Characterization of Infield Vehicle Activity and Exhaust Emissions from Diesel Powered Off-road Equipment

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September 6, 2002

Problem Statement

- The current certification test, the ISO-8178 Type C 8-mode test, provides inaccurate estimates of some off-highway equipment contributions to emission inventories.
- Transient results differ from steady-state results because of factors such as the acceleration and deceleration rates encountered in the actual operation of the vehicle
- One set of weighting factors created for the 8-mode test is meant to represent all off-highway equipment

  -steady-state equipment (pumps, generators, etc.)

  -transient equipment (loaders, street sweepers, etc.)

Global Objective

- To measure emissions from off-road equipment, operating in steady-state and transient modes, for emission inventory models

Specific Objectives

- Derive transient cycles for selected off-road vehicles that accurately represent their “real world” operations
- Determine if raw CO_2 emissions (measured in-field) can be used to accurately predict engine power output
- Determine the effects of cycle re-creation accuracy and cycle nature on brake-specific emissions results
- Operate both engines on ISO-8178 8-mode Type C tests and compare the weighted brake-specific results with integrated transient results

Approach

- Investigate the feasibility of power inference from raw CO_2 emissions in preliminary laboratory tests
- Collect raw CO_2 emissions and engine speed data during infield operation
- Predict the in-use engine power from infield CO_2 emissions, and develop an appropriate transient test cycle for each vehicle
- Use the transient cycle developed from the infield data to measure emissions in the laboratory using a full-flow dilution tunnel

Test Vehicles and Engines

John Deere 444 Rubber-Tired Loader

John Deere 6059 Engine

- **-Naturally-Aspirated**
- **-Inline Six-Cylinder**
- **-5.9 Liter**
- **-111hp @ 2375rpm**
- **-281ft-lbs @ 1010rpm**
- **-pre-1996**

Test Vehicles and Engines

Elgin Series P Streetsweeper
John Deere 4039T Engine

- **-Turbocharged**
- **-Inline Four-Cylinder**
- **-3.9 Liter**
- **-114hp @ 2100rpm**
- **-300ft-lbs @ 1710rpm**
- **-post-1996**

Test Vehicles and Engines

Komatsu PC400LC3 Excavator
Komatsu S6D 125-1 Engine

- **-Turbocharged**
- **-Inline Six-Cylinder**
- **-11.05 Liter**
- **-250 hp @ 1800 rpm**
- **-745 ft-lbs @ 1350 rpm**
- **-pre-1996**

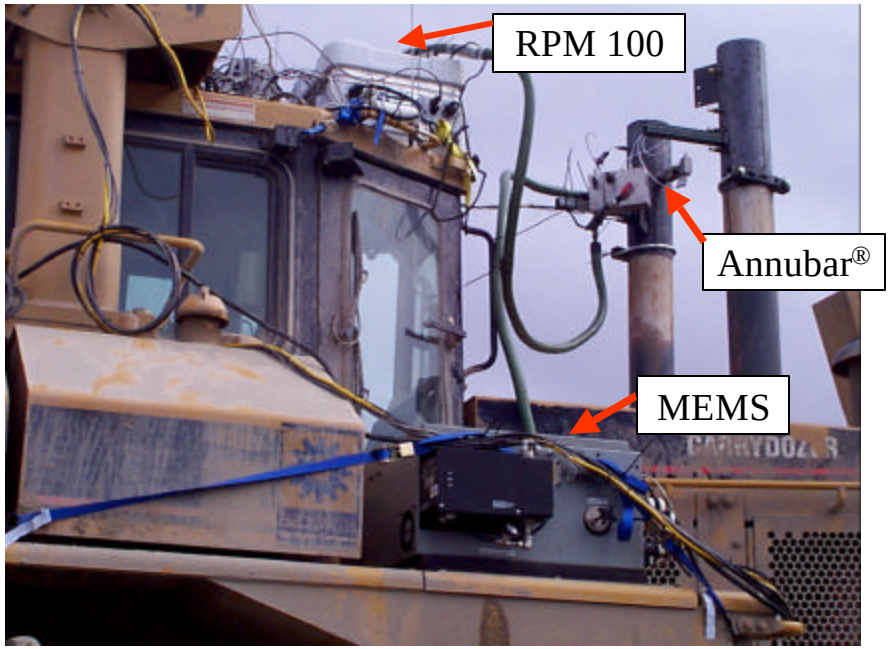
Test Vehicles and Engines

Caterpillar D-11R CD Track-Type Tractor

Caterpillar 3508B TA Engine

- **-Turbocharged**
- **-V-8 Cylinder**
- **-35 Liter**
- **-850 hp @ 1800rpm**
- **-post-1996**

Test Vehicles and Engines



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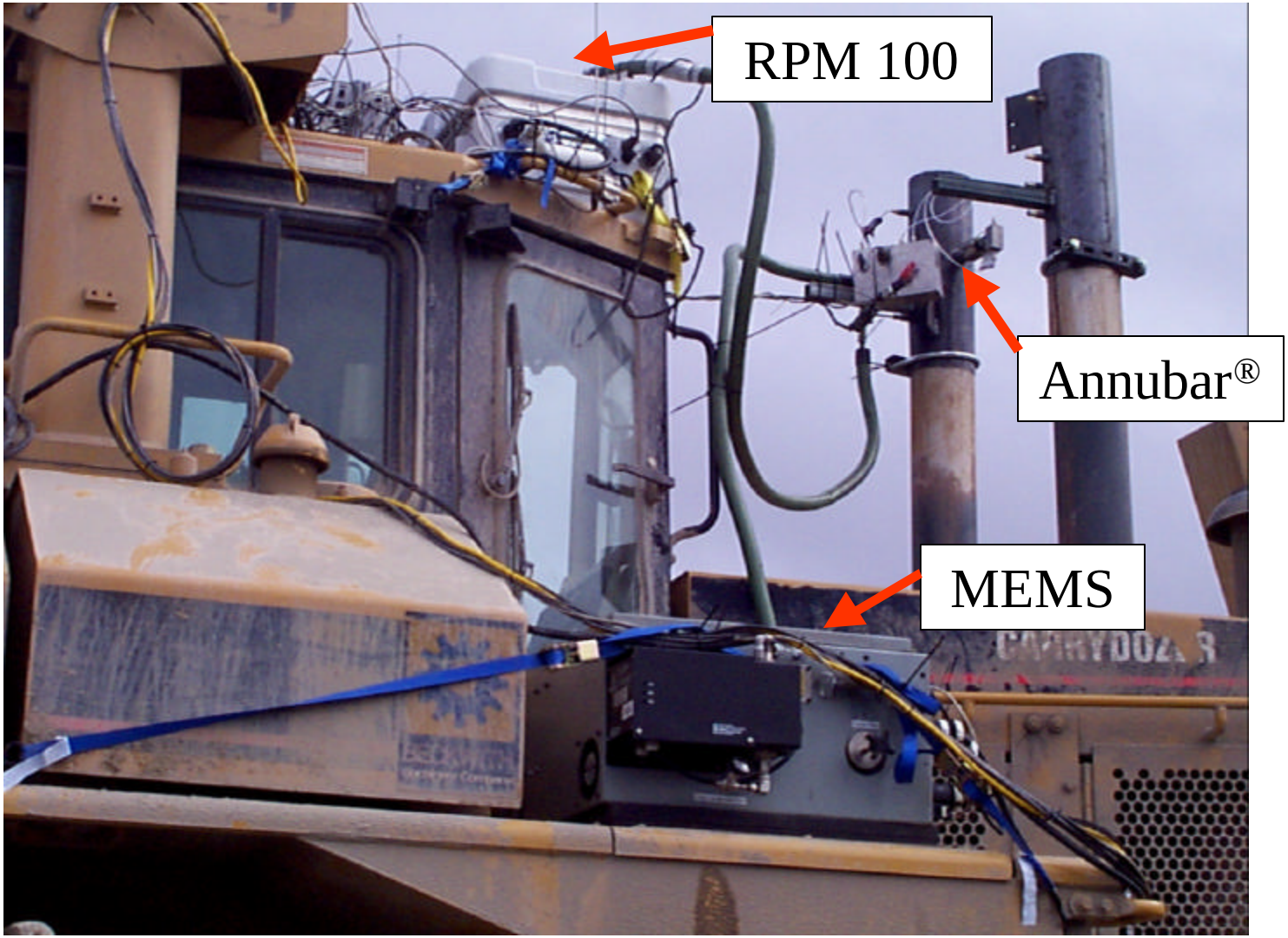
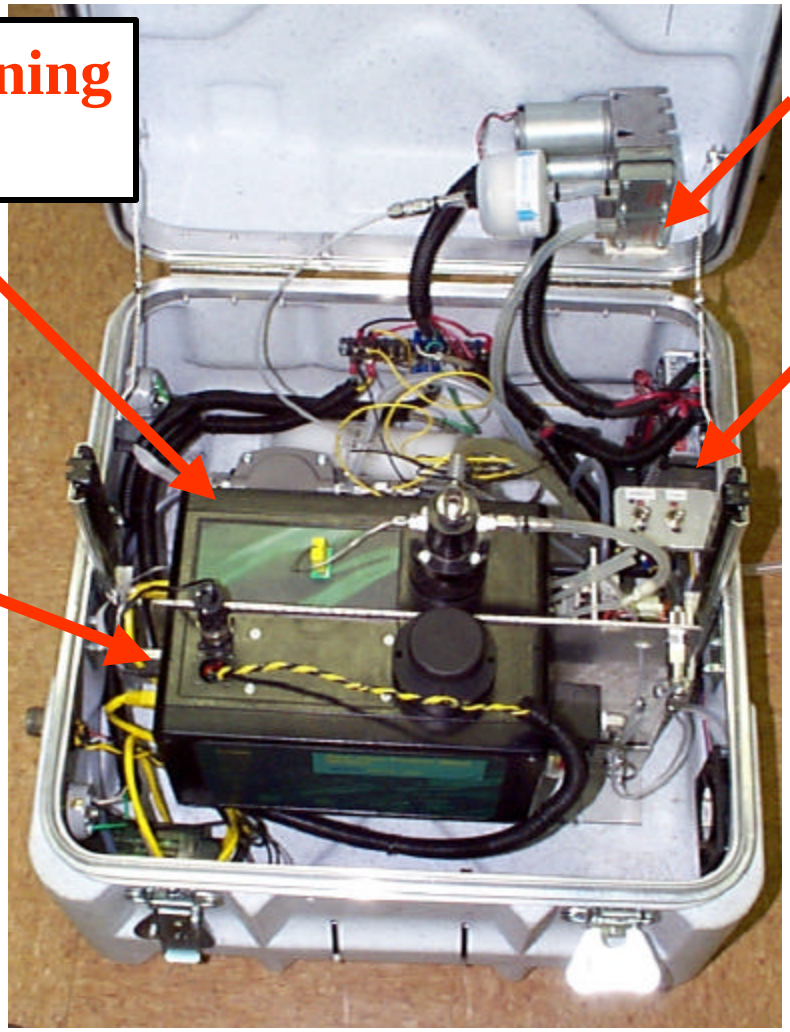
Caterpillar D11 Dozer with a 3508 V-8 Engine Operating at a Strip Mine in WV

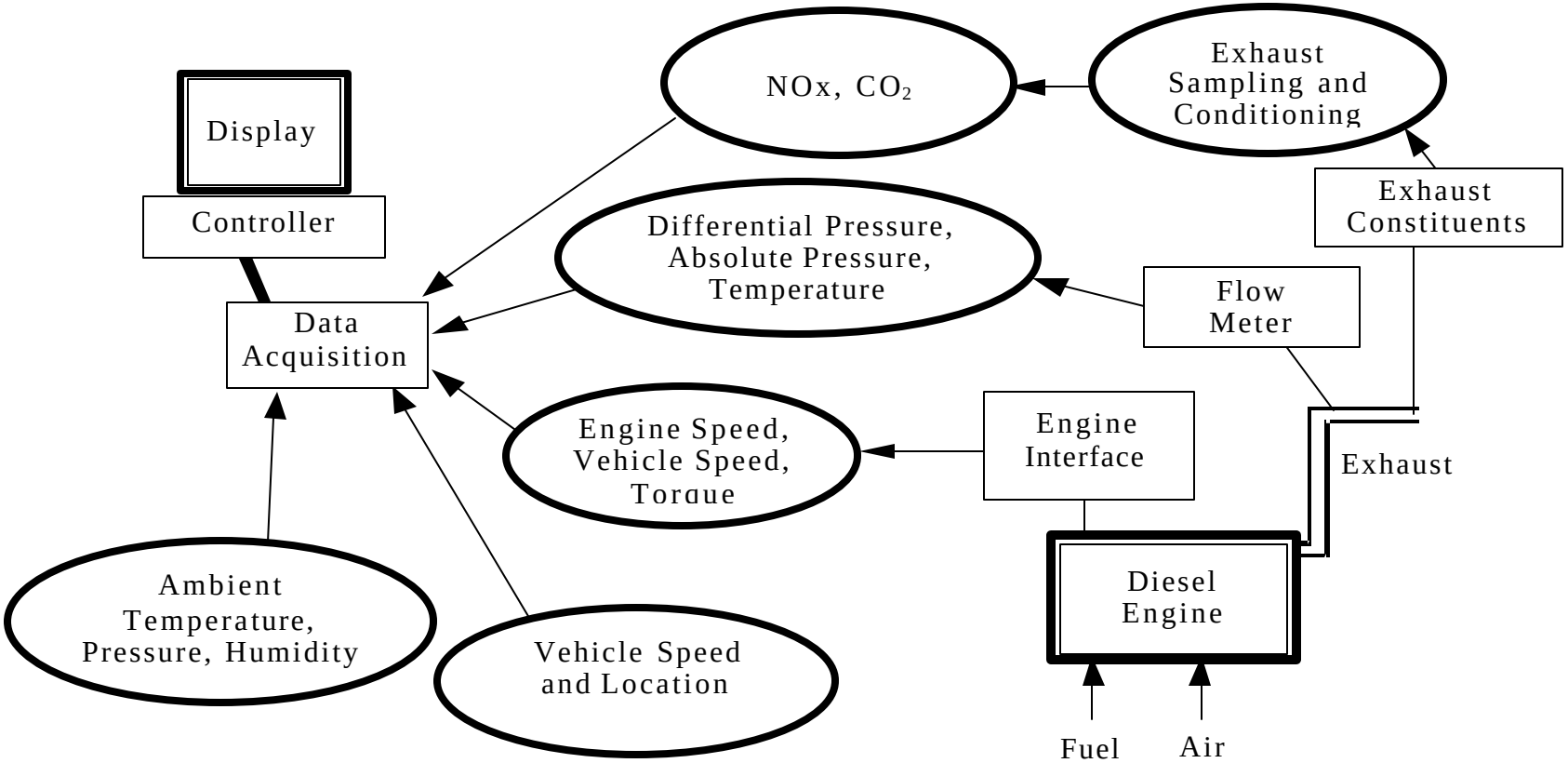
MEMS and RPM 100 on a CAT D11 Dozer with a 3508 V-8 Engine



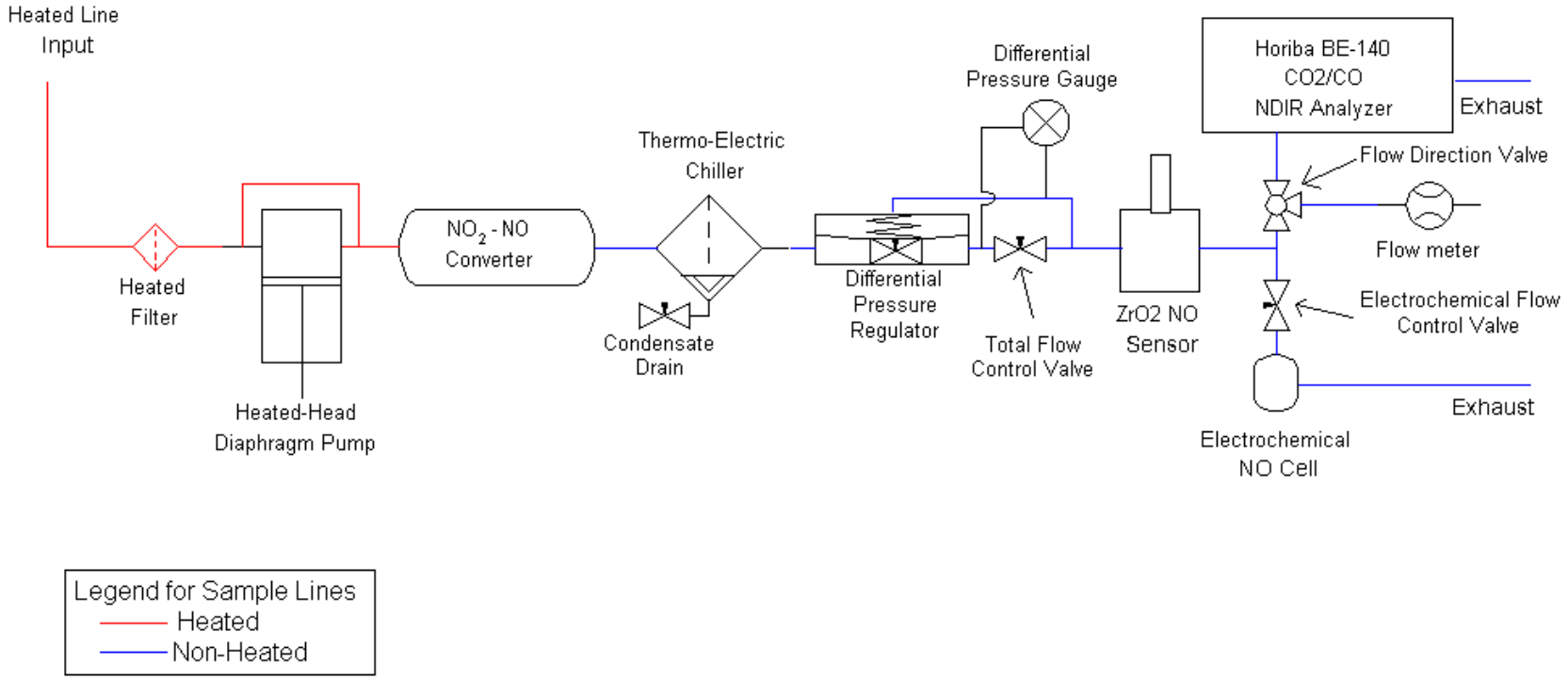
RPM-100 Packaged for the In-field Emissions Measurement from the D-11 Dozer



