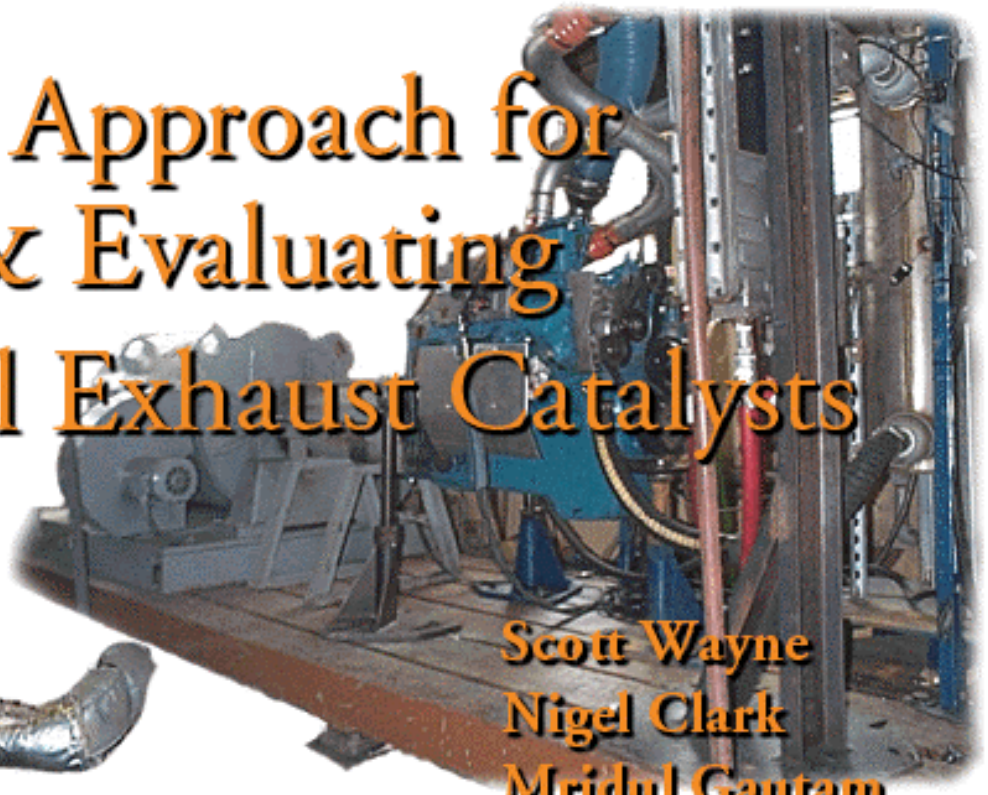
Engine & Emissions Research Laboratory

West Virginia University

Research Approach for Aging & Evaluating Diesel Exhaust Catalysts



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DECSE Diesel Emission Control - Sulfur Effects Program

Objective

- To determine the impact of diesel fuel sulfur levels on emissions control devices that could lower emissions of oxides of nitrogen (NO_X) and particulate matter (PM) from on-highway trucks and buses in the 2002-2004 model years.
- West Virginia University is evaluating:
  - Diesel Oxidation Catalysts
  - Lean NO_X Catalysts

Catalysts

- **Diesel Oxidation Catalyst** (DOC) – reduce HC, CO and the SOF of diesel PM.
  - High Temperature DOC – low precious metal loading
  - Low Temperature DOC – high precious metal loading

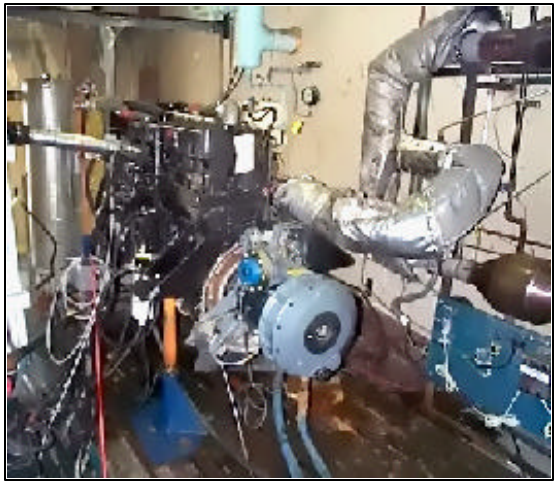
- **Lean-NO_X Catalyst** – reduce diesel NO_X with the assistance of supplemental HC reducing agent under lean (oxygen-rich) exhaust conditions.
  - High Temperature Lean-NO_X (350°-600°C) – base metal
  - Low Temperature Lean-NO_X (170°-300°C) – precious metal

Experimental Matrix

Technology	250 Hours Aging					Catalyst Evaluation[1]					Engine
	3	30	150	350	30R[2]	3	30	150	350	30R[2]	
HT DOC	4-mode Cummins aging cycle					4 stabilized OICA modes and heavy-duty FTP[3]					ISM 370 (Cummins)
LT DOC	4-mode Navistar aging cycle					4 stabilized Nav-9 modes and simulated FTP-75					T444E (Navistar)
HT Lean-NO_X	4-mode Cummins aging cycle					4 stabilized OICA modes					ISM 370 (Cummins)
LT Lean-NO_X	4-mode Navistar aging cycle					4 stabilized Nav-9 modes					T444E (Navistar)

[1] Evaluations performed after 0, 50, 150, and 250 hours of aging.
[2] Recovery experiment.
[3] Non-standard FTP cycle due to use of split exhaust.

