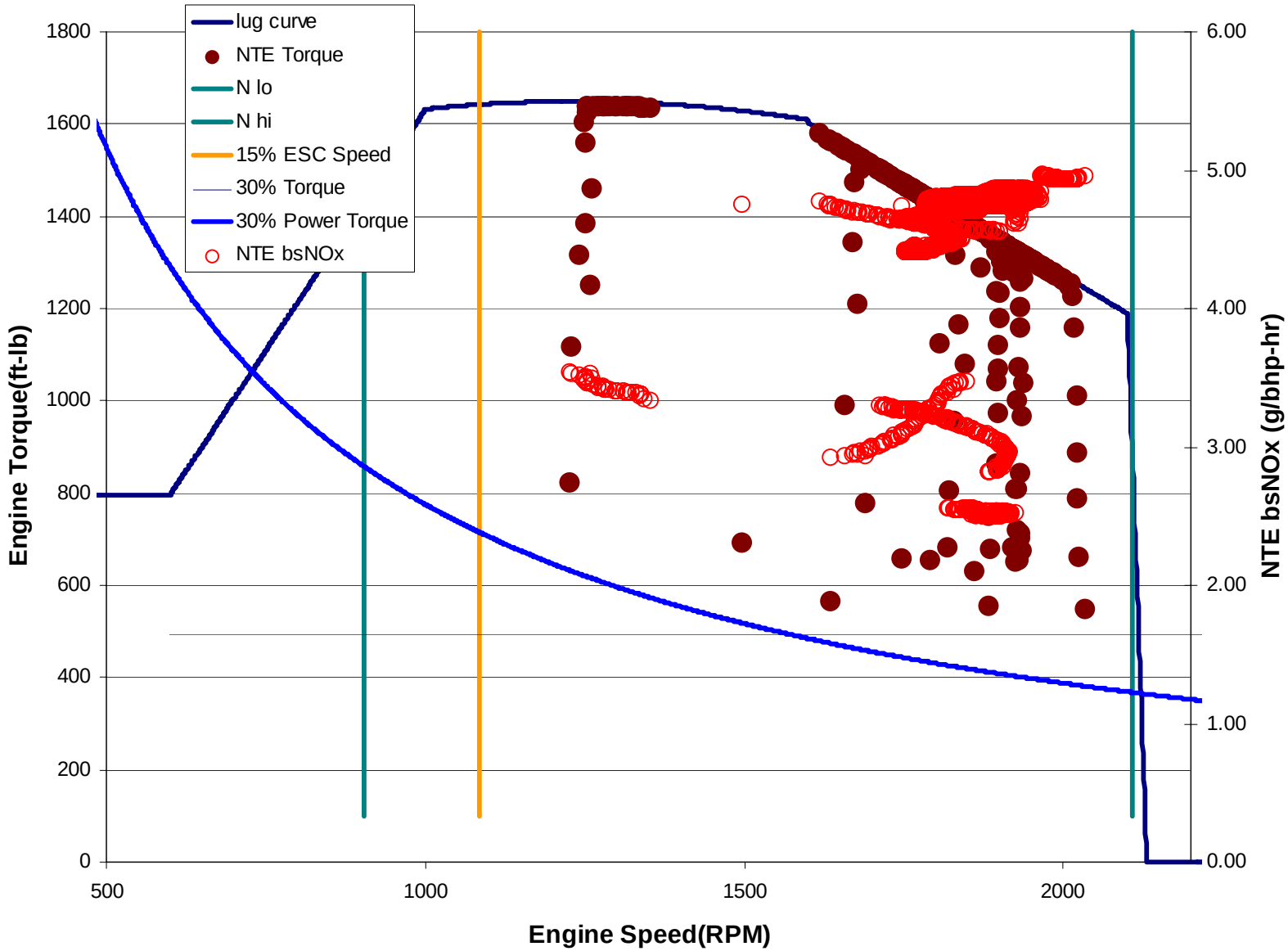
- NOx concentration
- CO_2 concentration
- Fuel H:C ratio