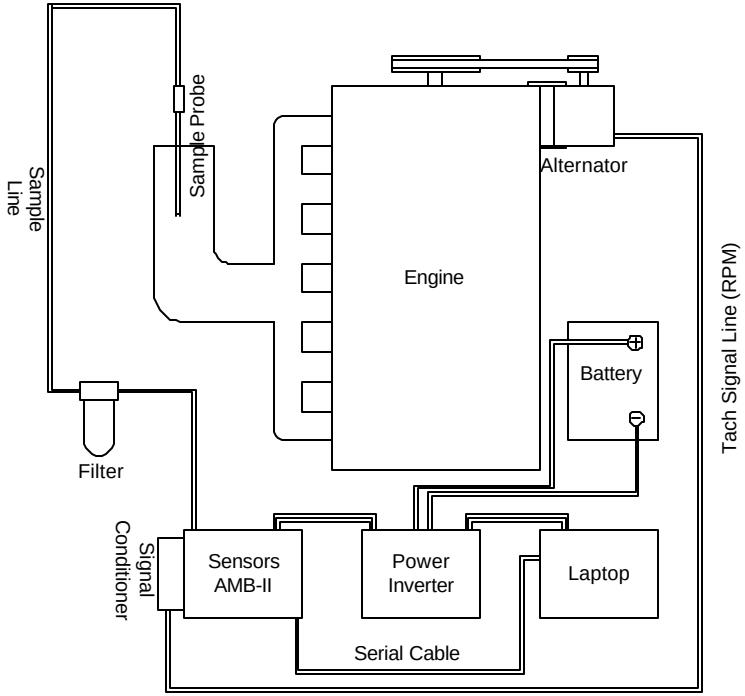
Schematic of the WVU Mobile Emissions Measurement System (MEMS)



MEMS Sample Flow Schematic

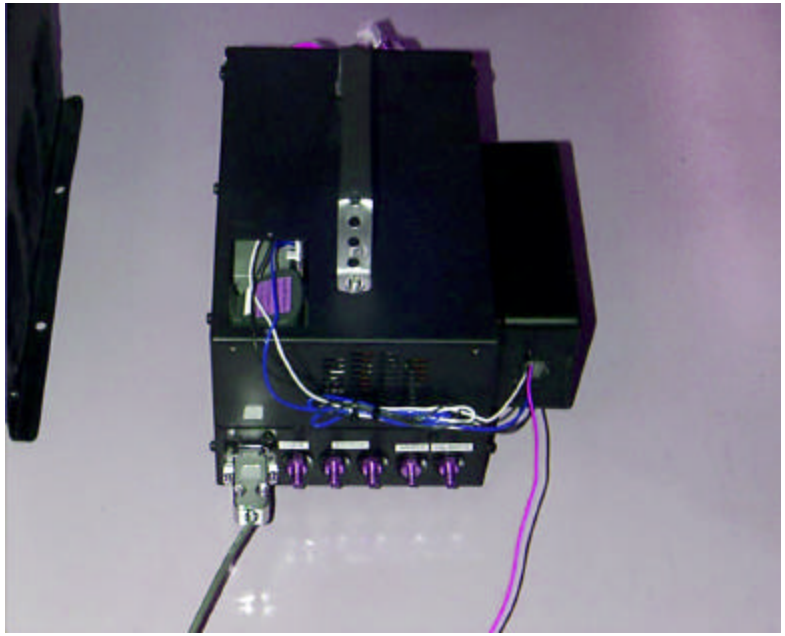


Infield Data Acquisition System



- Solid-state NDIR
- Exhaust sample transfer system
- Power inverter
- Engine speed signal conditioning unit
- Laptop computer

Multigas Analyzer

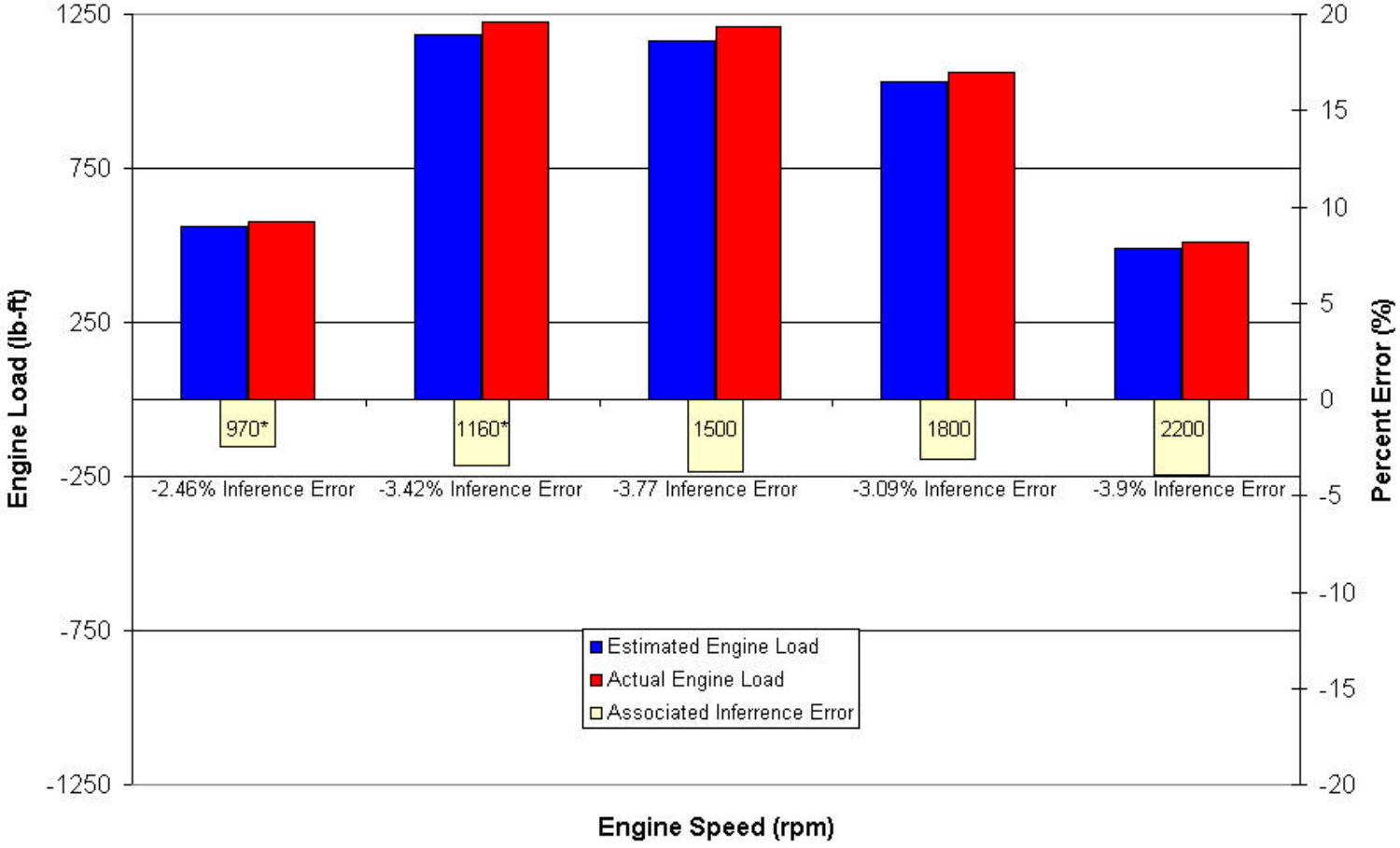


- “Toaster”
- Solid state Non-Dispersive Infrared (NDIR) HC, CO, and CO_2 Detection
- Electrochemical Cell NO and O_2 Detection
- TTL-Type Signal Input for Engine Speed Measurement

Preliminary Torque Inference Testing

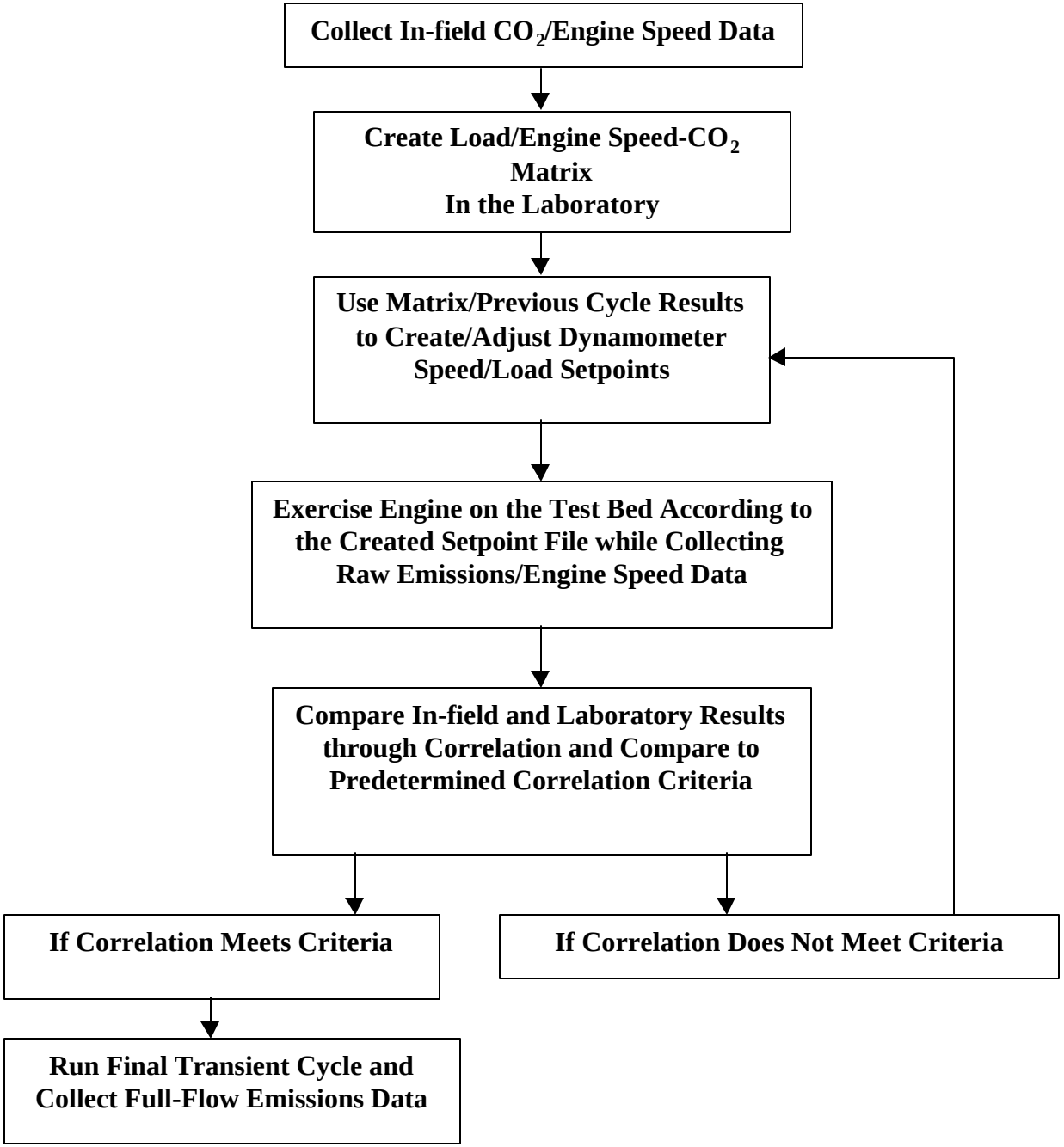
- Testing was performed on an on-highway Cummins ISM370 diesel engine that was available in the EERL
- Five engine load cycles were run while raw emissions were collected with the Sensors AMB-II (motored, idle, 25%, 50%, 75%, and 100%)
- CO_2/load curves were created for different speed points (970rpm, 1160rpm, 1500rpm, 1800rpm, and 2200rpm)
- Torque was estimated for the ISM370 operating on a pre-determined load-step cycle from this data

Results of Torque Inference Testing

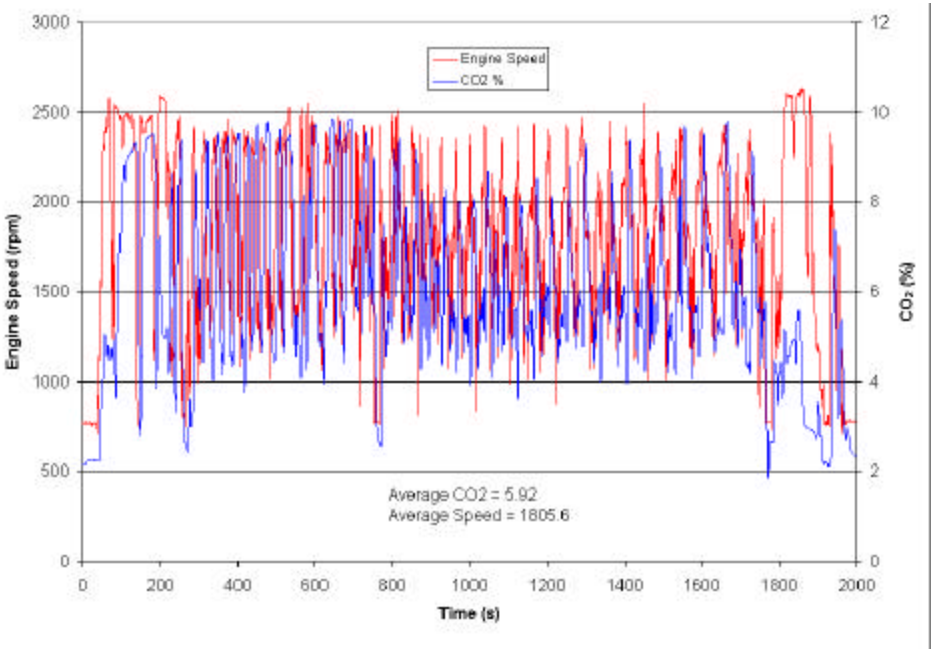


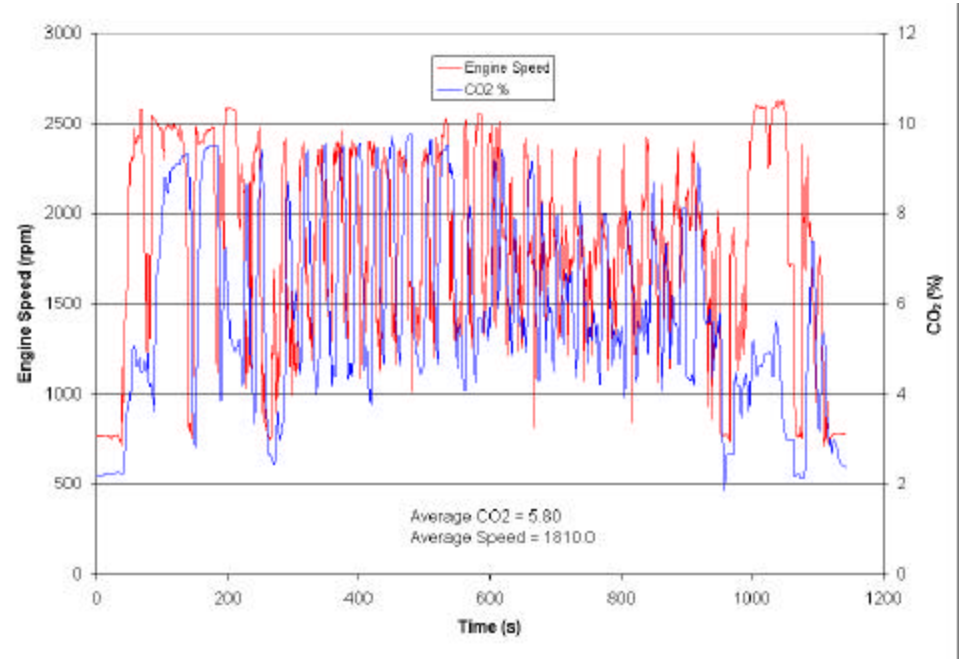
Cycle Development

- Collect infield CO_2/engine speed data
- Remove engine from the vehicle
- Install and instrument the engine on an eddy-current dynamometer test bed
- Produce an engine speed/load-CO_2 matrix
- Use this matrix data to determine the loads encountered during the collection of infield data to create the full test cycle speed/load setpoints
- Shorten the full infield cycle while maintaining similarity
- Operate the engine according to the created cycle while collecting raw CO_2/engine speed data on the dynamometer
- Compare the continuous data traces collected in the laboratory to the infield data traces
- Adjust and repeat the dynamometer test on the new cycle
- Continue iteration until convergence criteria is met


