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

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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

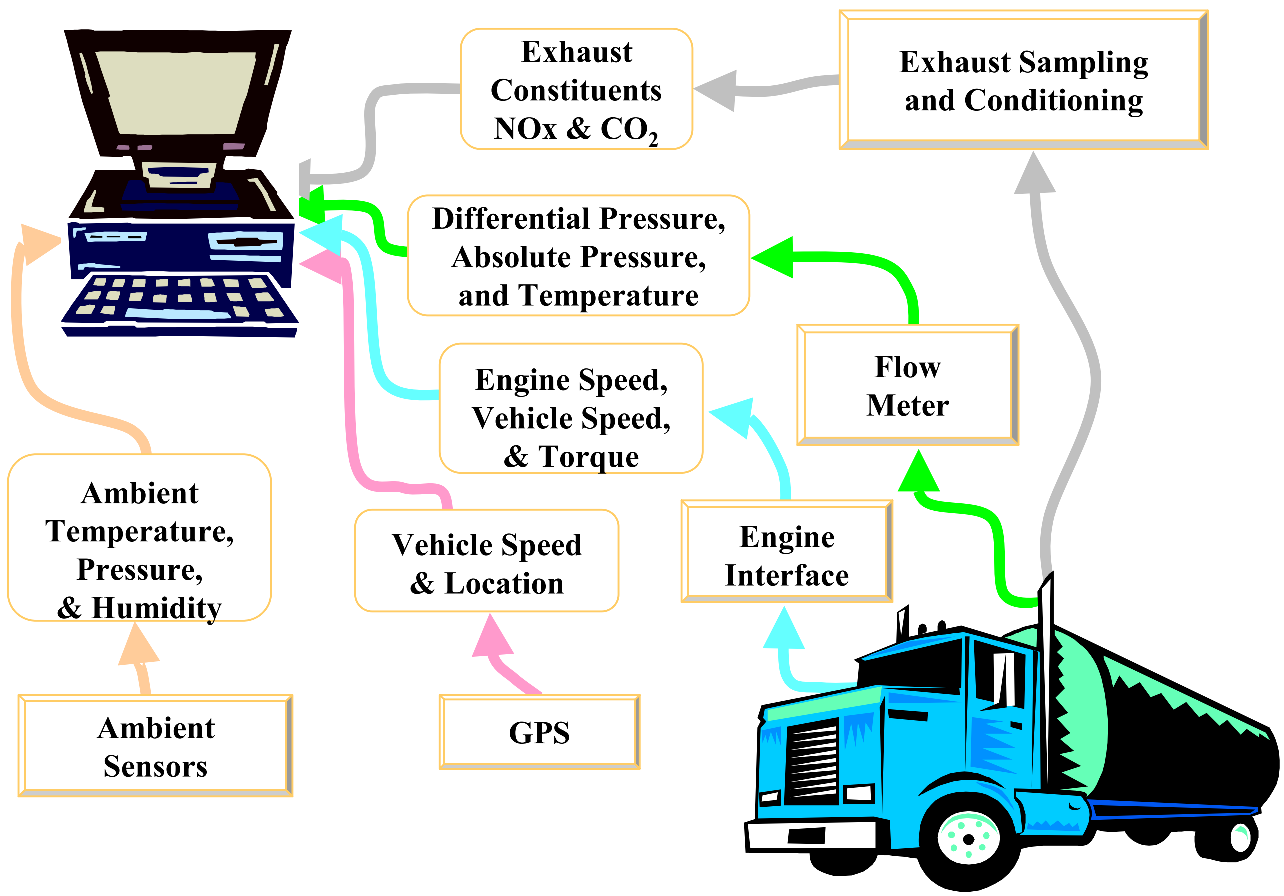
- **PHASE I: DEVELOPMENT OF A STATE-OF-THE-ART MOBILE EMISSIONS MEASUREMENT SYSTEM FOR ON-BOARD, IN-USE HEAVY-DUTY VEHICLE APPLICATIONS**
- **PHASE II: DEVELOPMENT OF IN-USE EMISSIONS TESTING PROCEDURES, AND TEST ROUTES**
- **PHASE III: CONDUCT EMISSIONS TESTING ON A VARIETY OF IN-SERVICE DIESEL ENGINES 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)

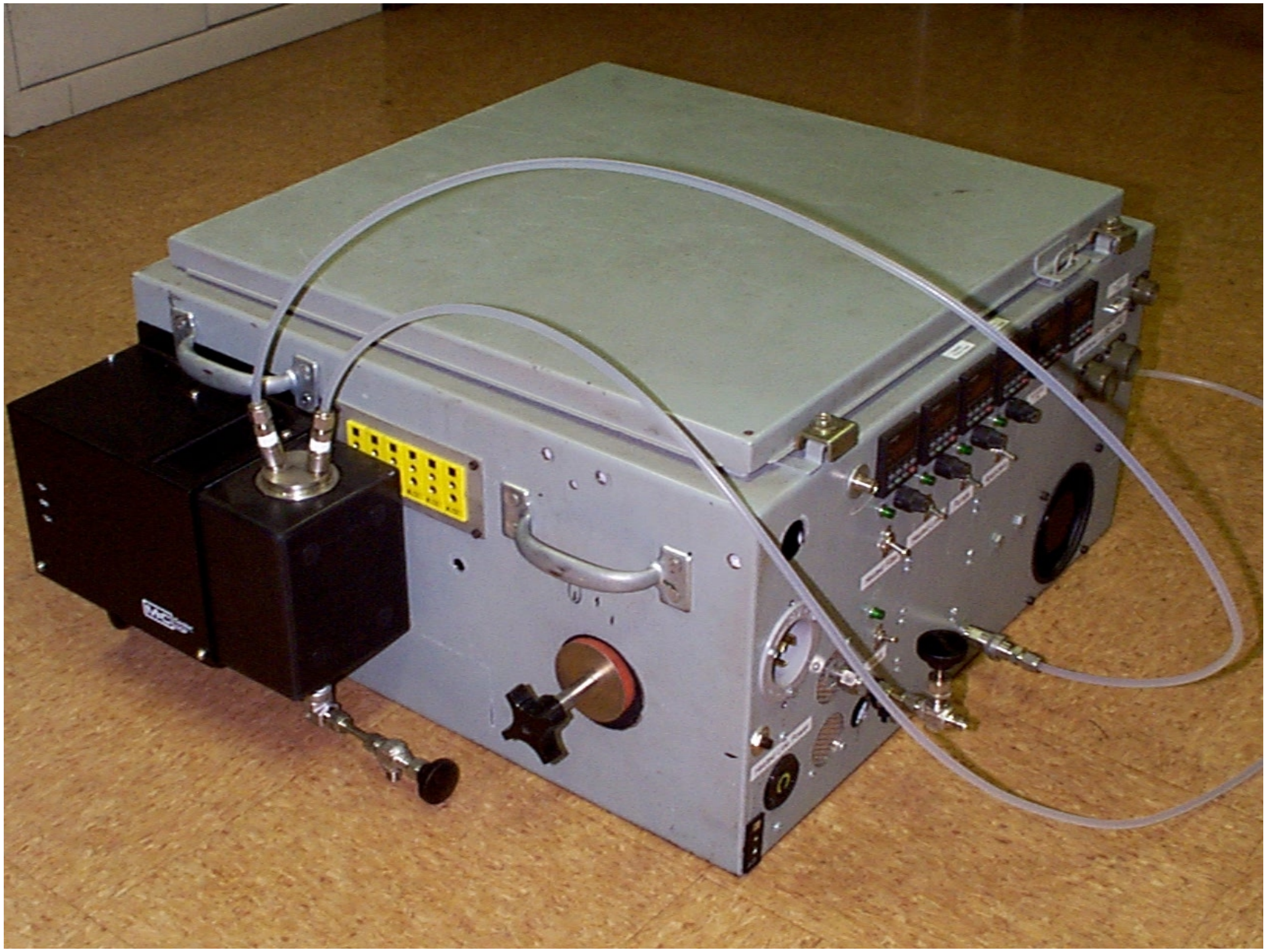
- **PHASE IV: CONDUCT ON-ROAD COMPLIANCE MONITORING OF HEAVY-DUTY DIESEL VEHICLES USING THE MONITORING TECHNOLOGY, AND PREVIOUSLY DEFINED TESTING PROCEDURES (AND DRIVING ROUTES) DEVELOPED BY WVU, AND APPROVED BY THE US EPA.**

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 CO_2
- Zirconium Oxide Sensor for NOx
- NO_2 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

