NOx and PM Emission Levels from Heavy-duty Diesel Engines in Southern California
and
Challenges in In-use Emissions Measurements

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Study reported in this presentation:

CRC Project No. E-55/E-59

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WVU In-House Research Programs

In-use Emissions Measurements

Objectives

Program E-55/59 had the objectives of acquiring regulated emissions and non-regulated emissions data from in-use trucks in southern California.

- Particle Sizing
- Tampering & Mal-maintenance
- Weight Effects
- Cycle Effects
- MY effects
- HHDDT & MHDDT & MHDGT

THIS PRESENTATION WILL FOCUS ON DISTANCE-SPECIFIC NOx AND PM EMISSIONS OVER THE TRANSIENT AND CRUISE MODES OF OPERATION

Vehicles Examined in E-55/59 Program

- Phase 1
  - 25 Vehicles (25 HHDDT)
- Phase 1.5
  - 12 Vehicles (12 HHDDT) + 1 idle only
- Phase 2
  - 19 Vehicles (10 HHDDT, 7 MHDDT, 2 MHDGT)
- Phase 3
  - 19 Vehicles (9 HHDDT, 8 MHDDT , 2 MHDGT)
- Total
  - 75 Vehicles (56 HHDDT, 19 MHDT)

TRANSPORTABLE LABORATORY

Vehicle Emissions Measurements

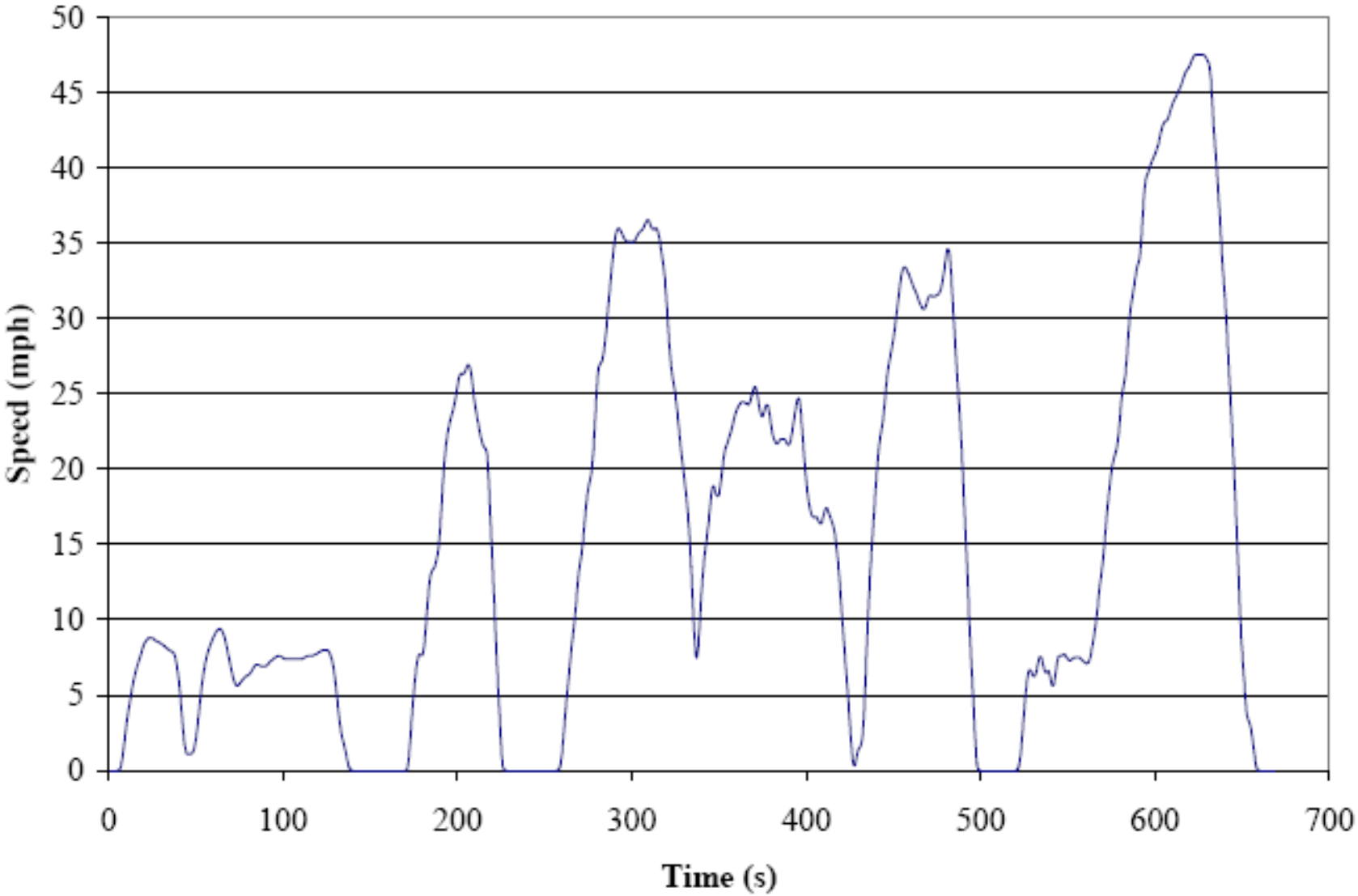
- Vehicle exhaust diluted with ambient air in an 18 inch diameter dilution tunnel, with flow controlled by a critical flow venturi.
- Samples taken at a plane located 10 diameters from the introduction point to allow for proper mixing.
- Measurements of gaseous emissions concentrations made using research grade analyzers.
- Particulate emissions measured by passing dilute exhaust through 70mm filters.
- PM data were acquired in Phases 1.5, 2 and 3 using both conventional filters and a Tapered Element Oscillating Microbalance (TEOM).
- Two chemiluminescent NO_x analyzers were used to assure quality of measurements.

Federal and CARB Emissions Standards

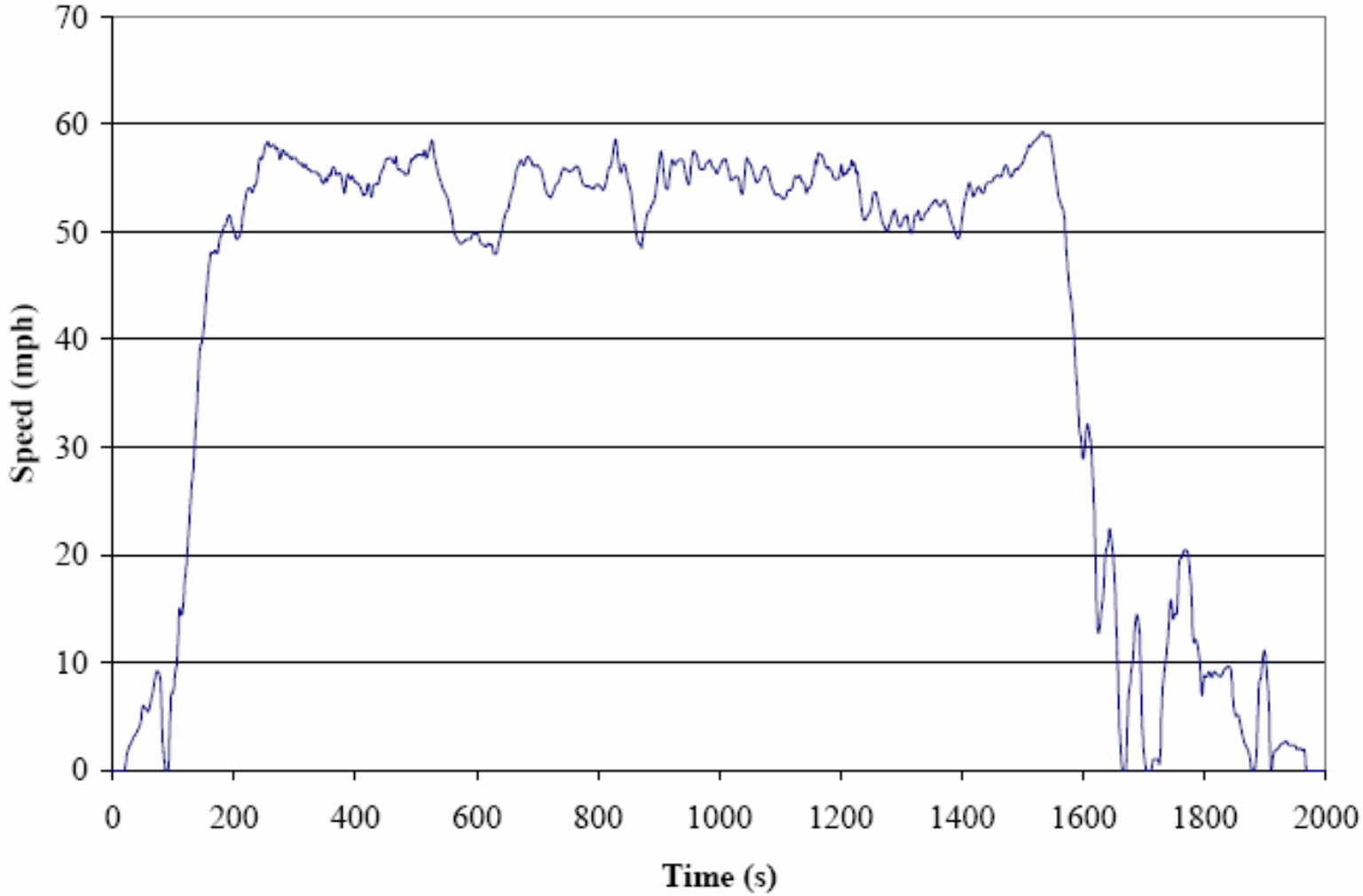
FEDERAL HEAVY-DUTY TRUCK STANDARDS						CALIFORNIA HEAVY-DUTY TRUCK STANDARDS					
MODEL YEAR	HC[1]	CO	NO_X	PM	*HC+NO_X*	MODEL YEAR	HC[1]	CO	NO_X	PM	HC+NO_X
	g/bhp-hr						g/bhp-hr				
						1975-76	---	30.0	---	---	10.0
1974-78	---	40.0	---	---	16.0	1977-79	1.0	25.0	7.5	---	---
1979-83	1.5	25.0	---	---	10.0	1980-83	1.0	25.0	---	---	6.0
1984-87	1.3	15.5	10.7	---	---	1984-86	1.3	15.5	5.1	---	---
1988-90	1.3	15.5	10.7	0.60	---	1987-90	1.3	15.5	6.0	0.60	---
1991-93	1.3	15.5	5.0	0.25	---	1991-93	1.3	15.5	5.0	0.25	---
1994-97	1.3	15.5	5.0	0.10	---	1994-97	1.3	15.5	5.0	0.10	---
1998	1.3	15.5	4.0	0.10	---	1998	1.3	15.5	4.0	0.10	---
2004	0.5[2]	15.5	2.5	0.10	---	2004	0.5[2]	15.5	2.5	0.10	---

[1] Note: the HC standards shown are total hydrocarbons except for model year 2004 which is NMHC.
[2] Assumes 2.5 g/bhp-hr (NO_X+NMHC) with 0.5 g/bhp-hr NMHC. NOx : 2.4 if NMHC is not reported

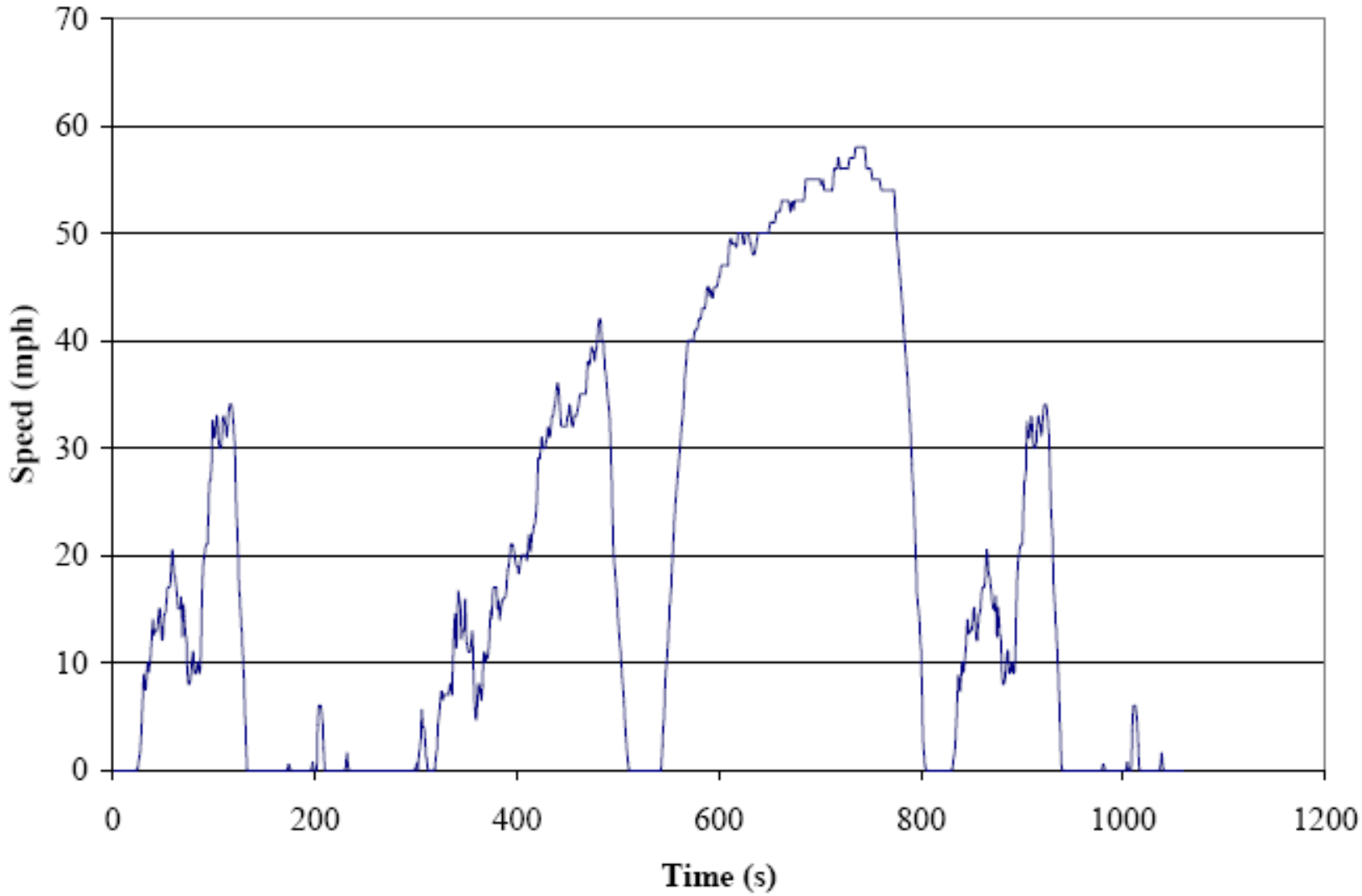
TRANSIENT MODE (Trans3)