Collect In-field CO_2/Engine Speed Data
Create Load/Engine Speed-CO_2 Matrix In the Laboratory
Use Matrix/Previous Cycle Results to Create/Adjust Dynamometer Speed/Load Setpoints
Exercise Engine on the Test Bed According to the Created Setpoint File while Collecting Raw Emissions/Engine Speed Data
Compare In-field and Laboratory Results through Correlation and Compare to Predetermined Correlation Criteria
If Correlation Meets Criteria
If Correlation Does Not Meet Criteria
Run Final Transient Cycle and Collect Full-Flow Emissions Data

Rubber-Tired Loader Full and Shortened Infield Cycles





Full Infield Cycle

Integrated CO_2/cycle = 5.9%

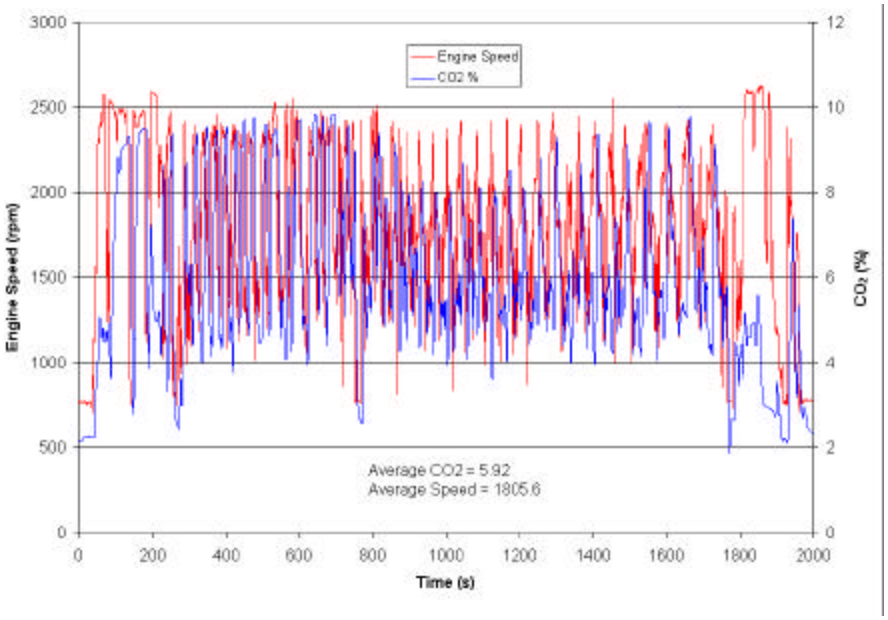
Average Engine Speed/cycle = 1806 rpm

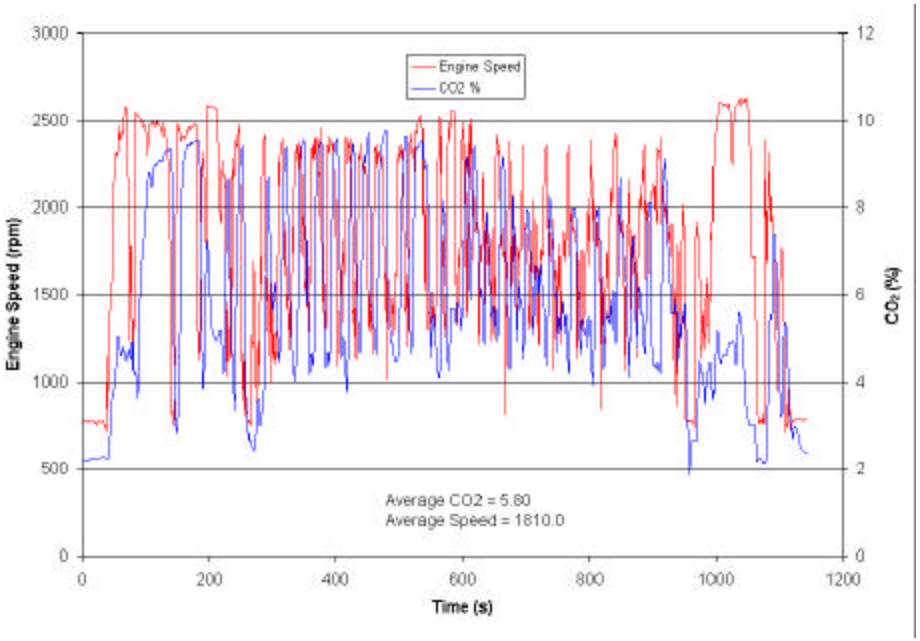
Shortened Infield Cycle

Integrated CO_2/cycle = 5.8%

Average Engine Speed/cycle = 1810 rpm

Rubber-Tired Loader Full and Shortened Infield Cycles





Full Infield Cycle

Integrated CO_2/cycle = 5.9%

Average Engine Speed/cycle = 1806 rpm

Shortened Infield Cycle

Integrated CO_2/cycle = 5.8%

Average Engine Speed/cycle = 1810 rpm

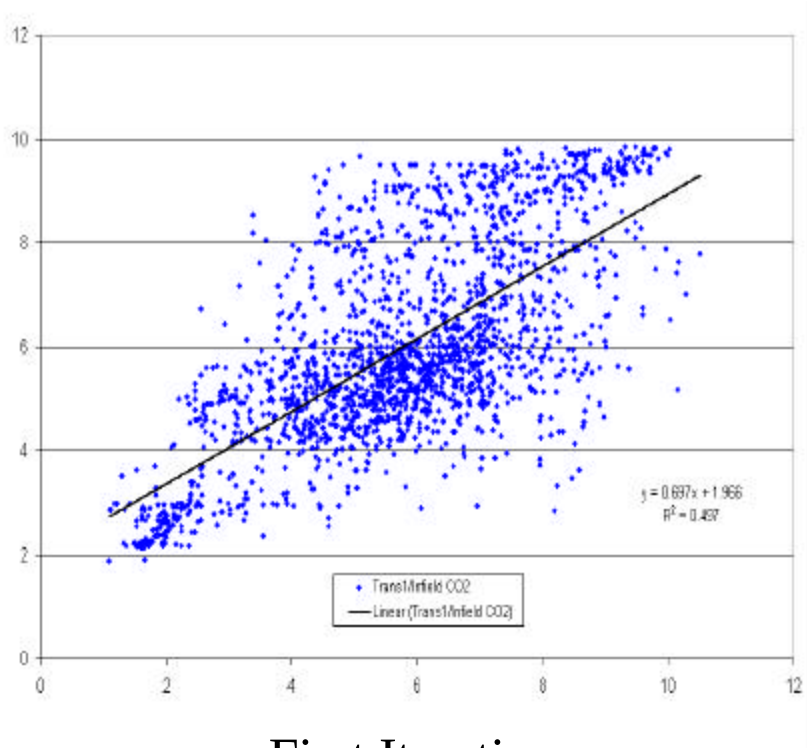
Engine Speed/Load-CO_2 matrix for the John Deere 6059 Loader Engine

Engine Speed	% Load										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
700	1.29	4.99	4.97	4.95	4.98	6.06	7.18	8.24	9.35	10.25	11.77
800	1.31	2.11	2.92	3.80	4.70	5.82	6.88	7.93	9.32	10.21	12.24
900	1.34	2.10	2.93	3.81	4.73	5.85	6.97	8.10	9.31	10.23	12.29
1000	1.35	2.09	2.89	3.86	4.79	5.95	6.95	8.10	9.54	10.48	12.43
1100	1.39	2.11	2.91	3.84	4.84	5.94	6.99	8.09	9.37	10.24	12.21
1200	1.43	2.10	2.91	3.83	4.76	5.84	6.92	7.98	9.24	10.11	12.19
1300	1.46	2.16	2.97	3.83	4.78	5.83	6.89	7.95	9.20	10.06	12.08
1400	1.51	2.19	2.97	3.85	4.76	5.77	6.90	7.94	9.12	9.99	11.86
1500	1.55	2.22	3.04	3.86	4.78	5.77	6.82	7.88	9.17	9.93	11.99
1600	1.60	2.26	3.07	3.91	4.75	5.77	6.85	7.84	9.12	9.90	11.84
1700	1.66	2.30	3.13	4.02	4.84	5.80	6.77	7.86	9.03	9.79	11.75
1800	1.72	2.38	3.13	3.99	4.85	5.82	6.81	7.78	8.92	9.65	11.63
1900	1.81	2.47	3.22	4.08	4.91	5.84	6.84	7.88	8.95	9.68	11.61
2000	1.88	2.56	3.25	4.06	4.92	5.85	6.85	7.79	8.89	9.56	11.49
2100	1.97	2.65	3.33	4.10	5.00	5.94	6.94	7.81	8.85	9.51	11.28
2200	2.10	2.71	3.38	4.13	5.02	5.87	6.85	7.77	8.81	9.38	11.21
2300	2.23	2.76	3.42	4.16	5.01	5.86	6.84	7.71	8.66	9.24	11.02
2400	2.28	2.82	3.41	4.07	4.83	5.60	6.48	7.33	8.20	8.63	10.15
2500	2.35	2.72	2.87	2.93	3.12	3.36	3.56	3.84	4.02	4.10	4.65
2600	2.50	3.47	3.49	3.55	3.48	3.52	3.62	3.68	3.71	3.50	3.81
2700	2.50	3.47	3.49	3.55	3.48	3.52	3.62	3.68	3.71	3.50	3.81

Comparison of Engine Speed Discretized Average Load Values between the Full and Shortened In-field Loader Cycles

Engine Speed (RPM)	Shortened Cycle Average Load (ft-lbs)	Full Cycle Average Load (ft-lbs)	% Difference
750	36.1	41.2	-12.47
850	100.4	95.6	4.99
950	73.8	59.5	24.10
1050	128.1	113.8	12.57
1150	109.4	98.8	10.71
1250	106.4	98.6	7.96
1350	115.8	114.3	1.26
1450	123.4	119.4	3.36
1550	116.4	119.5	-2.58
1650	124.0	119.8	3.49
1750	114.6	119.2	-3.85
1850	125.7	127.1	-1.03
1950	114.5	122.5	-6.50
2050	117.3	116.1	1.00
2150	95.3	100.3	-5.04
2250	100.3	104.7	-4.17
2350	103.1	106.0	-2.73
2450	140.5	134.6	4.37
2550	94.4	89.0	6.10
2650	1.4	1.4	0.00