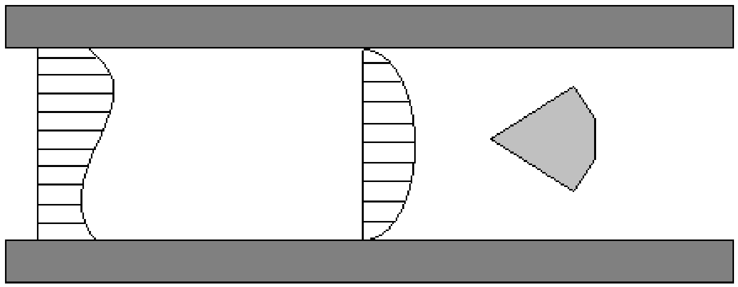
Accuracy to +/- 0.5%

Repeatability to 0.1%

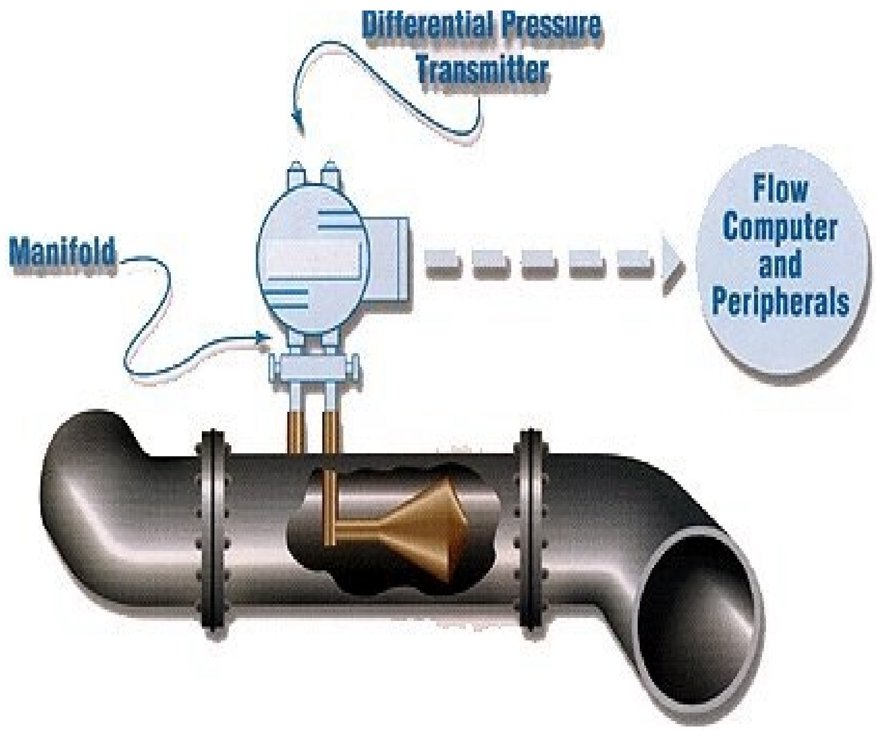
Low headloss

Low maintenance

No recalibration

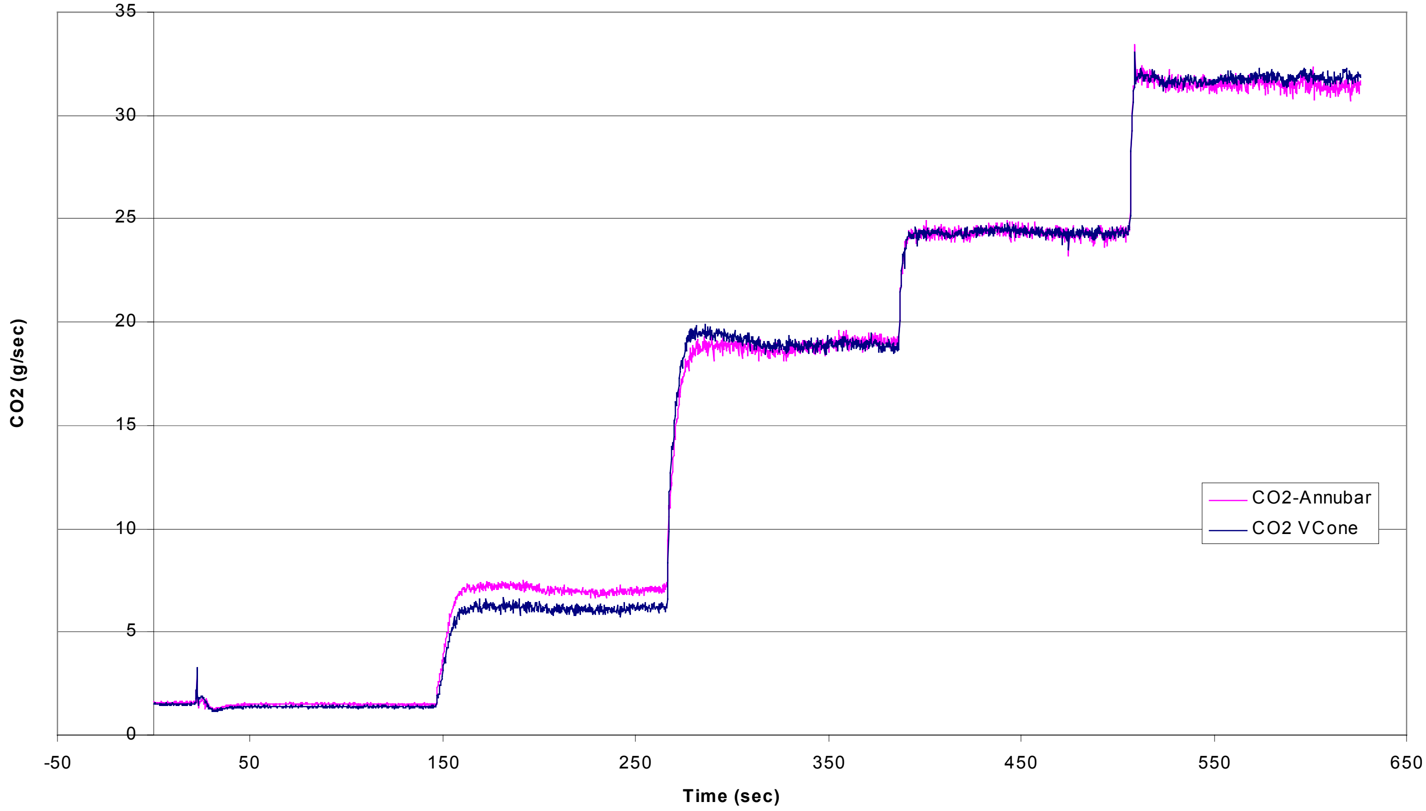


V-Cone®

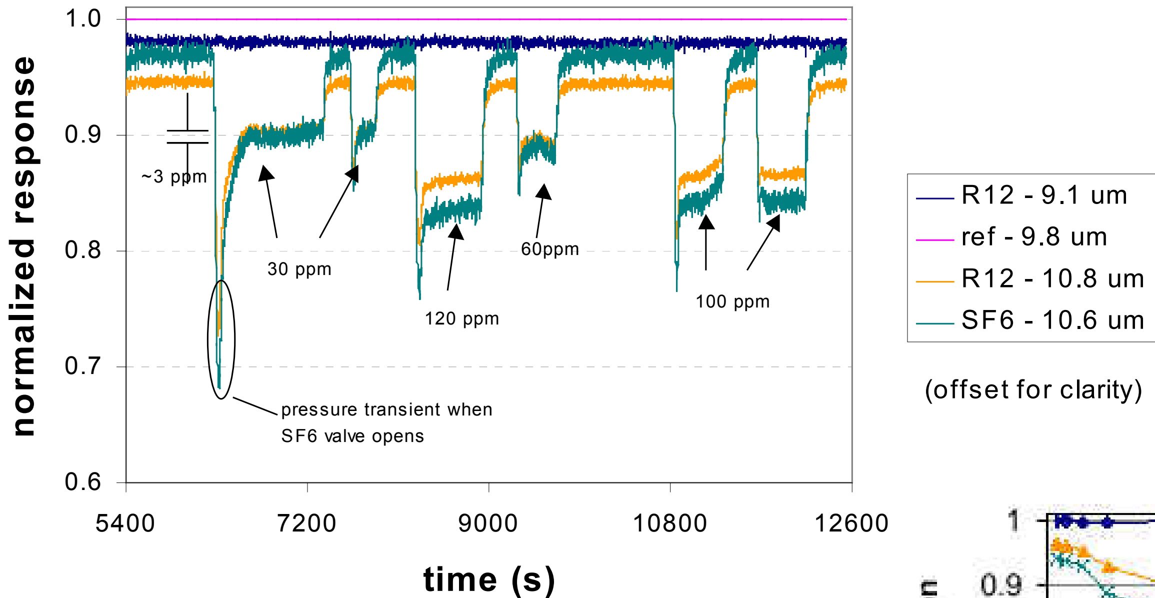

Differential Pressure
Transmitter
Manifold
Flow
Computer
and
Peripherals

CO_2 Mass Emission Rates Using V-Cone® and Annubar®

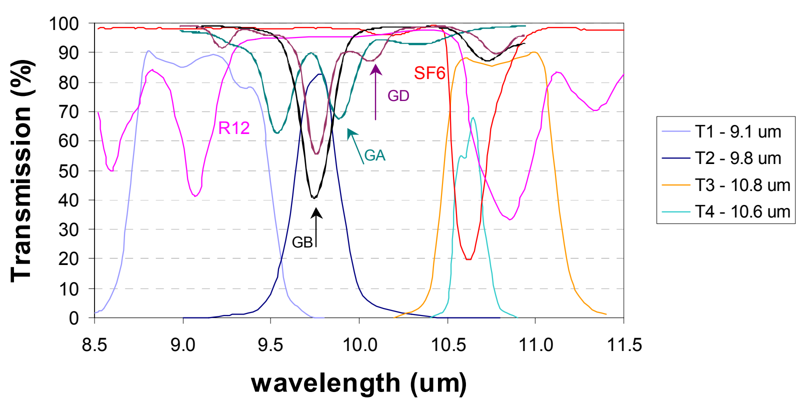
(DDC Series 60, MY2000)