CRUISE MODE (Cruise3)

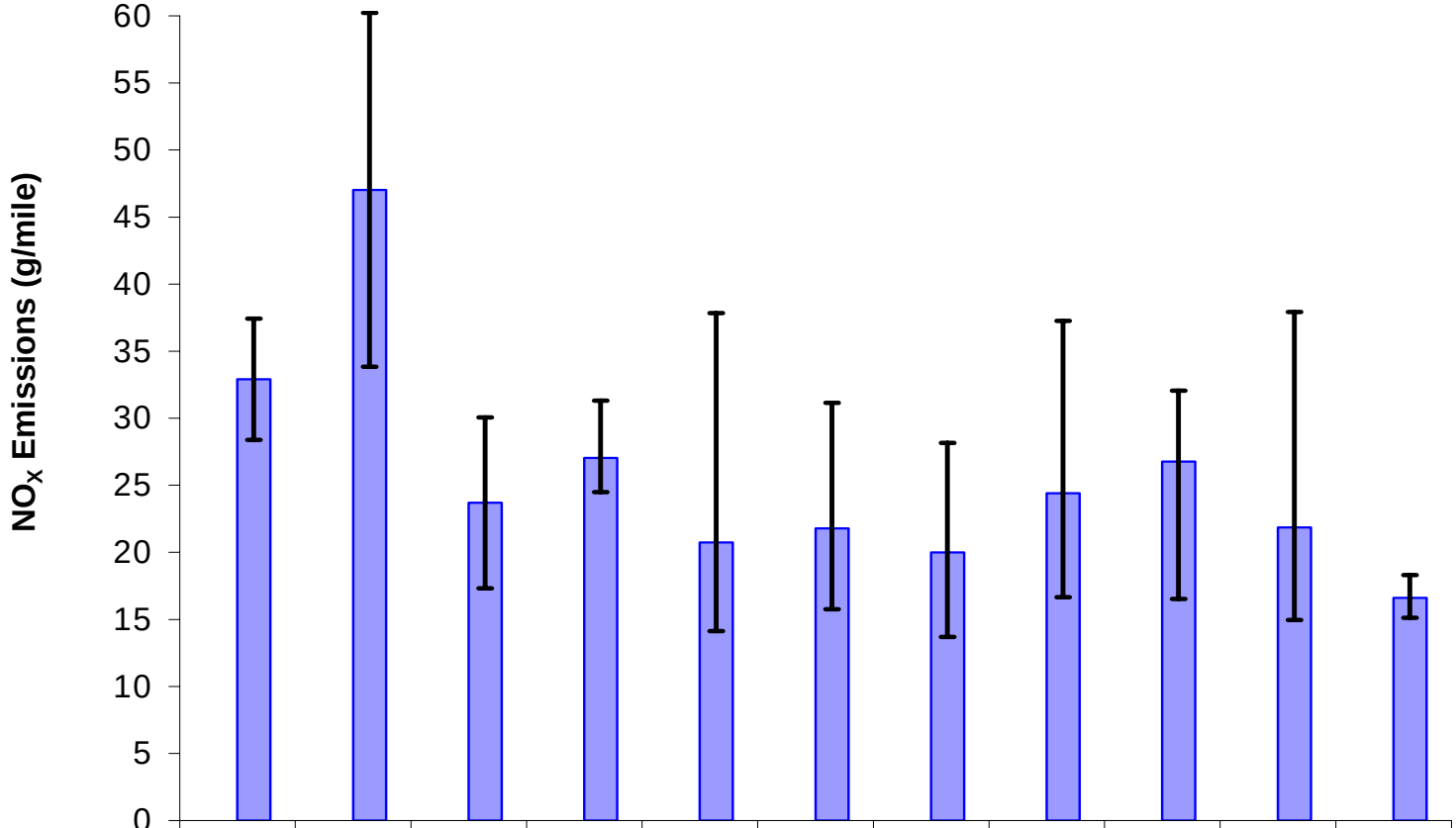


UDDS



HHDDT Oxides of Nitrogen Emissions

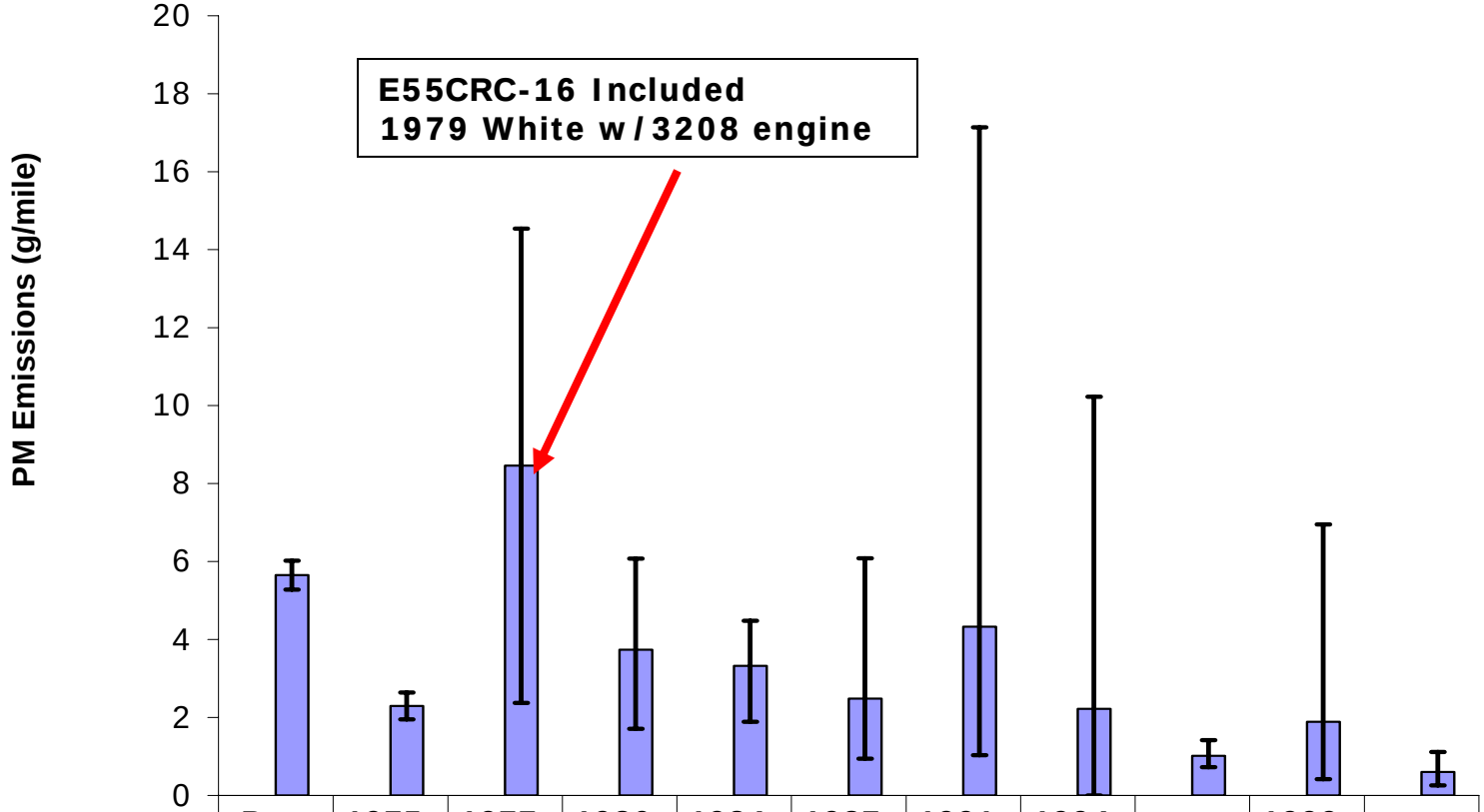
(Average of measurements over the Transient Mode @ 56,000 lb. simulated weight)



	Pre-1975	1975-1976	1977-1979	1980-1983	1984-1986	1987-1990	1991-1993	1994-1997	1998	1999-2002	2003+
Number of Vehicles	2	2	2	3	5	8	6	8	4	11	5
NOx (g/mile)	32.90	47.03	23.69	27.03	20.73	21.78	19.99	24.39	26.77	21.84	16.61

HHDDT Particulate Matter Emissions

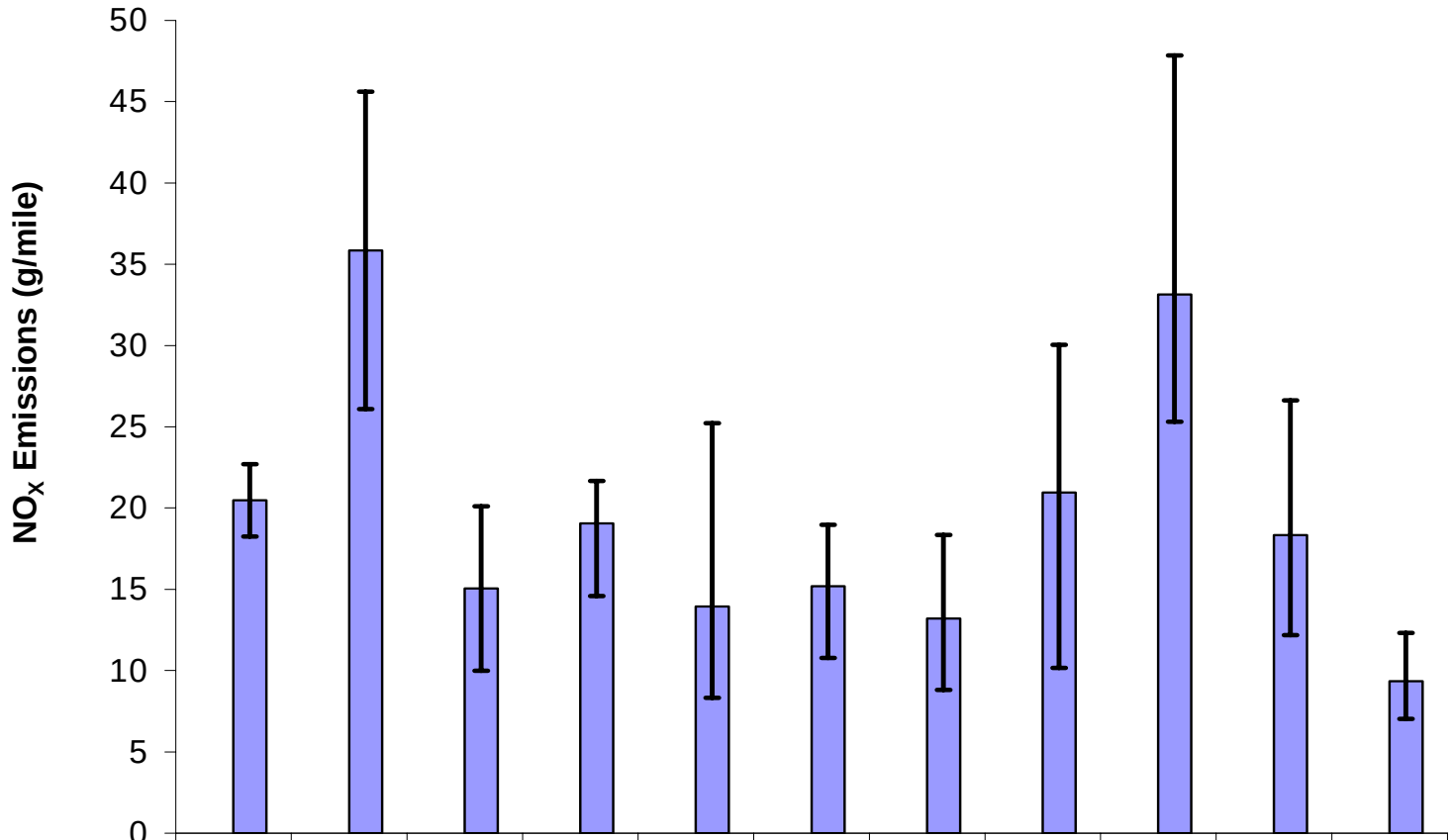
(Average of measurements over the Transient Mode @ 56,000 lb. simulated weight)