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

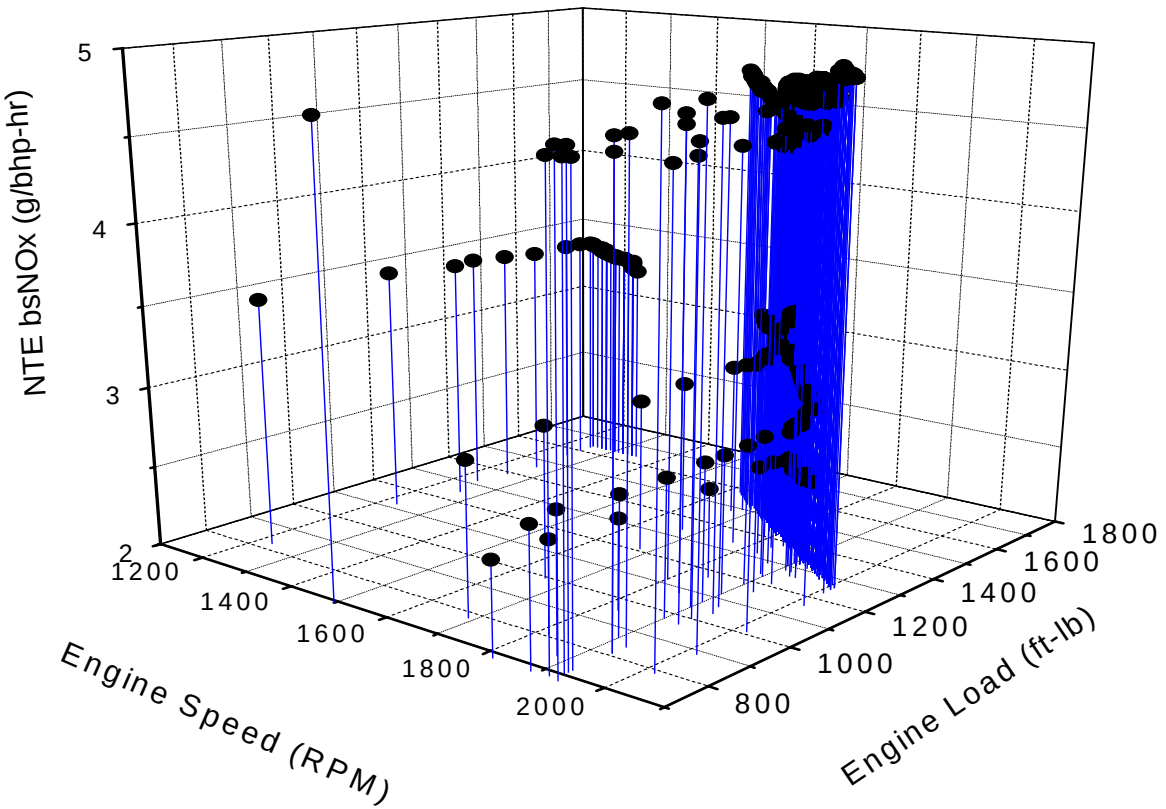
Engine Operation Over an On-road Route



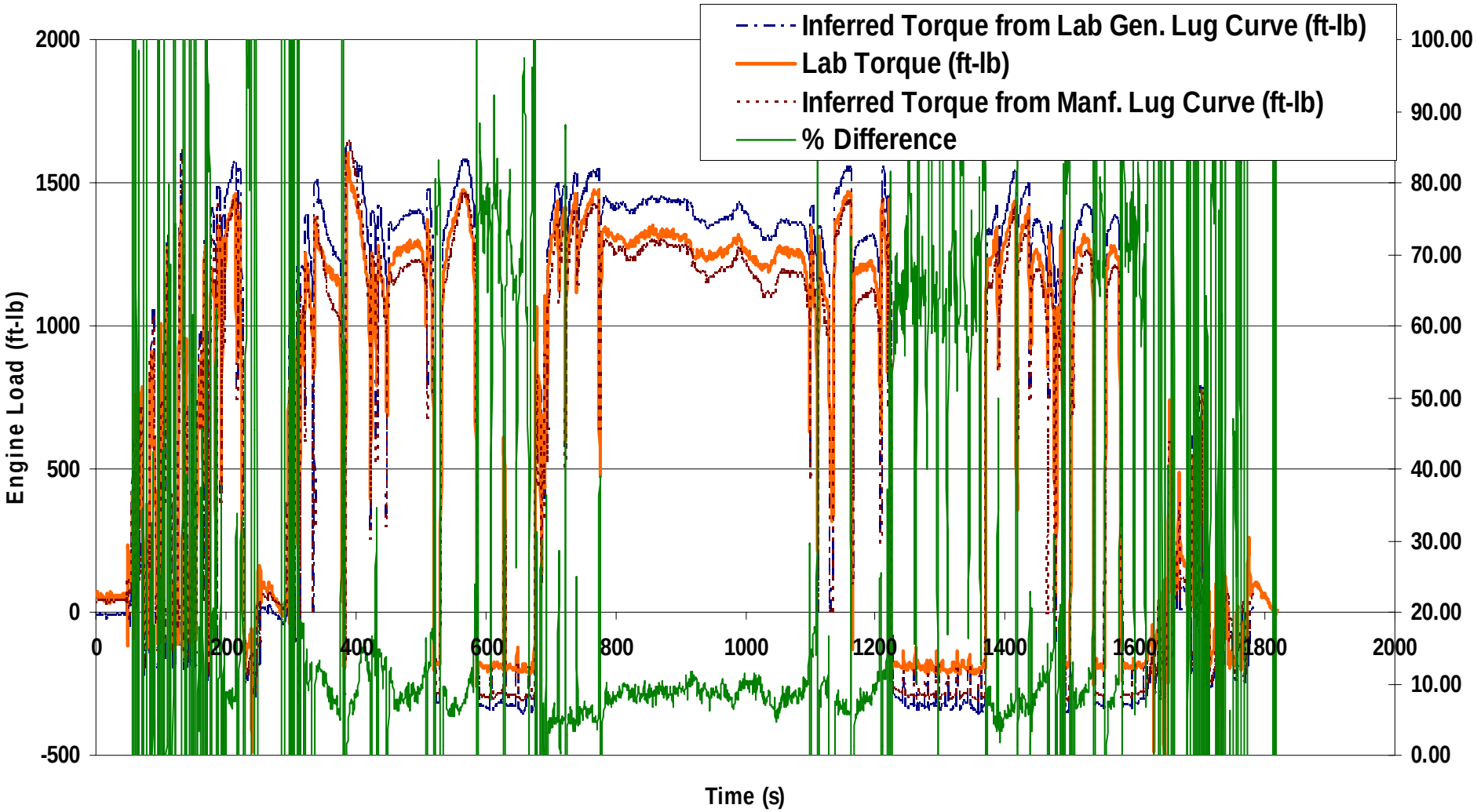
NTE Zone: Engine Operation and Brake Specific NOx as a function of Engine Speed and Engine Load