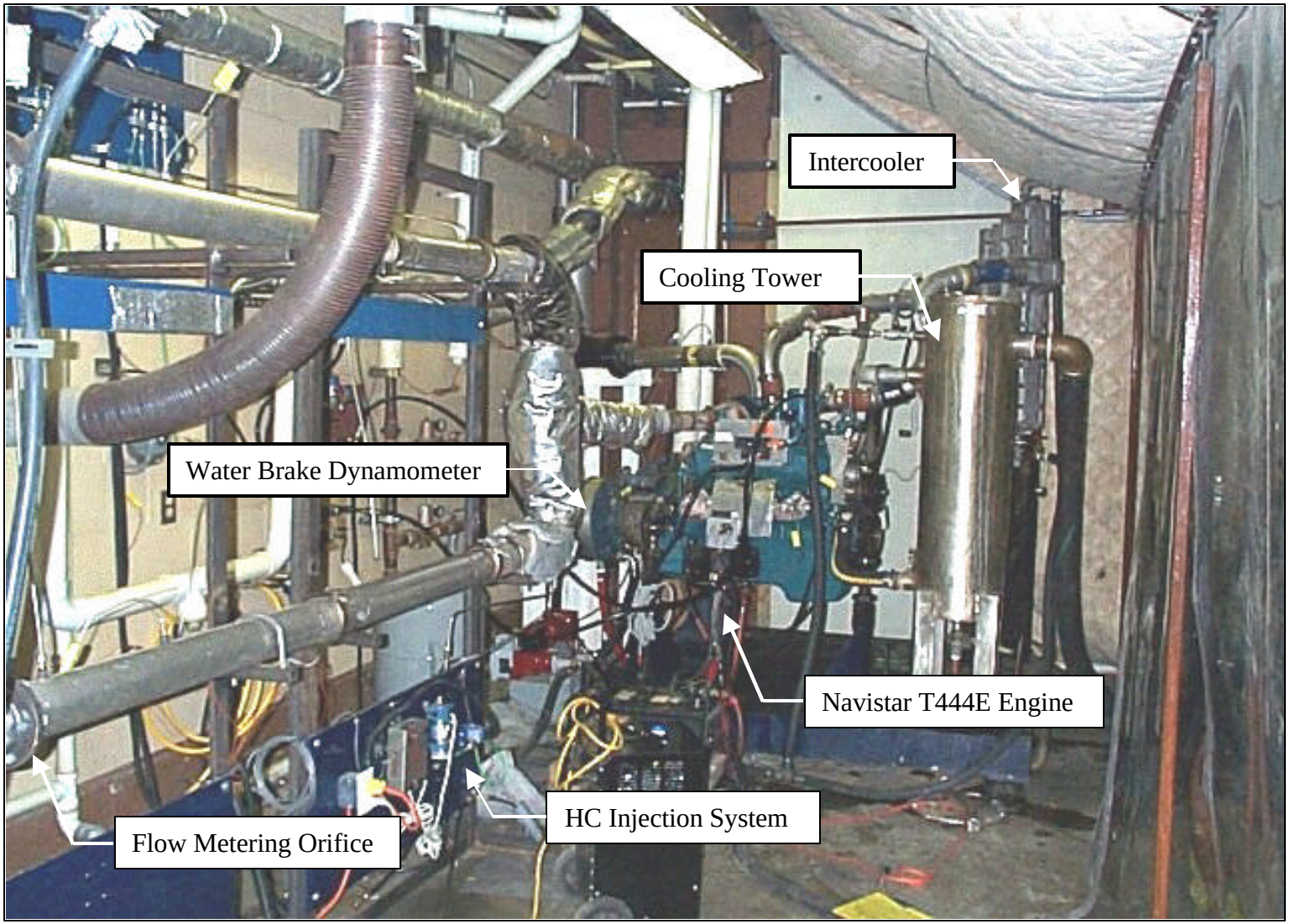
Test Engines



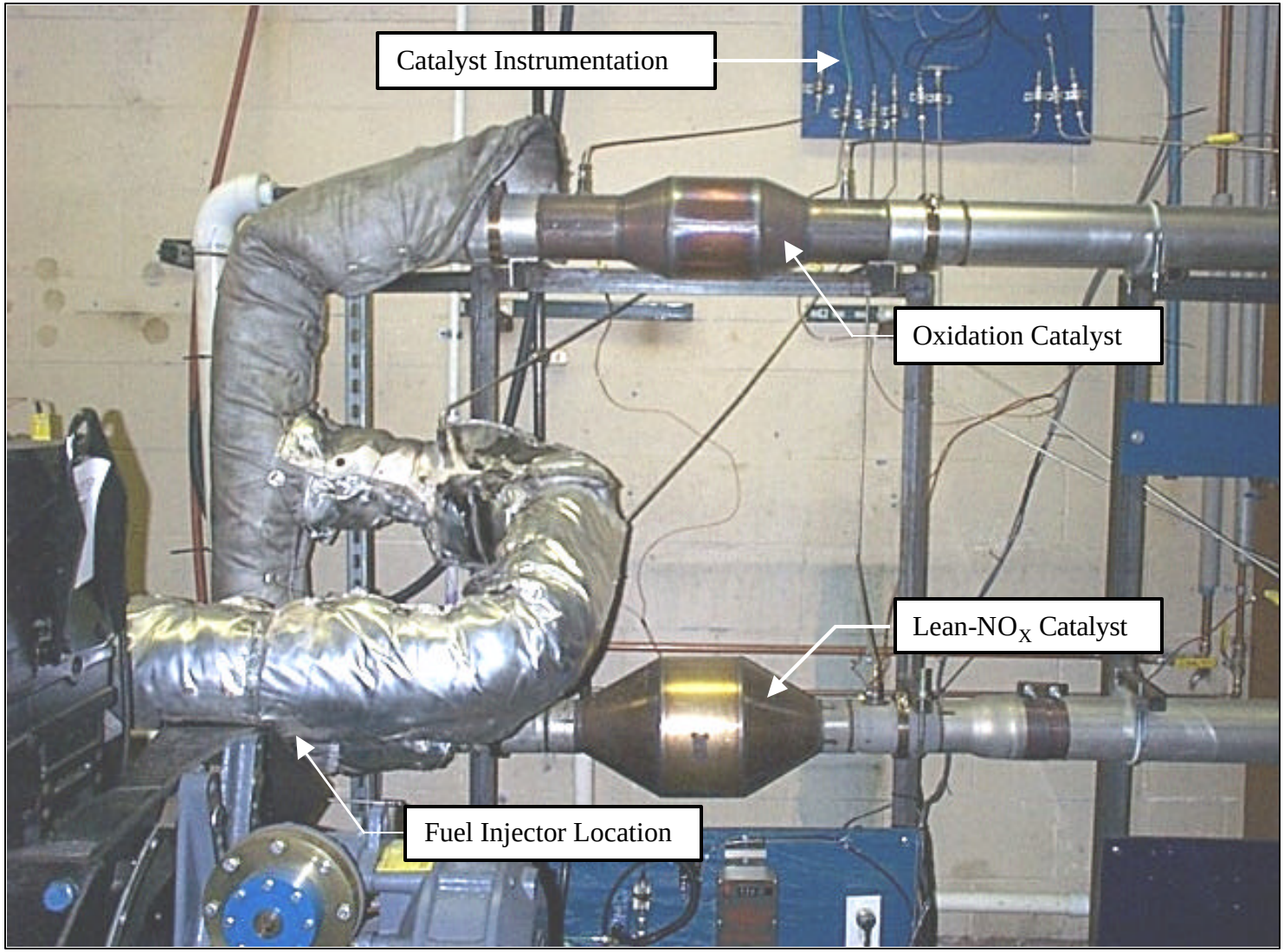
- **1999 Cummins ISM 370ESP**
  - 10.8 liter in-line 6-cylinder
  - Typical heavy-duty line-haul truck
  - Rated Power (370 hp @ 2100 rpm)
  - Rated Torque (1350 ft-lb @ 1200 rpm)

- **1999 Navistar T444E**
  - 7.3 liter V-8
  - Lighter-duty, lower exhaust temperatures
  - Rated Power (210 hp @ 2300 rpm)
  - Rated Torque (520 ft-lb @ 1500 rpm)

Low Temperature Catalyst Aging Cell



High Temperature Catalyst Aging Cell



Catalyst Aging Cycles

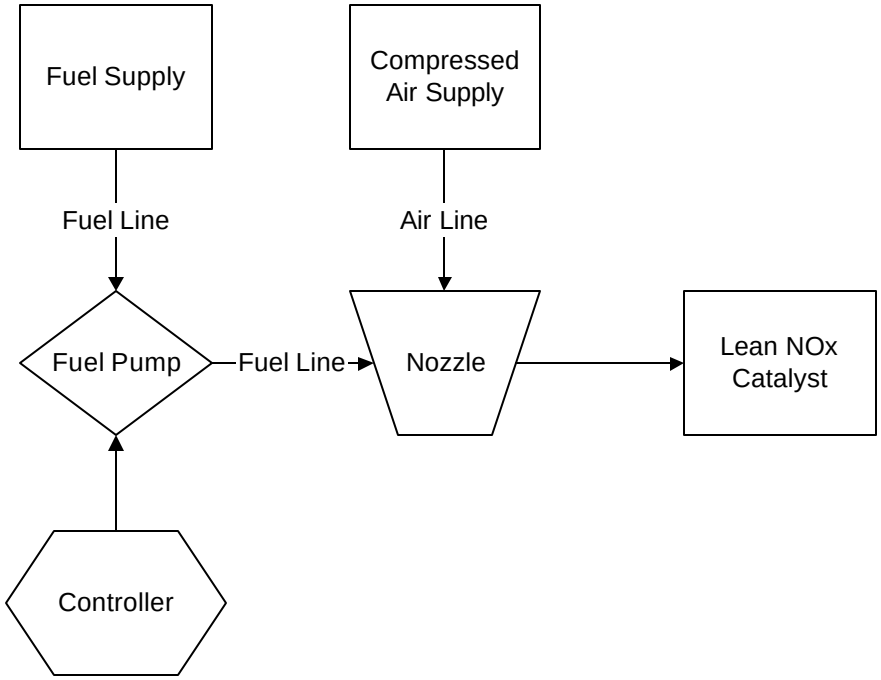
- High Temperature Catalyst (Cummins Engine)

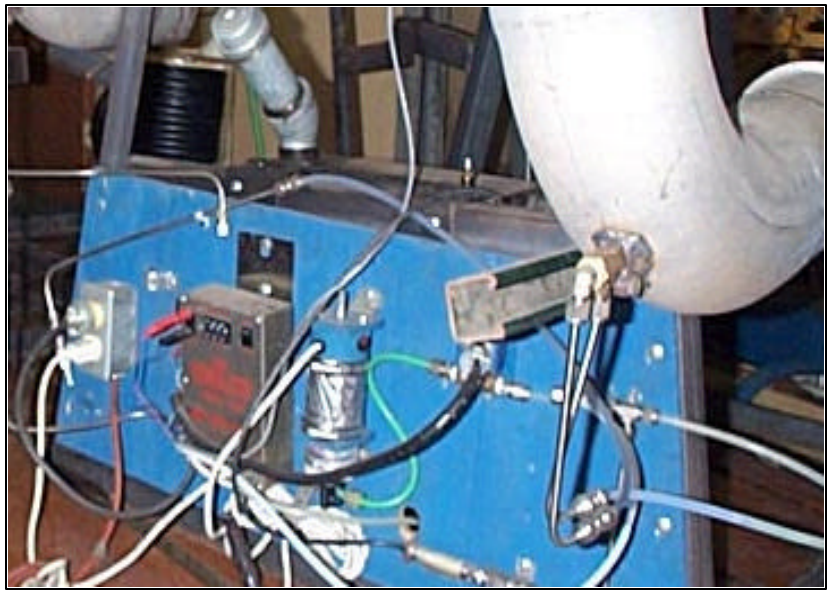
OICA Mode	Time (min)	Speed (rpm)	Torque (ft-lb)	Description
2	24	1282	1244	High torque, high temperature
10	6	1585	595	Rated condition
3	24	1888	992	Road load
11	6	1888	248	Low temperature

- Low Temperature Catalyst (Navistar Engine)