	Pre-1975	1975-1976	1977-1979	1980-1983	1984-1986	1987-1990	1991-1993	1994-1997	1998	1999-2002	2003+
Number of Vehicles	2	2	2	3	5	8	6	8	4	11	5
PM (g/mile)	5.65	2.30	8.46	3.74	3.32	2.48	4.33	2.22	1.01	1.89	0.60

HHDDT Oxides of Nitrogen Emissions

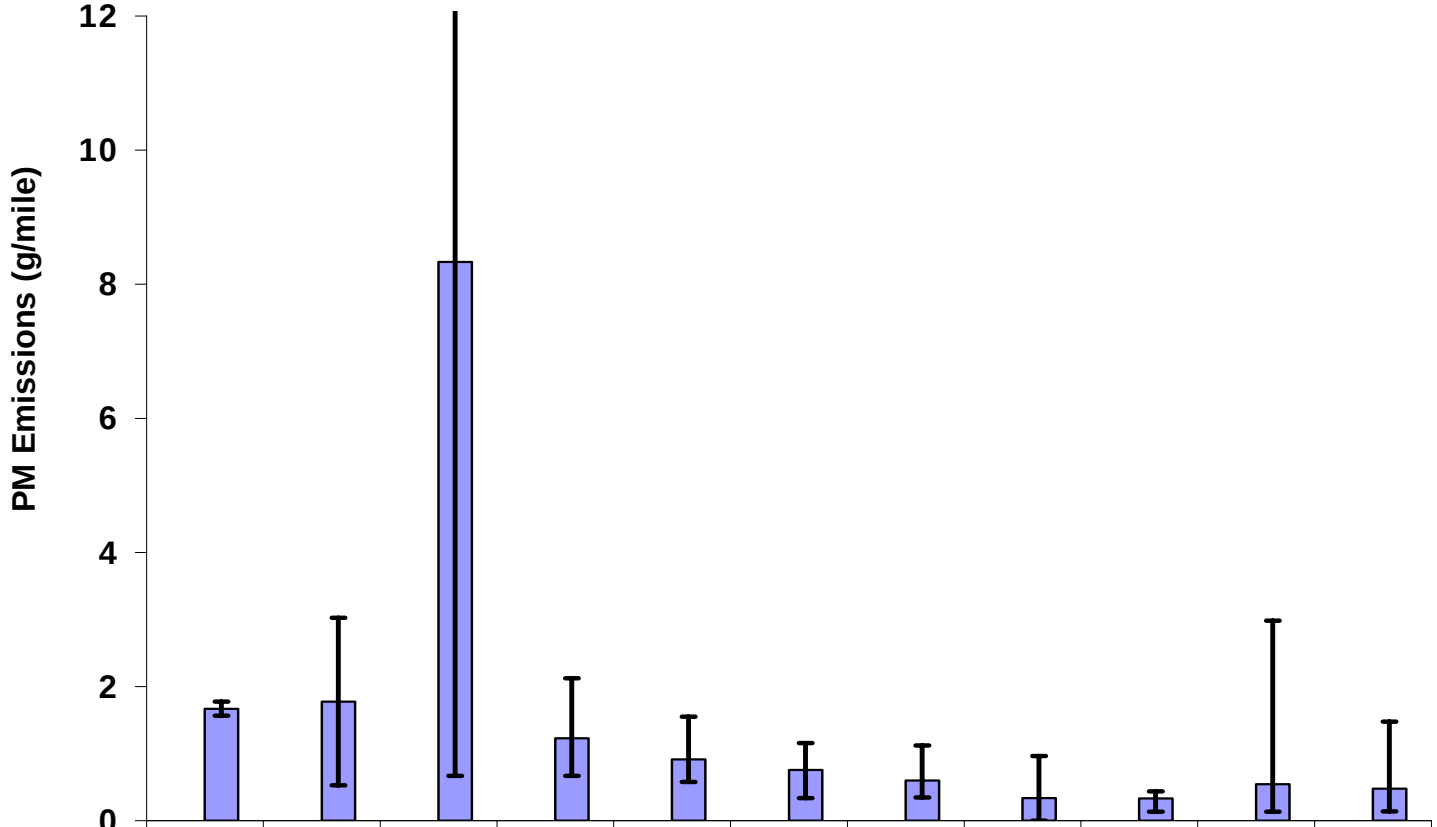
(Average of measurements over the Cruise Mode @ 56,000 lb. simulated weight)



	Pre-1975	1975-1976	1977-1979	1980-1983	1984-1986	1987-1990	1991-1993	1994-1997	1998	1999-2002	2003+
Number of Vehicles	2	2	2	3	5	8	6	8	4	11	5
NOx (g/mile)	20.47	35.85	15.05	19.05	13.94	15.19	13.20	20.96	33.14	18.34	9.35

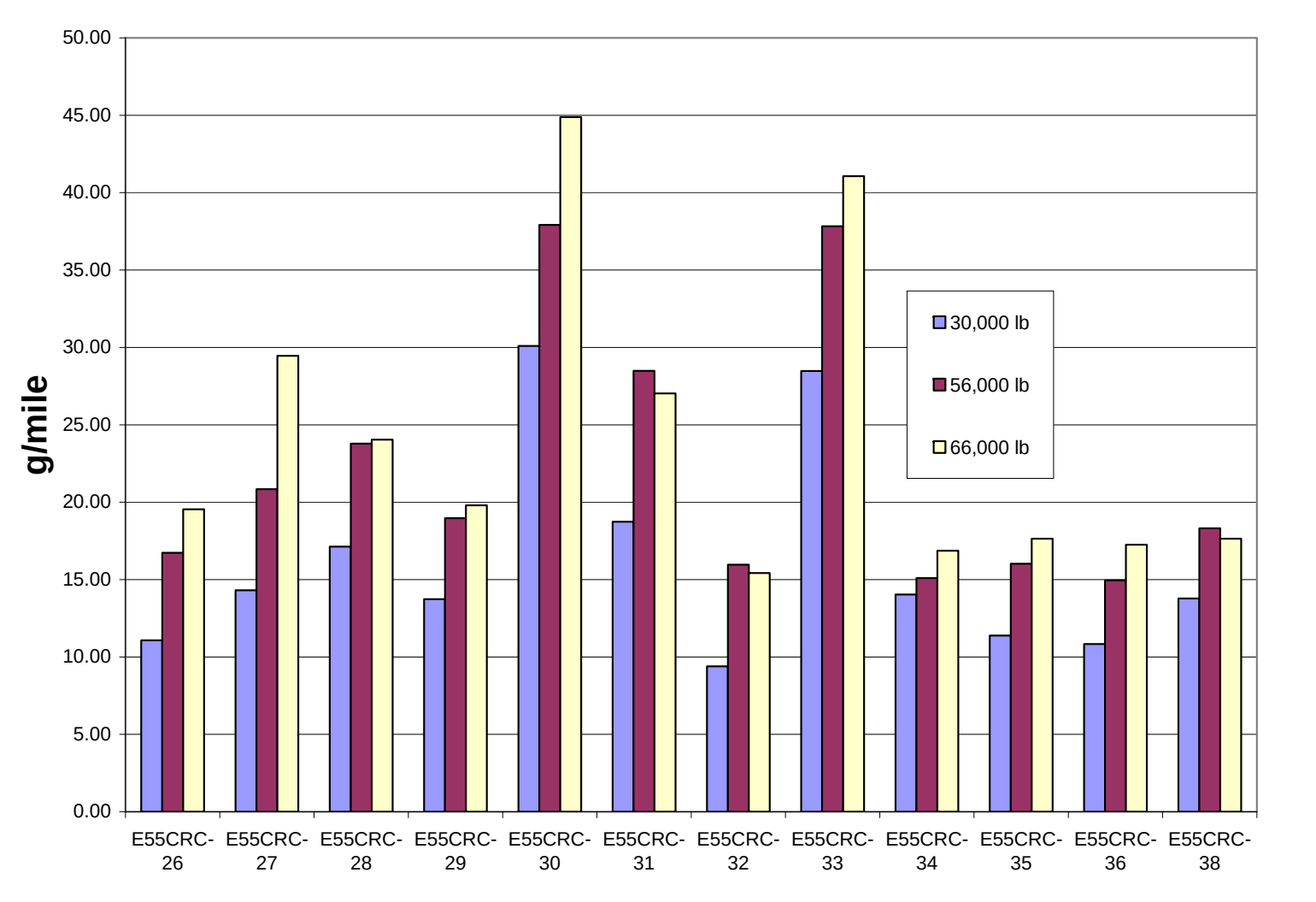
HHDDT Particulate Matter Emissions

(average of measurements over the Cruise Mode @ 56,000 lb. simulated weight)



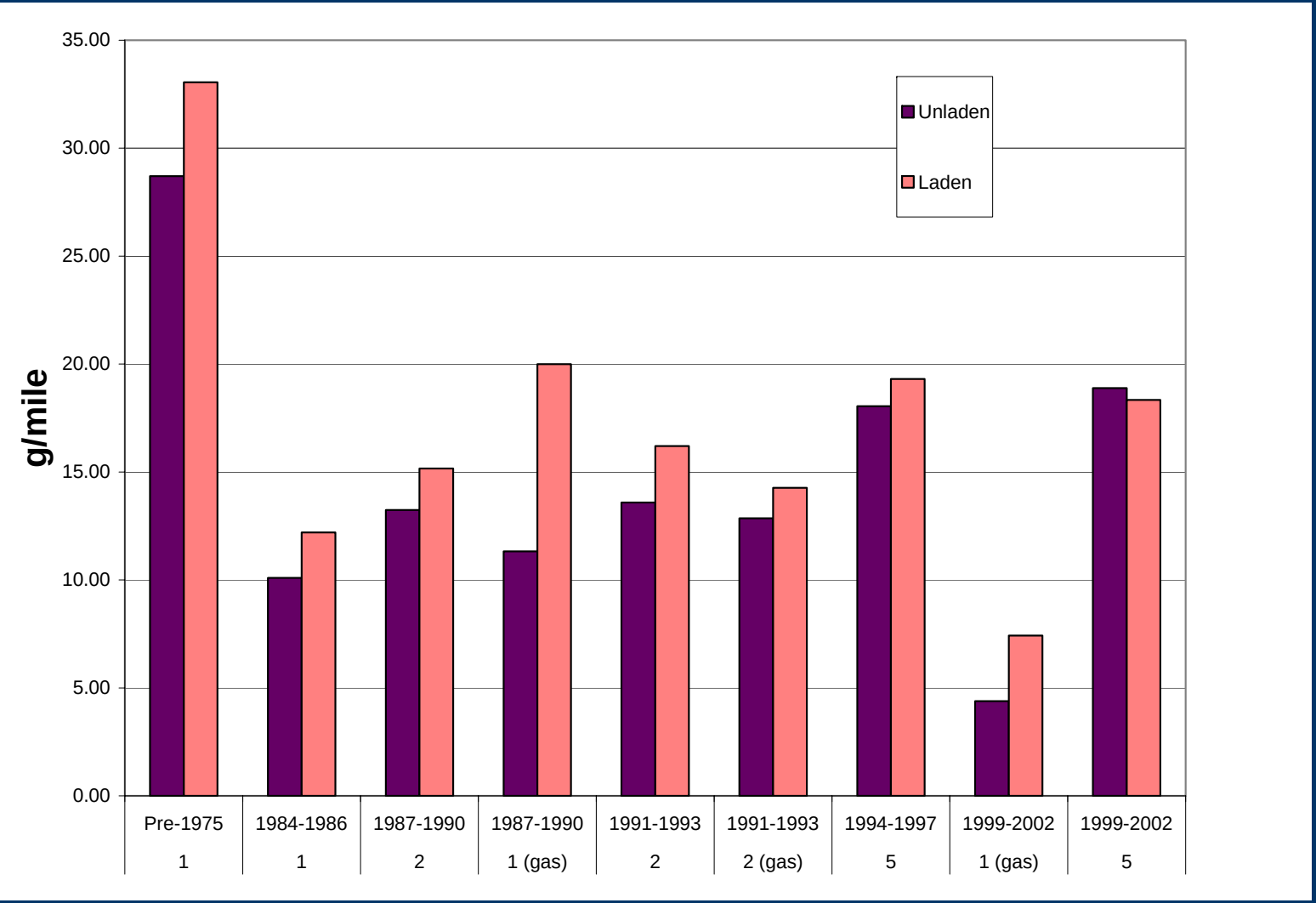
	Pre-1975	1975-1976	1977-1979	1980-1983	1984-1986	1987-1990	1991-1993	1994-1997	1998	1999-2002	2003+
Number of Vehicles	2	2	2	3	5	8	6	8	4	11	5
PM (g/mile)	1.67	1.77	8.33	1.23	0.91	0.75	0.60	0.34	0.33	0.54	0.48

Effect of Varying Test Weight of HHDDT on Oxides of Nitrogen Emissions over the Transient Mode



MHDDT Oxides of Nitrogen Emissions

(Average of measurements over the Low-speed Transient Mode Laden [75% GVW] and Unladen [50% GVW] simulated weights)



MAJOR CONCLUSIONS

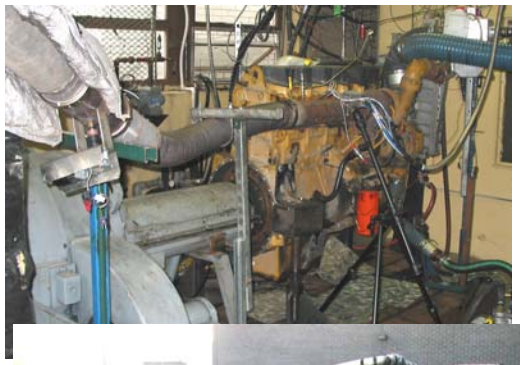
- For HHDDT vehicles, NO_X from transient operation declined from pre-1975 to 2004.
- For HHDDT vehicles, NO_X from transient operation showed an slight increase in the mid-1990s.
- Cruise HHDDT emissions peaked in early years and for 1994-98, but are now at their lowest.
- PM emissions have generally declined.
- Reflash reduced NO_X emissions on HHDDT vehicles.
- For MHDT vehicles, test weight had a more significant impact on PM than on NO_X.