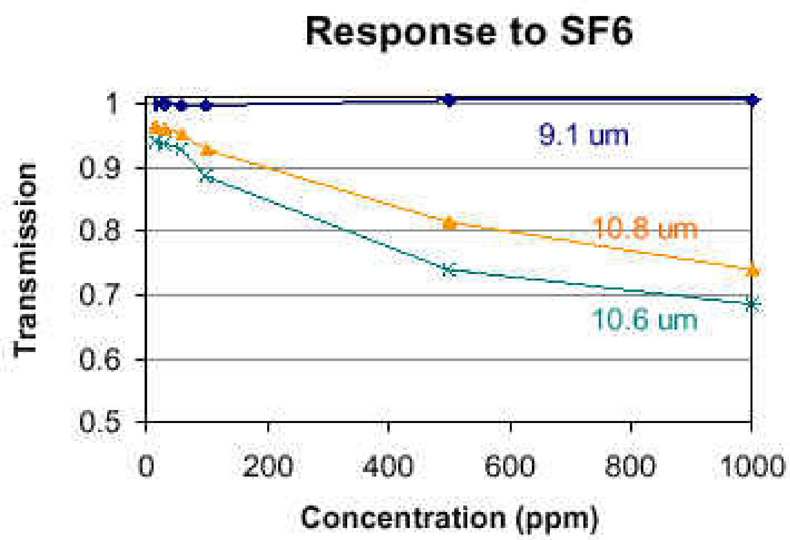


Solid State NDIR Sensor - Response to SF_6



The signal to noise ratio for these deflections indicates a sensitivity limit of ~3 ppm for SF_6 when the system response time is 1 second. Averaging over 5-10 seconds should improve sensitivity to better than 1 ppm.



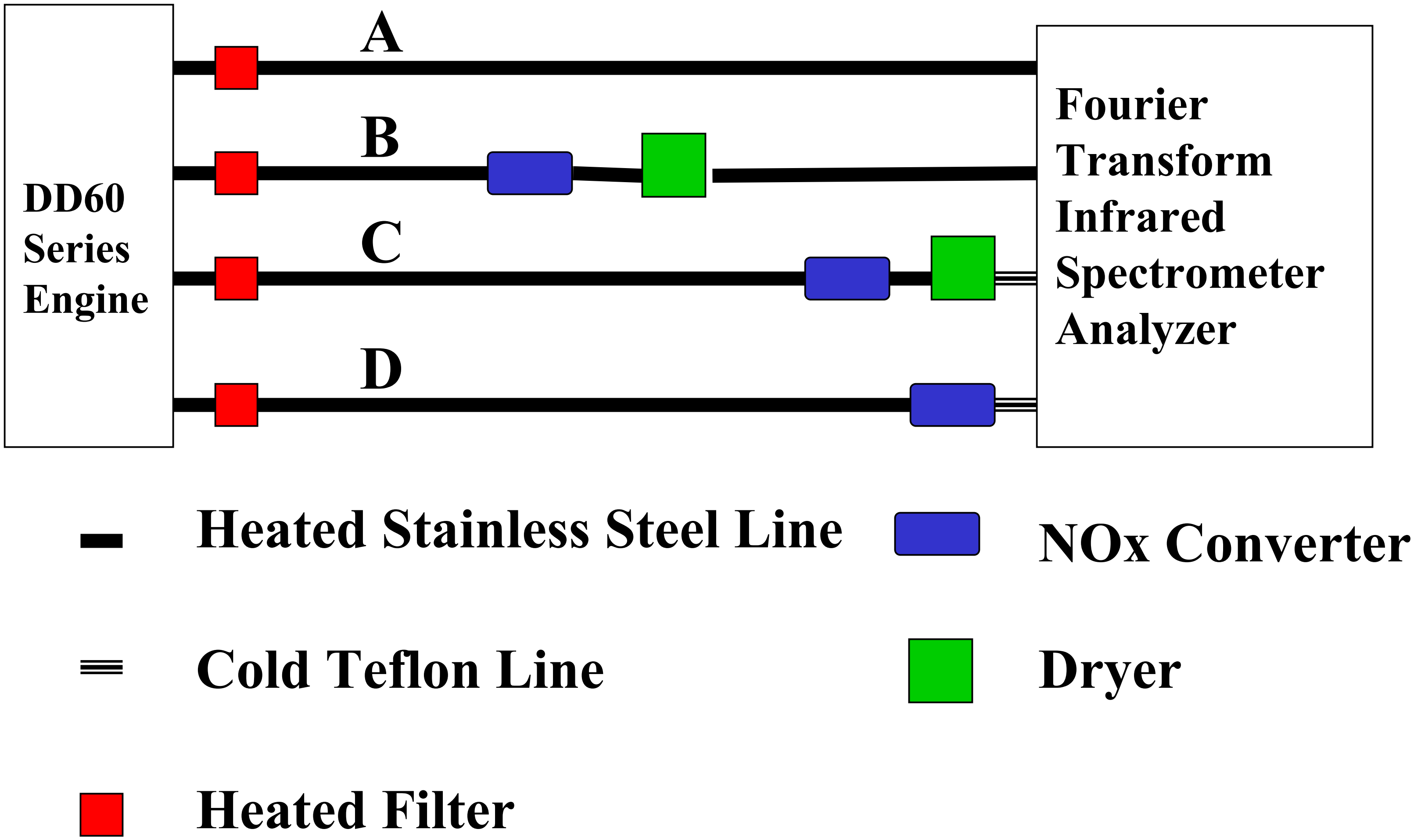


Source: Ion-Optics, Inc.

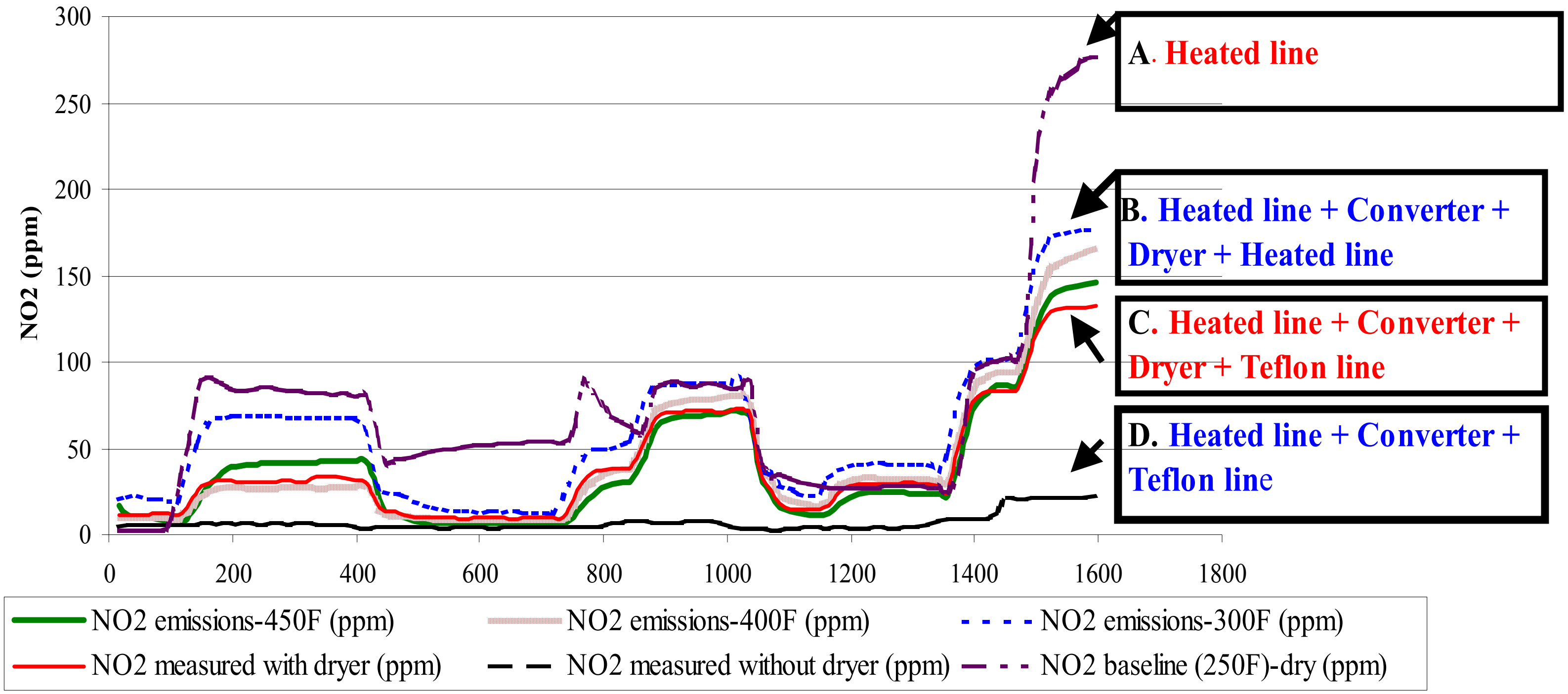
Percentage of NO_2 Reported by Zirconia Sensor

NO_2 Concentration (ppm) before NO_x Converter	Percent of NO_2 after Converter Reported by MEXA-120
62	-
124	70
186	78
248	82
310	78
372	74
434	70
496	65
558	62
620	58