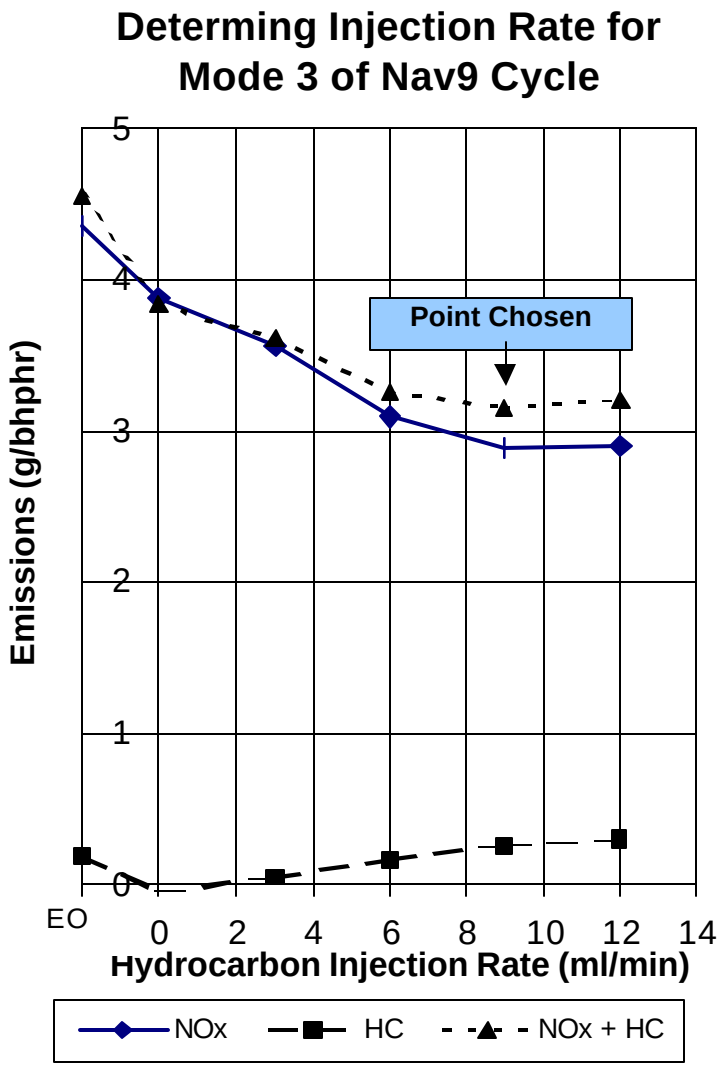
NAV-9 Mode	Time (min)	Speed (rpm)	Torque (ft-lb)	Description
2	12	1000	81	Low rpm, low torque, low temperature
3	12	1250	122	Low rpm, high torque, low temperature
7	12	2000	122	High rpm, low torque, low temperature
9	24	2200	406	High rpm, high torque, high temperature