In-use Emissions Measurements

- TECHNOLOGY DEVELOPMENT AND/OR ASSESSMENT
- ENFORCEMENT
- COMPLIANCE
- I/M
- SCREENING
- INVENTORY

Available Tools

- Engine Test Cells
  - FTP
  - Simulated Routes



- Chassis Dynamometers

- On-road, On-board Emissions Measurement Systems

  CATI, Albany, NY
  Horiba, Ann Arbor, MI
  Sensors, Saline, MI
  ….others

Challenges to Measurement of On-board, On-road Diesel Emissions

- Error minimization
- Torque broadcast (or percent load in pre-Consent Decree engines)
  - Including protocol adapters
- Exhaust flowrate measurement
- Fuel quality variability
- Environmental Conditions
- Emissions characteristics from current and future engines/exhaust aftertreatment systems (NO, NO_2, OC dominated PM emissions)
- Dual-torque engine maps
- Non-manufacturer-based flash files
- Instrumentation
  - Advances in novel ("super" compact) instrumentation development are not fast enough
  - Reliability, repeatability and accuracy issues exist

In-Use Emissions Under Real-World Driving Conditions

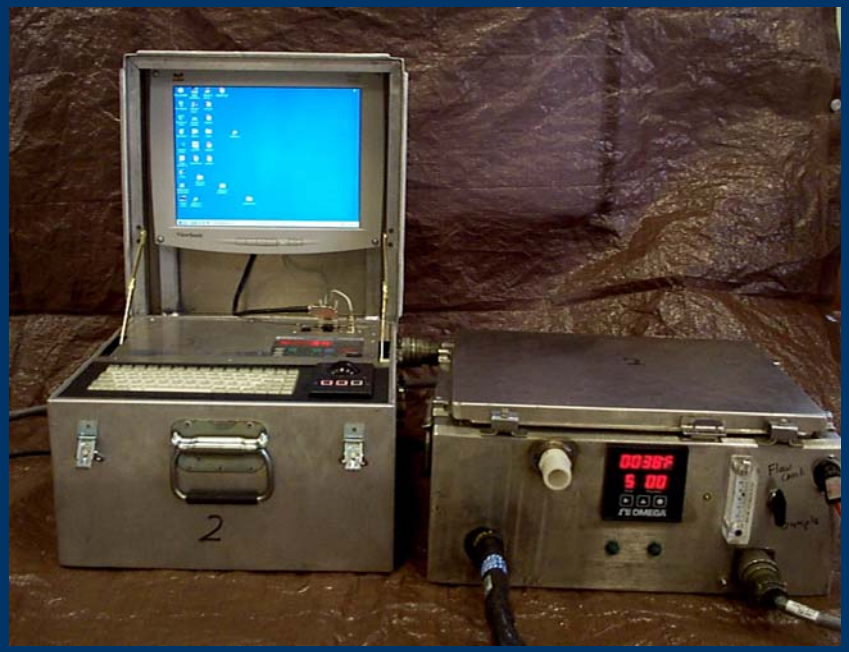
In-use, real-world emissions measurements

On-board emissions measurement instruments

Measurements are made over a real-world driving routes

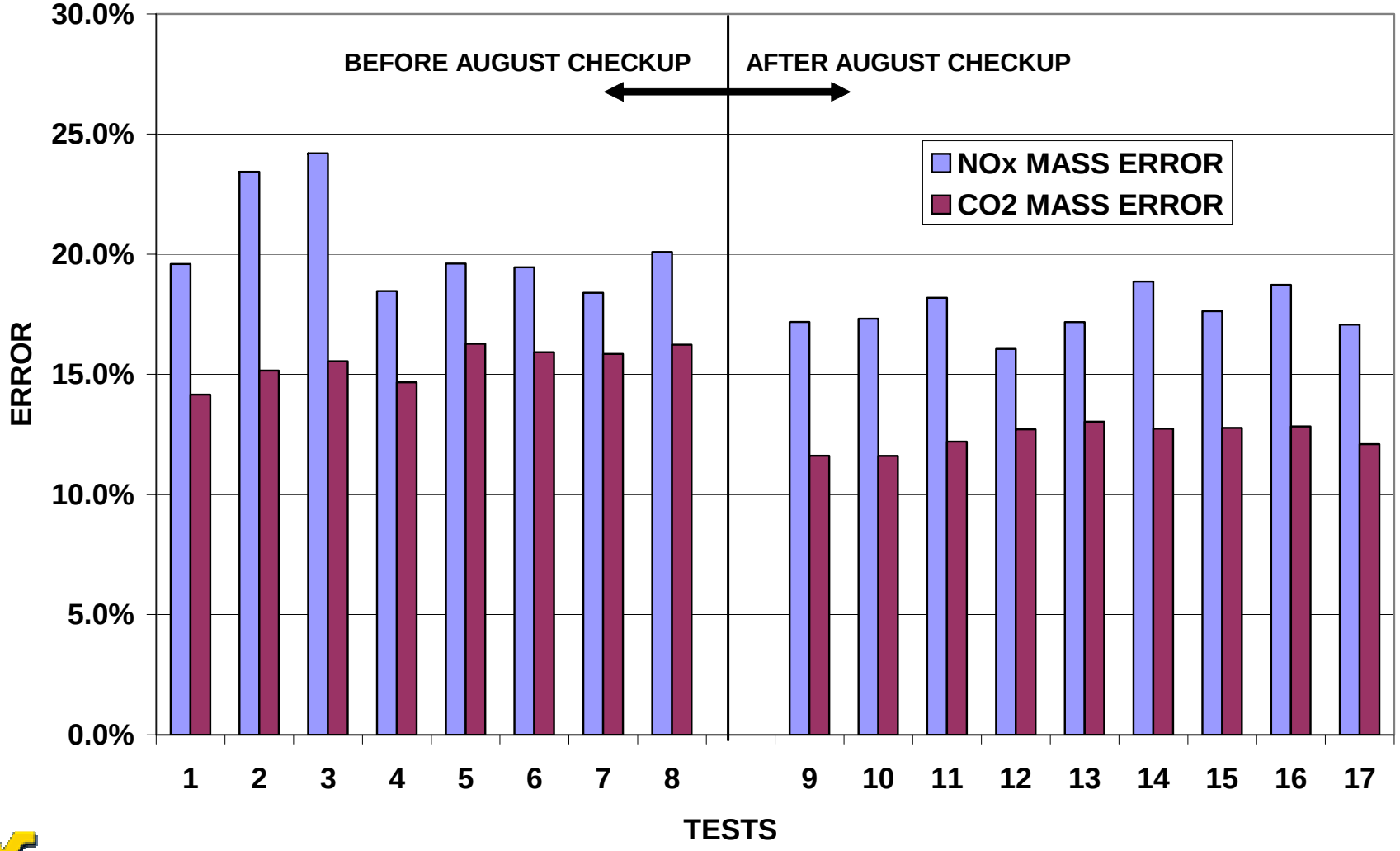
- **Highway, city-suburban, city traffic conditions**
- **Range of road/driving conditions**
- **Range of ambient conditions**
- **Real-world fuel**

Mobile Emissions Measurement System (MEMS)