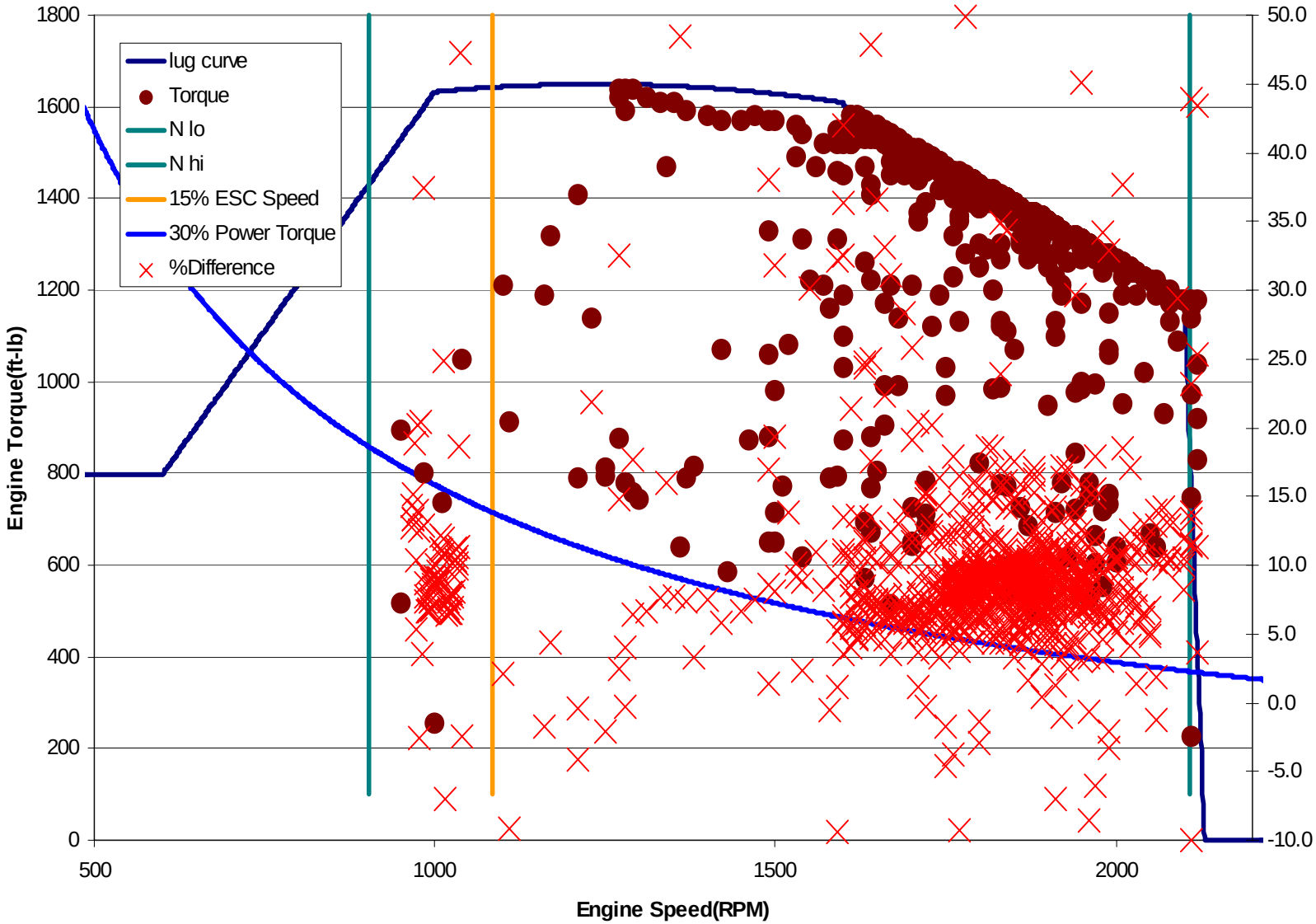
3-D plot of Brake Specific NOx as a function of Engine Speed and Engine Load