CO_2 Correlation for the First and Final Iterations of the Loader Cycle

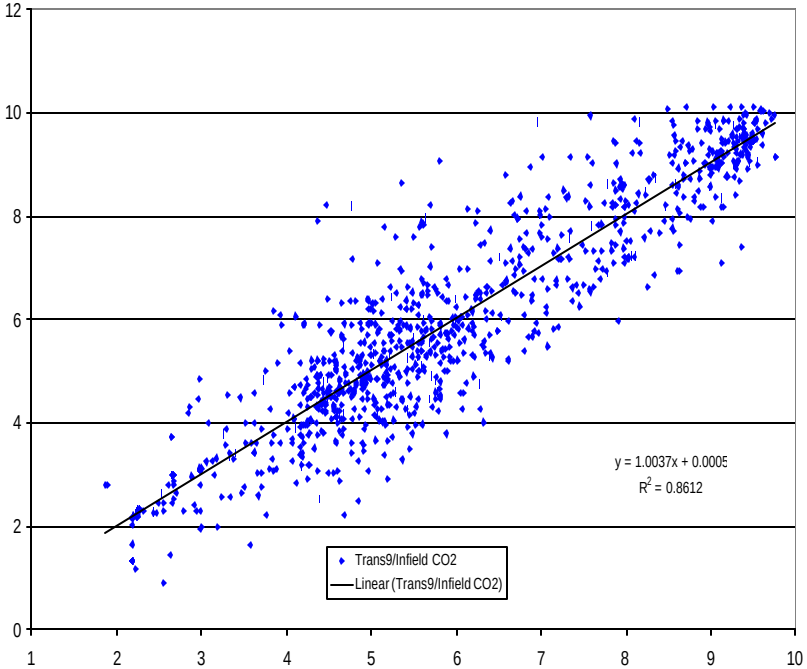


First Iteration

R^2 = 0.50

Trendline Slope = 0.70

Y-Intercept = 2.0%



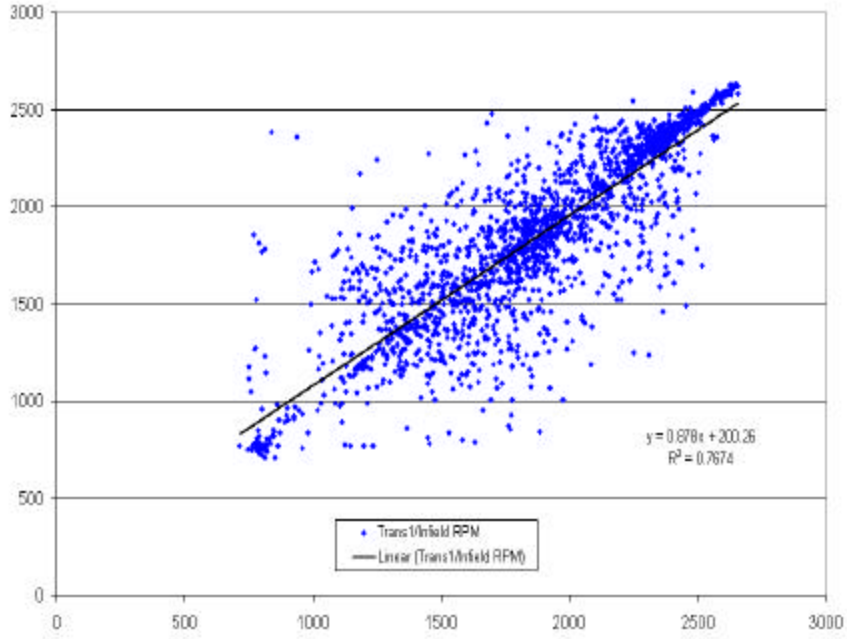
Final Iteration

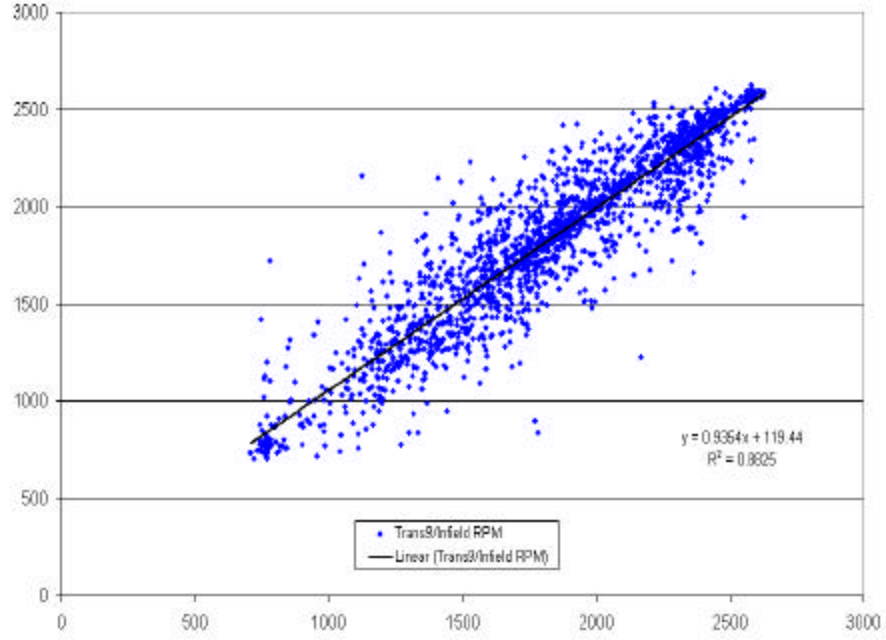
R^2 = 0.86

Trendline Slope = 1.00

Y-Intercept = 0%

Engine Speed Correlation for the First and Final Iterations of the Loader Cycle





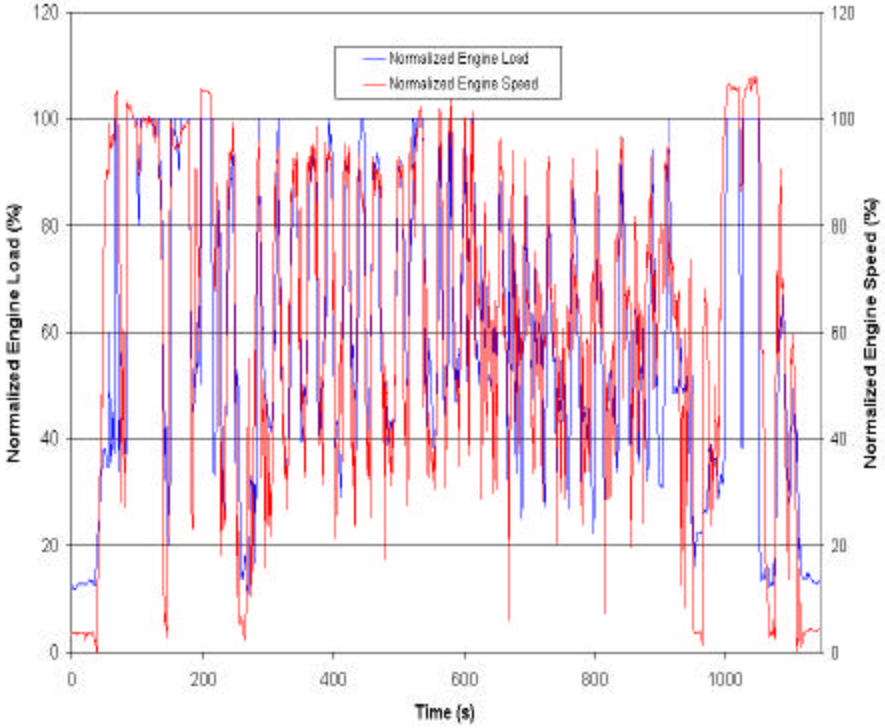
First Iteration

R^2	= 0.77
Trendline Slope	= 0.88
Y-Intercept	= 200 rpm

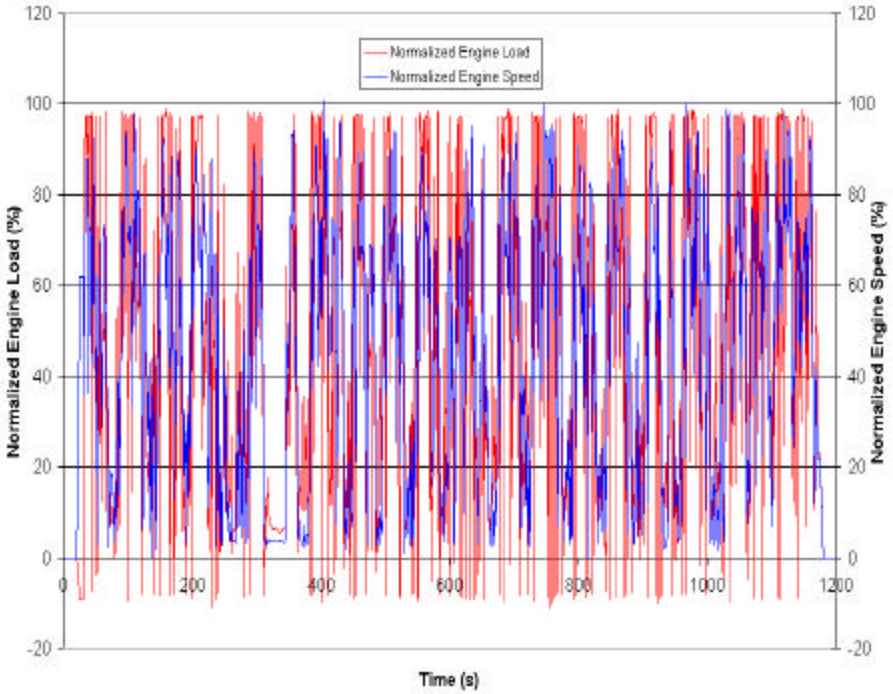
Final Iteration

R^2	= 0.88
Trendline Slope	= 0.94
Y-Intercept	= 119 rpm

Comparison of Normalized WVU and EPA Loader Cycles

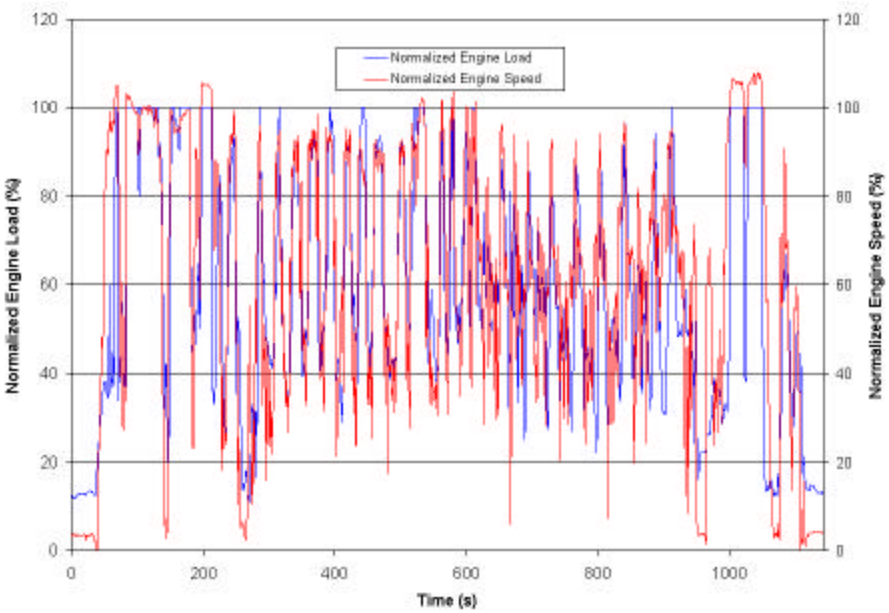


Shortened WVU Loader Cycle

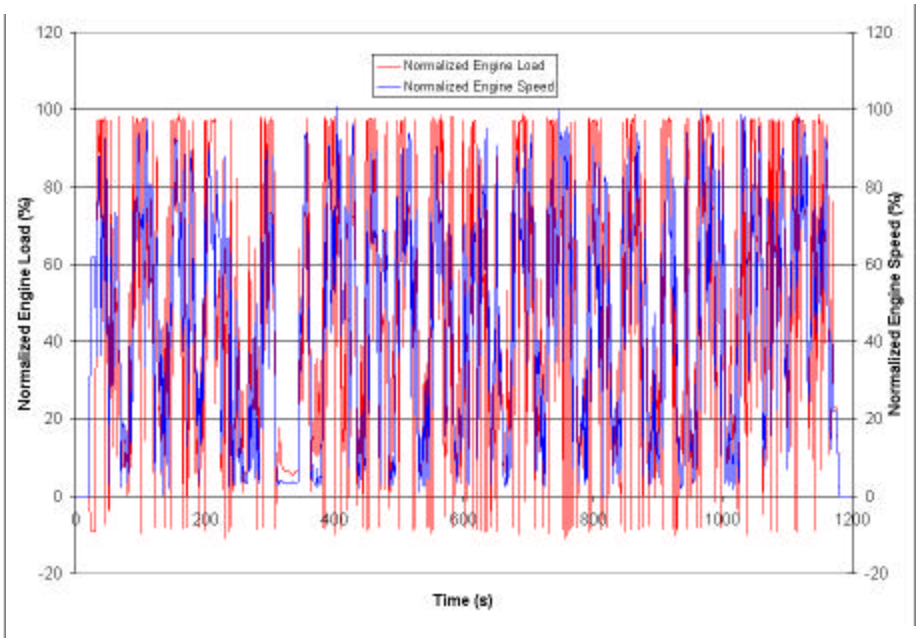


EPA Loader Cycle

Comparison of Normalized WVU and EPA Loader Cycles



Shortened WVU Loader Cycle



EPA Loader Cycle

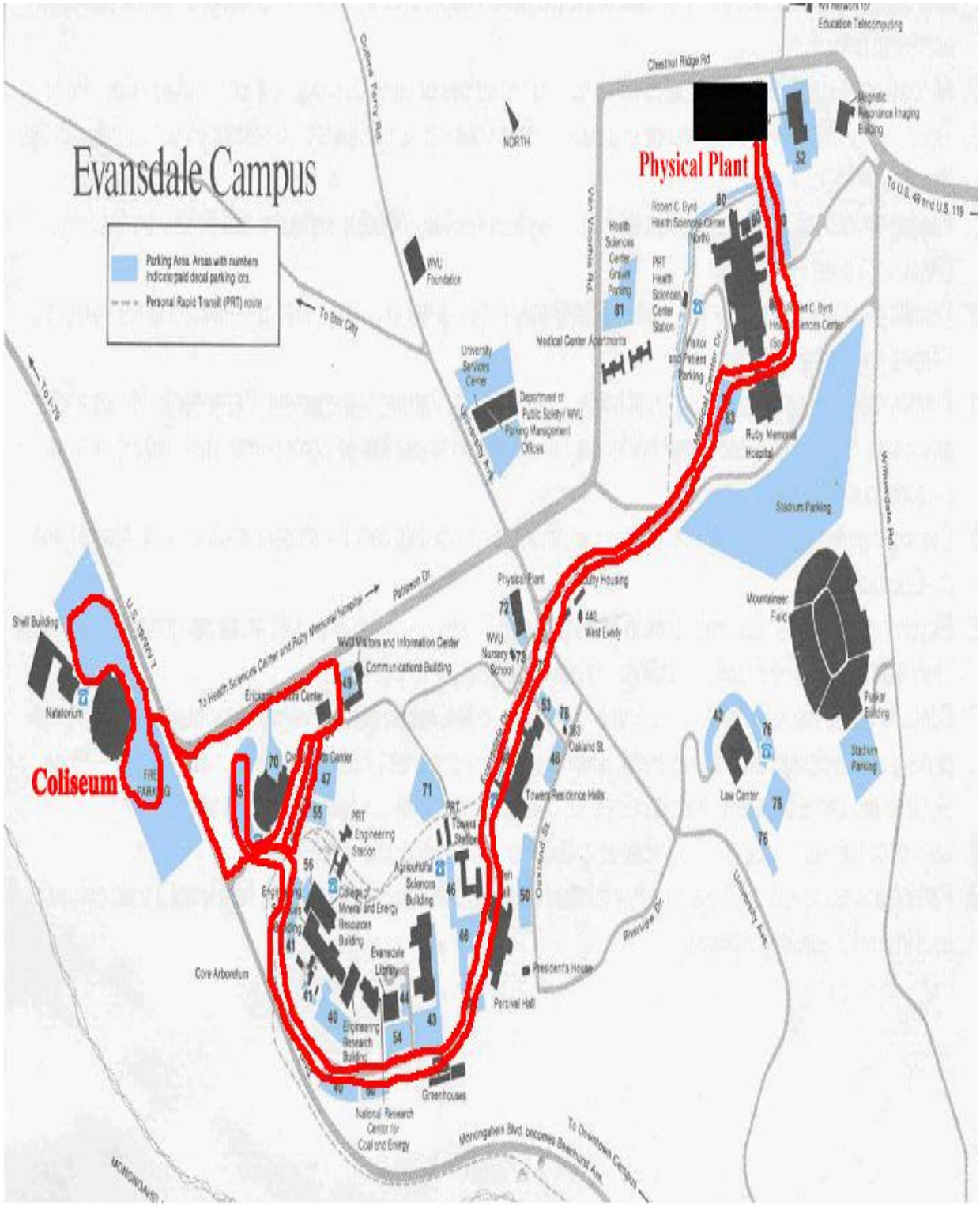
Cycle Normalization

Cycle normalization provides a means of evaluating various engines that may be used for specific vehicle applications

$$\text{Normalized Load} = \frac{\text{measured load}}{\text{maximum load achievable at that particular speed}}$$

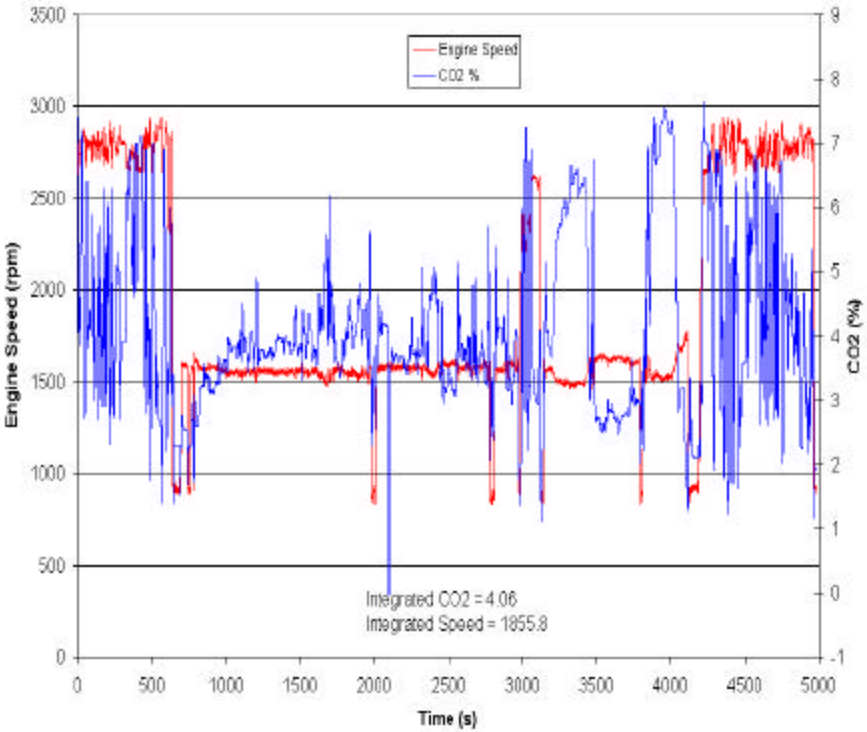
$$\text{Normalized Speed} = \frac{\text{measured speed - curb idle speed}}{\text{gsc - curb idle speed}}$$

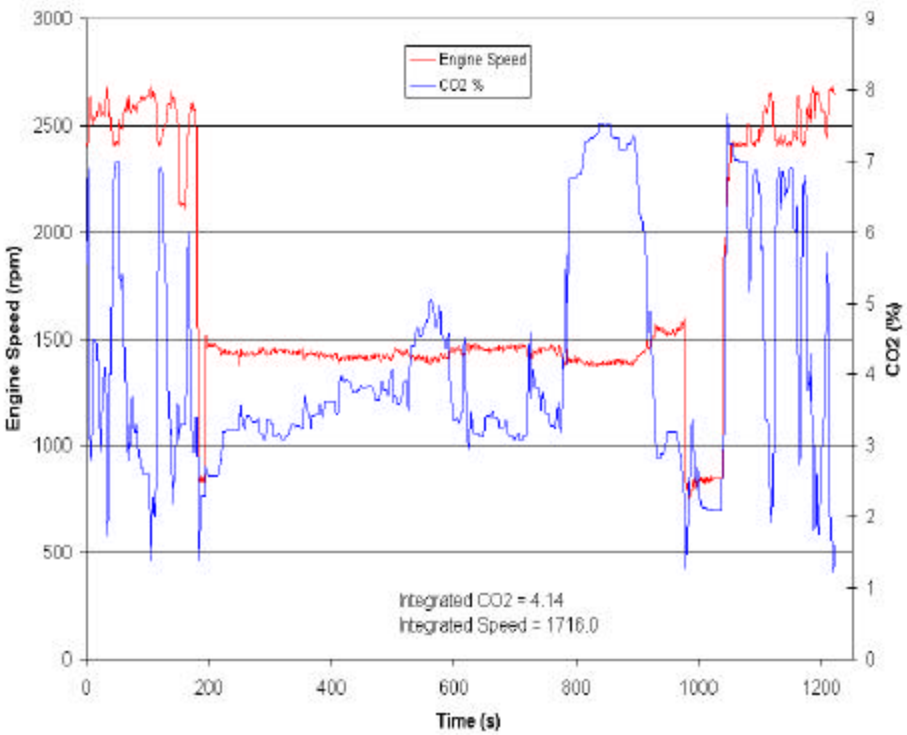
gsc (governed central speed) = the speed on a power map greater than max power at which 50% of max power is achieved