Lean NO_X Reductant Injection System



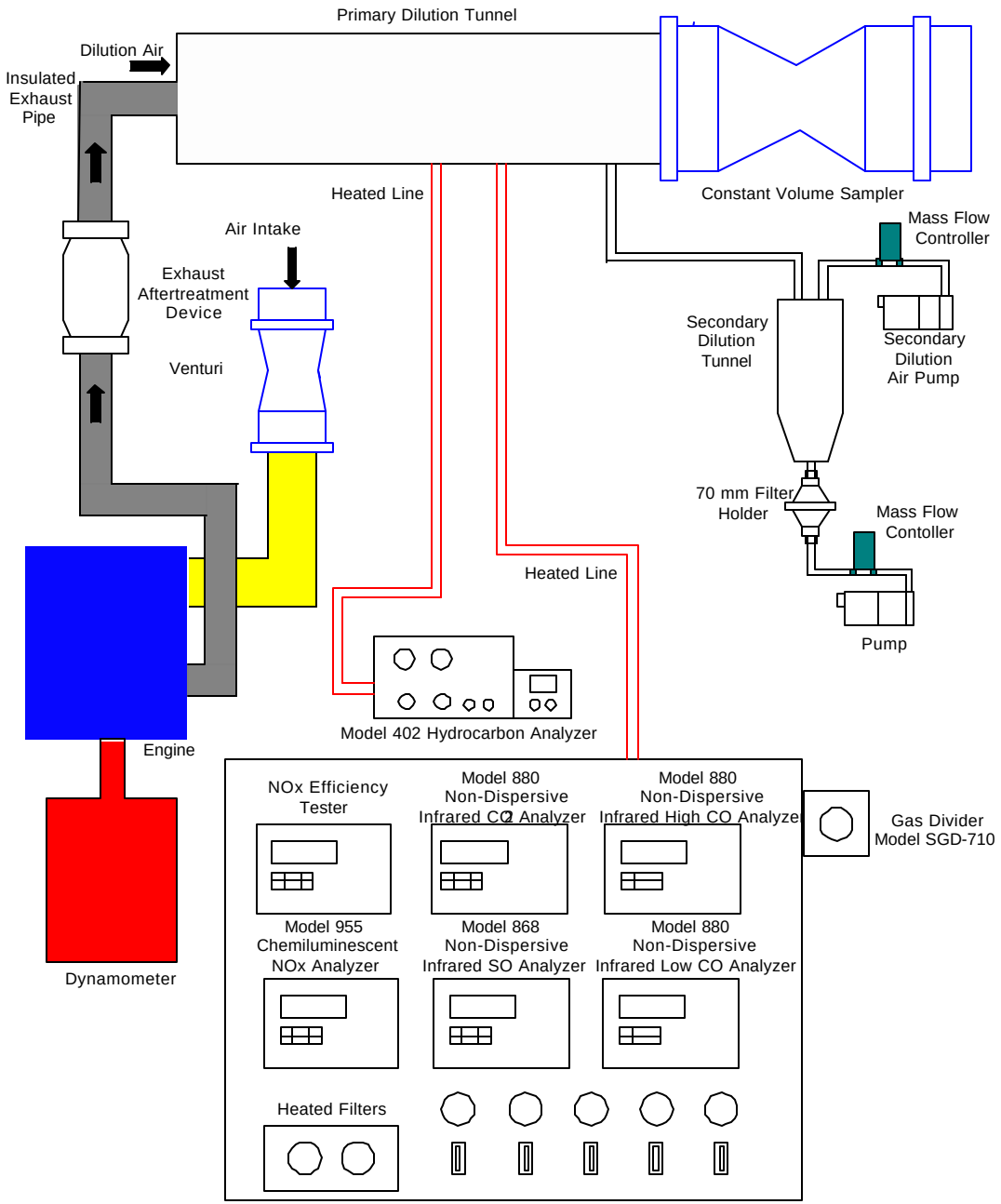


Lean NO_x Injection Rates

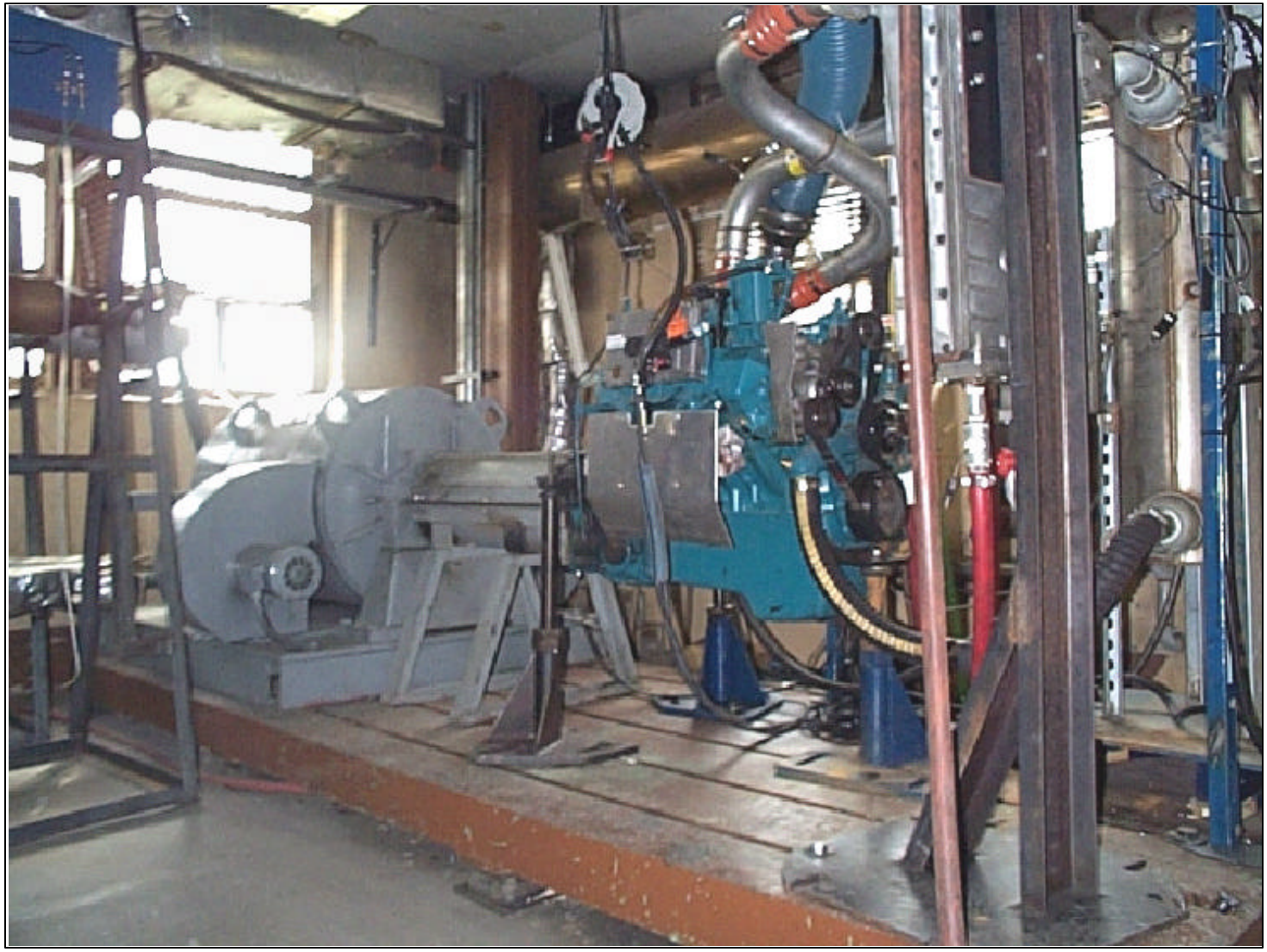


- No fuel is injected in Modes 1 and 2 of the OICA Cycle because the exhaust temperature falls outside of the catalyst temperature window.

Injection Rate for Lean NO_x Catalysts			
	OICA (Cummins ISM)		
Mode	Speed (rpm)	Torque (ft-lb)	Rate (ml/min)
1	1888	248	0
2	1585	595	0
3	1888	992	16.2
4	1282	1244	33.8
	Nav-9 (Navistar T444E)		
	Speed (rpm)	Torque (ft-lb)	Rate (ml/min)
1	1000	81	1.25
2	1250	122	6.8
3	2000	122	9
4	2200	406	6


Primary Dilution Tunnel
Dilution Air
Insulated Exhaust Pipe
Heated Line
Constant Volume Sampler
Mass Flow Controller
Air Intake
Exhaust Aftertreatment Device
Venturi
Secondary Dilution Tunnel
Secondary Dilution Air Pump
70 mm Filter Holder
Mass Flow Contoller
Heated Line
Pump
Model 402 Hydrocarbon Analyzer
Engine
Dynamometer
NOx Efficiency Tester
Model 880 Non-Dispersive Infrared CO2 Analyzer
Model 880 Non-Dispersive Infrared High CO Analyzer
Gas Divider Model SGD-710
Model 955 Chemiluminescent NOx Analyzer
Model 868 Non-Dispersive Infrared SO Analyzer
Model 880 Non-Dispersive Infrared Low CO Analyzer
Heated Filters

Evaluation Engine Setup



Steady State Evaluation Cycles

	OICA (Cummins ISM)			Nav-9 (Navistar T444E)		
Mode	Time (min)	Speed (rpm)	Torque (ft-lb)	Time (min)	Speed (rpm)	Torque (ft-lb)
1	2	700	0	2	700	0
2	20	1888	248	20	1000	81
3	20	1585	595	20	1250	122
4	20	1888	992	20	2000	122
5	20	1282	1244	20	2200	406
6	5	1200	Motoring	5	1200	Motoring

- A single PM filter was used for each steady state test
- Emissions data were recorded in the last few minutes of each mode.
- Sampling times were adjusted to yield adequate PM mass and maintain the specified mode weighting factors.
- Emissions data is not recorded on modes 1 (idle) and 6 (cool down).
- To reduce catalyst stabilization times, the steady state modes were run in the order of increasing exhaust temperature.

FTP-75 Mimic Cycle

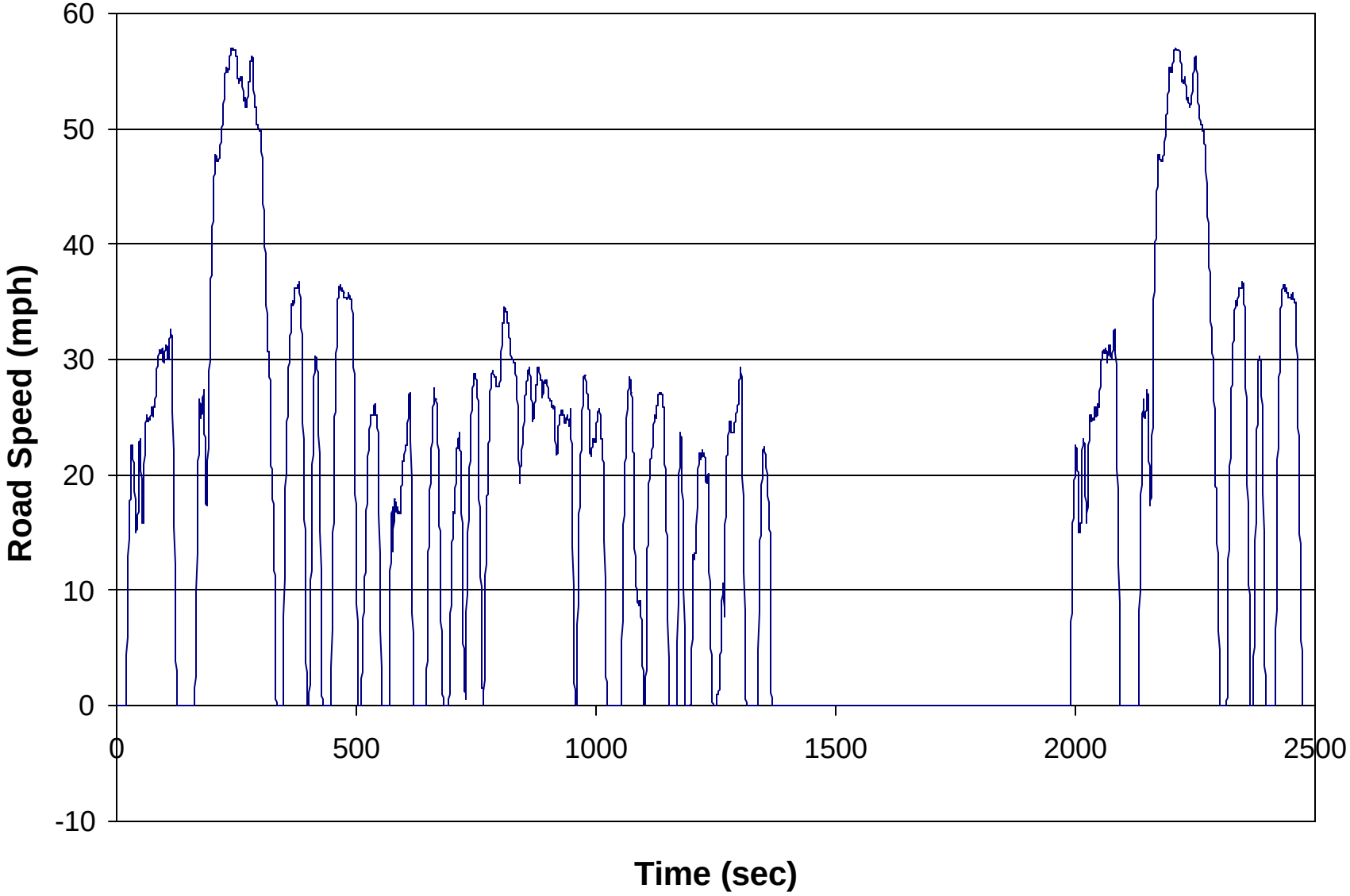
- Engine speed for the mimicked FTP-75 was determined from the vehicle speed trace of the chassis dynamometer FTP-75 schedule.
- Gear shifts were modeled after on-road driving experience.
- Torque versus time was derived using the road load equation.