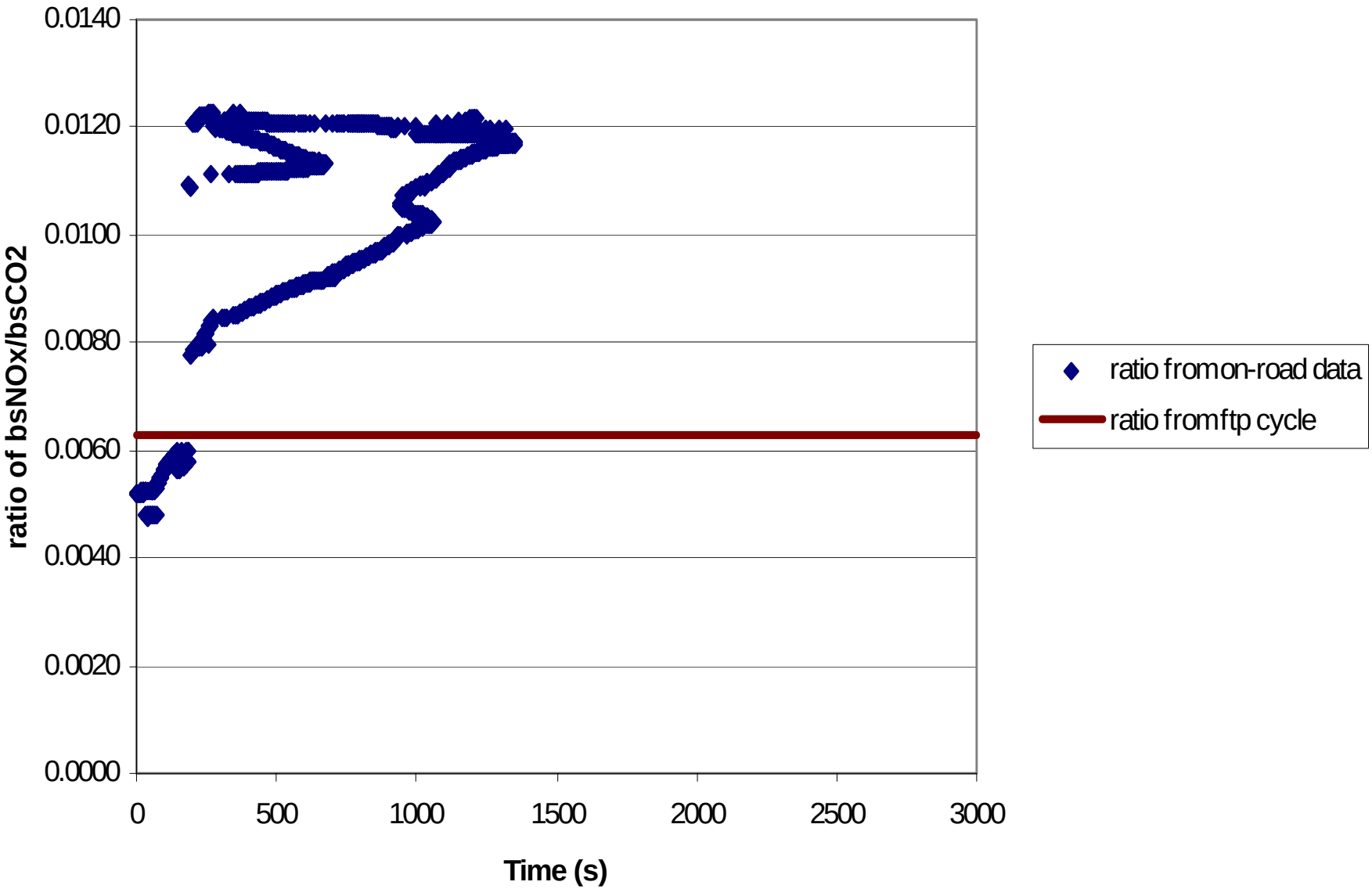
Errors in Torque Broadcast (Simulated SAB-to-BM Route)