Evansdale Campus
Parking Area. Areas with numbers indicate paid decal parking lots.
Personal Rapid Transit (PRT) route
Physical Plant
Coliseum
NORTH
Chestnut Ridge Rd
Van Voorhis Rd.
Collins Ferry Rd.
To Stor City
To I-79
To U.S. 49 and U.S. 119
Magnetic Resonance Imaging Building
Robert C. Byrd Health Sciences Center (North)
Health Sciences Center Gravel Parking
PRT Health Sciences Center Station
Medical Center Apartments
Visitor and Patient Parking
Medical Center Dr.
Ruby Memorial Hospital
University Services Center
Department of Public Safety/ WVU Parking Management Offices
University Ave.
Stadium Parking
Withowdale Rd.
Mountaineer Field
Pulskar Building
Stadium Parking
Law Center
Physical Plant
Faculty Housing
West Evelyn
WVU Nursery School
Shell Building
Natatorium
U.S. 19/WV 7
Patteson Dr.
To Health Sciences Center and Ruby Memorial Hospital
WVU Visitors and Information Center
Communications Building
Oakland St.
Towers Residence Halls
PRT Engineering Station
PRT Towers Station
Agricultural Sciences Building
College of Mineral and Energy Resources Building
Evansdale Library
Core Arboretum
Engineering Research Building
Greenhouses
National Research Center for Coal and Energy
President's House
Percival Hall
Riverview Dr.
University Ave.
Monongahela Blvd. becomes Beechurst Ave.
To Downtown Campus

Streetsweeper Full and Shortened Infield Cycles





Full Infield Cycle

Integrated CO_2/cycle = 4.1%

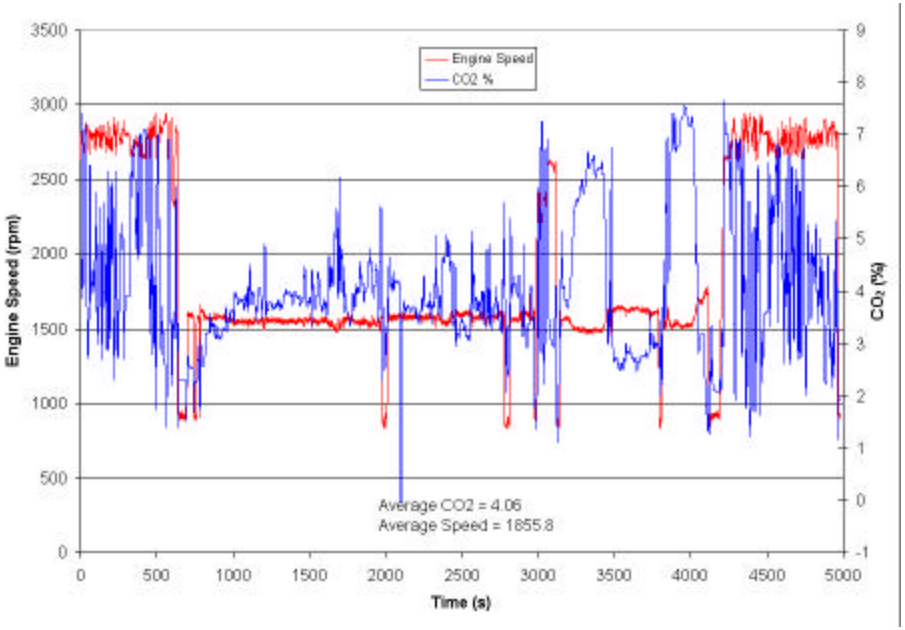
Integrated Engine Speed/cycle = 1856 rpm

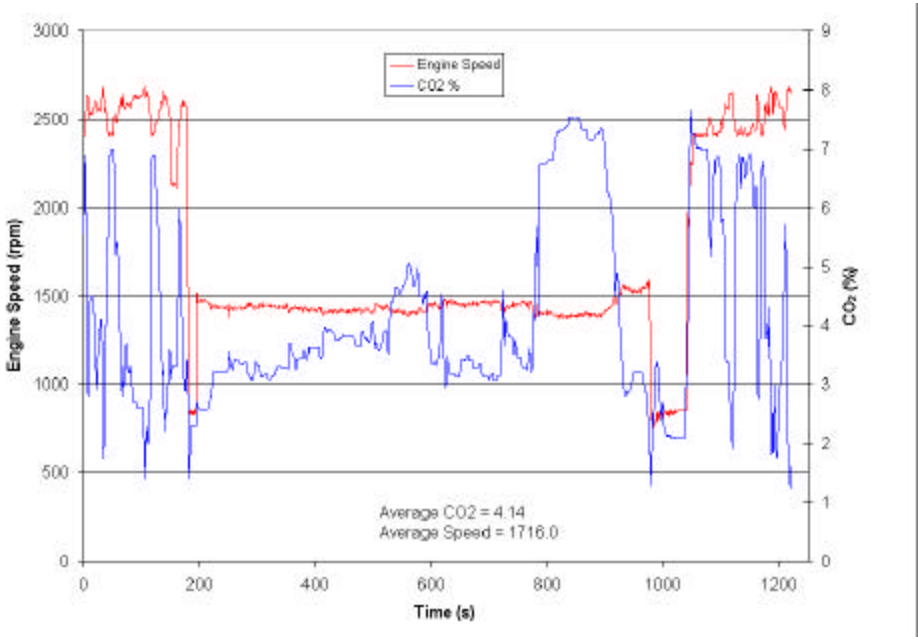
Shortened Infield Cycle

Integrated CO_2/cycle = 4.1%

Integrated Engine Speed/cycle = 1716 rpm

Streetsweeper Full and Shortened Infield Cycles





Full Infield Cycle

Integrated CO_2/cycle = 4.1%

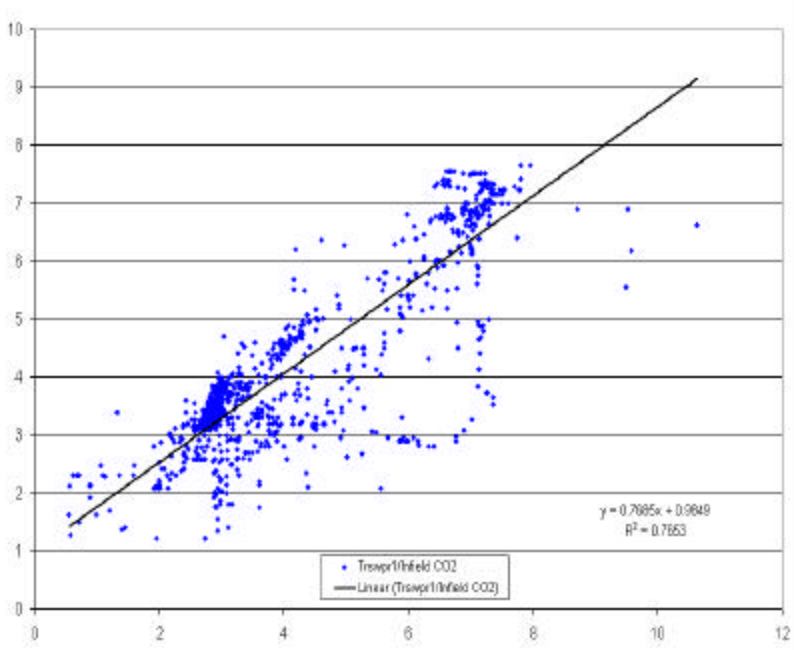
Average Engine Speed/cycle = 1856 rpm

Shortened Infield Cycle

Integrated CO_2/cycle = 4.1%

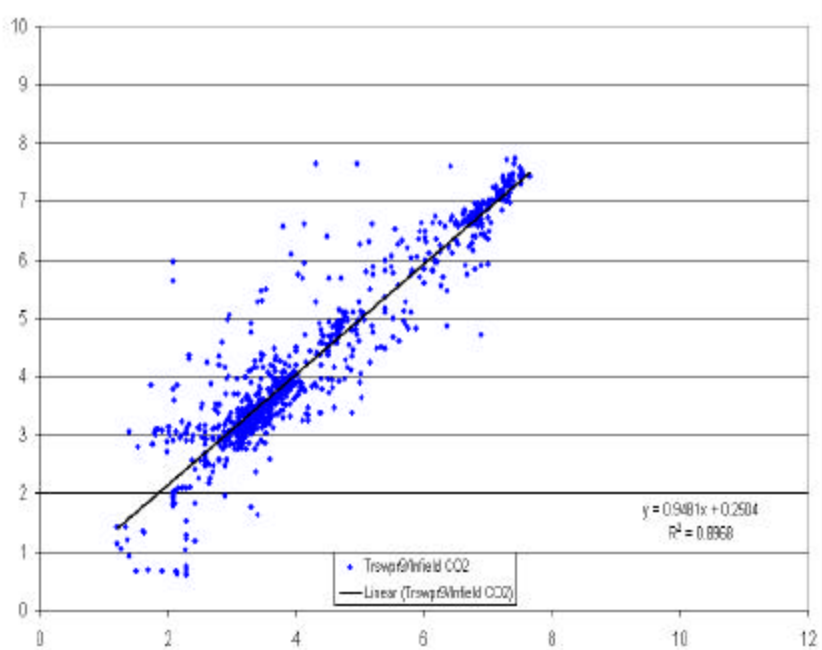
Average Engine Speed/cycle = 1716 rpm

CO_2 Correlation for the First and Final Iterations of the Street Sweeper Cycle



First Iteration

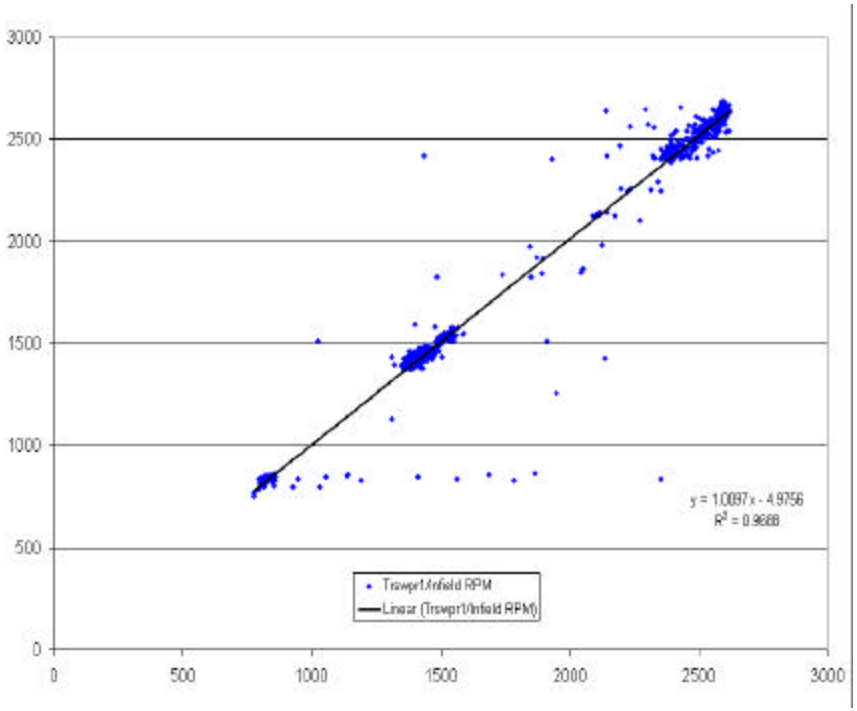
R^2 = 0.77
Trendline Slope = 0.77
Y-Intercept = 0.98%



Final Iteration

R^2 = 0.90
Trendline Slope = 0.95
Y-Intercept = 0.25%

Engine Speed Correlation for the First and Final Iterations of the Street Sweeper Cycle

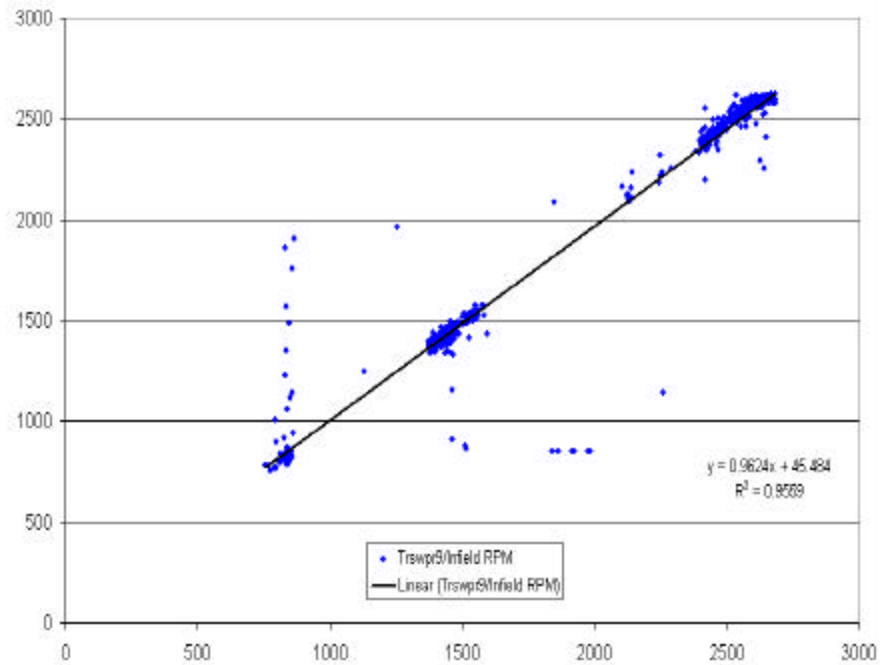


First Iteration

R^2 = 0.97

Trendline Slope = 1.01

Y-Intercept = 5 rpm



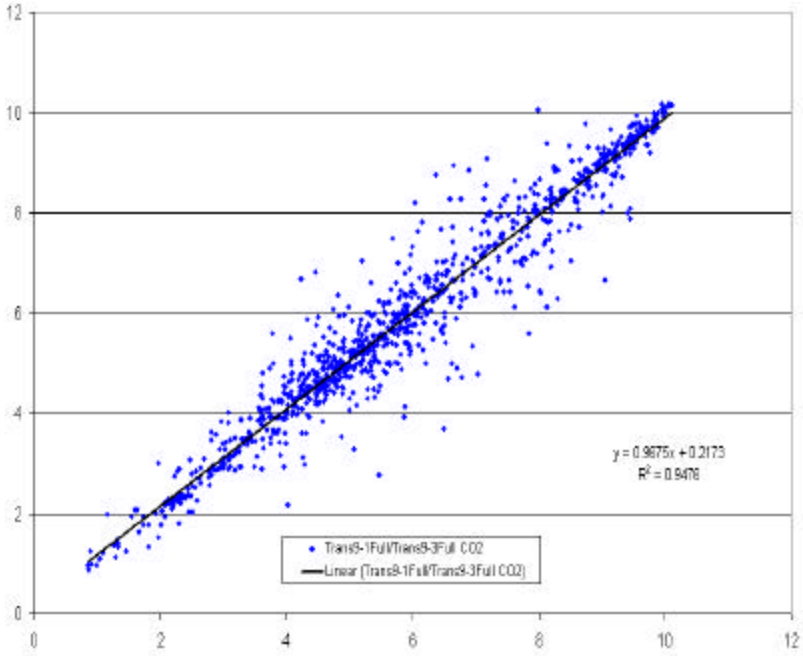
Final Iteration

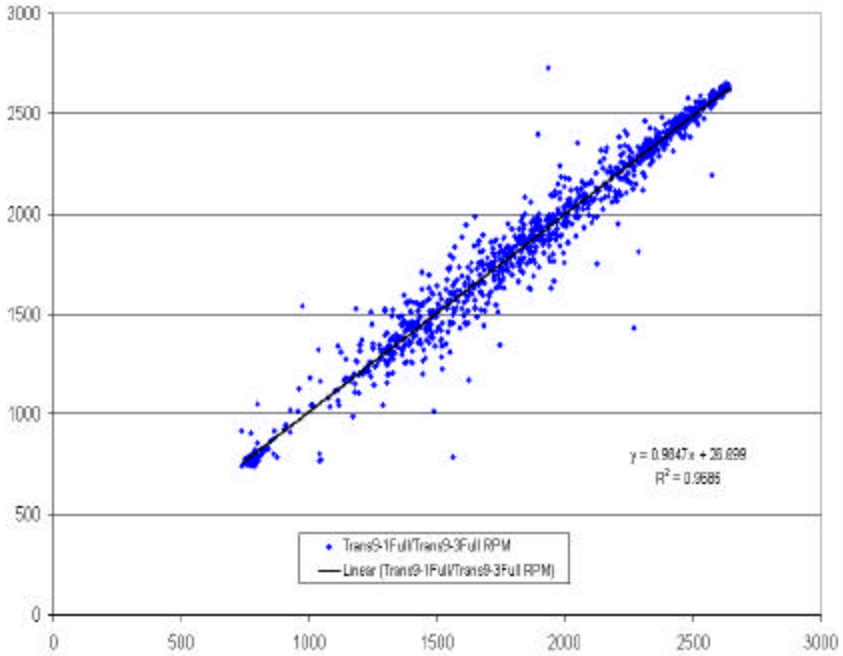
R^2 = 0.96

Trendline Slope = 0.96

Y-Intercept = 45 rpm

CO_2 and Engine Speed Correlation for Two Repeat Runs of the Final Loader Transient Cycle