Parameters for 1999 Ford F-250 Superduty Pick-up Truck

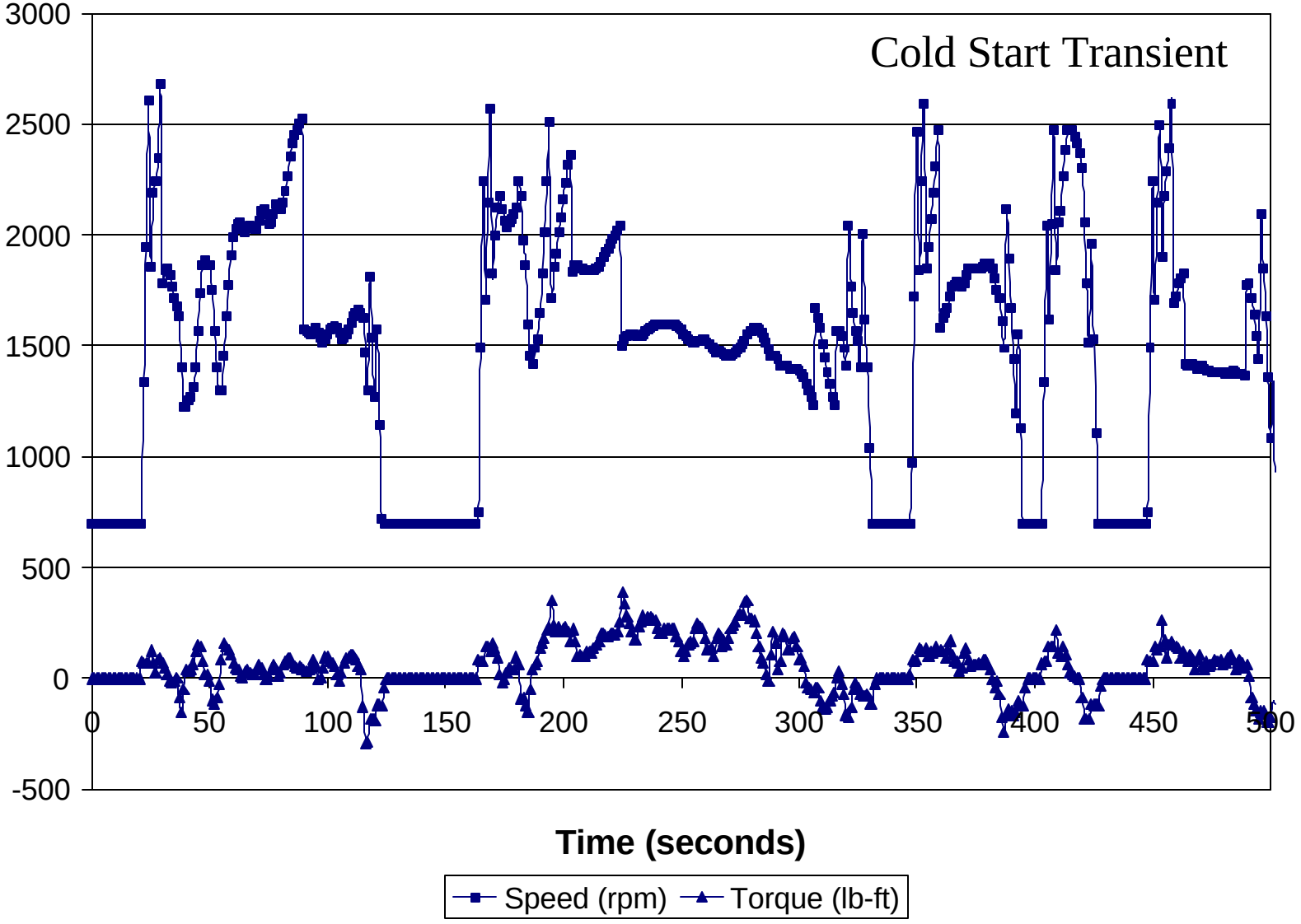
Gear	Reduction	Parameter	Value	Unit
1	5.79	Mass	3632	kg
2	3.31	Frontal Area	5	m^2
3	2.1	Drag Coefficient	0.88	
4	1.31	Air Density	1.177	kgm^{-3}
5	1	Rolling Resistance	0.0098	
6	0.72	Tire Diameter	0.8125	m
Differential	3.73			