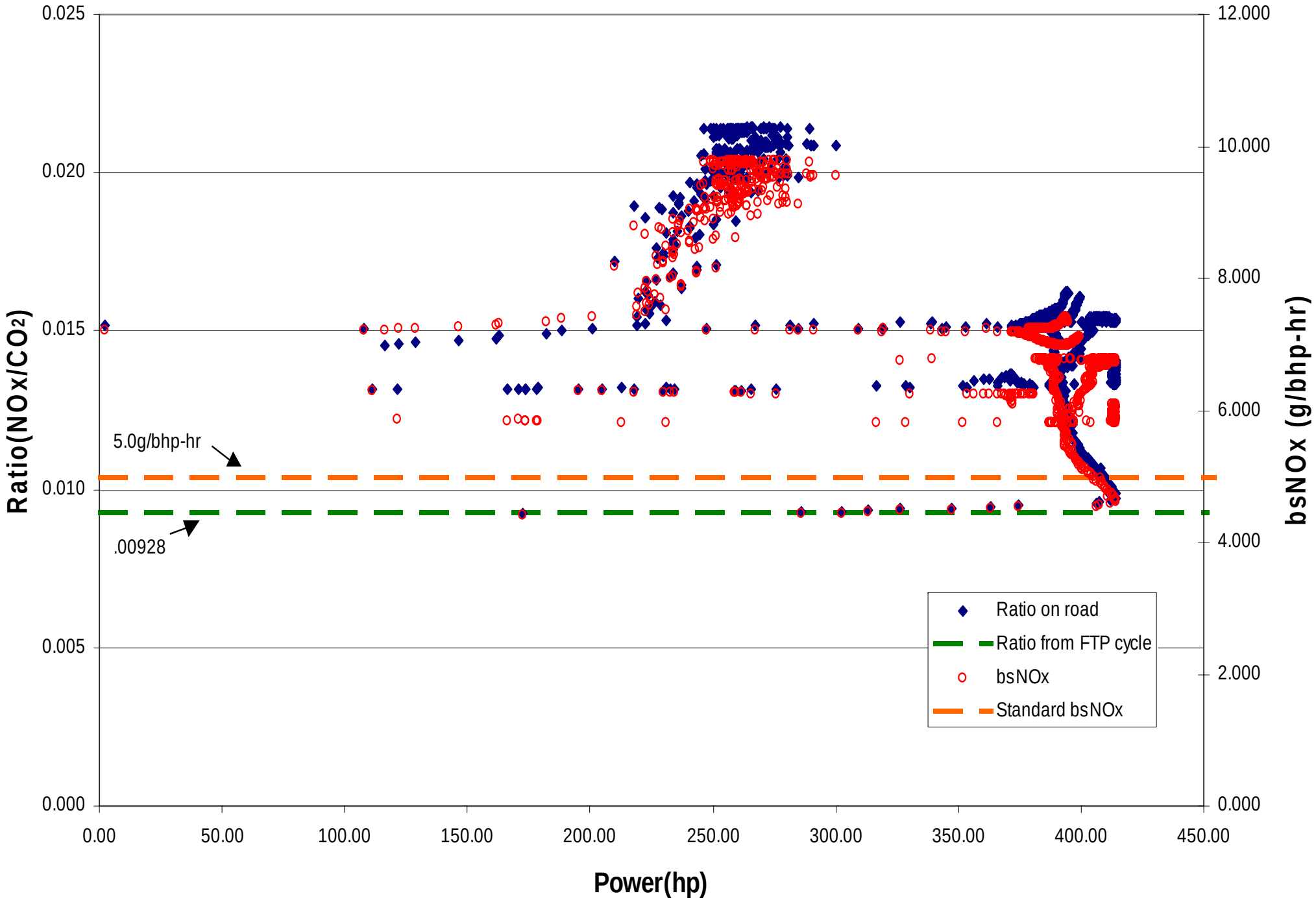
Simulated SAB-to-BM Route – NTE Zone



Ratio of bsNOx/bsCO2 vs. Time



Ratio of bsNOx/bsCO2 vs. Power



In-use Particulate Matter Emissions

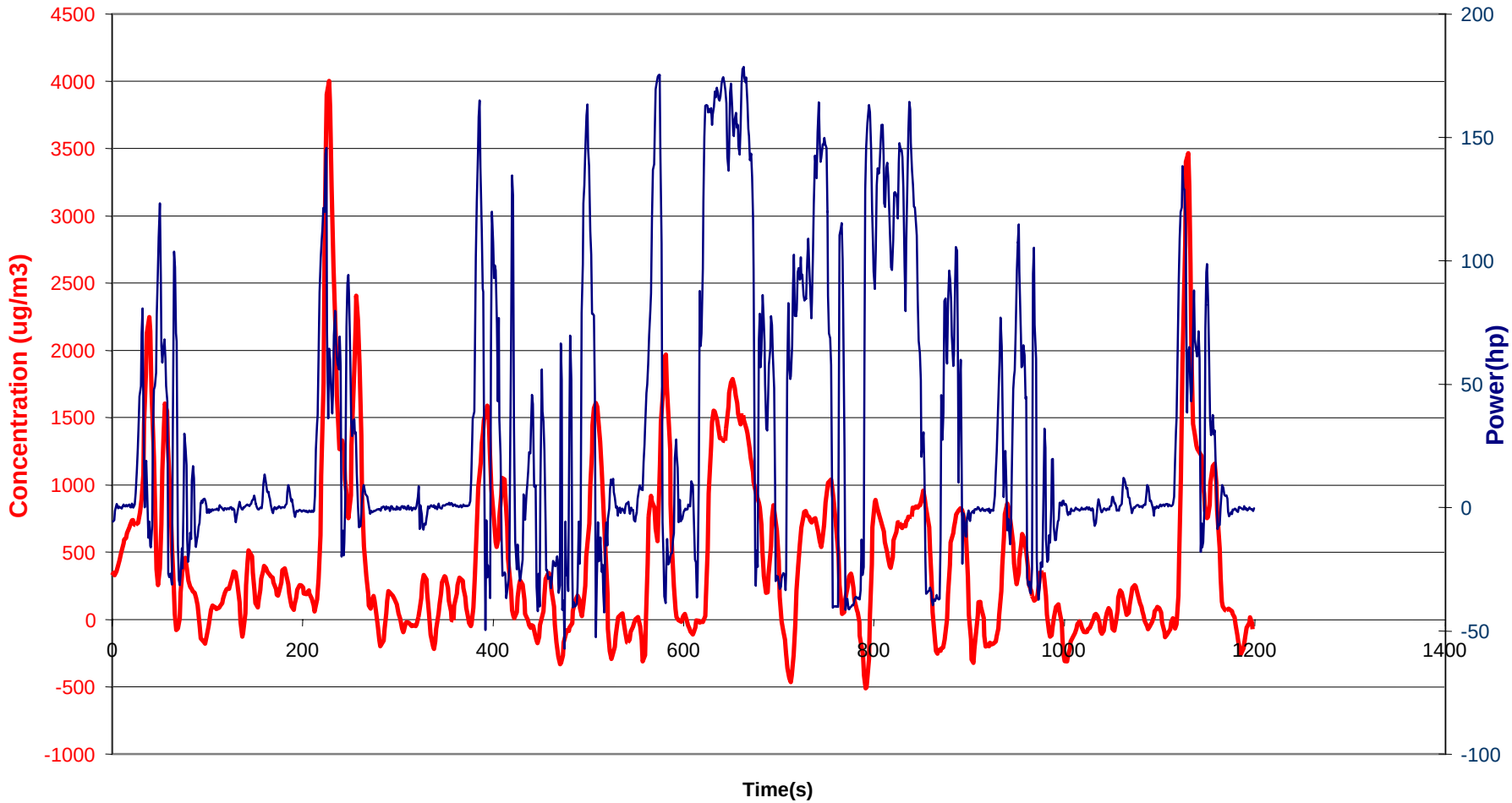
Major Challenge:

- 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.**

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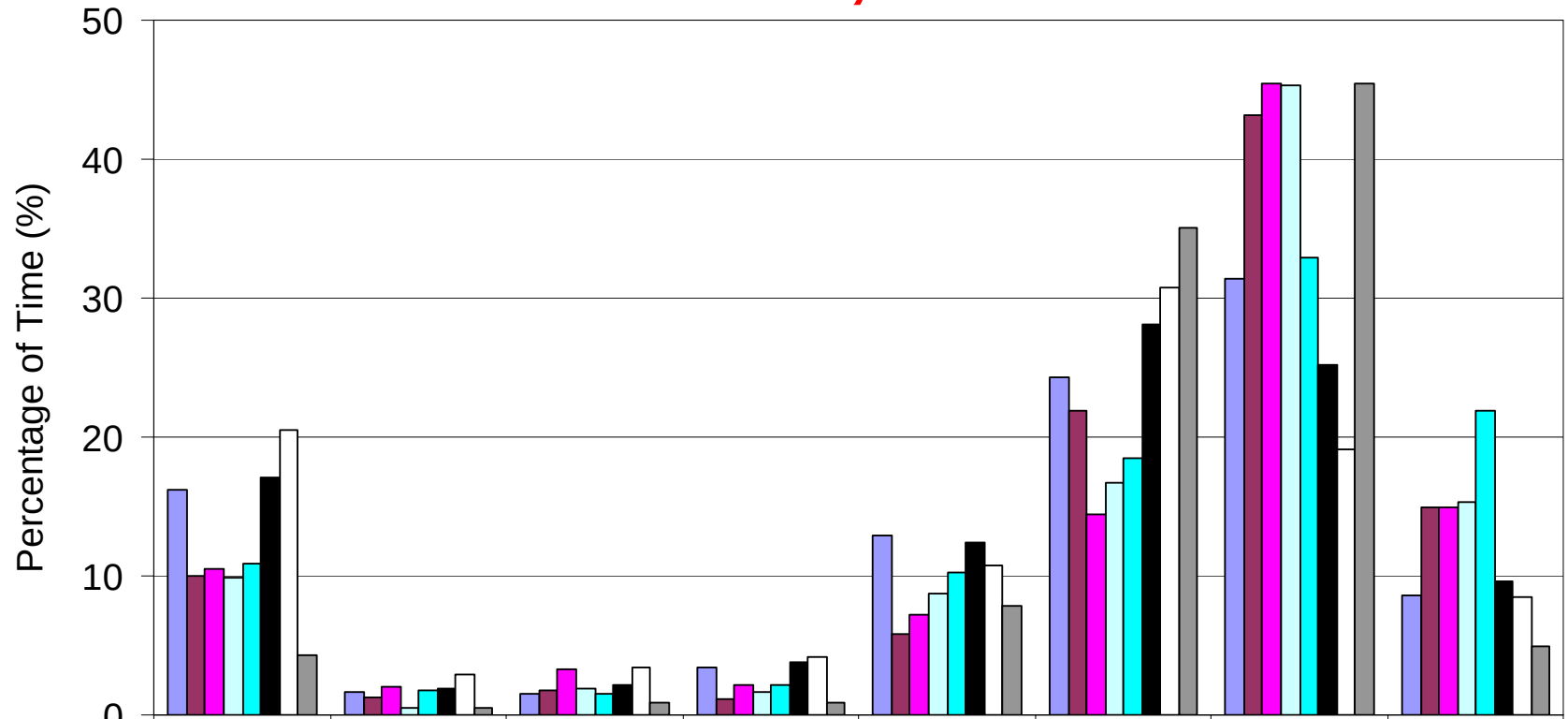
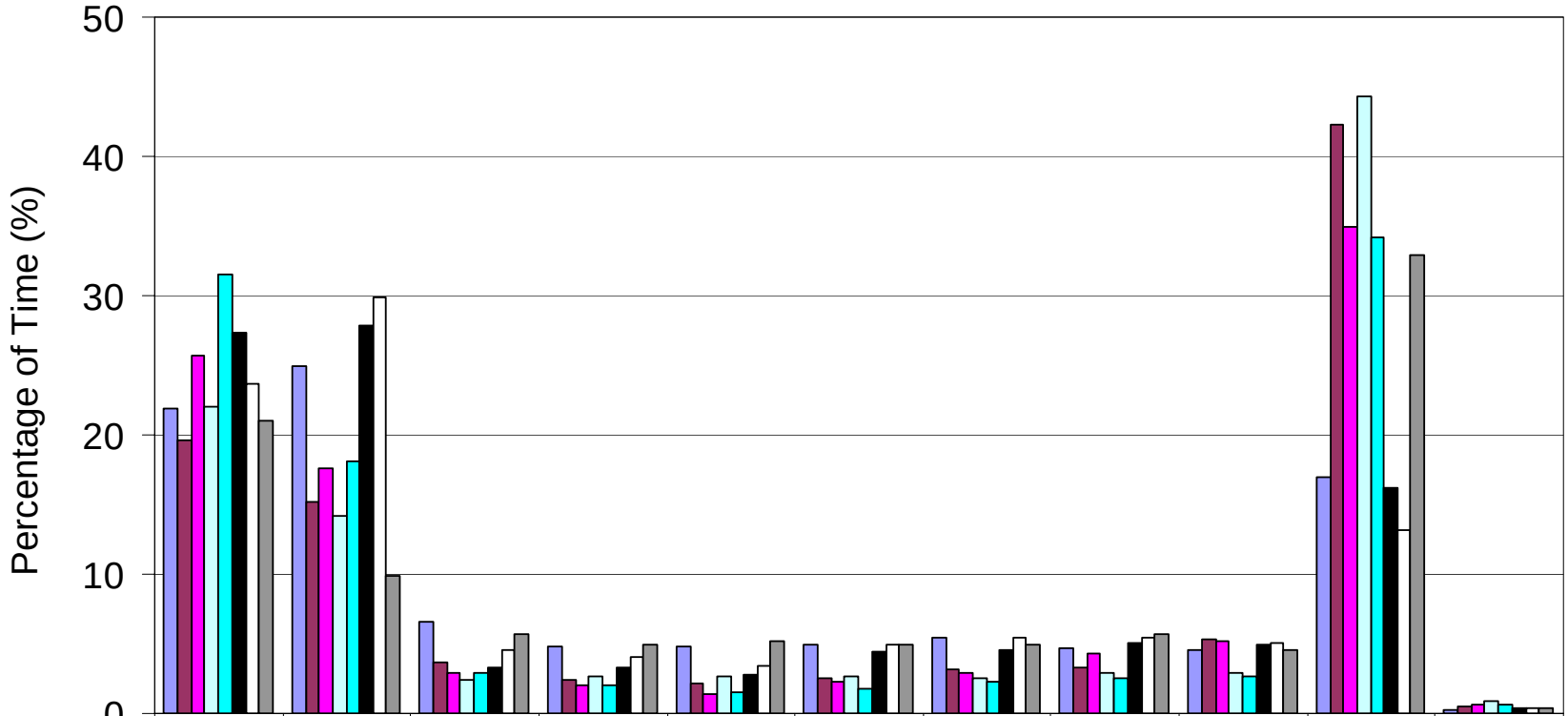
Engine Speed Histogram for the Candidate Routes
Mack CH Tractor and Trailer
With a Nominal 60,000 lbs GVW