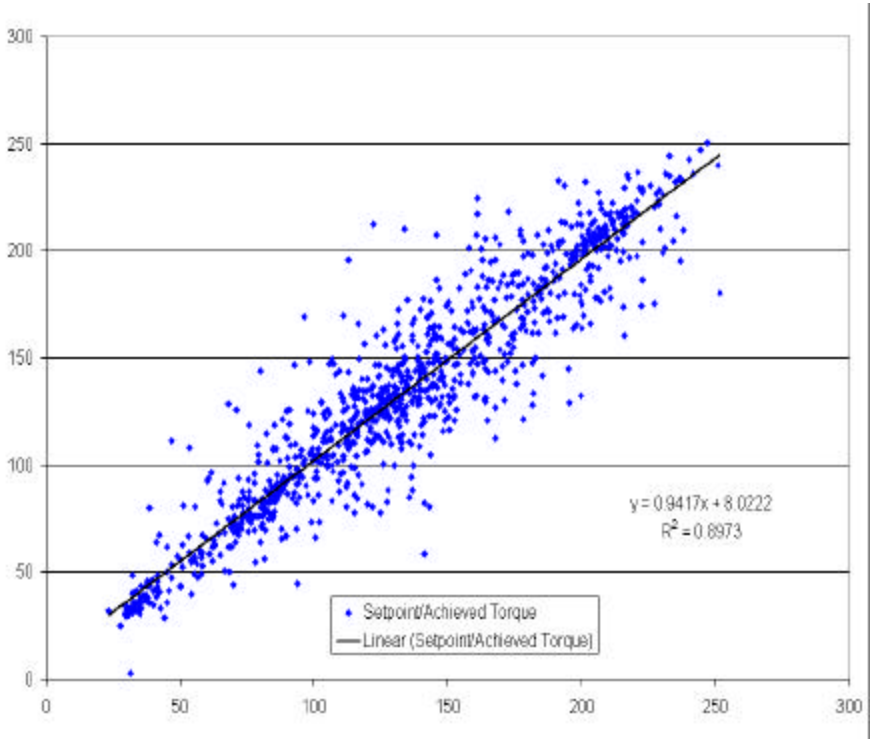
Repeat Test CO_2 Correlation

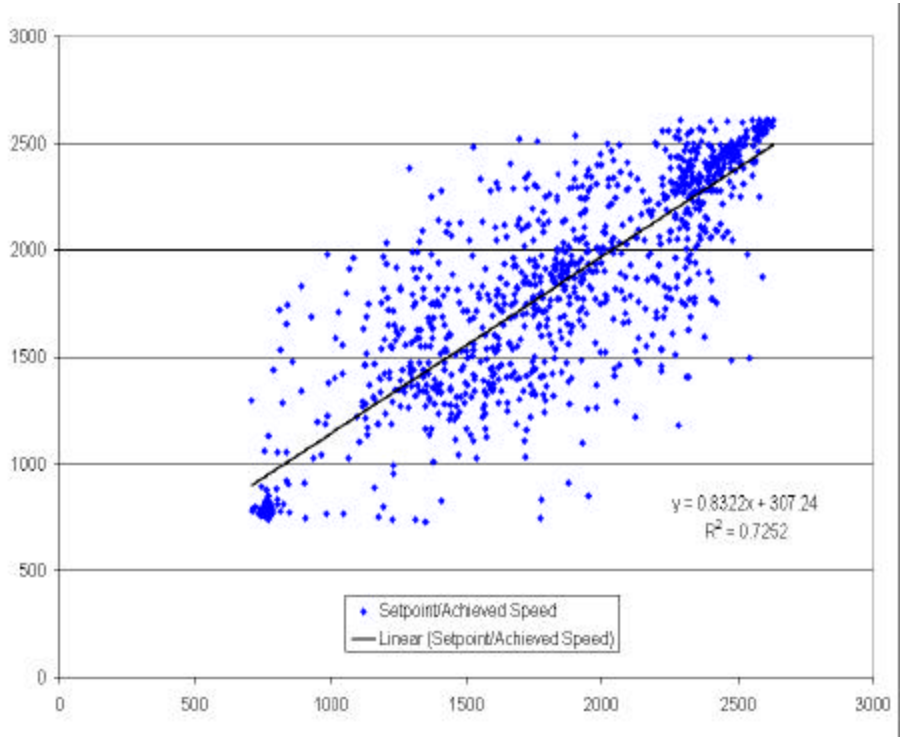
R^2	=	0.95
Trendline Slope	=	0.97
Y-Intercept	=	0.2 %

Repeat Test Engine Speed Correlation

R^2	=	0.97
Trendline Slope	=	0.97
Y-Intercept	=	27 rpm

CO_2 and Engine Speed Correlation for the Desired vs. Achieved Speed/Load Setpoints of the Loader Cycle





Desired/Achieved Torque Correlation			Desired/Achieved Engine Speed Correlation		
R^2	=	0.90	R^2	=	0.73
Trendline Slope	=	0.94	Trendline Slope	=	0.83
Y-Intercept	=	8 %	Y-Intercept	=	307 rpm

Regression Criteria for Certification Transient Cycle Test Validity as Outlined in the CFR 40 Part 86 Subpart N

Criteria	Speed	Torque
Slope of Regression Line, m	**0.970-1.030**	0.83-1.03
Coefficient of Determination, R^2	0.9700	0.8800
Regression line y intercept, b	+-50rpm	+-15 ft-lb

Test Cycles

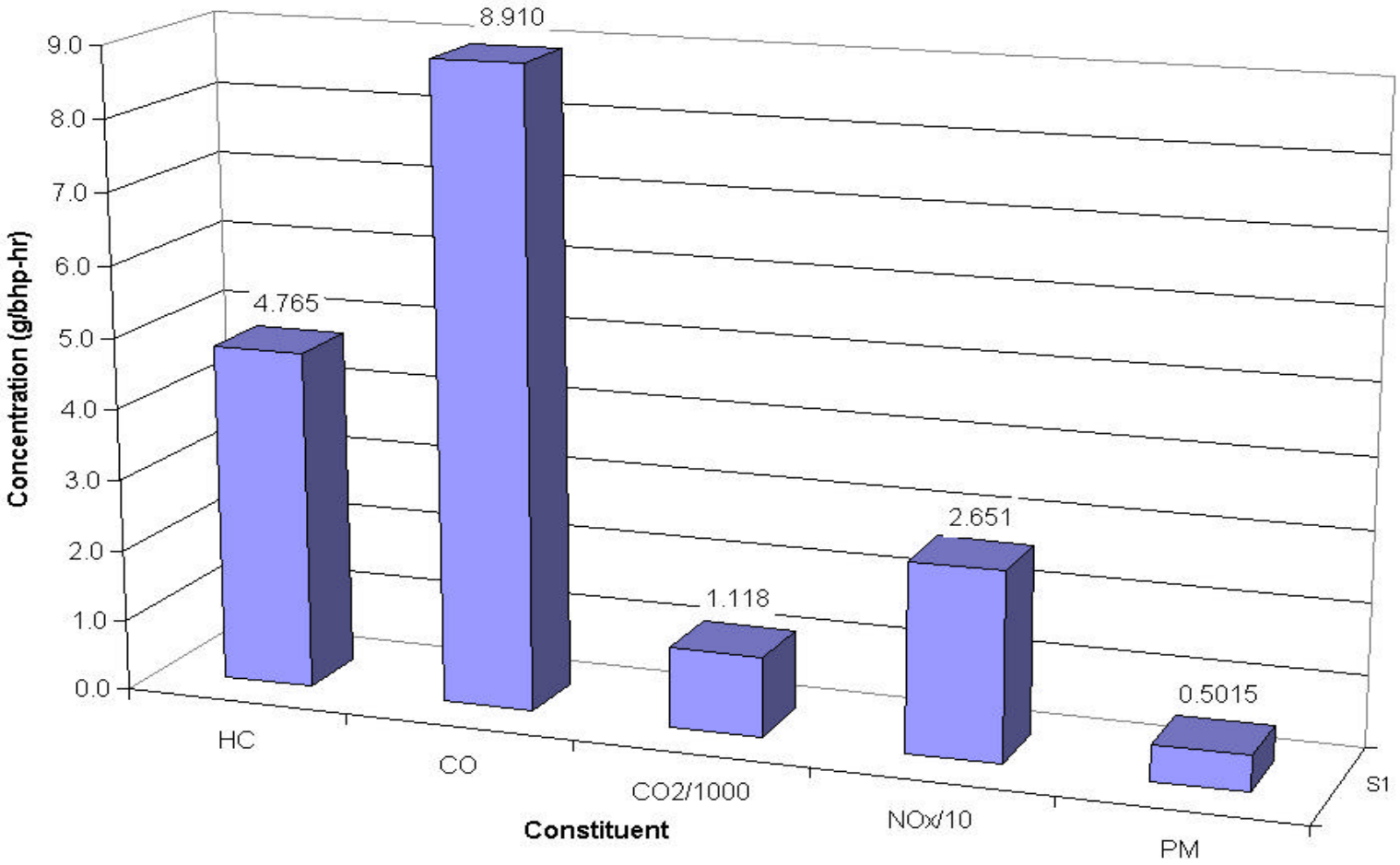
John Deere 444 Loader

- ISO-8178 8-mode
- Transient tests on final loader cycle

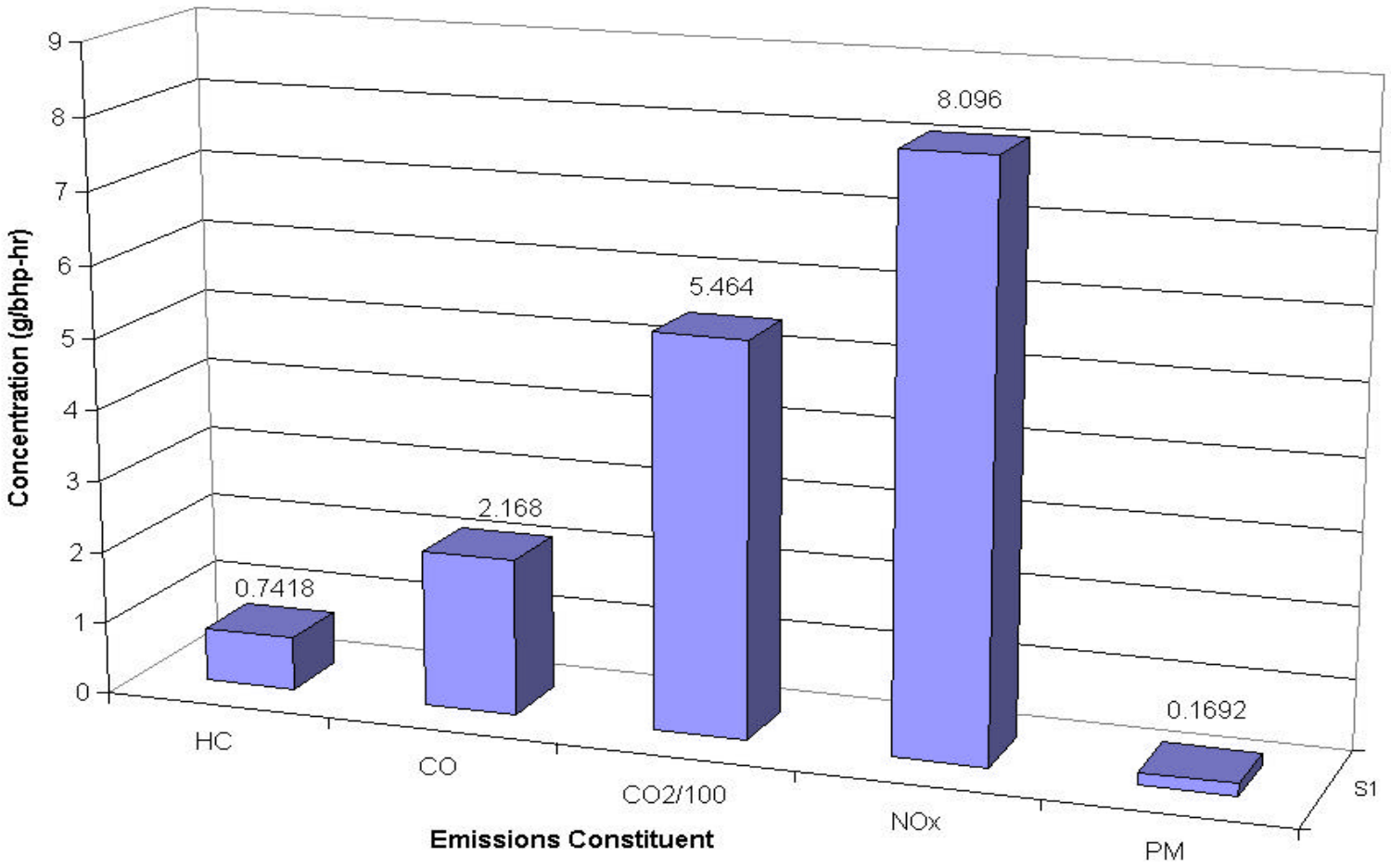
Elgin Streetsweeper

- ISO-8178 8-mode
- Transient tests on final sweeper cycle
- Transient tests on final loader cycle

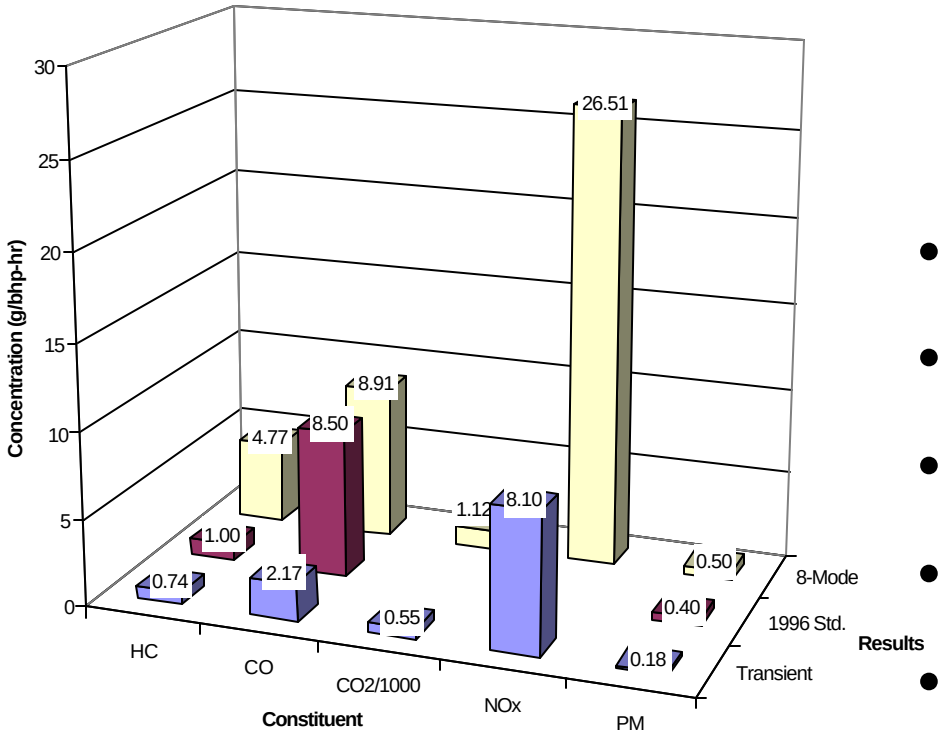
Weighted Brake-Specific 8-Mode Results for the John Deere 6059 Loader Engine