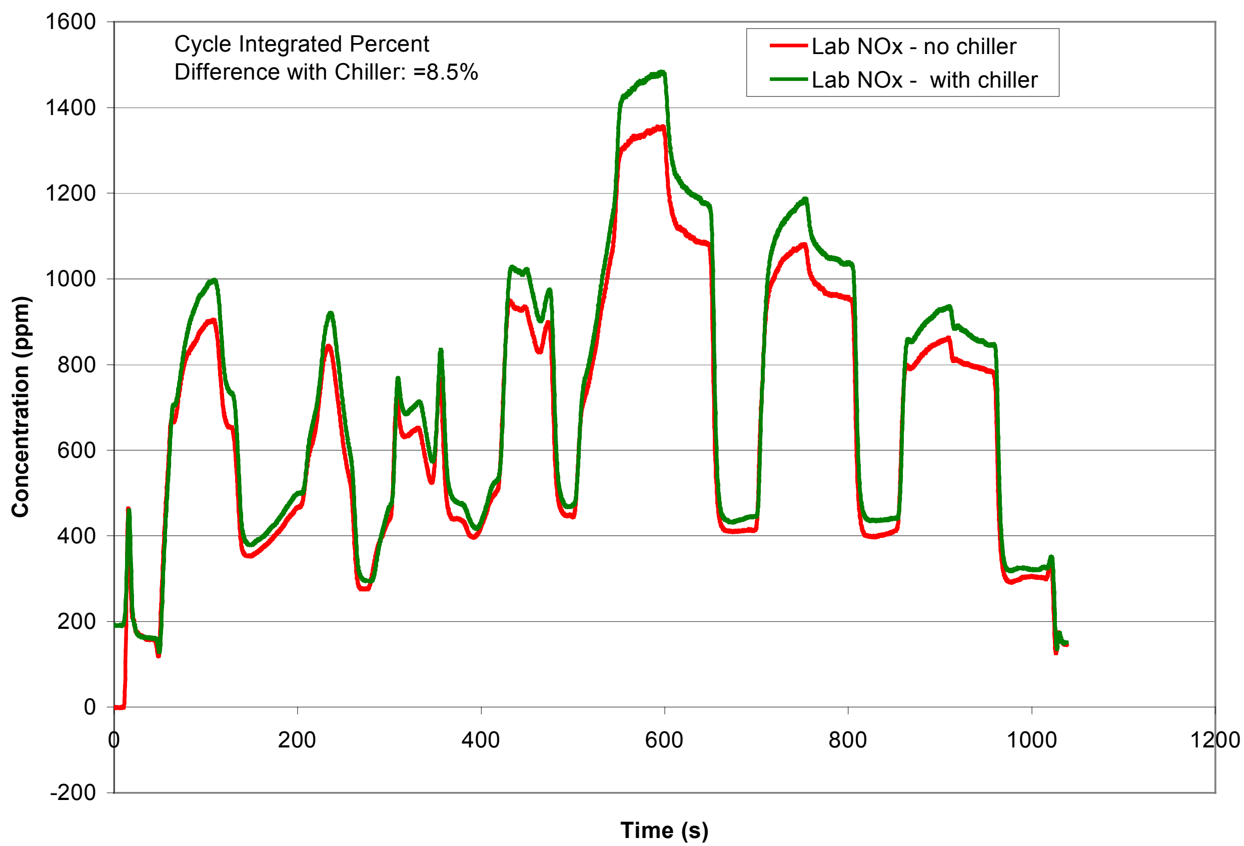
Effect of Sampling Lines on NOx Measurements



Effect of Sampling Lines on NOx Measurements



Comparison of Concentrations Reported by the 955 NO_x Analyzer with Wet and Dry Exhaust Samples from a Mack E7-400 Engine



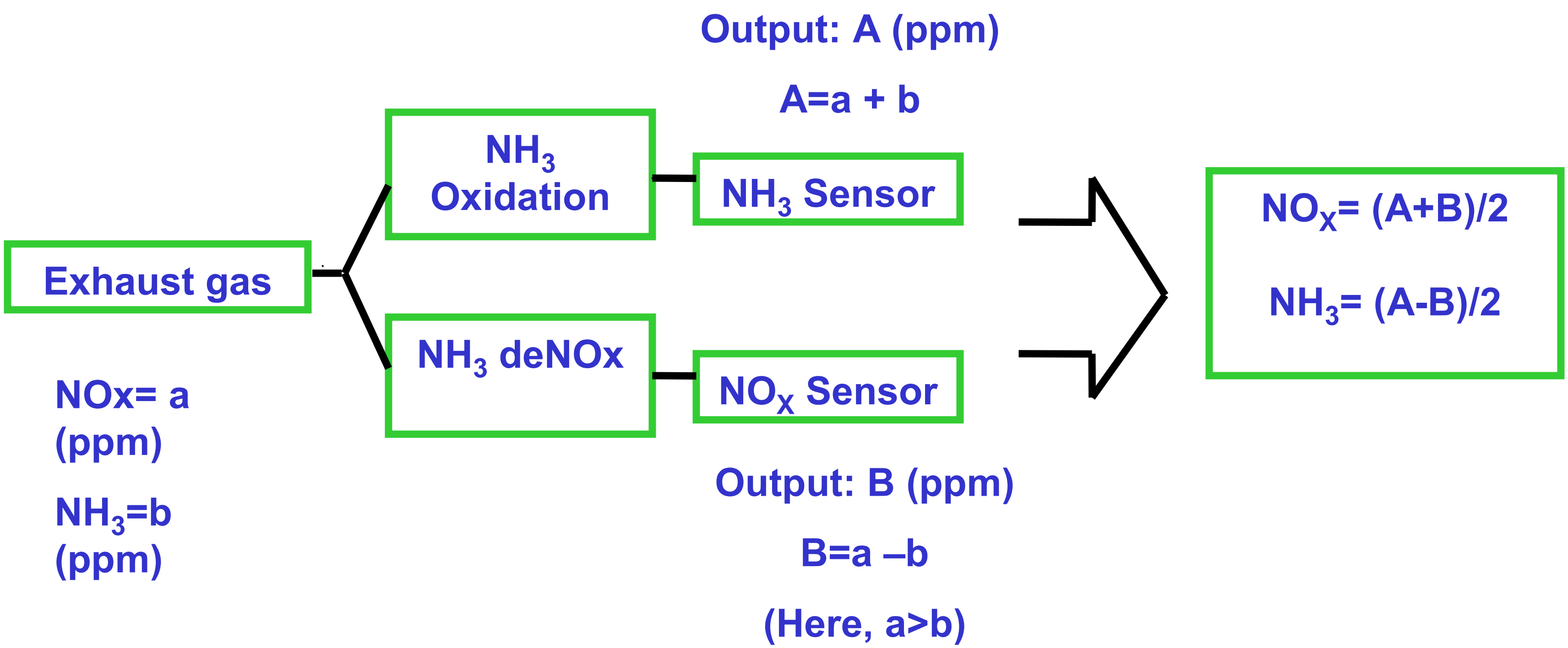
NO_X Index

grams of NOx / kg of Fuel

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

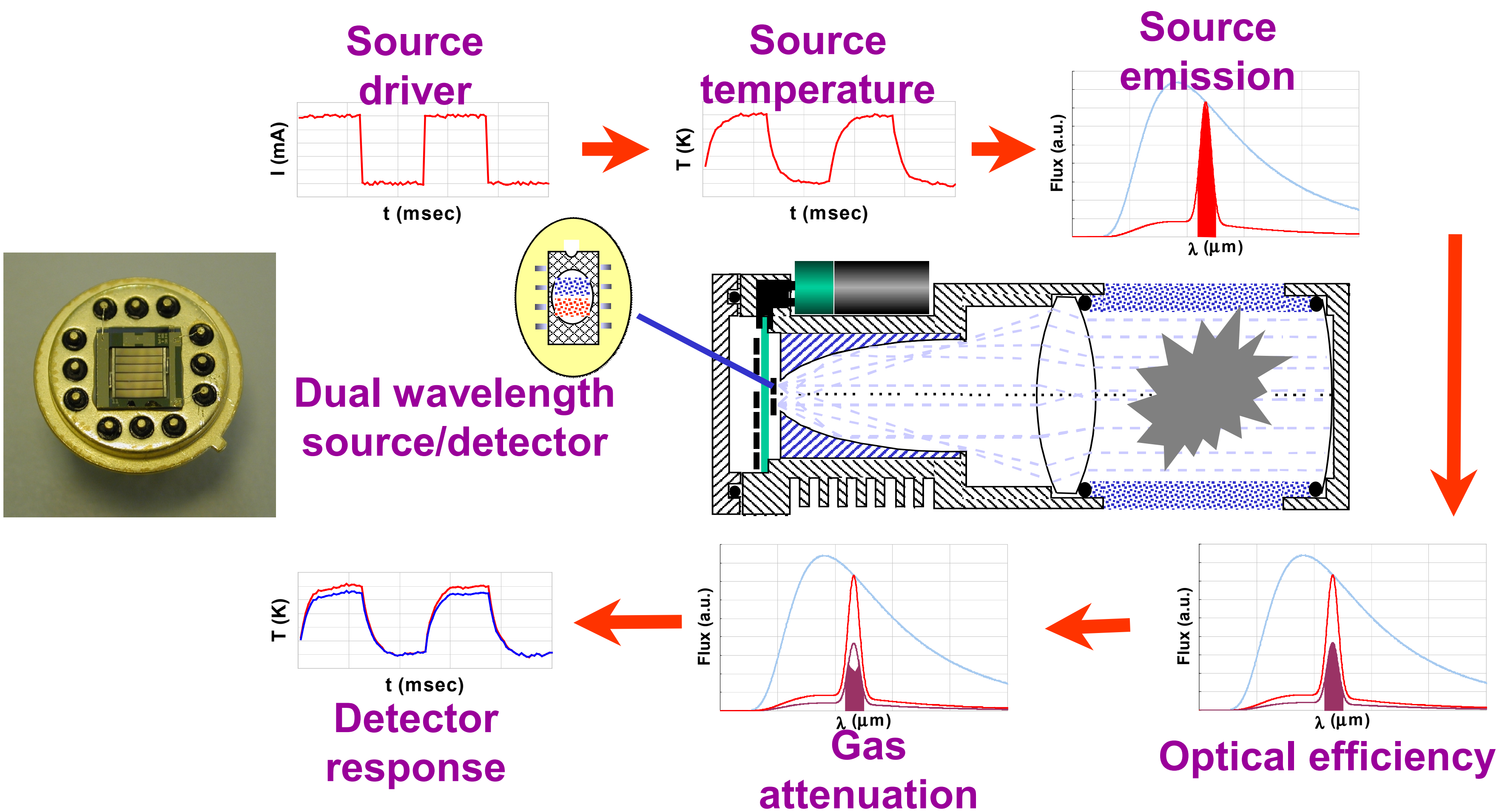
$$\frac{(\text{Concentration of NOx}) \times (\text{Exhaust flow rate}) \times MW_{NOx}}{(\text{Concentration of } CO_2) \times (\text{Exhaust flow rate}) \times (12.011+1.008*(H:C))}$$