Road Load Equation: Power = $.5*\rho*Cd*A*v^3 + \mu*m*g*v + m*v*a$

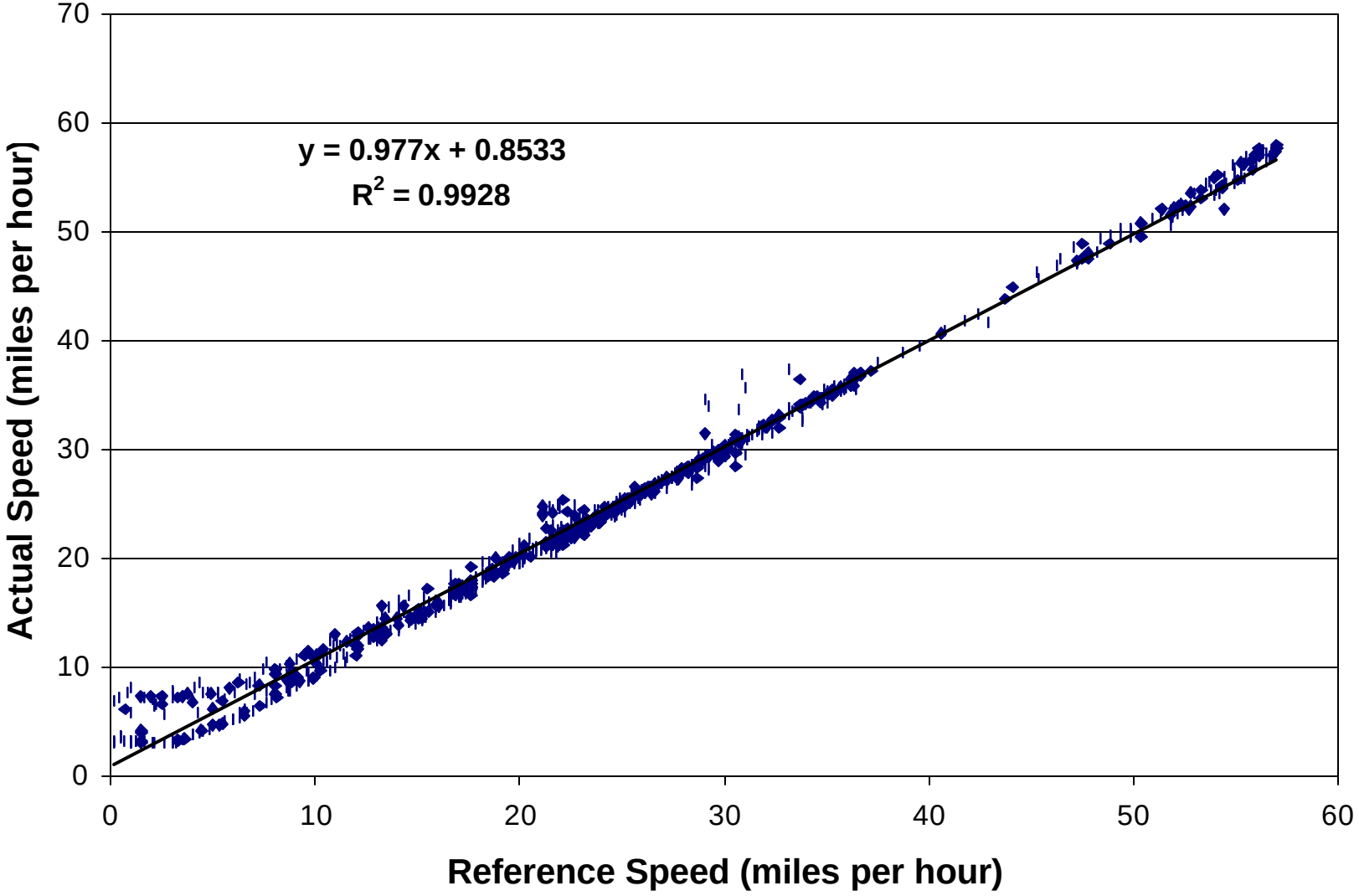
FTP-75 Chassis Cycle Schedule



Mimicked FTP-75 Speed and Load

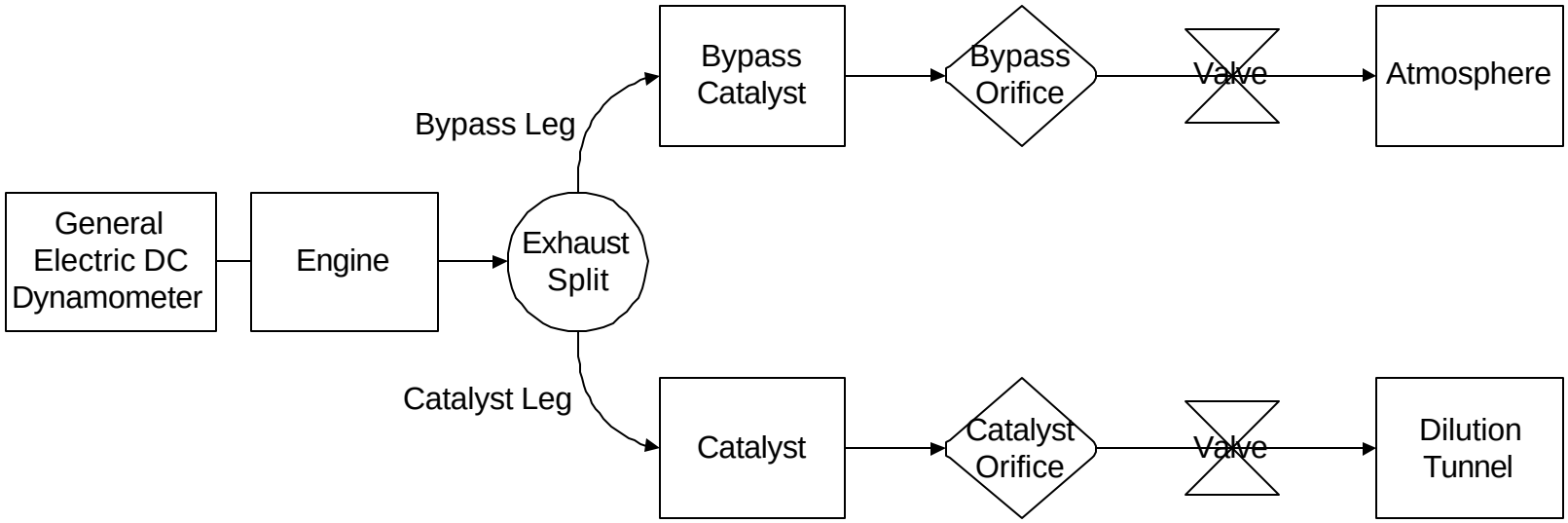


FTP-75 Speed Regression

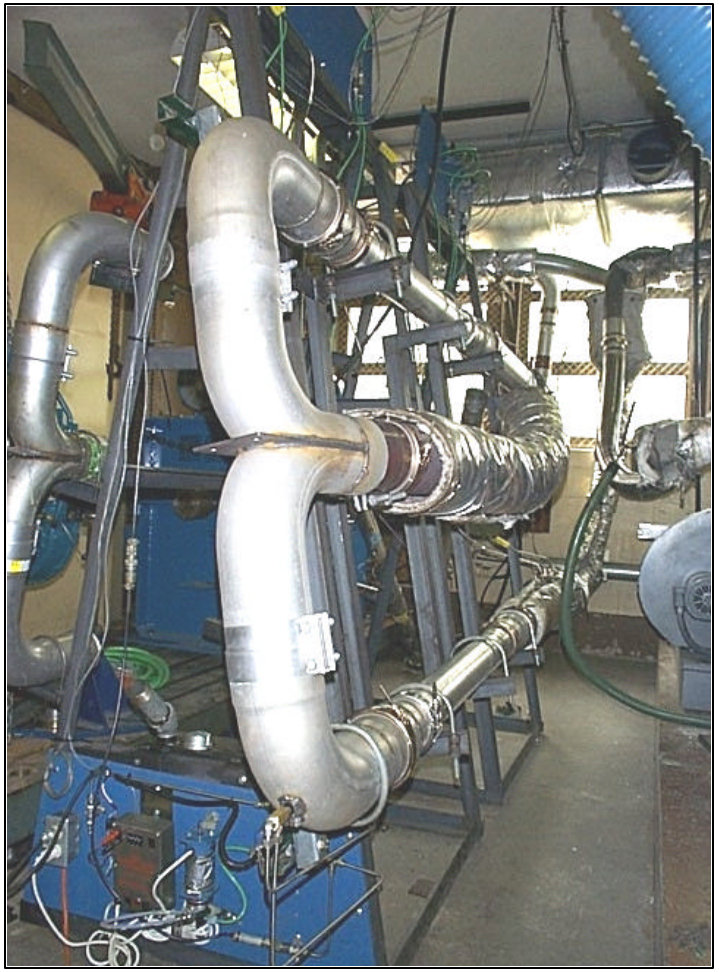


Split Exhaust in Test Cell

- Valves in each exhaust branch are adjusted until approximately half of the CO_2 measured in a full flow exhaust is passing through the catalyst while maintaining the desired engine backpressure