Brake-Specific Transient Results for the John Deere 6059 Loader Engine



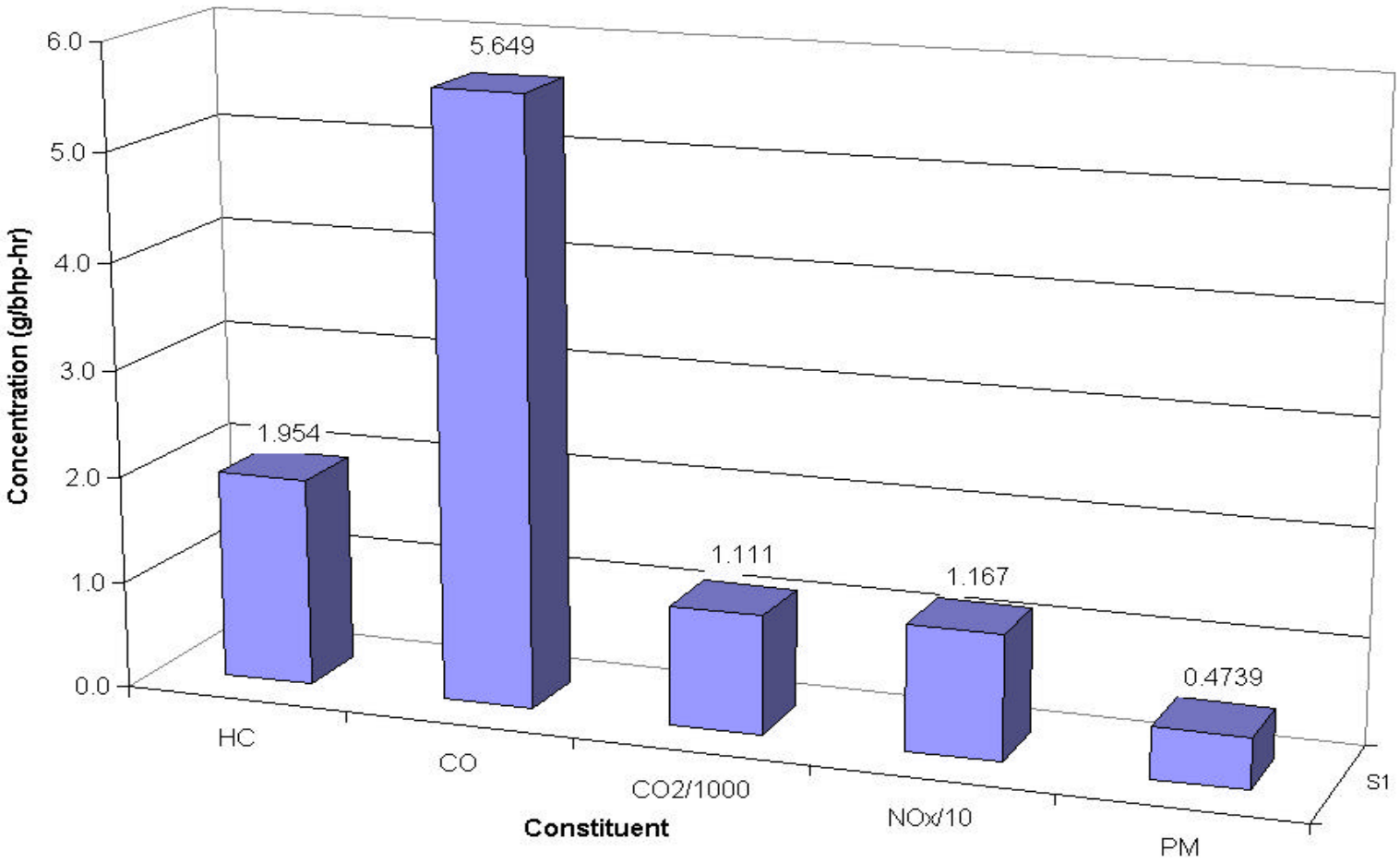
Comparison of Weighted 8-mode and Integrated Transient Emissions for the John Deere 6059 Loader Engine



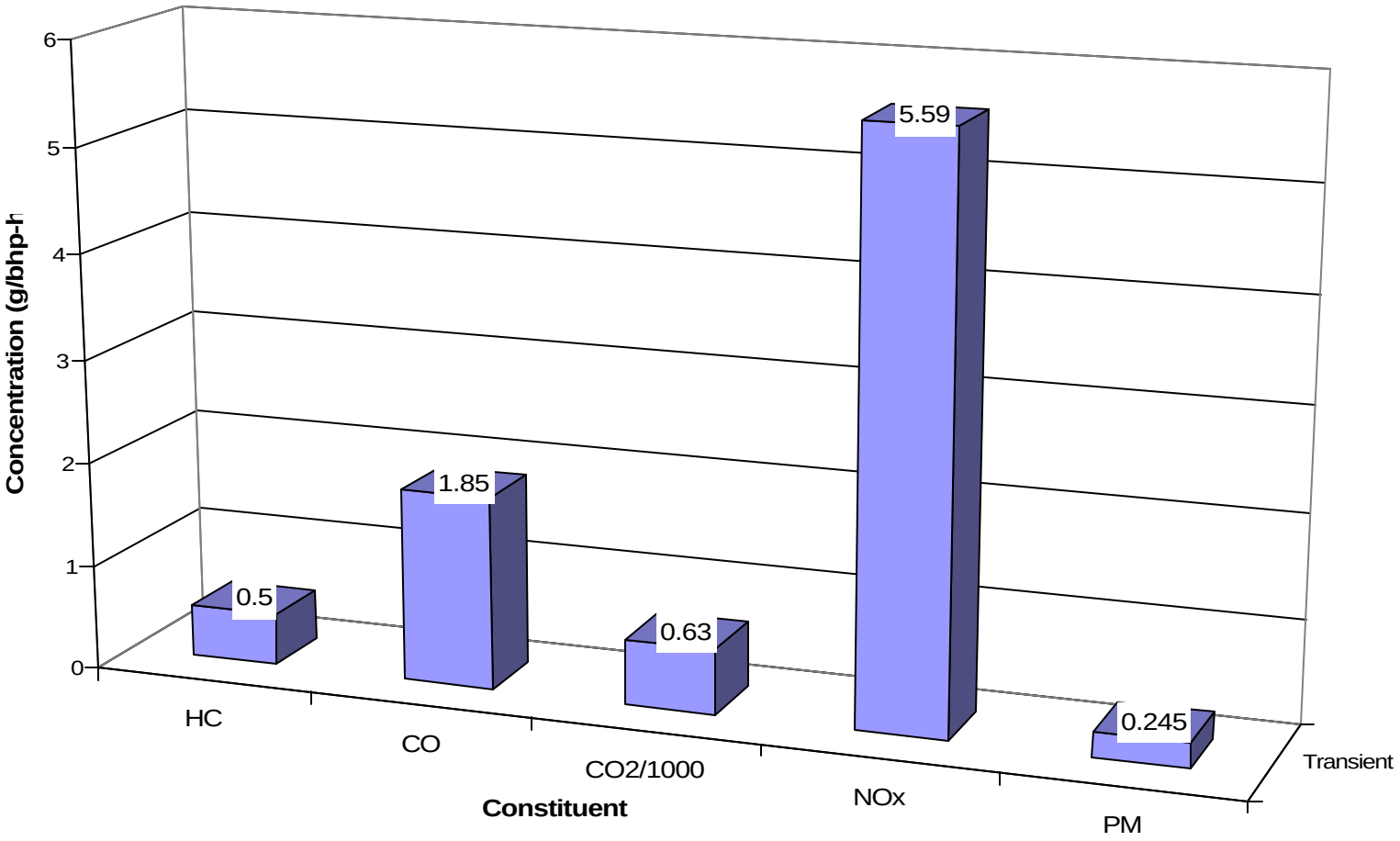
8-Mode Steady State vs. Transient Test Results

- HC increased 545%
- CO increased 311%
- CO_2 increased 105%
- NO_x increased 227%
- PM increased 177%

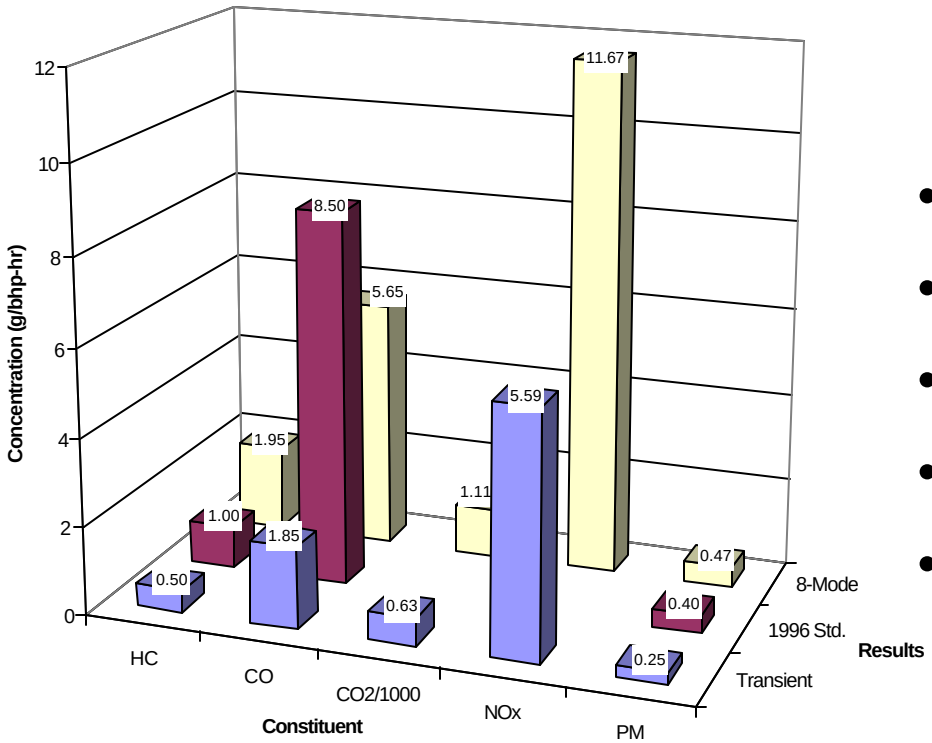
Weighted Brake-Specific 8-Mode Results for the John Deere 4039T Street Sweeper Engine



Brake-Specific Transient Results for the John Deere 4039T Street Sweeper Engine



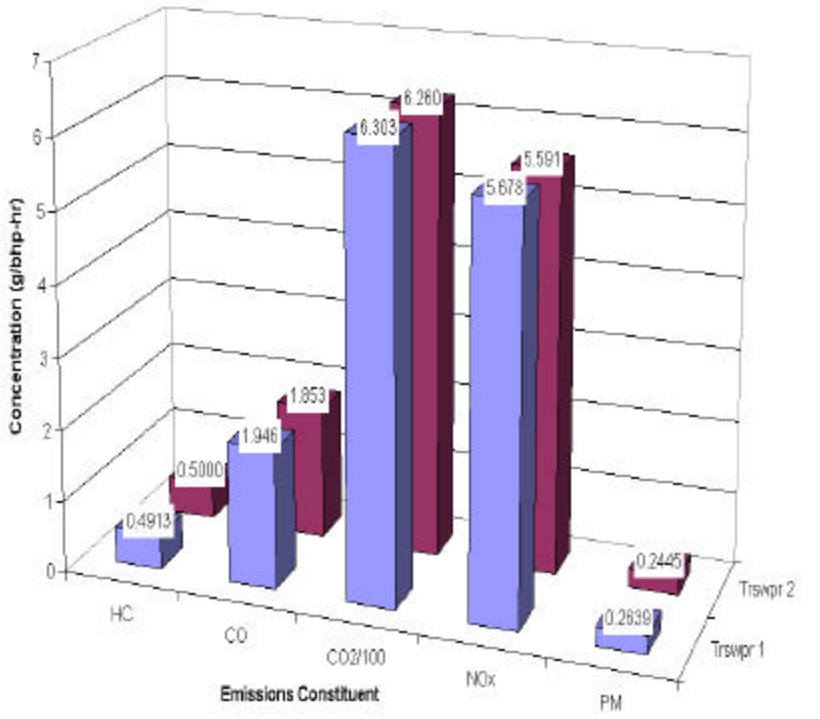
Comparison of Weighted 8-mode and Integrated Transient Emissions for the John Deere 4039T Street Sweeper Engine



8-Mode Steady State vs. Transient Test Results

- HC increased 290%
- CO increased 205%
- CO_2 increased 78%
- NO_x increased 109%
- PM increased 94%

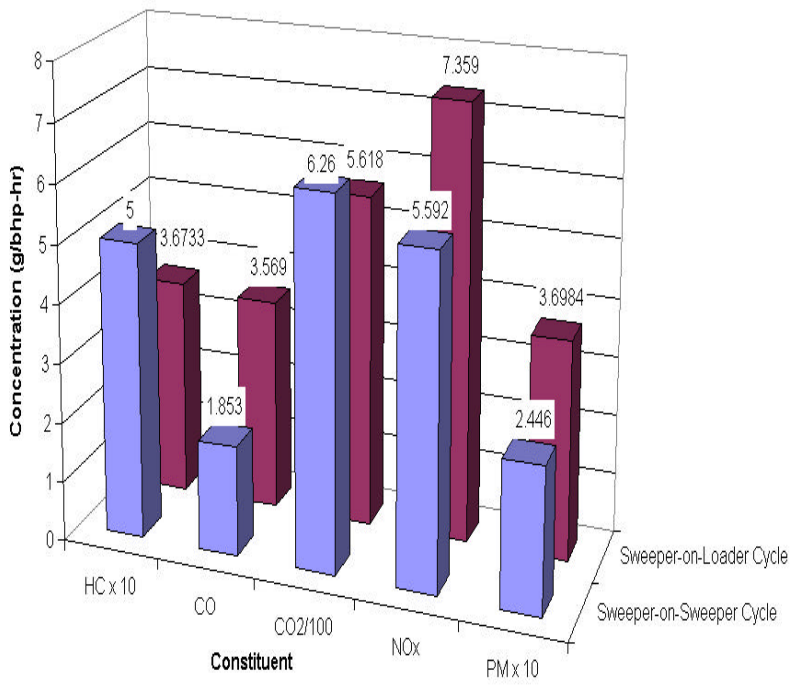
Comparison of Street Sweeper Results Operating on the First and Final Street Sweeper Cycles



Final Iteration vs. First Iteration Results

- HC increased 2%
- CO decreased 5%
- CO_2 decreased 1%
- NO_x decreased 2%
- PM decreased 7%

Comparison of Street Sweeper Results Operating on the Final Street Sweeper and Loader Cycles



Sweeper Tested on Sweeper Cycle vs. Sweeper Tested on Loader Cycle Results

- HC decreased 27%
- CO increased 93%
- CO_2 decreased 10%
- NO_x increased 32%
- PM increased 51%

Excavator Operations

Digging

Excavator Tramming (or Hauling)

Trenching

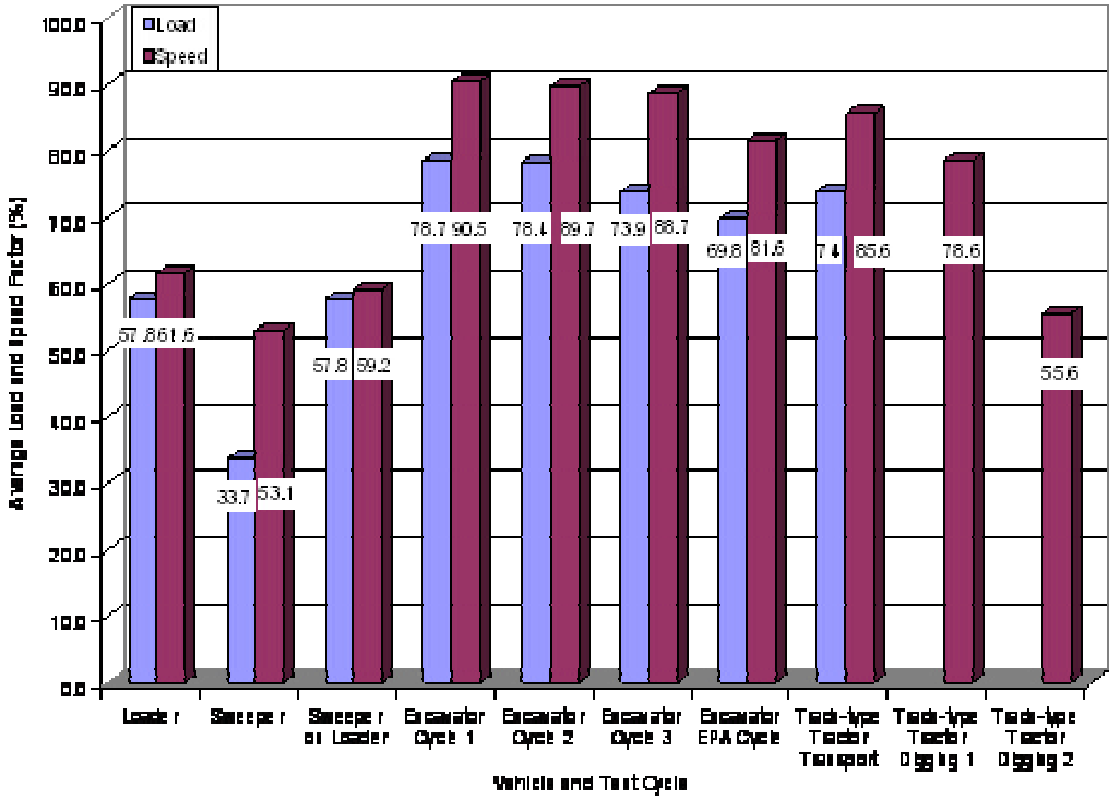
Komatsu S6D125-1 Excavator Engine Weighted and Average Transient Test Results (g/bhp-hr)

	Weighted 8-Mode Results	Transient Cycle 1 Results	Transient Cycle 2 Results	Transient Cycle 3 Results	% Diff Cycle1 to 8-Mode	% Diff Cycle 2 to 8-Mode	% Diff Cycle 3 to 8-Mode
HC	2.49	1.202	1.145	1.100	-51.7	-54.0	-55.8
CO	2.55	0.915	0.871	0.853	-64.1	-65.8	-66.5
CO_2	609.91	538.43	533.49	525.59	-11.7	-12.5	-13.8
NO_x	8.26	5.366	5.390	5.327	-35.0	-34.7	-35.5
PM	0.633	0.277	0.280	0.332	-56.2	-55.7	-47.5