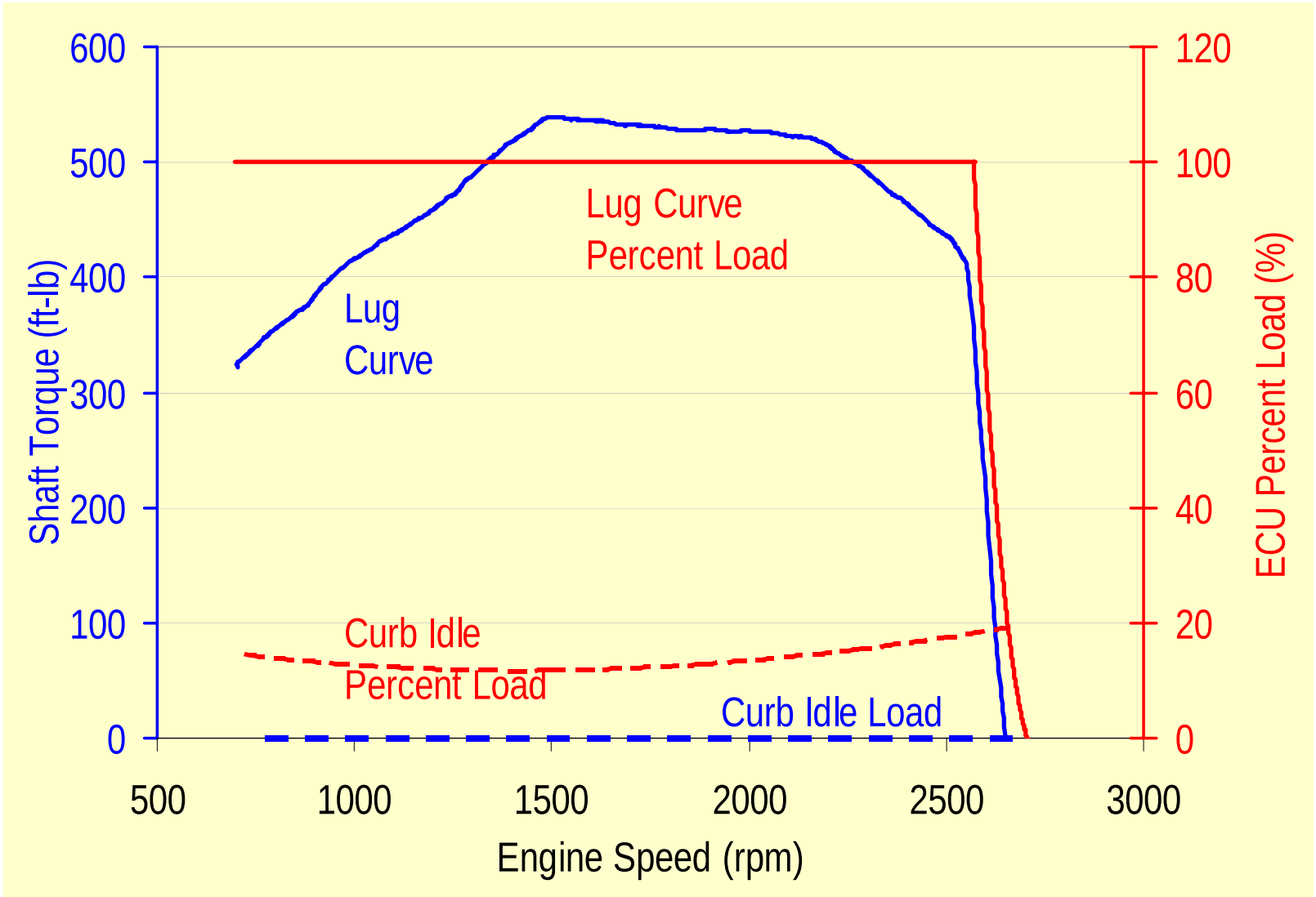
Eng. Spd. (rpm)	0 - 700	700 - 900	900 - 1100	1100 - 1300	1300 - 1500	1500 - 1700	1700 - 1900	1900 - 3000
SAB2SAB	16.22	1.69	1.49	3.42	12.86	24.30	31.43	8.59
SAB2SW	9.99	1.23	1.80	1.14	5.81	21.95	43.17	14.90
SW2SAB	10.50	1.97	3.34	2.20	7.19	14.42	45.40	14.98
SAB2BM	9.81	0.53	1.96	1.69	8.68	16.77	45.31	15.27
BM2SAB	10.86	1.83	1.51	2.20	10.31	18.48	32.86	21.93
WAHSPA1	17.04	1.87	2.12	3.79	12.35	28.13	25.14	9.57
WASHPA2	20.46	2.87	3.40	4.14	10.79	30.78	19.10	8.45
WASHPA3	4.36	0.56	0.89	0.87	7.84	35.04	45.44	4.99