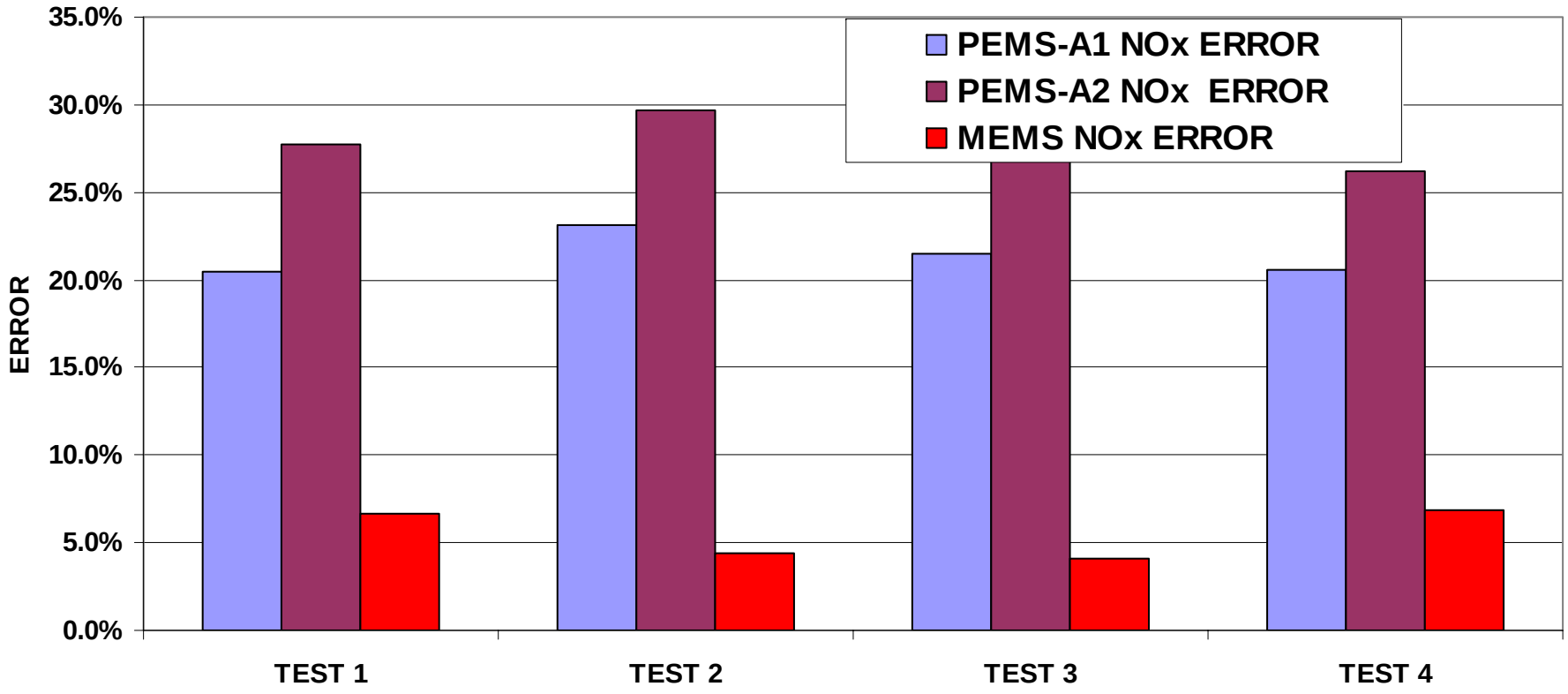


In-Use On-board Emissions Measurements

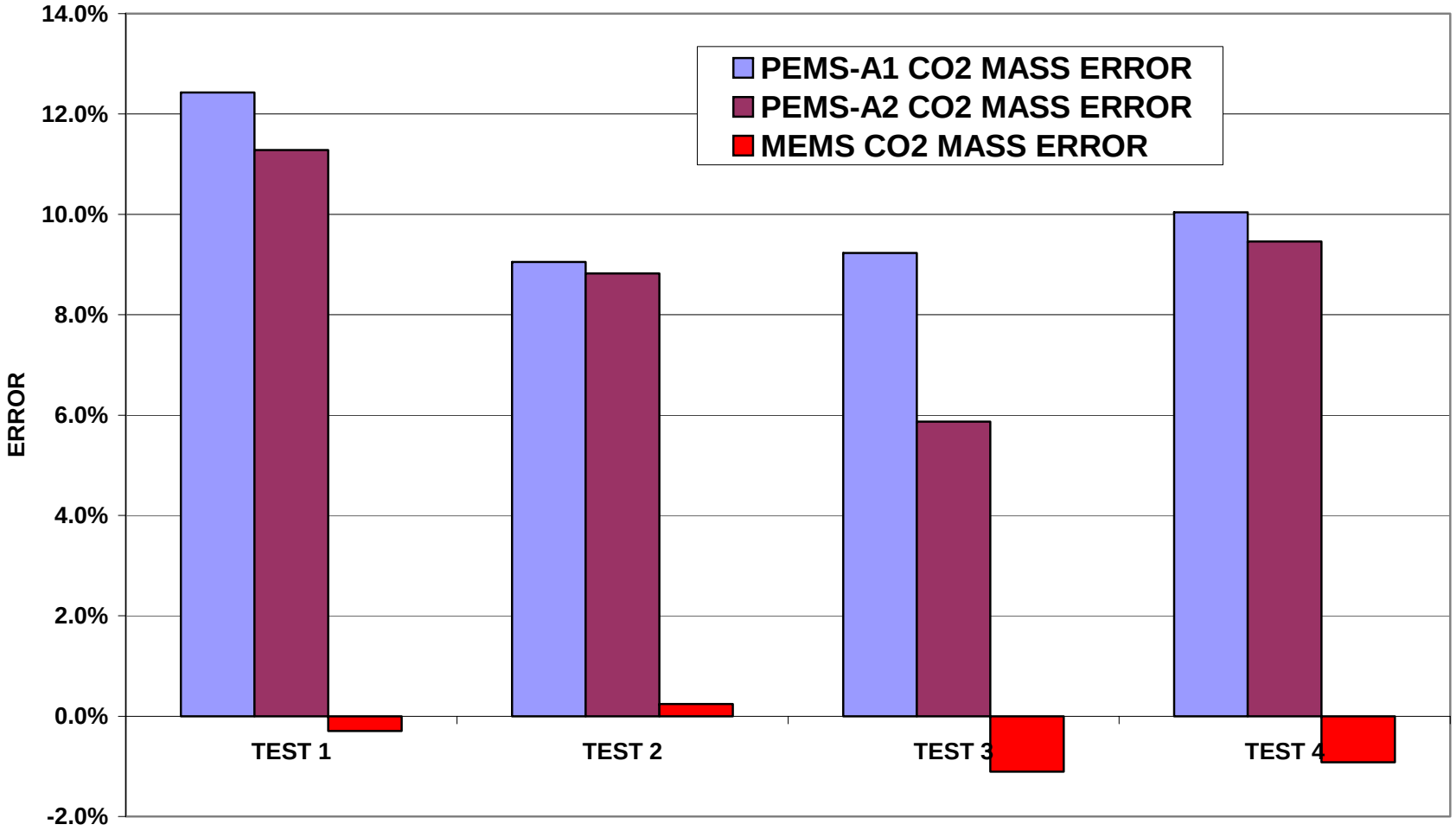
FTP: PEMS-A1 INTEGRATED PERCENT ERRORS COMPARED TO WVU ENGINE LAB



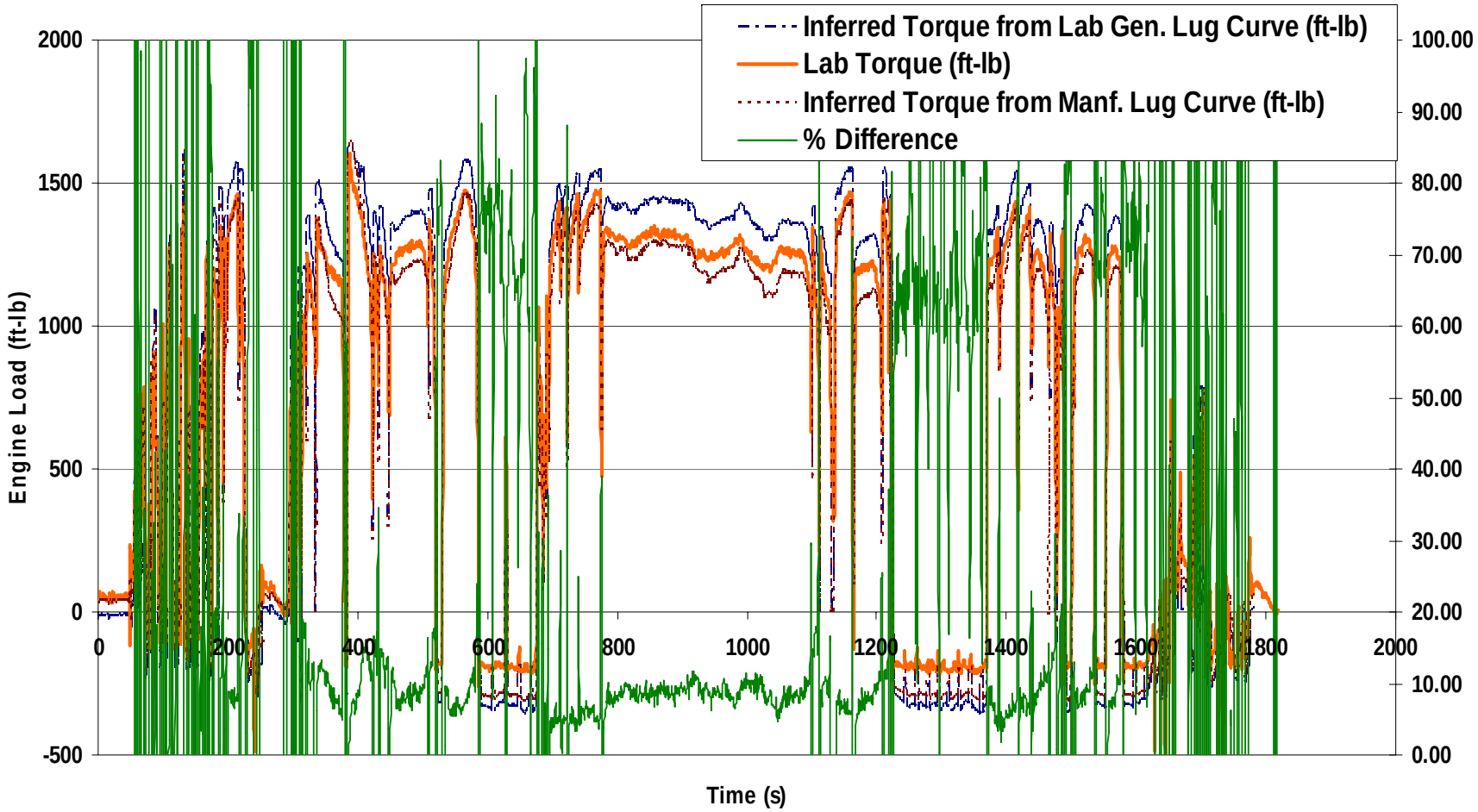
FTP: NOx MASS INTEGRATED PERCENT ERROR COMPARED TO WVU ENGINE LAB



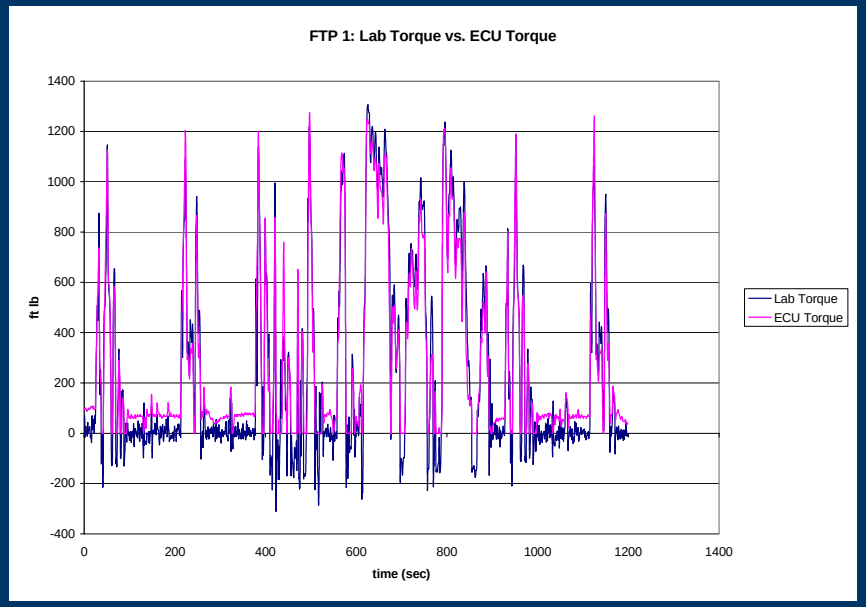
FTP: CO_2 MASS INTEGRATED PERCENT ERROR COMPARED TO WVU ENGINE LAB

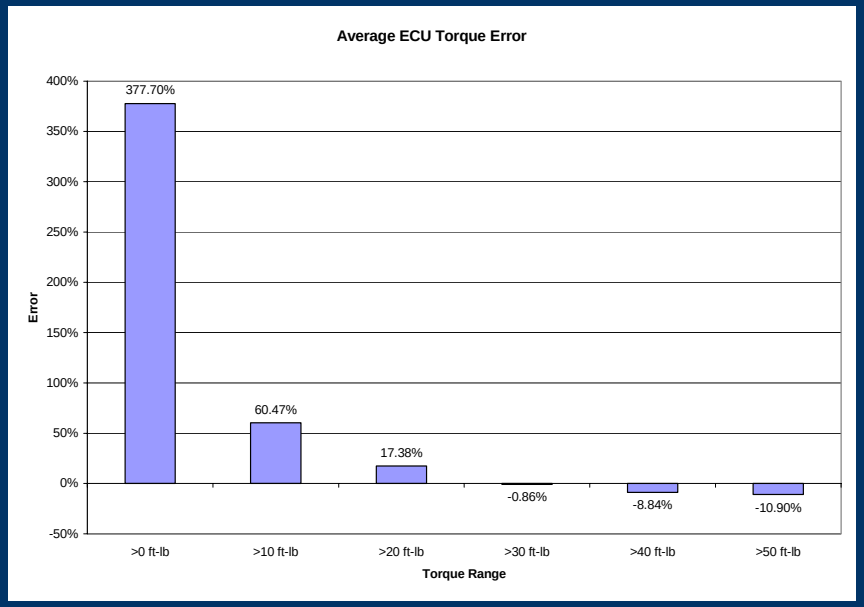


Errors in Torque Broadcast (Simulated SAB-to-BM Route)



Comparison of ECU-derived Torque vs. Measured Shaft Torque

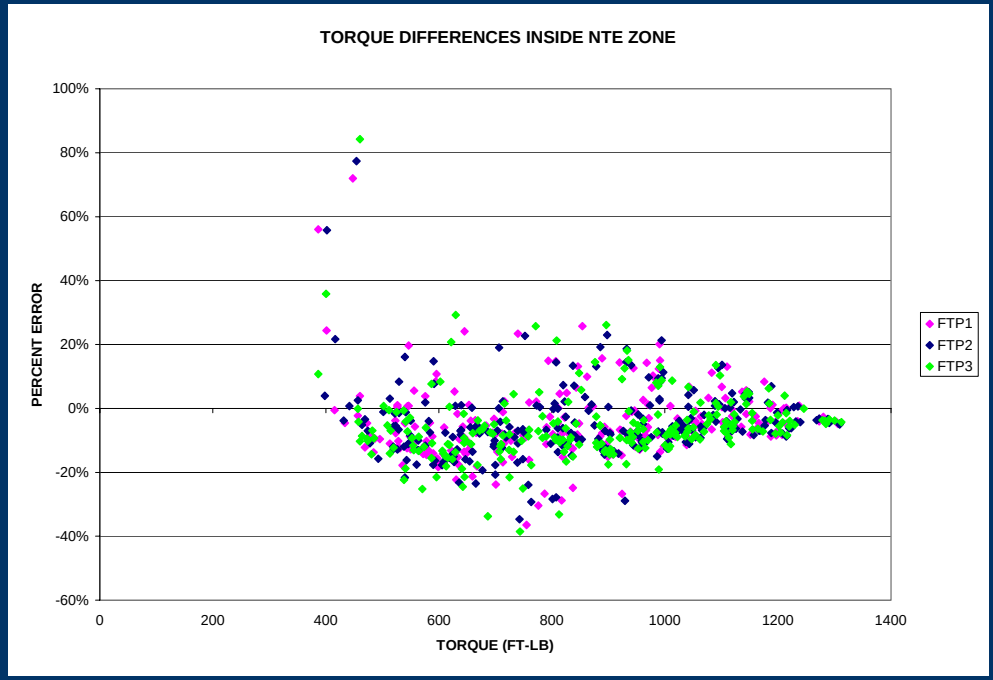




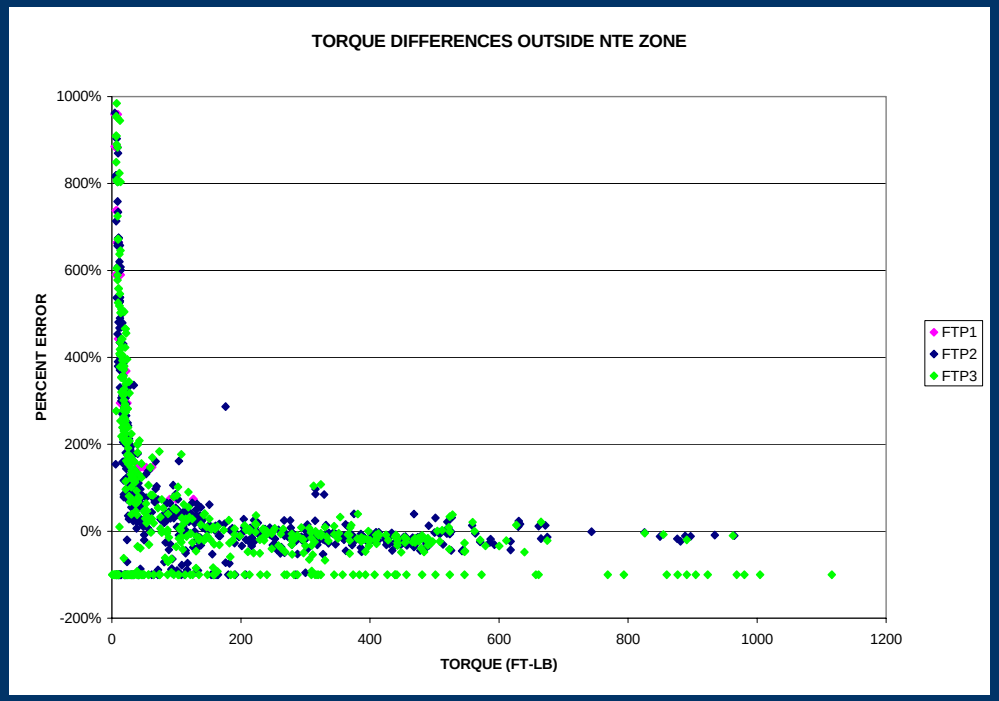
- Engine dynamometer FTP test

Torque Errors Within the NTE Region

- Data collected from 3 FTPs
- ECU torque calculated using broadcast percent load and engine lug curve
- Average error = -3.48%