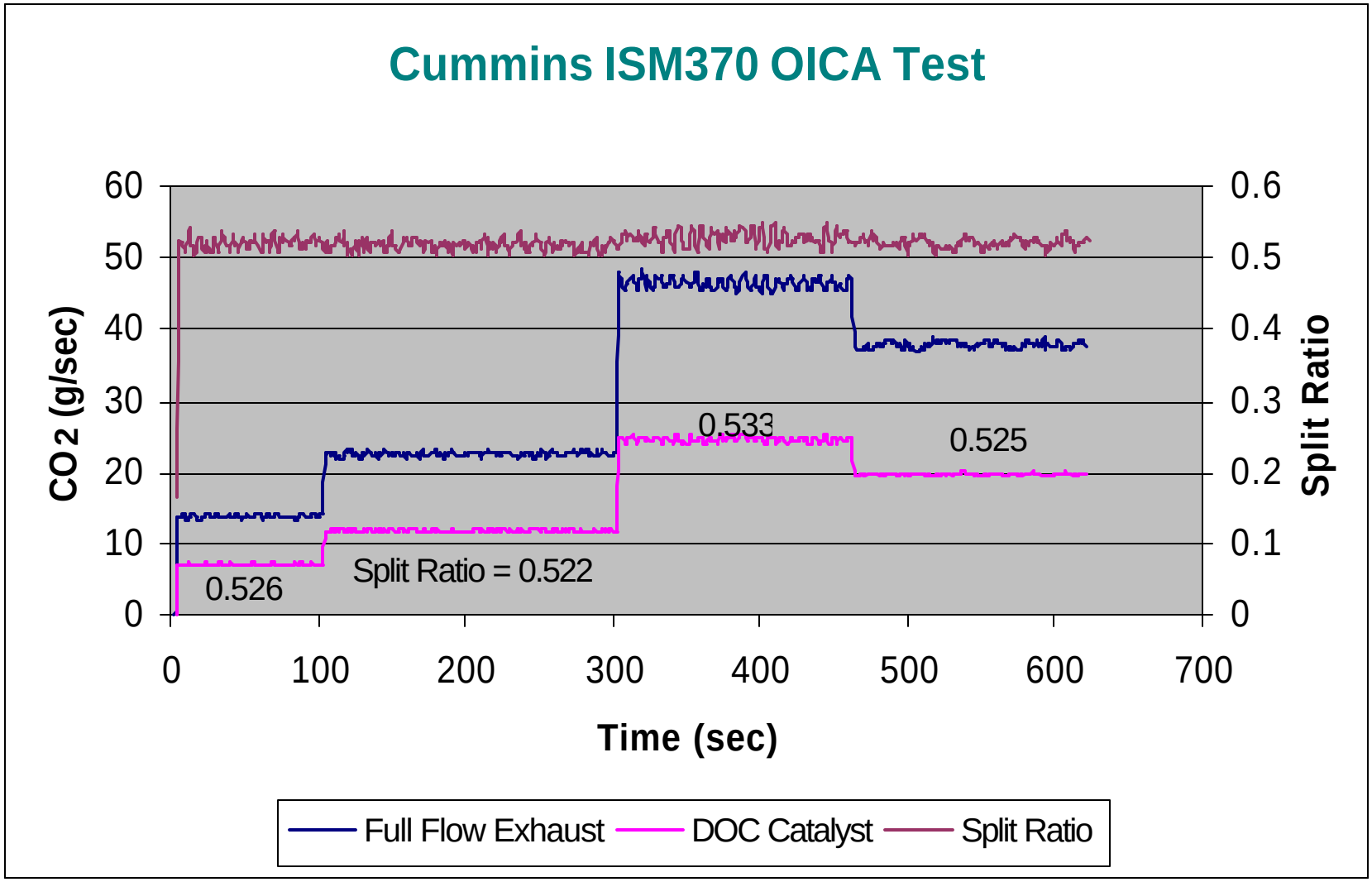
Split Exhaust in the Engine Test Cell



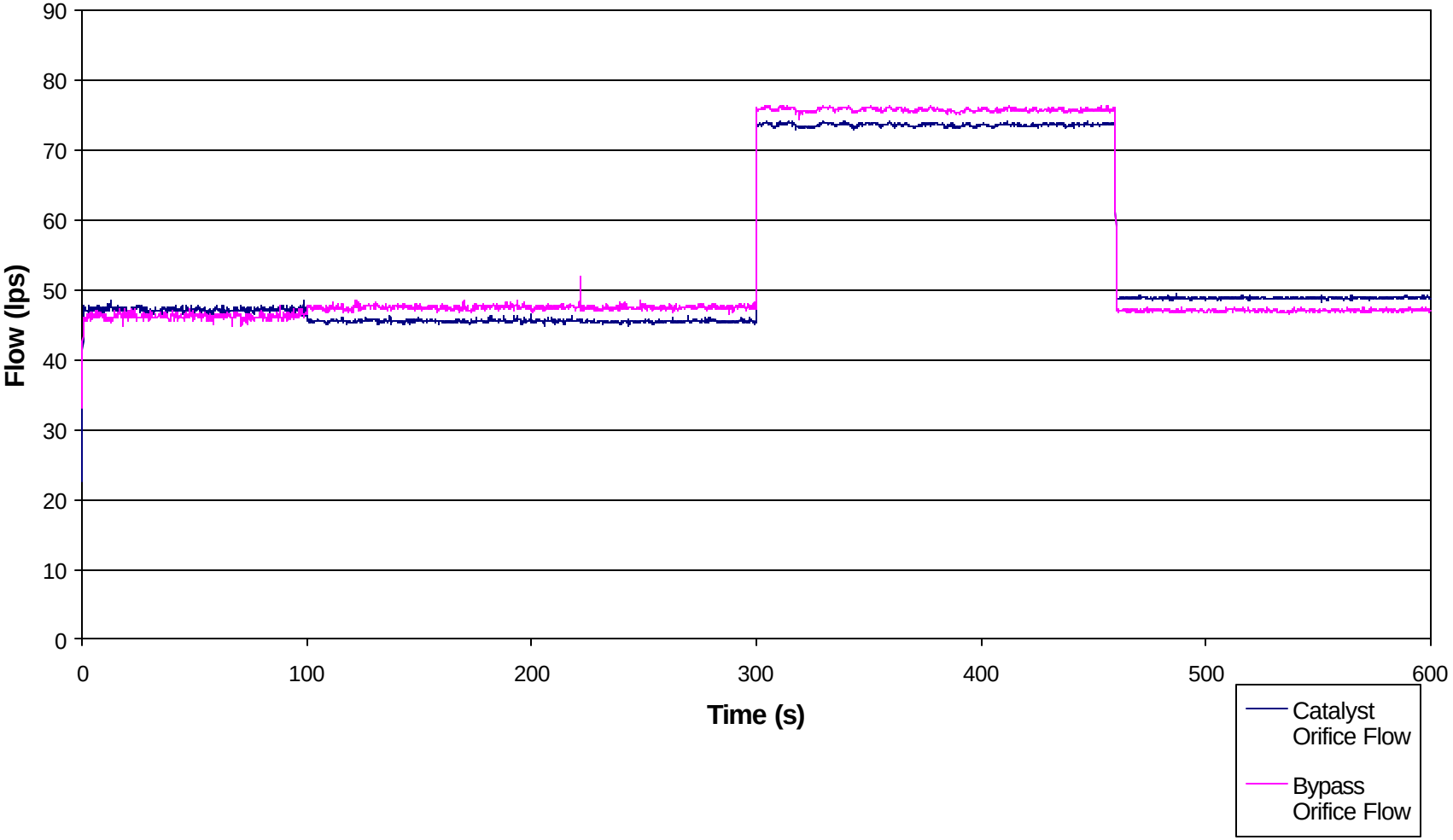
- Measured spit flow exhaust emissions are corrected back to full flow levels.

$$(NO_X)_{CORR} = (NO_X)_{SPLIT}\left[\frac{(CO_2)_{FULL}}{(CO_2)_{SPLIT}}\right]$$

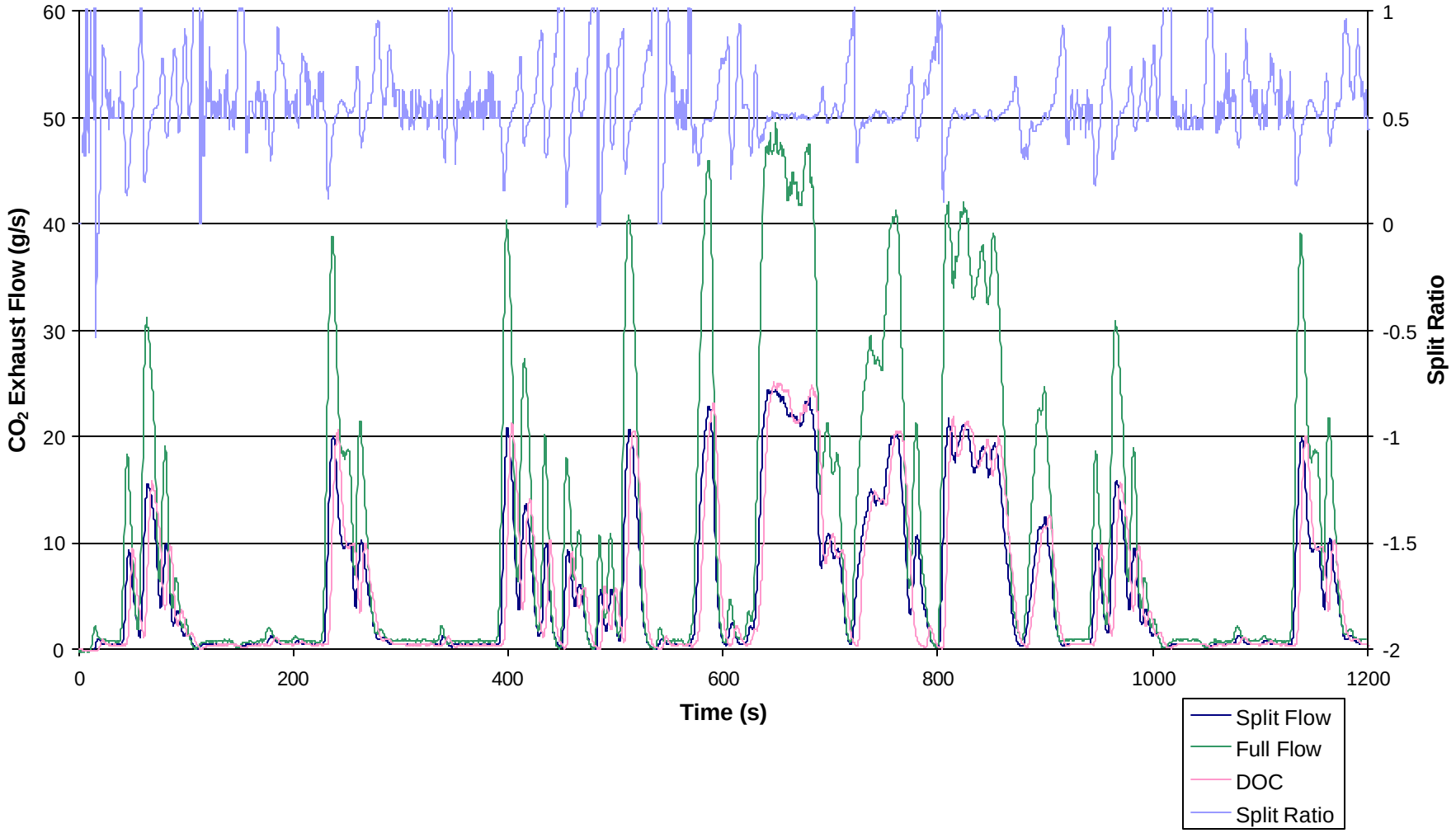
Split Flow Correction



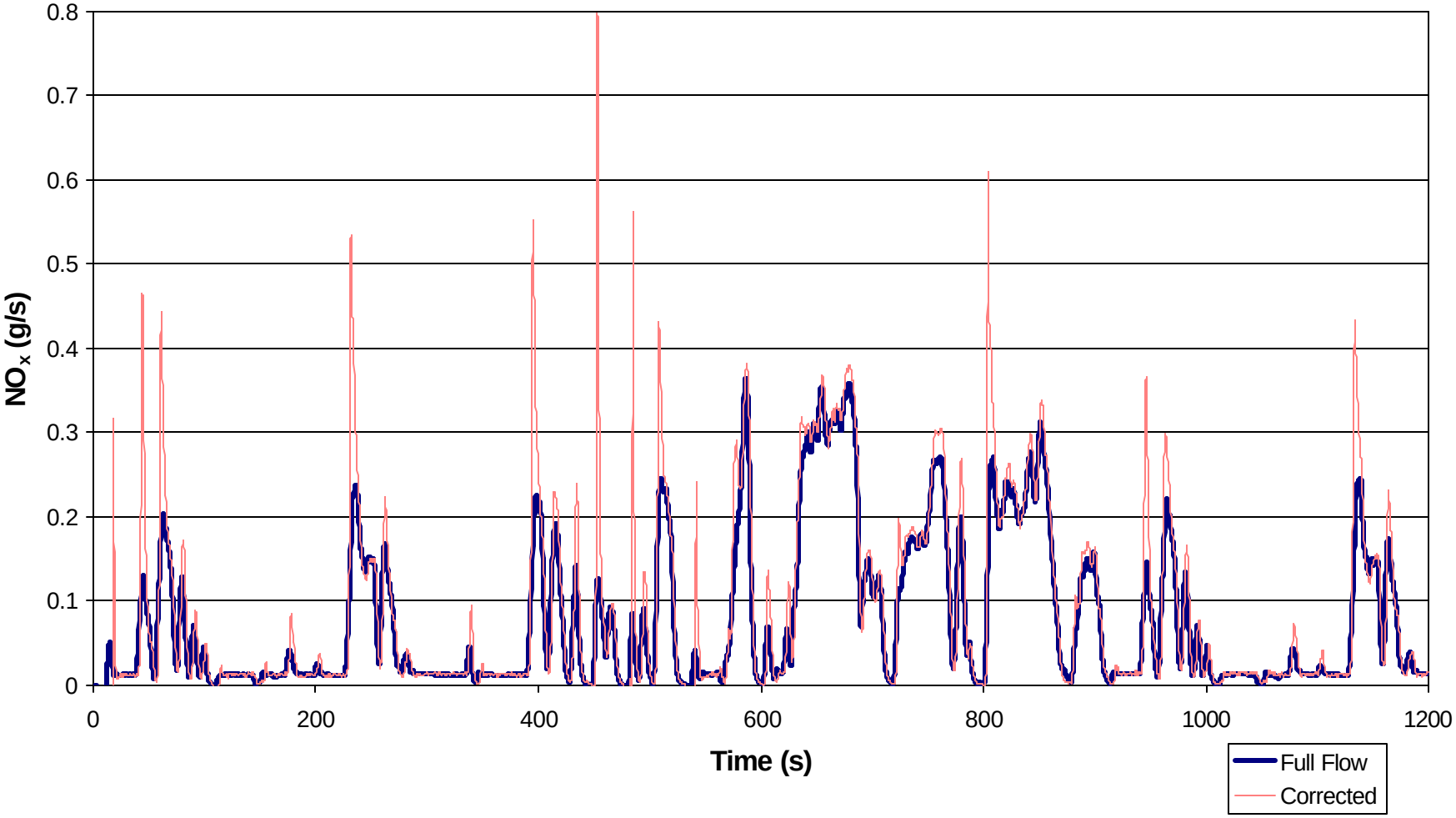
Measured Flow in Exhaust Branches for a Steady State Test