ECU-Derived Engine Power Histogram for the Candidate Routes Mack CH Tractor and Trailer With a Nominal 60,000 lbs GVW

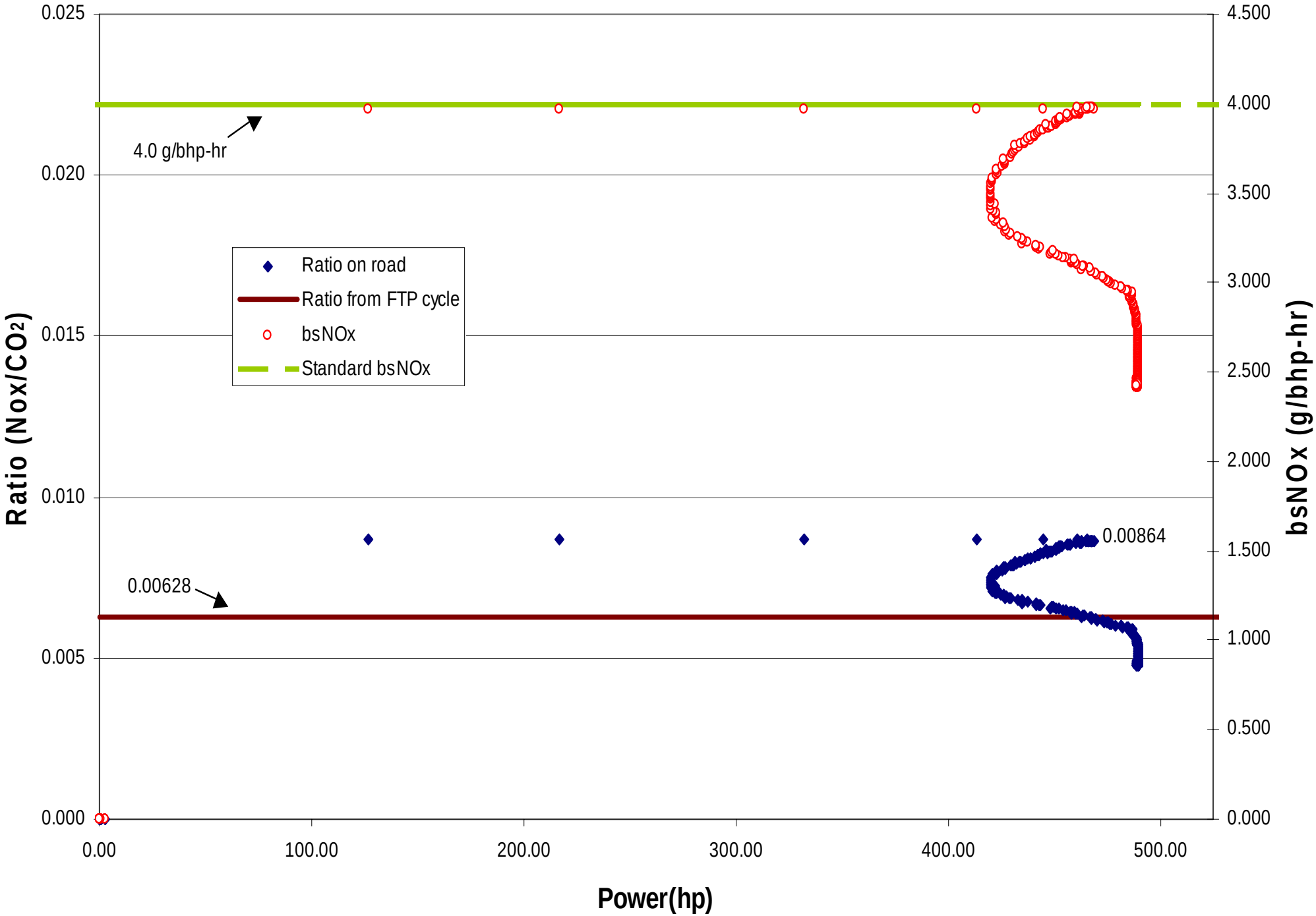


ECU Power (hp)	-200 - -25	-25 - 25	25 - 75	75 - 125	125 - 175	175 - 225	225 - 275	275 - 325	325 - 375	375 - 425	425 - 475
SAB2SAB	21.95	24.97	6.62	4.81	4.78	4.97	5.38	4.69	4.53	17.01	0.28
SAB2SW	19.56	15.18	3.62	2.40	2.14	2.48	3.16	3.34	5.26	42.29	0.56
SW2SAB	25.75	17.65	2.96	2.05	1.46	2.24	2.91	4.35	5.13	34.89	0.62
SAB2BM	21.96	14.13	2.40	2.69	2.61	2.60	2.59	2.89	2.86	44.36	0.90
BM2SAB	31.52	18.16	2.91	2.01	1.47	1.80	2.23	2.58	2.62	34.13	0.58
WAHSPA1	27.31	27.88	3.27	3.26	2.82	4.42	4.58	5.01	4.91	16.19	0.35
WASHPA2	23.72	29.83	4.55	4.08	3.47	4.88	5.43	5.47	5.08	13.18	0.32
WASHPA3	21.01	9.85	5.71	4.92	5.13	4.92	4.89	5.70	4.55	32.96	0.36

Inference of Engine Power



Ratio of bsNOx/bsCO2 vs. Power



Results – Steady State Instantaneous Engine Speed and Torque

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