Torque Errors Outside the NTE Region



- Data collected from 3 FTPs
- ECU torque calculated using broadcast percent load and engine lug curve
- Average error = 377.7%
  - $Error_{Torque > 10\ ft\text{-}lb} = 60.5\%$
  - $Error_{Torque > 20\ ft\text{-}lb} = 17.4\%$
  - $Error_{Torque > 30\ ft\text{-}lb} = -0.9\%$

In-use Fuels Study

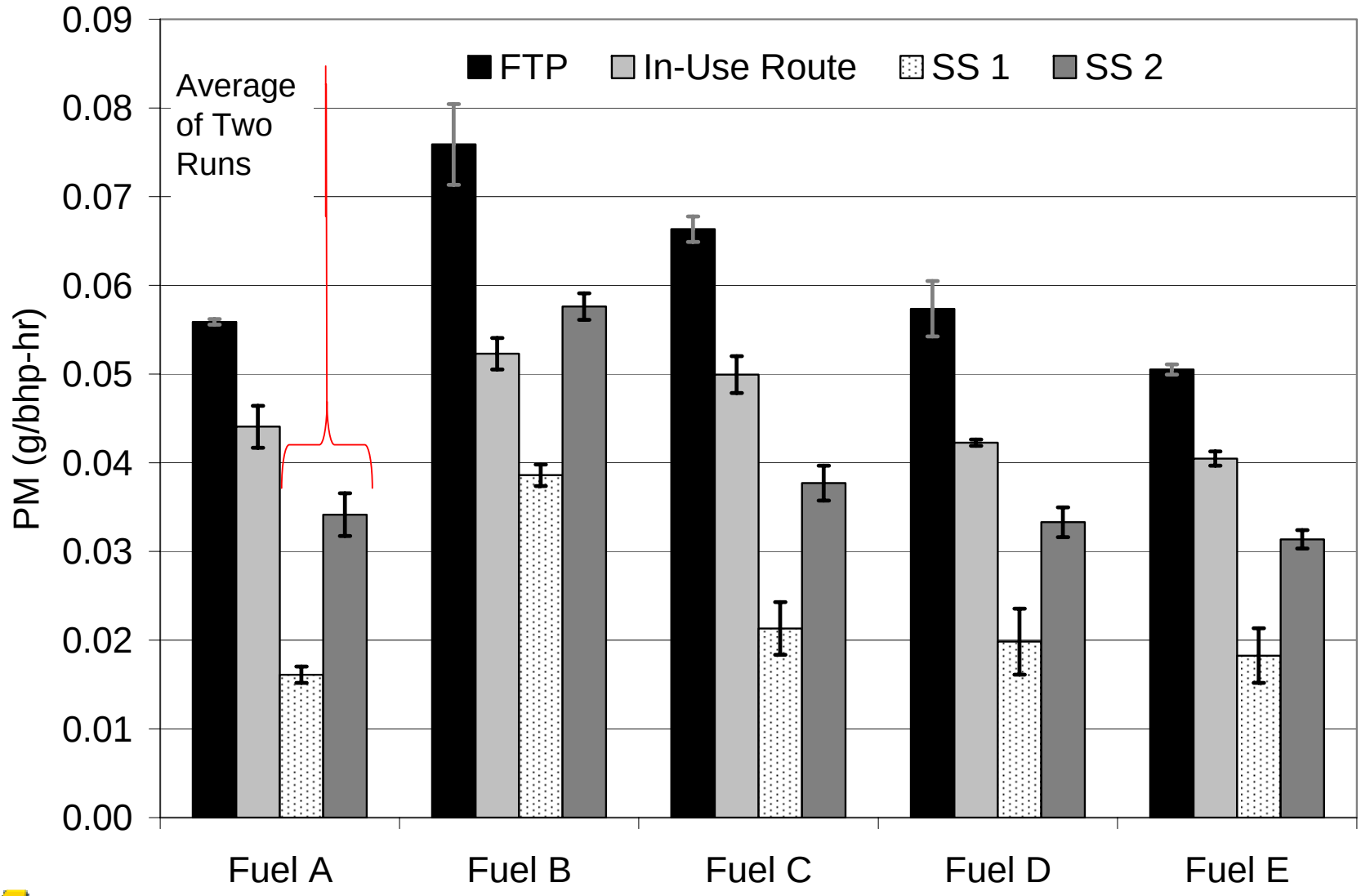
- Four D2 fuels drawn from four separate local public filling stations in Northern West Virginia, and Southwestern Pennyslvania

- One California D2 market basketblend (Aromatic Content: 9%; Fuel Sulfur : 0.017 wt%)

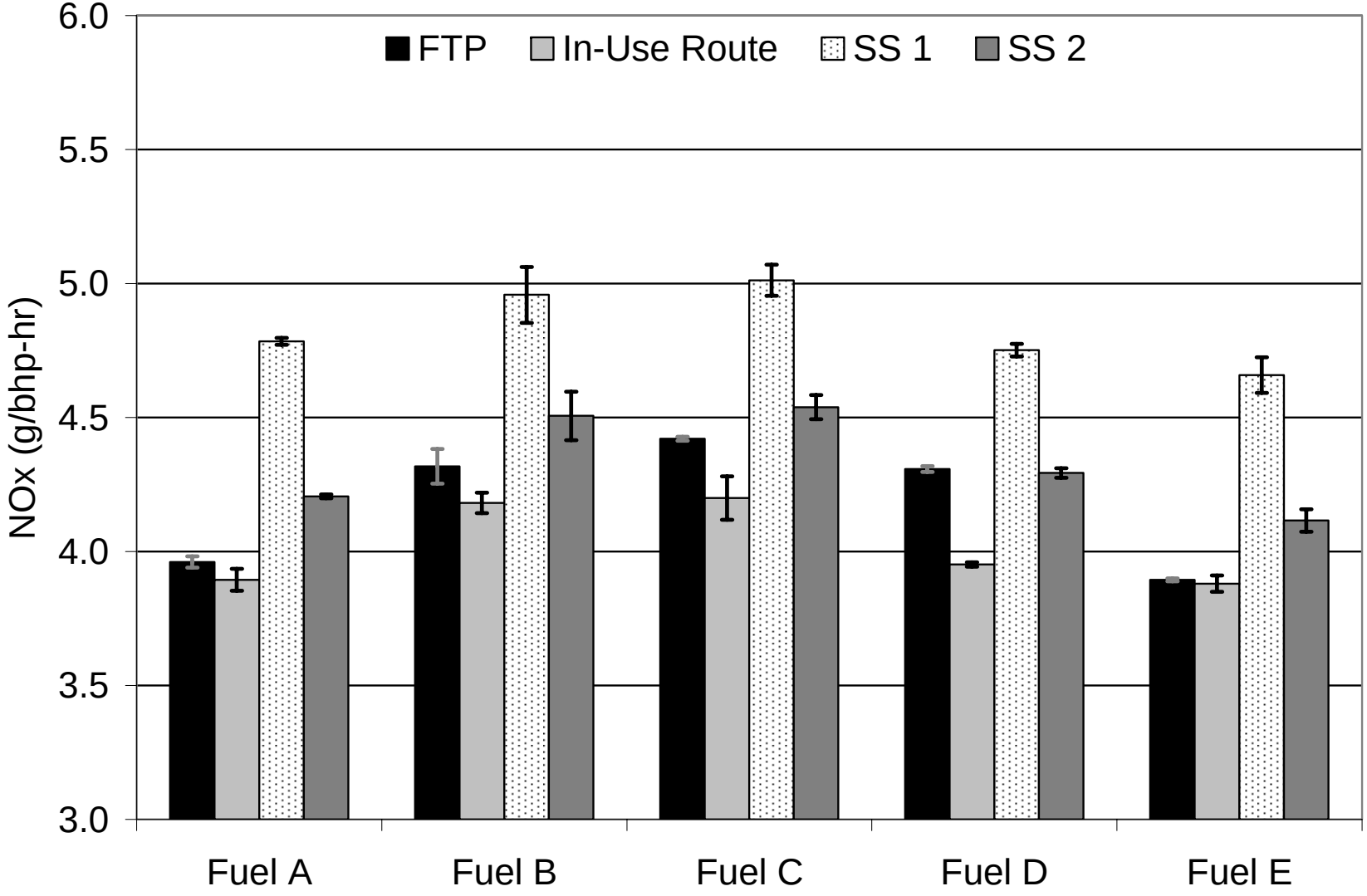
Properties of Fuels

Parameter	Units	ASTM	Fuel A	Fuel B	Fuel C	Fuel D	Fuel E
API Gravity @ 60 Deg. F	° API	D-1298	42.4	35.2	36.3	36.4	**43.2**
Carbon	wt%	D-5291M	85.77	86.86	**86.88**	86.17	85.93
Cetane Index, Calculated	-	D-976	54.2	46.9	46.3	46.3	**57.6**
Cetane Number	-	D-613	53.8	45.4	45.4	44.6	**58.4**
Distillation							
IBP	°F	D-86	349.6	359.6	359.1	353.2	354.2
5% Rec			370.8	405.3	388.4	381.1	375.7
10% Rec			382.1	423.3	404.3	393.6	385.2
20% Rec			399.6	448.4	427.7	414.5	405.5
30% Rec			419.9	469.6	447.1	436.5	427.3
40% Rec			441.9	488.1	467.8	460.2	450.5
50% Rec			468.9	507	488.3	487.4	480.9
60% Rec			499.3	525.9	508.8	518.4	509.6
70% Rec			530.3	545.5	531.7	552.6	537.8
80% Rec			559.8	568.4	560	587.3	564.5
90% Rec			588.2	599.7	597	627.1	590.9
95% Rec			606.7	629.4	629.8	657.8	608.5
FBP			627.1	654.2	653.9	668.6	622.5
Recovery	%		98.7	98.1	98.1	97.8	98
Residue			1.1	1.1	1.2	1	1.3
Loss			0.2	0.8	0.7	1.2	0.7
Flash Point, PMCC	°F	D-93(A)	144.1	148	146	146.2	**148.2**
Hydrocarbon Type - FIA							
Aromatics	lv%	D-1319	14.3	**28.2**	26.8	9	12.8
Olefins			**1.8**	0.7	0.8	1	1.1
Saturates			83.9	71.1	72.4	**90**	86.1
Hydrogen Content	wt%	D-5291M	13.92	12.98	13.1	13.76	**14.2**
Kinematic Viscosity @40 °C	cSt	D-445	2.04	2.445	2.17	**2.64**	2.12
Specific Gravity @60 °F	-	D-1298	0.814	**0.849**	0.843	0.843	0.81
Total Sulfur	wt%	D-4294	0.038	**0.041**	0.04	0.017	0.041