NO_x/ NH_3 Zirconia Sensor



Kobayashi et al. (2001), Mitsubishi Heavy Industries, Ltd., Technical Review Vol. 38, No. 3, Oct. 2001

Sensor-on-a-Chip



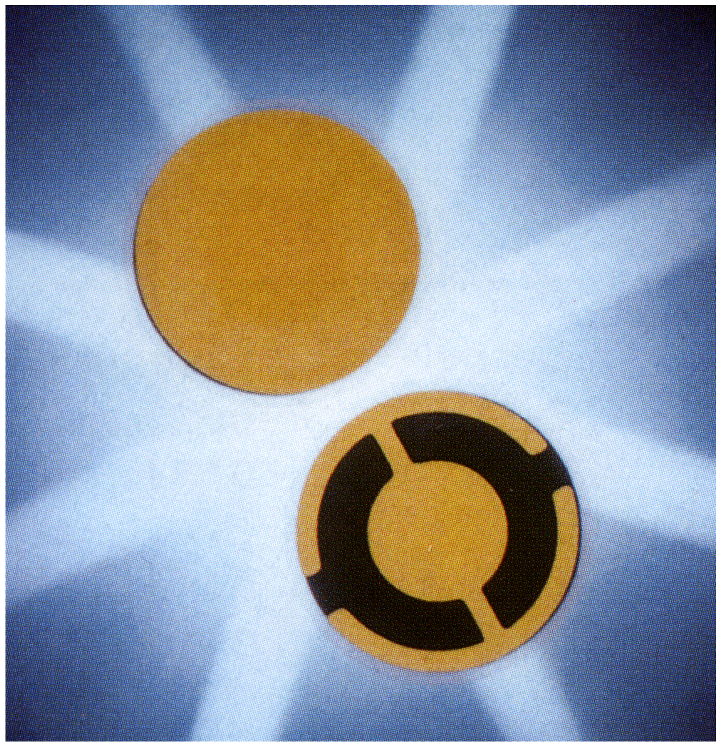
Source: Ion-Optics, Inc.

Real-Time Particulate Mass Monitor
MARI Model RPM 100®

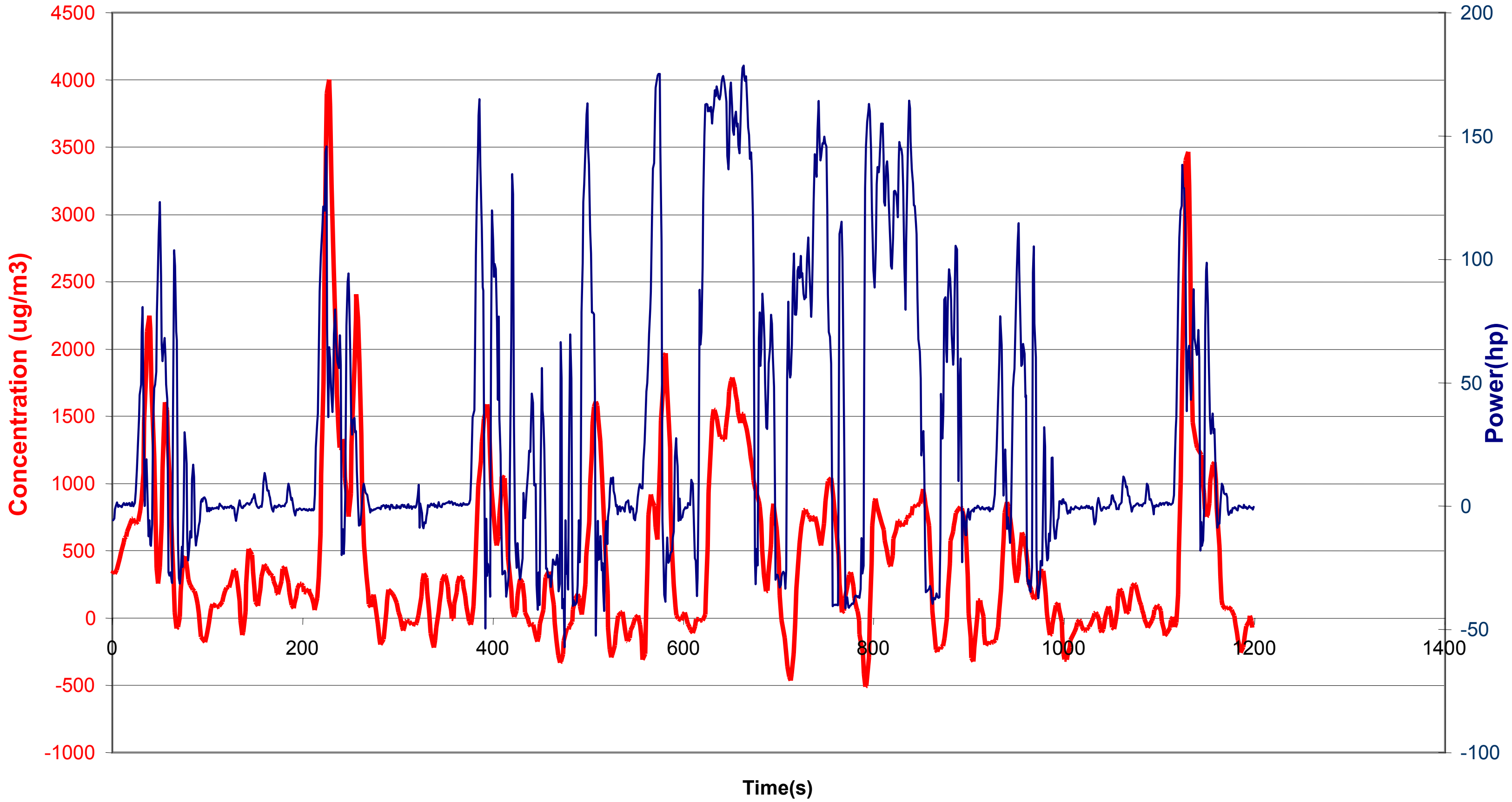
Sample Conditioning System and a Microbalance