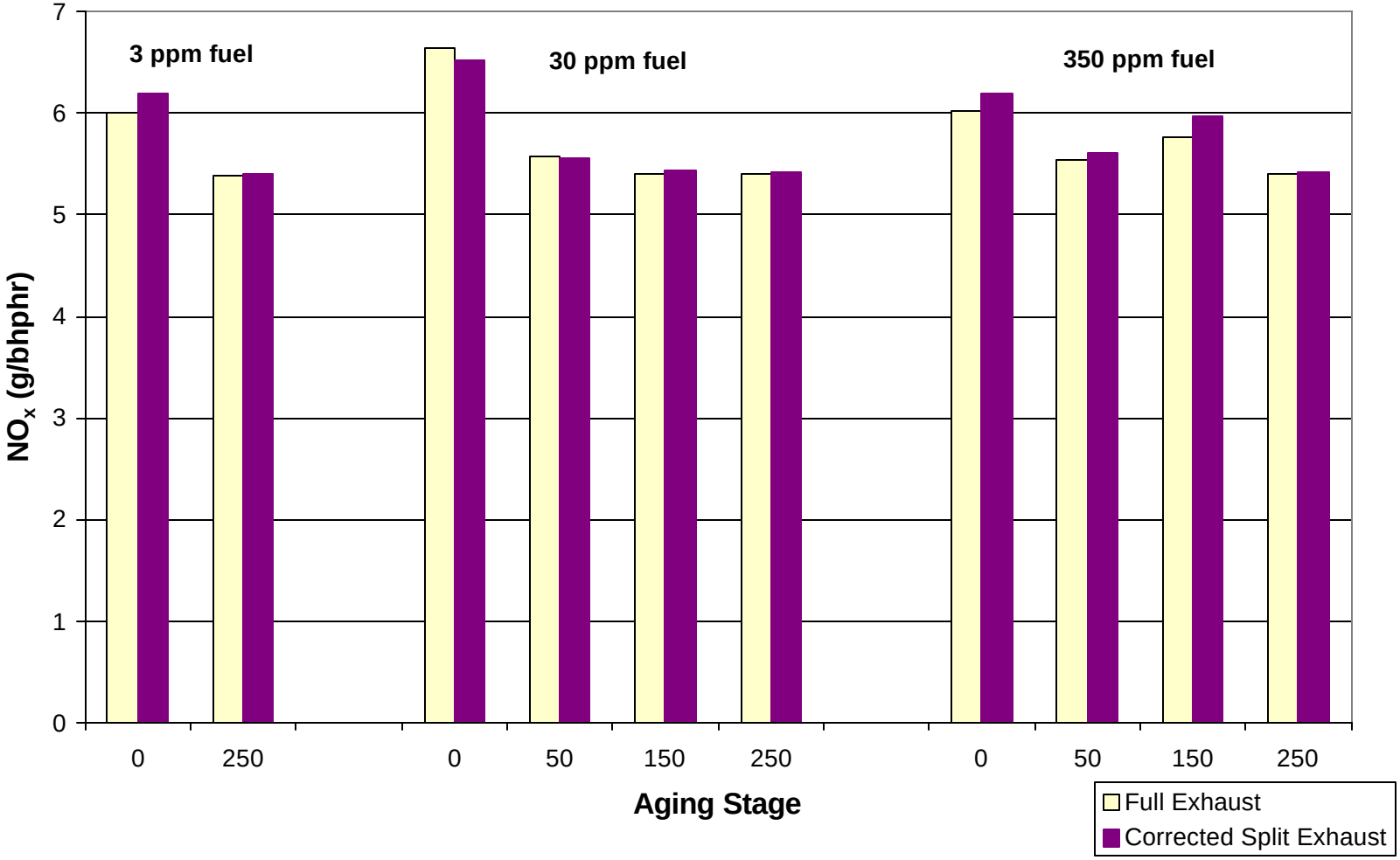
Measured CO_2 in Full Flow and Split Flow Exhaust Streams



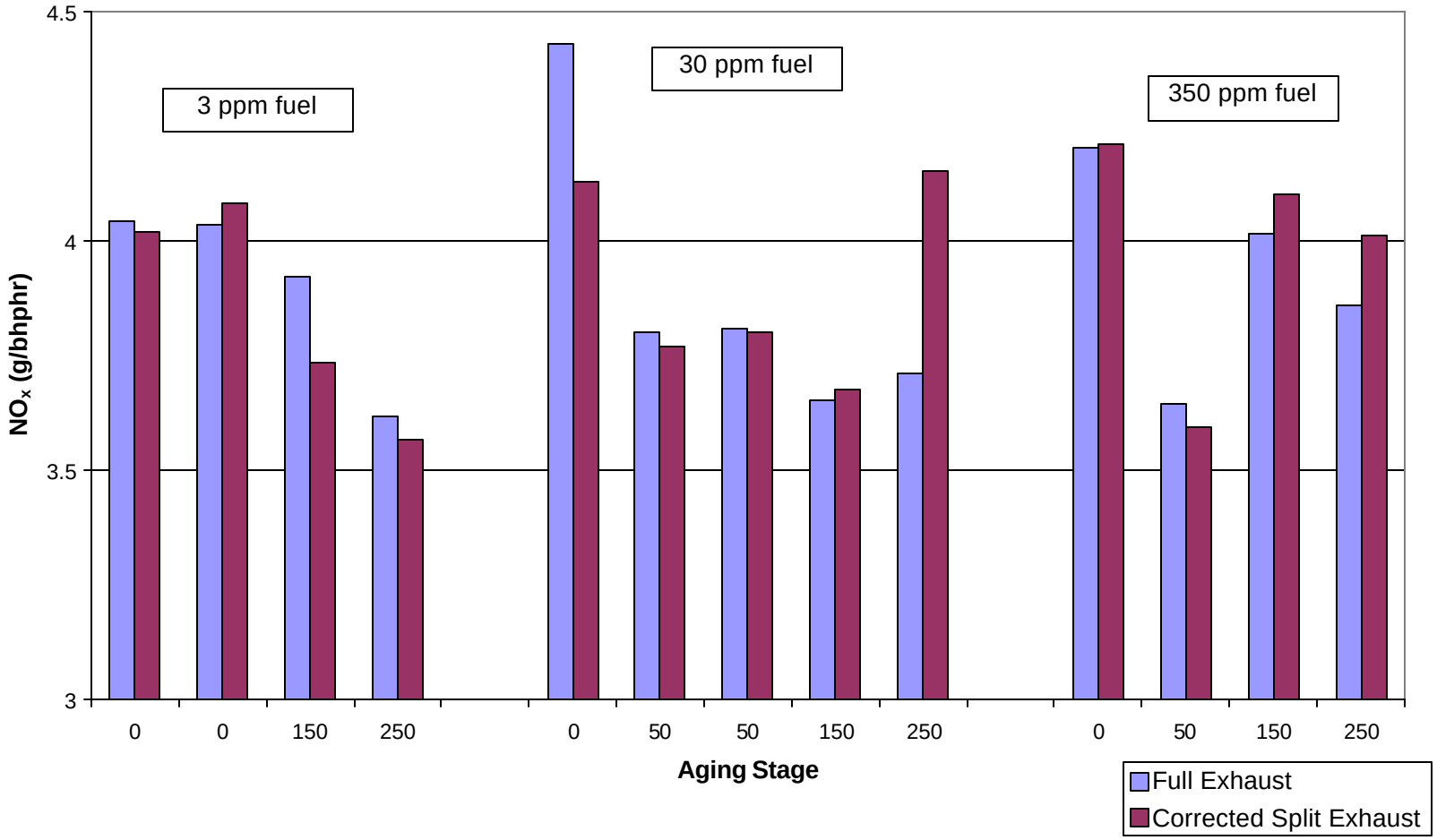
Full Flow NO_x and Corrected NO_x for FTP Cycle



Measured NO_x from Cummins ISM Performing the Steady State OICA



Measured NO_x from Cummins ISM Performing the FTP Cycle



Acknowledgements

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