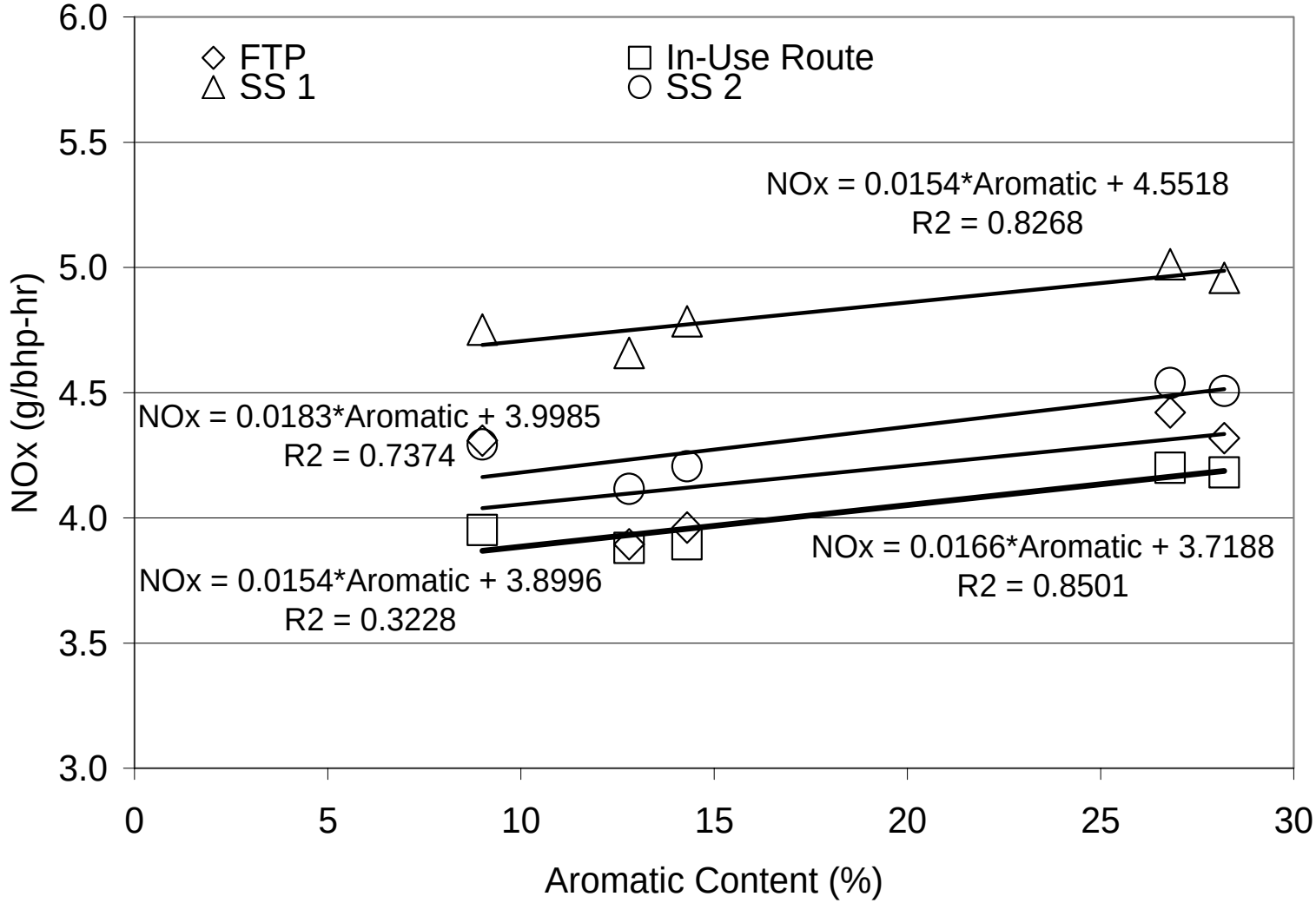
Fuel Effects on TPM Emissions



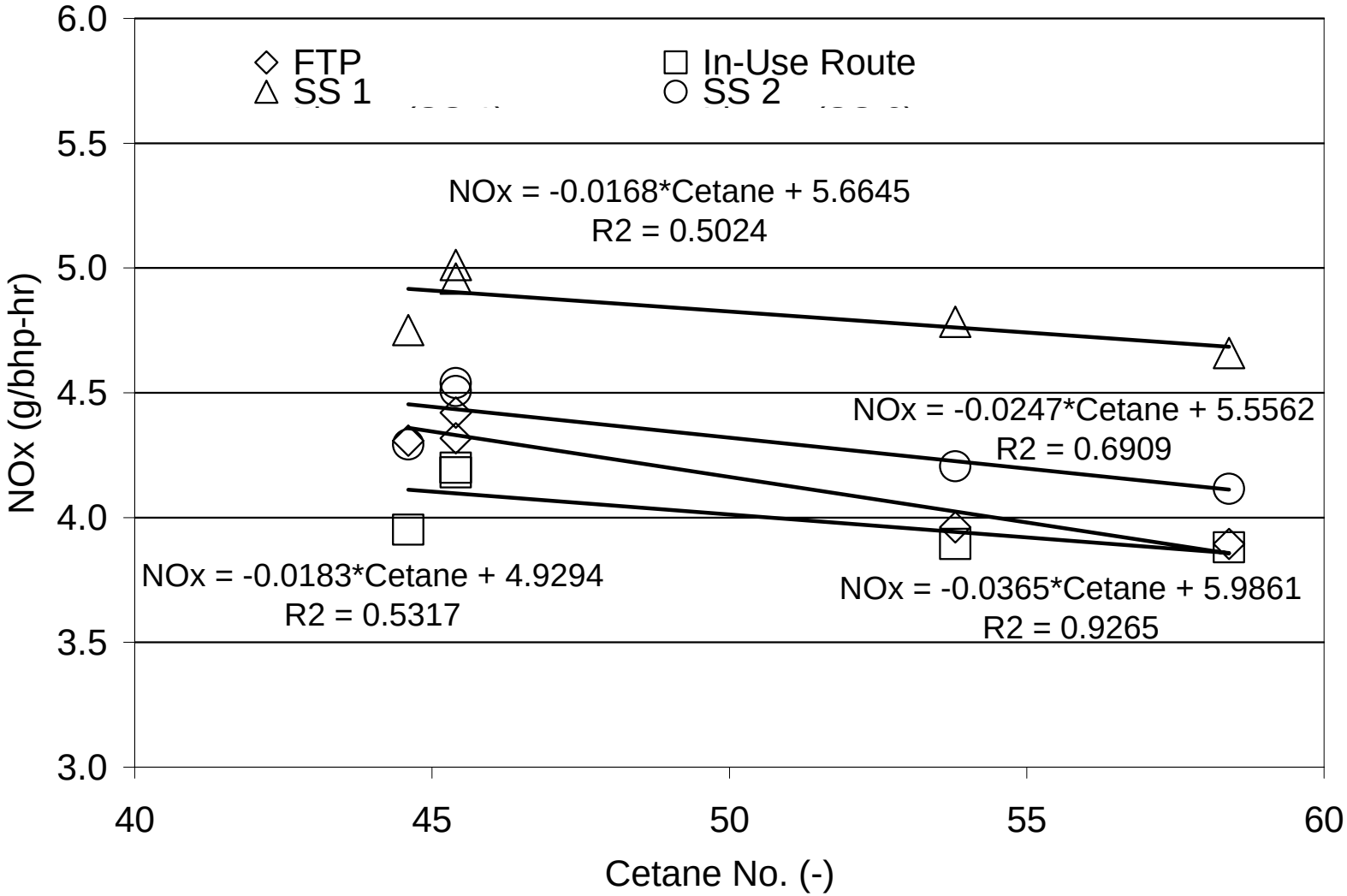
Fuel Effects on NOx Emissions



Effect of Aromatic Content on NOx Emissions



Effect of Cetane Number on NOx Emissions



Summary (Fuel Effects)

- Commercially available diesel fuel can have a significant effect on emissions
  - 12% variation in NOx
  - Over 50% variation in PM
  - 40% variation in CO and 17% variation in HC

- Unfortunately, engine manufacturers have little control over fuel properties. However, given the fact that "fuel composition sensors" are not likely, engine control algorithms may have to account for such variable fuel properties.

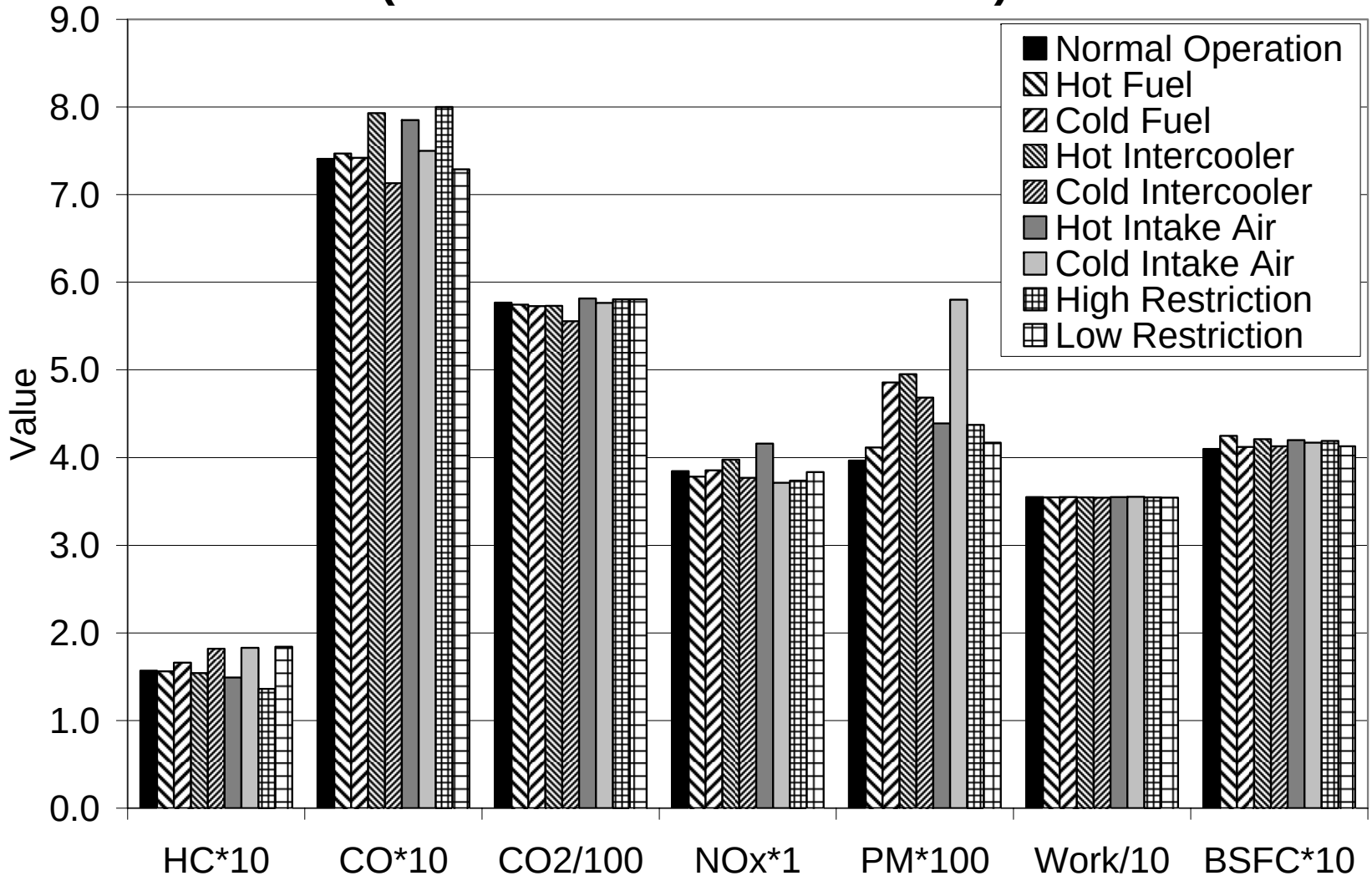
Environmental Effects Study

(Tests Conducted on Fuel E)

Parameter	Low	Base	High
Fuel Temperature (°F)	55	95	140
Pre-Turbo Air Temperature (°F)	55	77	120
Intercooler Temperature (°F)	42	77	97
Restriction			
Intake Depression (in H_20)	7.0	13.0	29.3
Exhaust Restriction (in H_20)	11.5	34	51.5

Environmental Effects Study

(Tests Conducted on Fuel E)



Summary (Environmental Effects)

- In-use emissions are not dependent not only on engine technology, but also on fuel properties, and environmental conditions.
  - 12% variation in NOx
  - 46% variation in PM
  - 11% variation in CO, and 30% variation in HC

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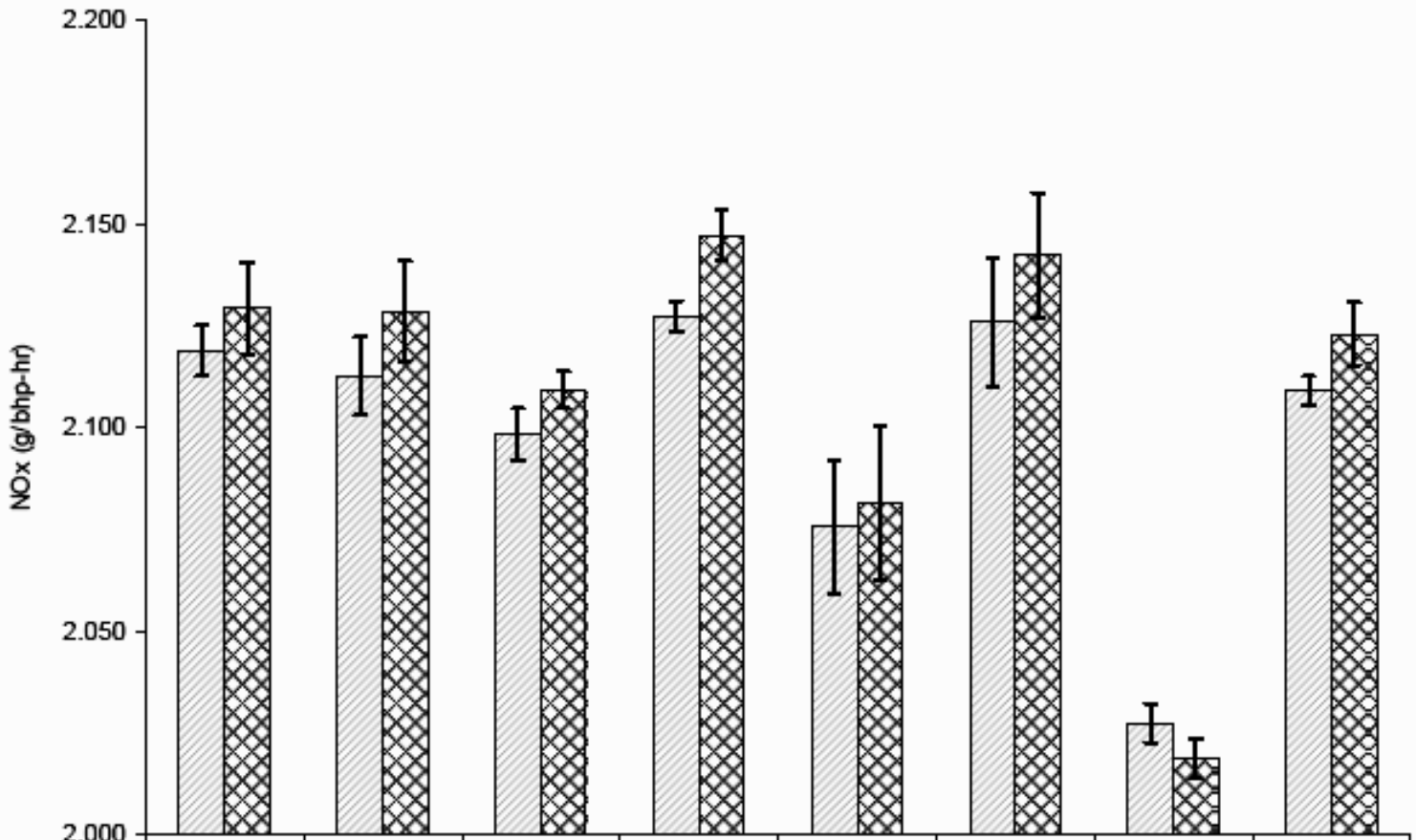
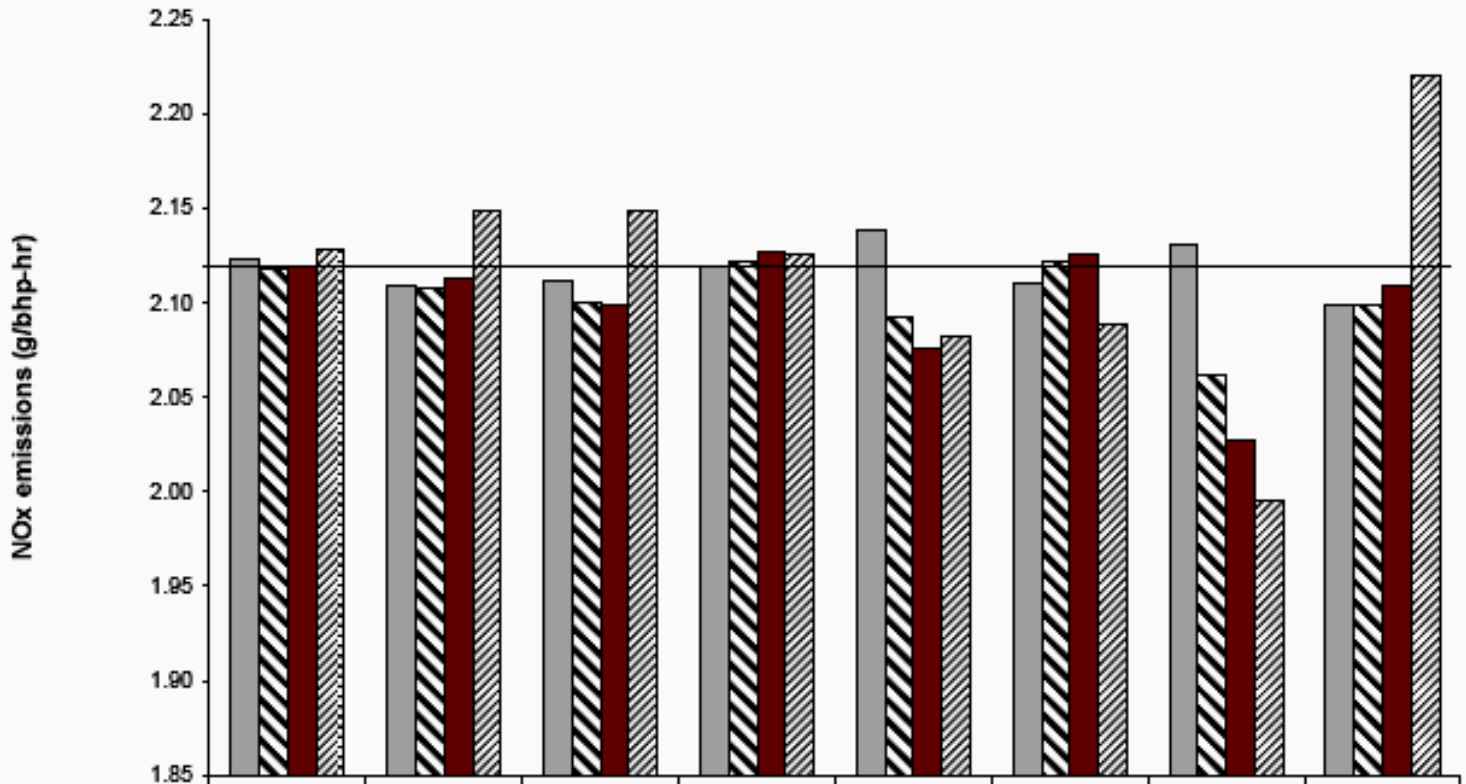
NOx Emissions at Various Intake Temperature and Humidity Conditions on 2004 Cummins ISM 370 Corrected by CFR correction factor