Dilution Ratios – 1:12 to 1:2000

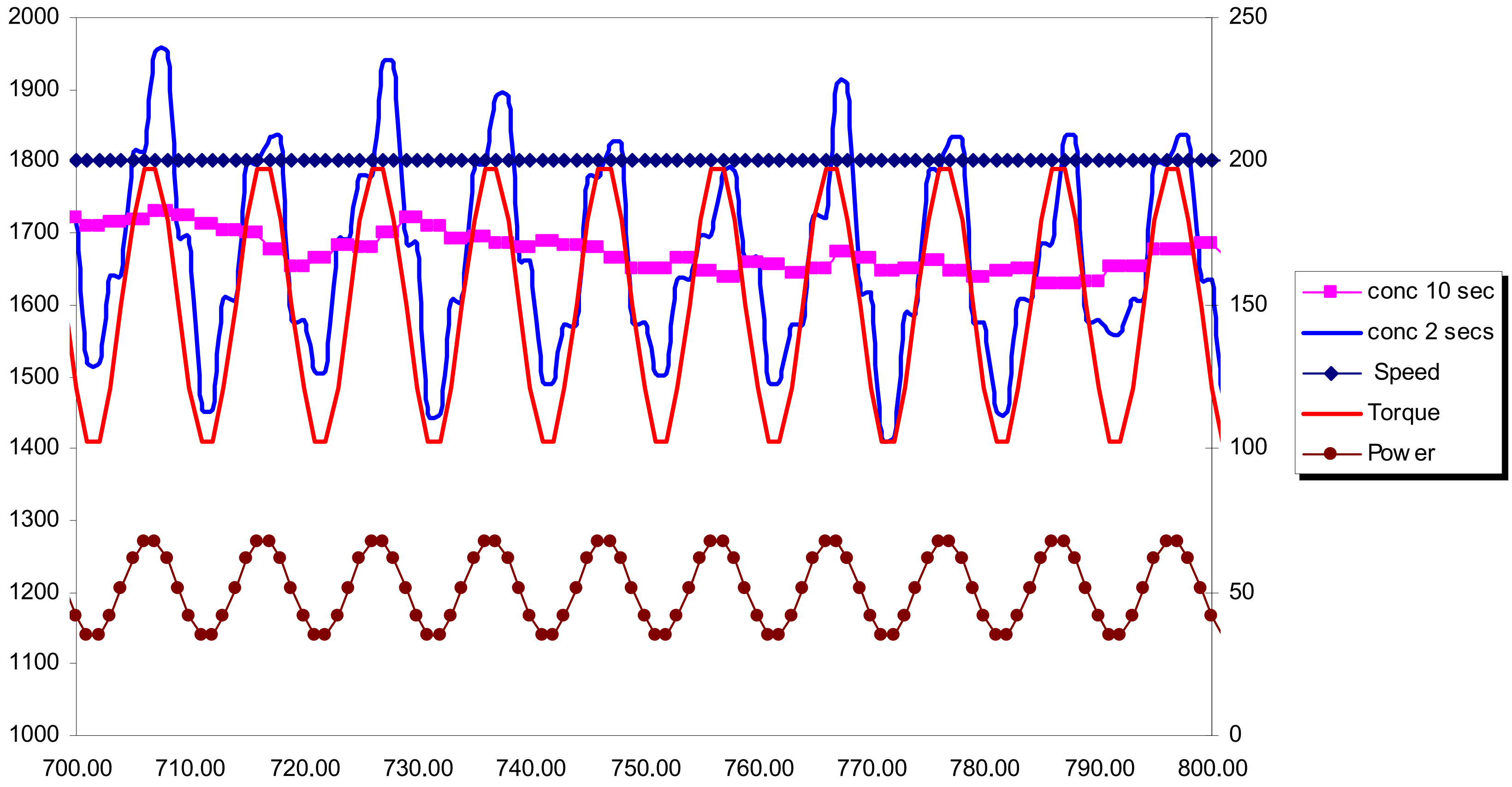
Crystal Surfaces



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

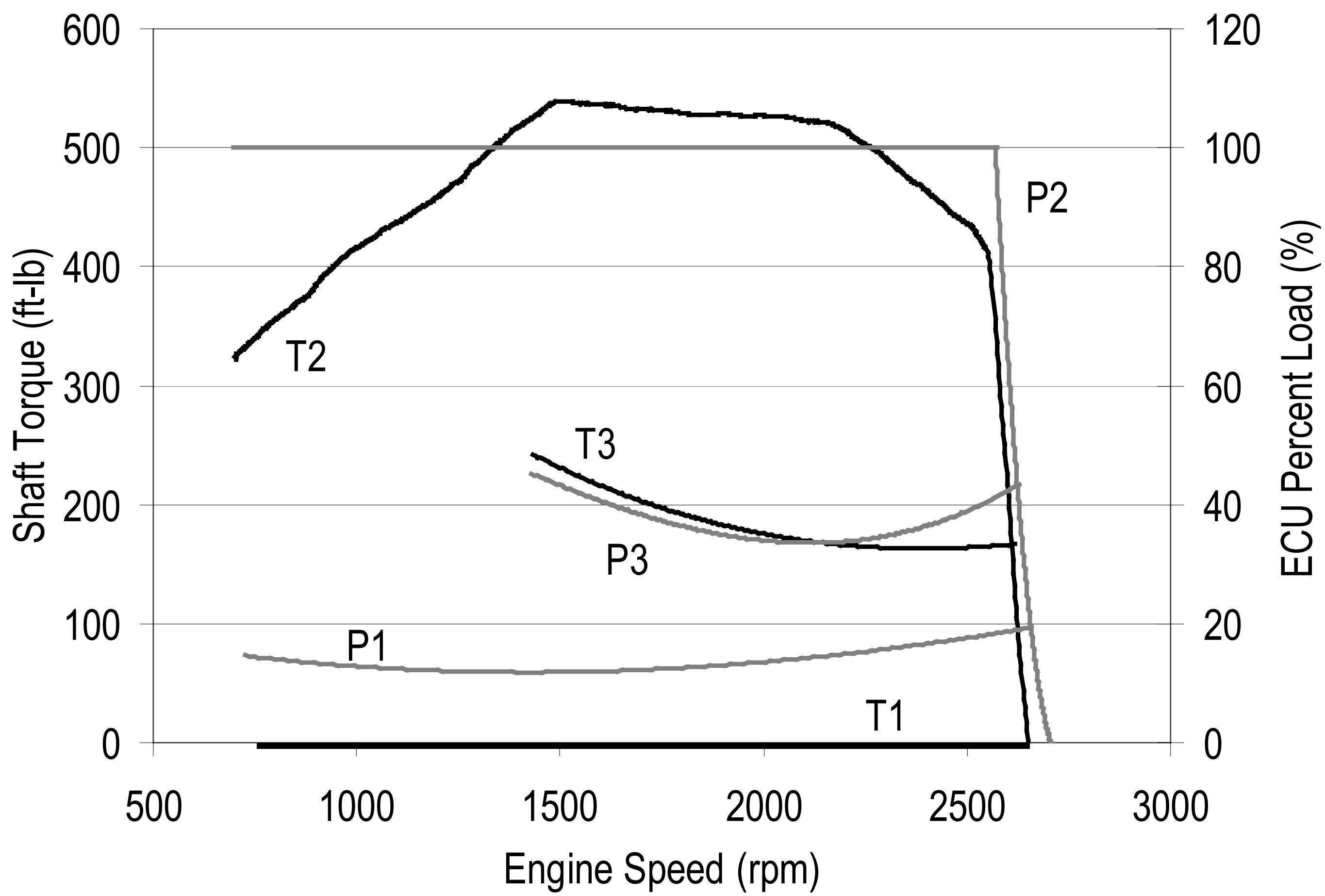
Function of: **Lug Curve**
Friction Torque (Zero Fueling Curve or Zero Flywheel (Zero Output Shaft Load)
Percent Load Curve

WVU Approach:

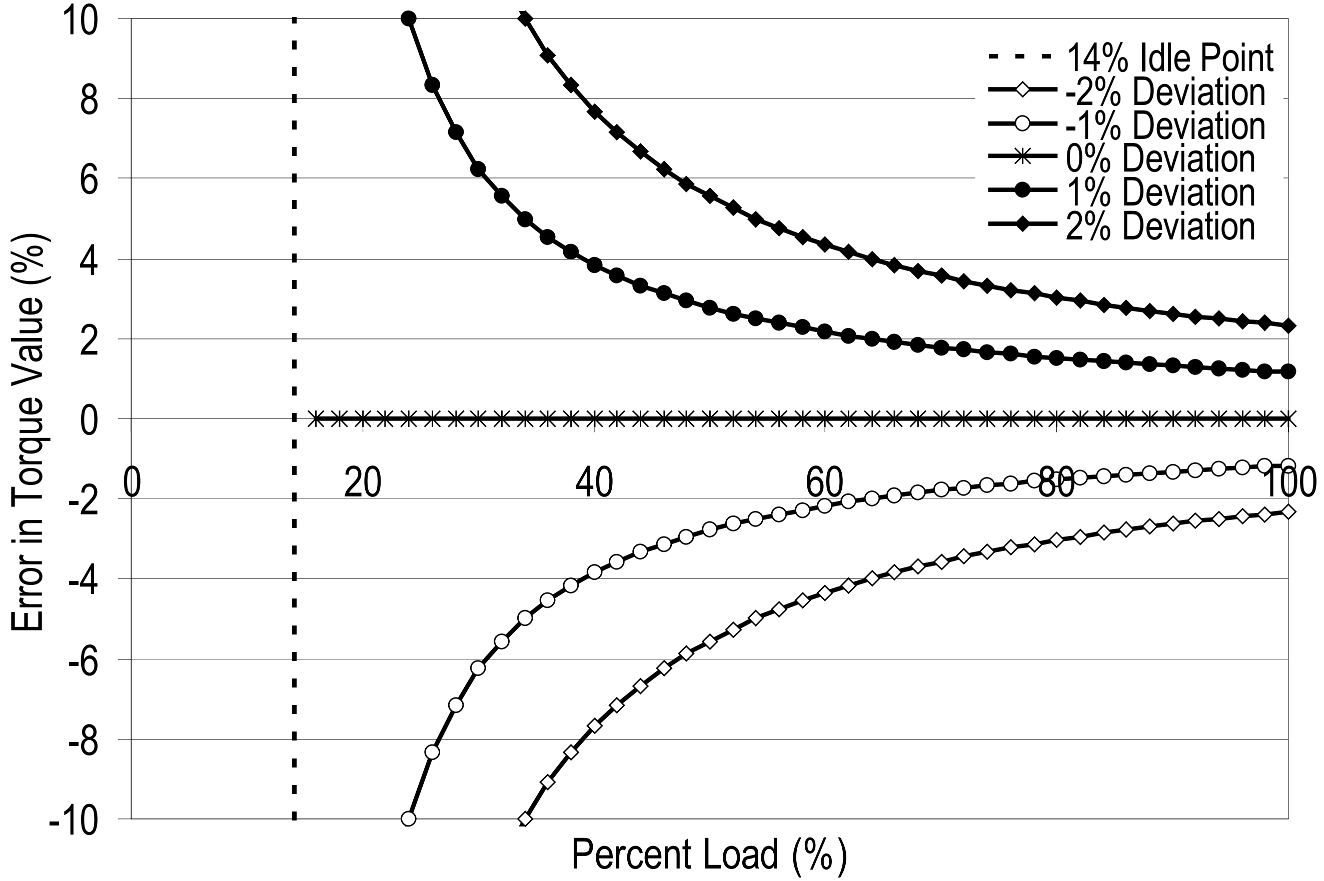
Measure the no-load percent load through the speed domain at the curb and employ the lug curve obtained through laboratory testing or from manufacturer-supplied data.

$$T^{rpm}(t) = \left(\frac{ECU_{\%}^{rpm} - ECU_{noload}^{rpm}}{ECU_{\%\max}^{rpm} - ECU_{noload}^{rpm}} \right) * T_{\max}^{rpm}$$

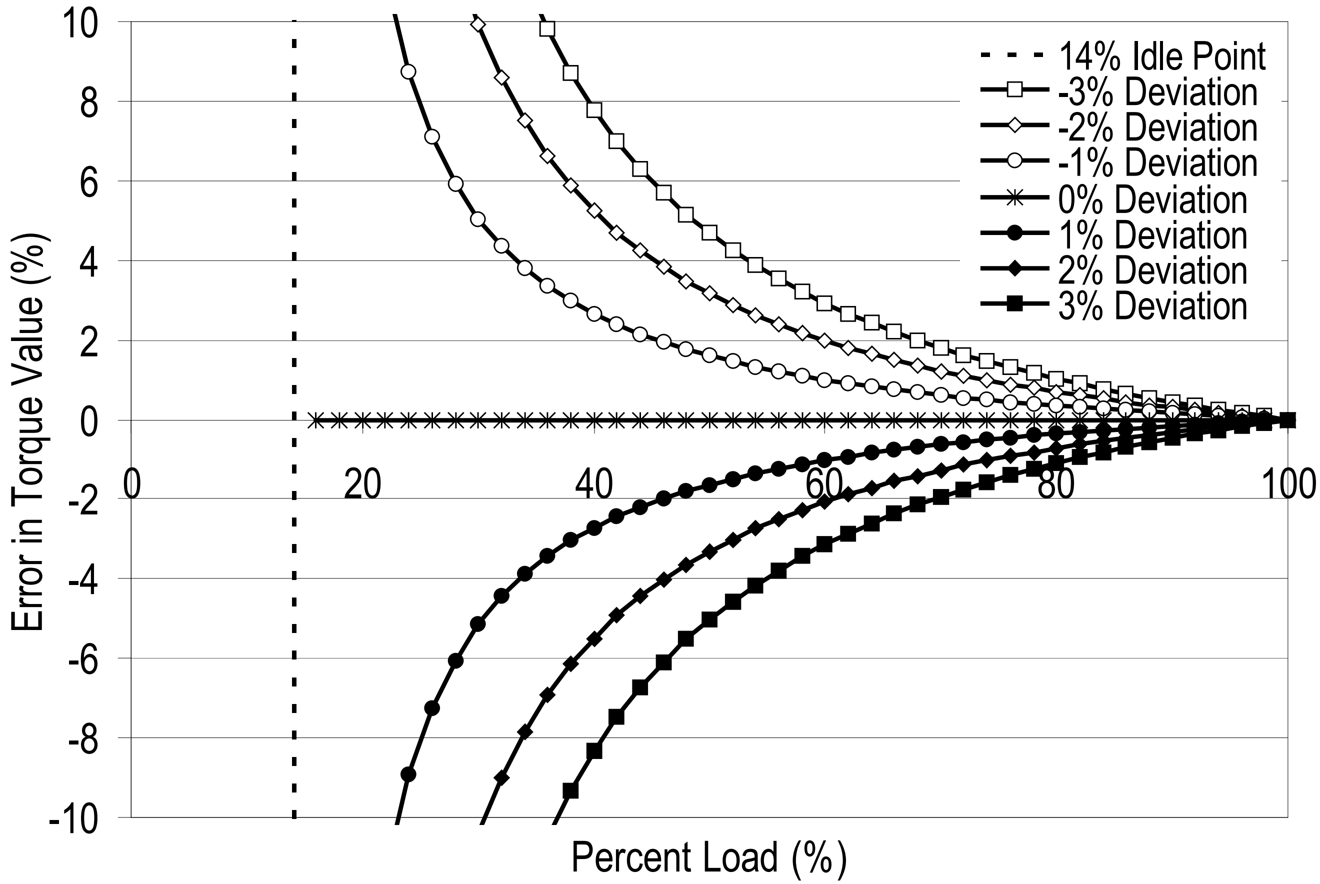
Shaft Torque and ECU Percent Load Variation for a Modern Electronically Controlled Engine



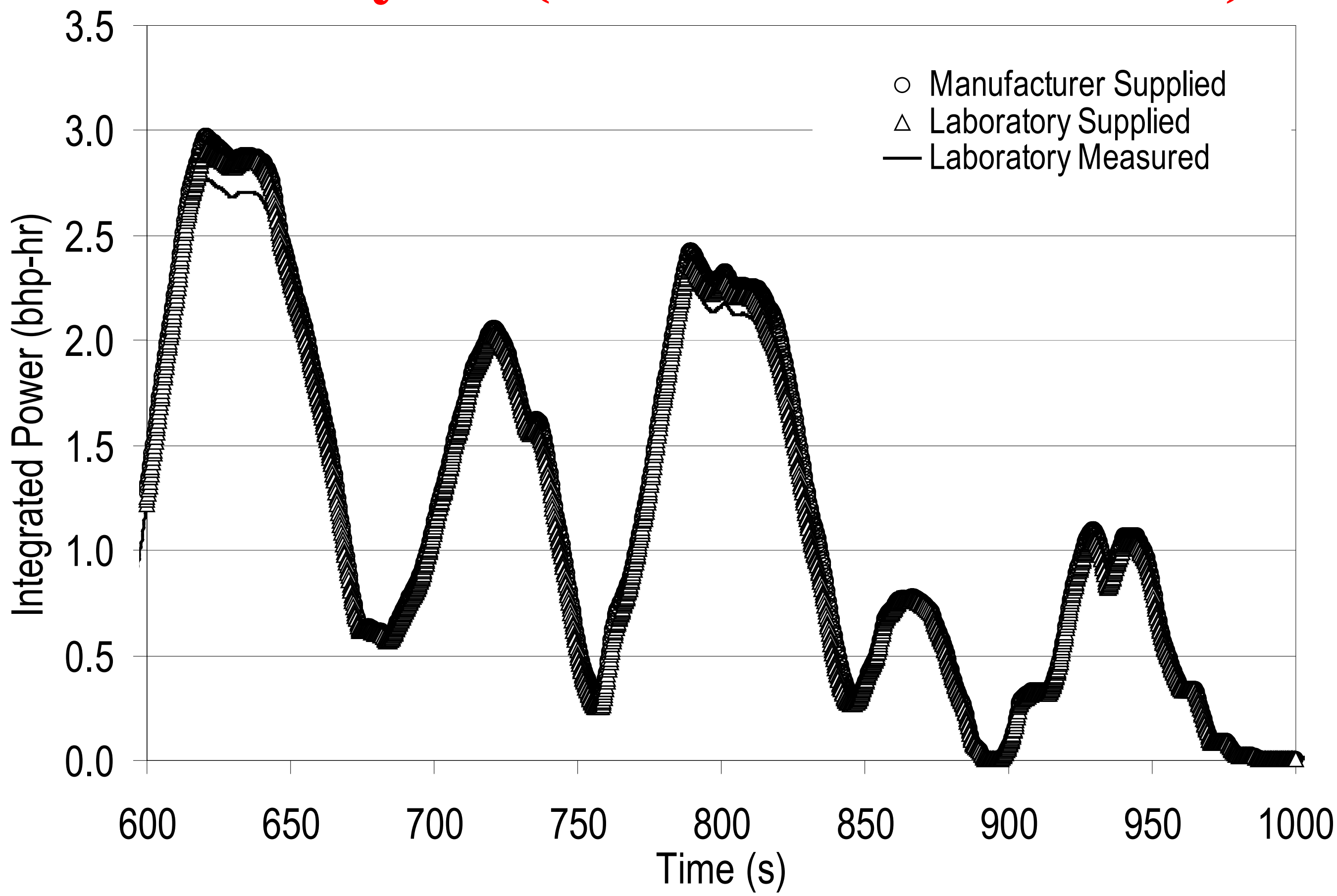
Error in the Inferred Torque Due to an Error in Measured Percent Load