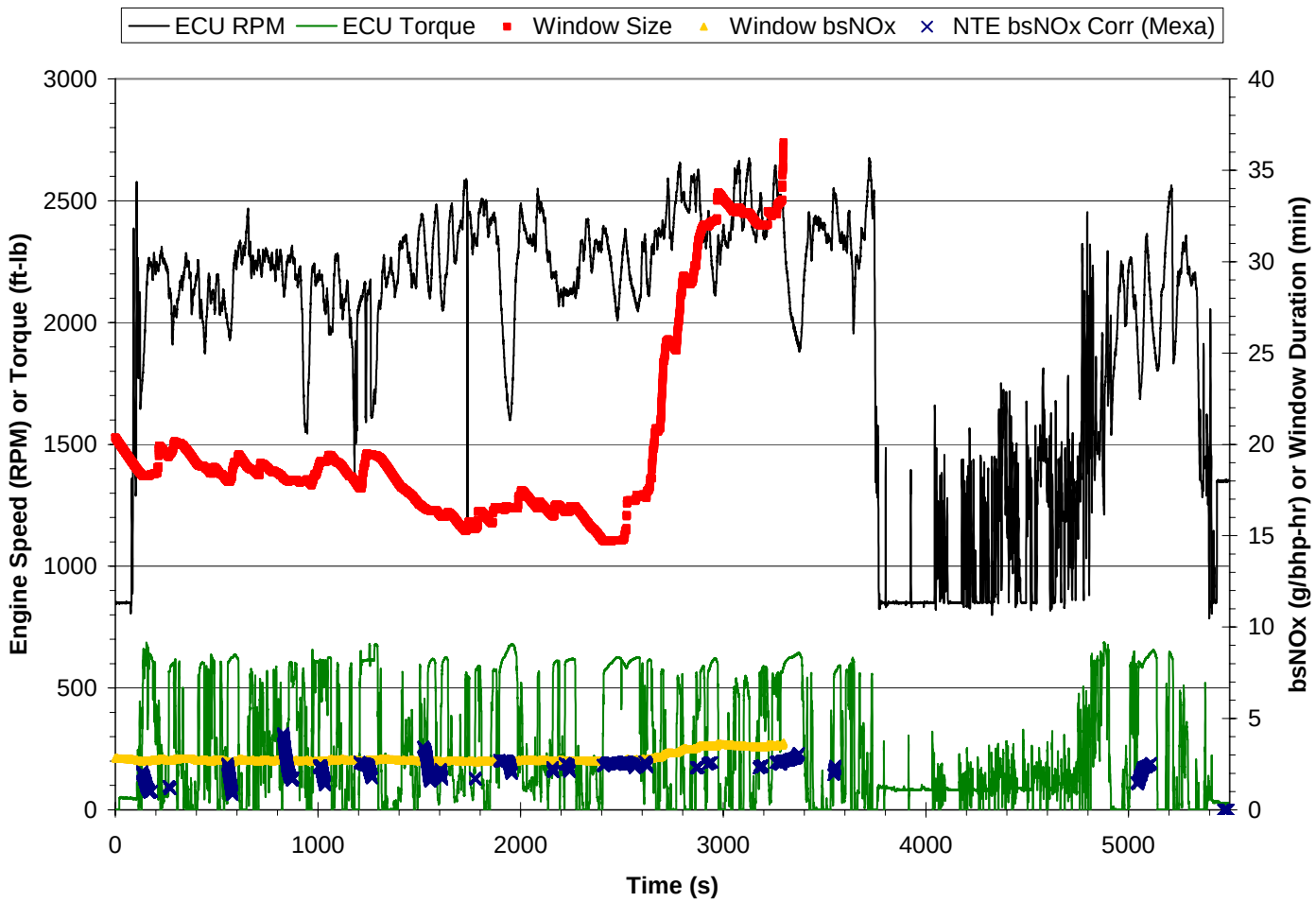
	77/50	68/55	68/75	77/35	77/75	86/30	86/75	55/80
NOx	2.119	2.113	2.098	2.127	2.076	2.126	2.027	2.109
NOx2	2.129	2.129	2.109	2.147	2.082	2.142	2.019	2.123

NOx Emissions at Different Set Points Based on Four Correction Factors



	77/50	68/55	68/75	77/35	77/75	86/30	86/75	55/80
CF-a	2.123	2.110	2.112	2.119	2.138	2.110	2.131	2.099
CF-b	2.118	2.107	2.100	2.121	2.092	2.121	2.062	2.099
CFR NOx	2.119	2.113	2.098	2.127	2.076	2.126	2.027	2.109
SwRI NOx	2.129	2.149	2.149	2.125	2.082	2.088	1.996	2.220

WashPA32Sab Test Comparing In-Use bsNOx Results based on a 30 second NTE window and an ETC Work Window (Window bsNOx) (without failure criterion)



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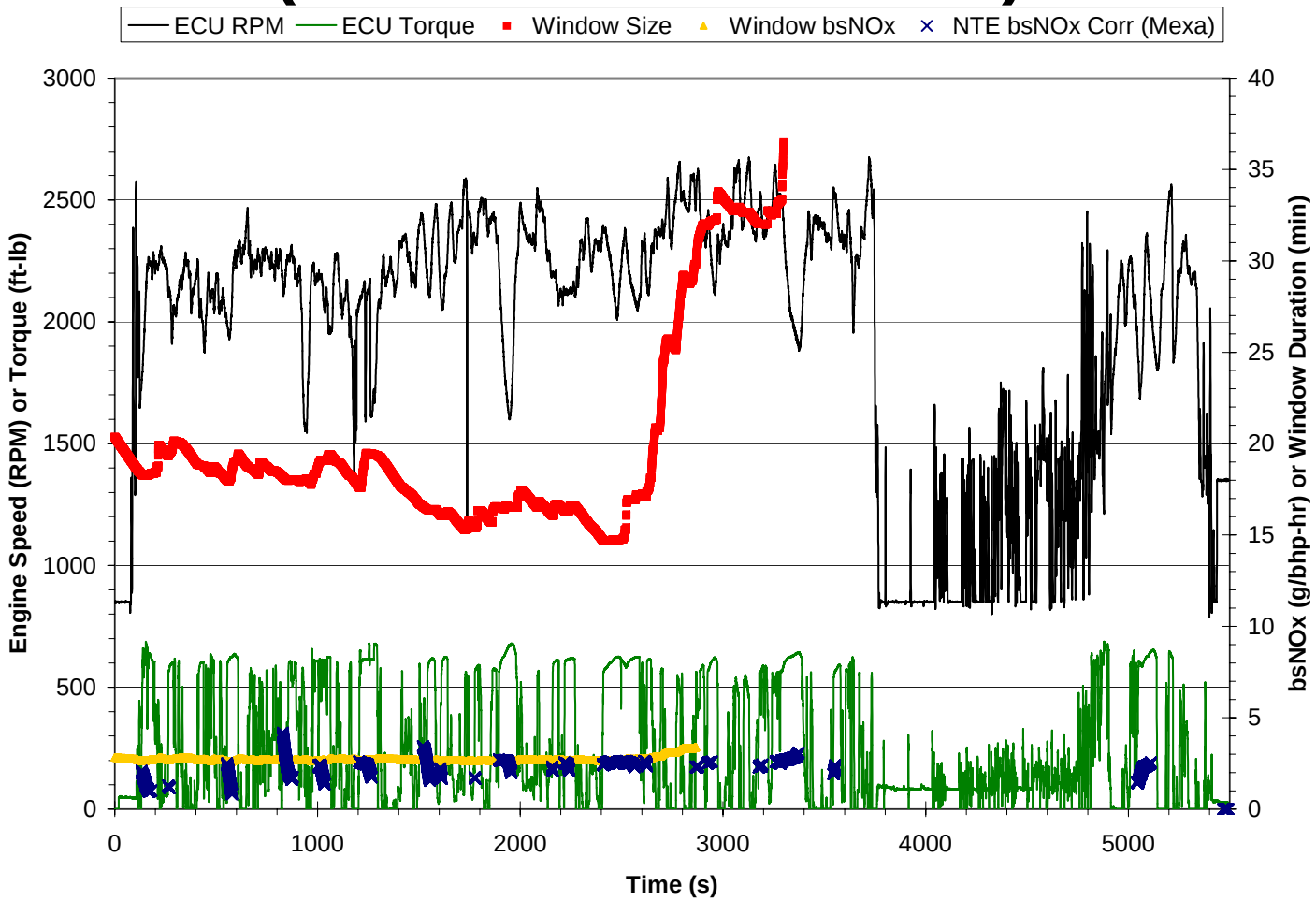

More Lessons Learned…

- **Driver impact is not as influential as originally anticipated. Peaks do vary, but NTE zones are not significantly affected.**
- **Low exhaust flow rates are difficult to quantify. This would affect the emissions results at lower engine speeds, near or below the lower engine speed region of the NTE boundary.**
- **Accurate, repeatable, continuous humidity measurements are more difficult to provide than anticipated. Atmospheric conditions are more variable than many would wish to concede. Continuous measurement, and subsequent integration of correction factors, should be used.**
- **The "as-tested" ECU configuration needs to be accurately documented. Problems arise when non-manufacturer-based flash fiels or break-out interfaces are implemented on the vehicle**.

More Lessons Learned…

- **With dual–torque engine maps we have no way of determining when the engine goes from a "360 hp" setting to the "400 hp" setting. The operation may not only be dual-mode, it could be n-mode. Hence, protocols need to be crafted, which will establish a firm rule on which 'label' or ECU entry will prevail in choosing the torque curve.**
- **QC/QA checks for on-board systems have to be more stringent and exhaustive than those for laboratory-based systems. Remember, once the in-use test is completed, the vehicle may be unavailable for future re-tests.**
- **Local fuel-quality can have a major difference on engine out emissions.**
- **Our tests have shown that lug-curve information that is specific to an engine (from dynamometer tests) yields higher brake-specific emission than the use of "sales" curves.**
- **Finally, we have a $140,000 commercially available system that has failed to give me reliable data. We have not even talked about the wear and tear on PEMS on typical real-world on-highway operation.**

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THANK YOU