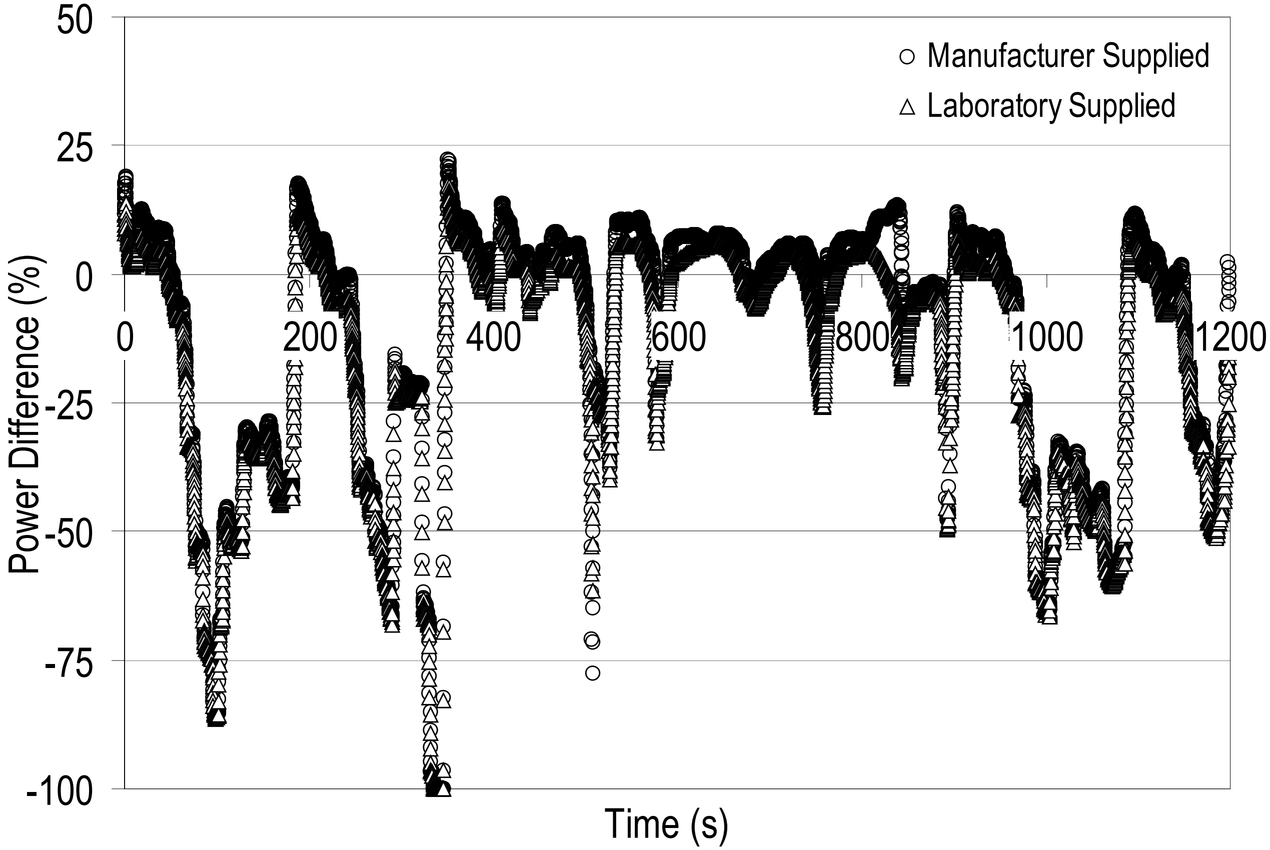
Error in the Inferred Torque Due to an Error in No-Load ECU Load Reading



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)



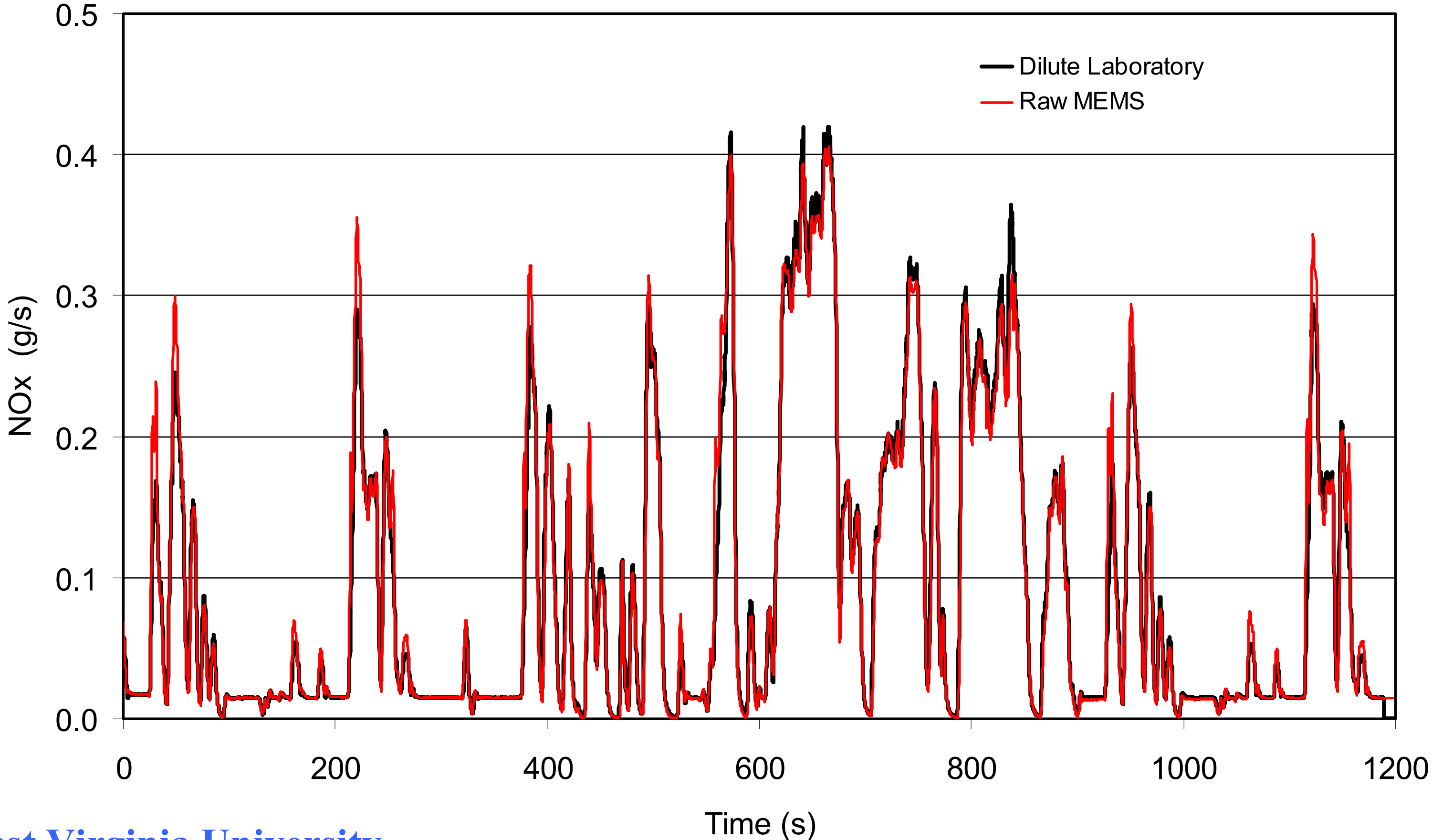
Integrated 30 Second Brake Power Windows Percent Difference Between Laboratory and ECU Inferred Data for a Modern Diesel Engine Exercised through the FTP Cycle



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$_X$ MASS EMISSION RATES ON FTP – REAL WORLD AND LABORATORY: CUMMINS ISM 370



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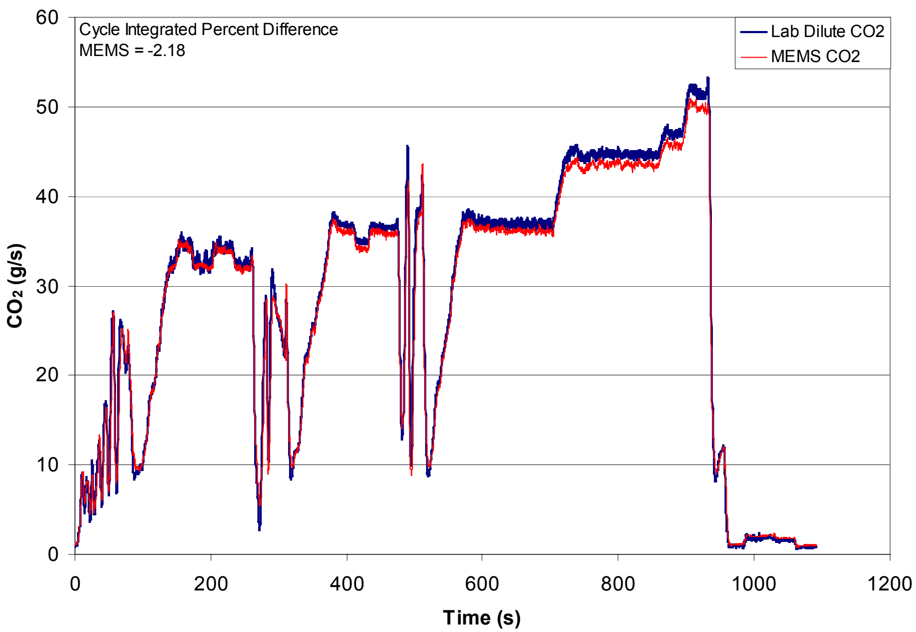
COMPARISON OF BRAKE SPECIFIC EMISSIONS RESULTS FROM THE FTP TEST CELL AND MEMS

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%

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%

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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, CO_2 analyzer; Horiba MEXA-120 NOx analyzer.
  - Horiba NOx converter, M&C Products thermoelectric chiller.
- MEMS is capable of reporting brake-specific emissions of CO_2 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.