Load Factor and Cycle Length Data

Cycle	Loader	Sweeper	Sweeper on Loader	Excavator 1	Excavator 2	Excavator 3	Excavator EPA
Load Factor	57.8	33.7	57.8	78.7	78.4	73.9	74
Cycle Length (s)	1144	1226	1144	650	645	646	1198

Average Load and Speed Factors for All Vehicles and Test Cycles



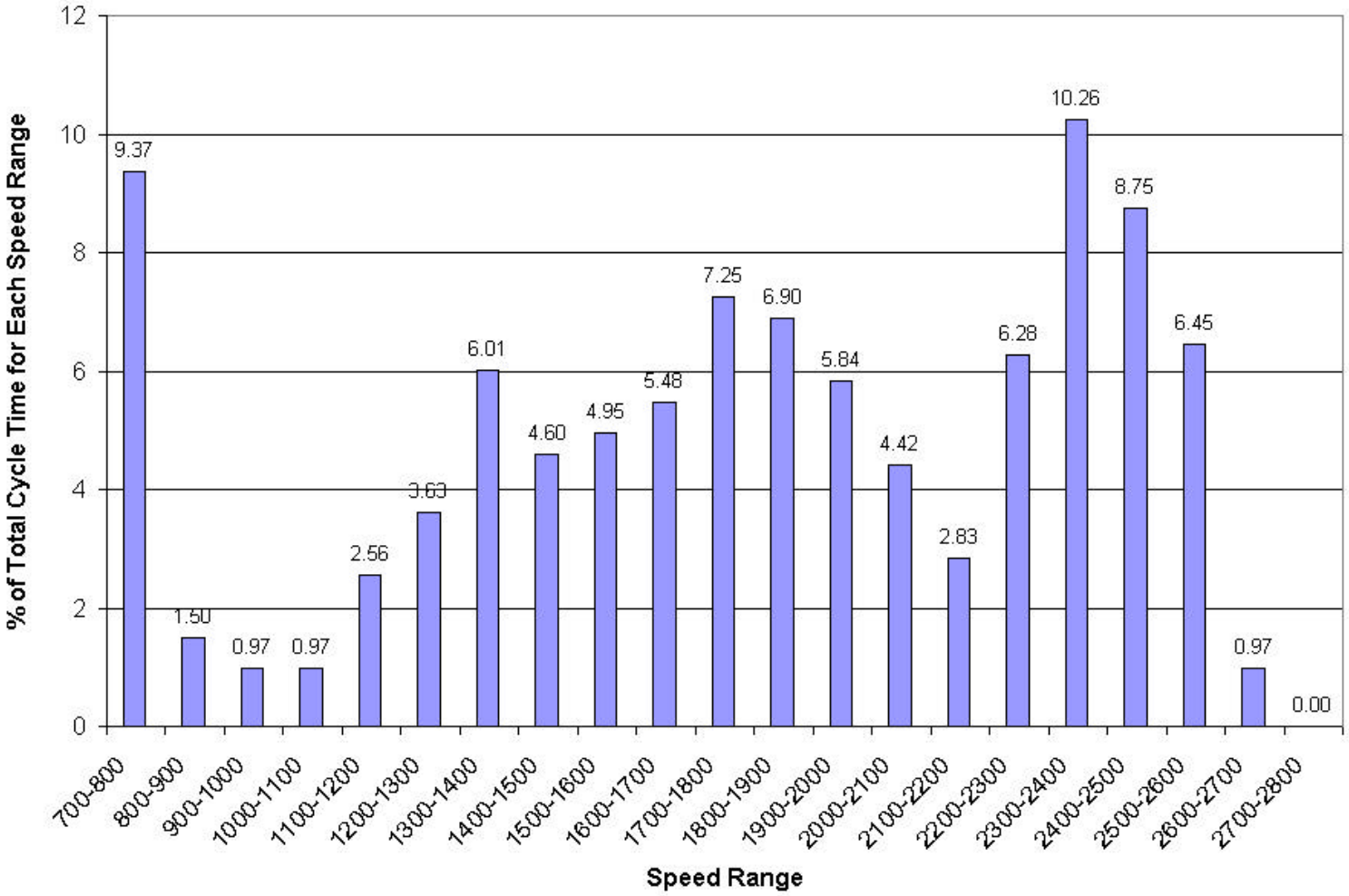
Comparison of Steady-State Dynamometer Test Results with the Current Off-Road Diesel Emissions Standards

	PM (g/bhp-hr)	CO (g/bhp-hr)	HC (g/bhp-hr)	NO_x (g/bhp-hr)
1996 Std.	0.40	8.5	1.0	6.9
Street Sweeper	0.47	5.65	1.95	11.67
Loader	0.50	8.91	4.77	26.51
Excavator	0.63	2.55	2.50	8.26

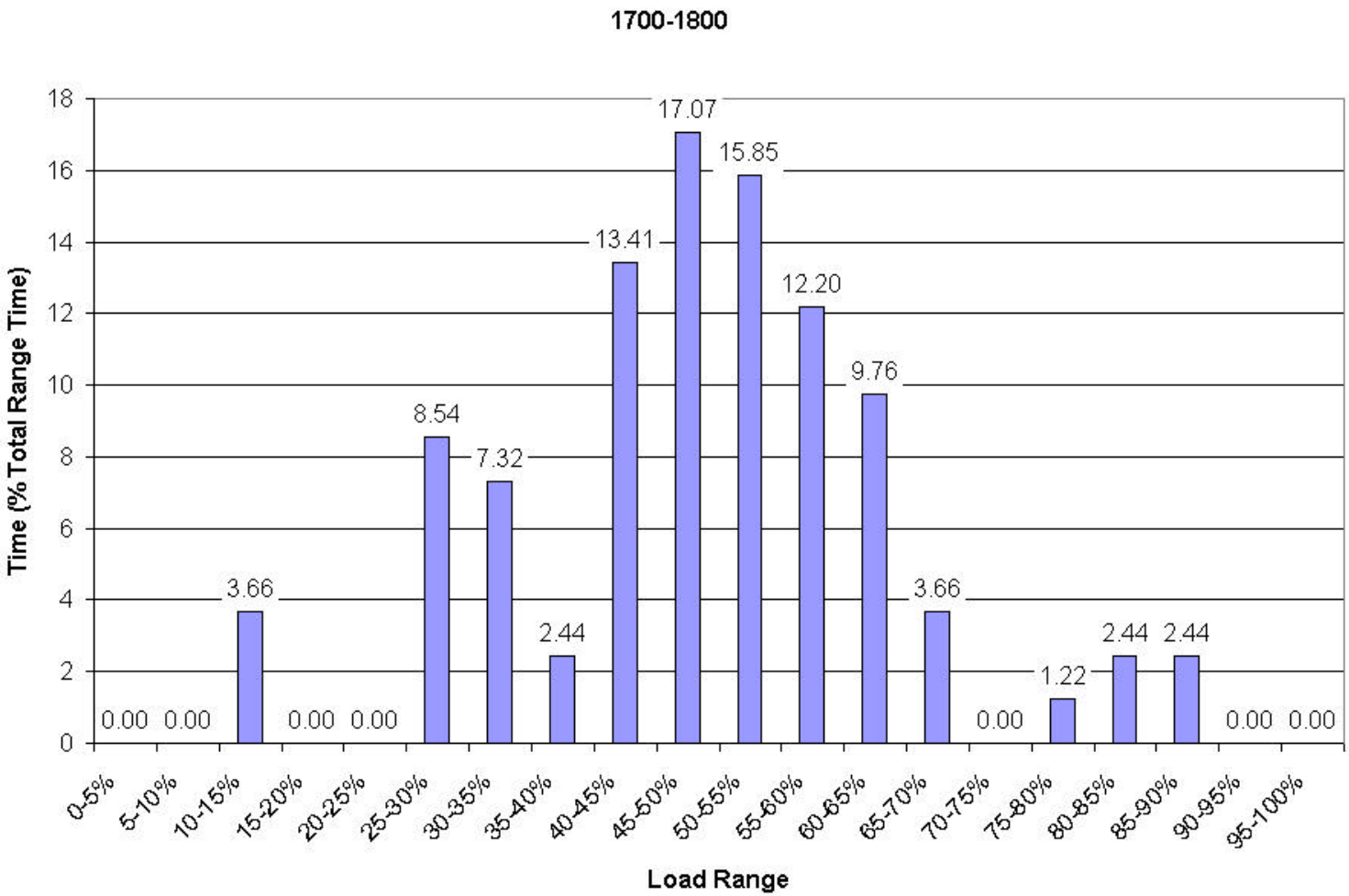
Emission Factors for Test Vehicles

Vehicle	Loader	Street Sweeper	Excavator	Track-type Tractor
Model Year	<1995	1995+	1987	2001
Total Hours	2756	6841	3263	2750
HC (g/hp-hr)	1.12	1.30	1.01	0.35
CO (g/hp-hr)	3.74	4.12	4.56	0.97
NOx (g/hp-hr)	9.31	10.13	11.83	6.54
PM (g/hp-hr)	0.83	1.03	0.68	0.17

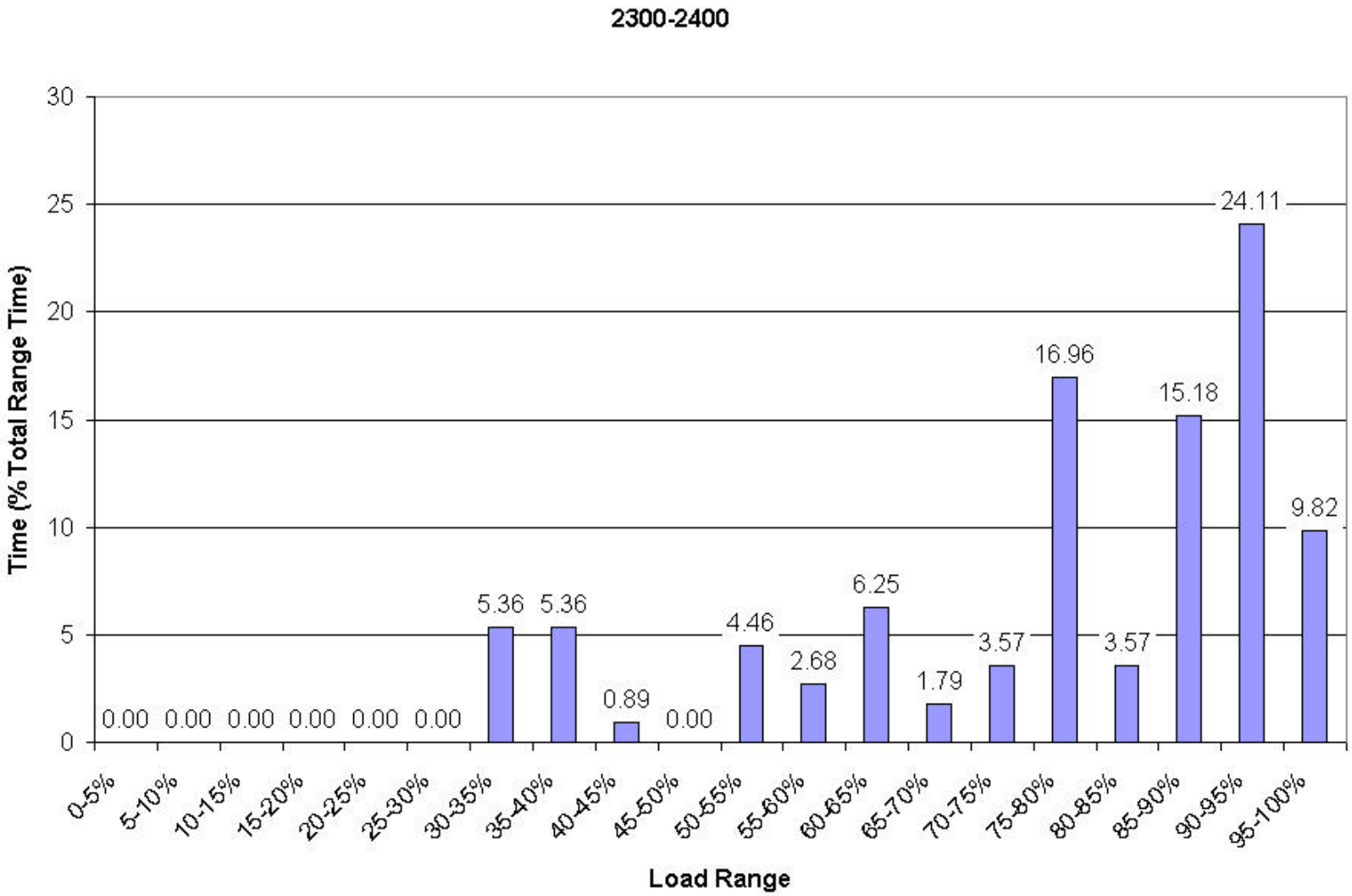
Percentage of Total Cycle Time Spent In Each Speed Range for the John Deere 6059 Loader Engine



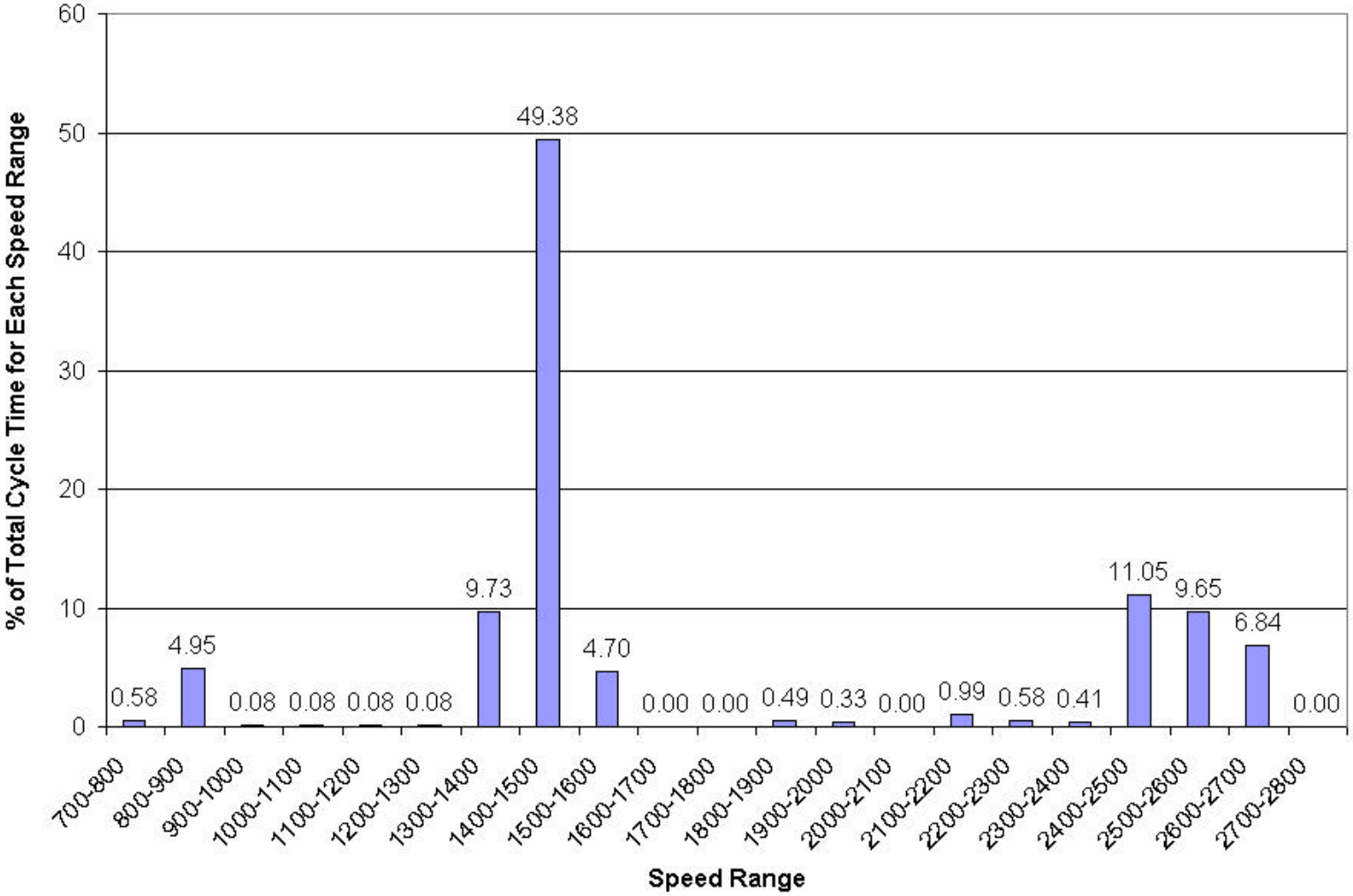
Percent Load vs. Percent Total Intermediate Speed Time for the John Deere 6059 Loader Engine



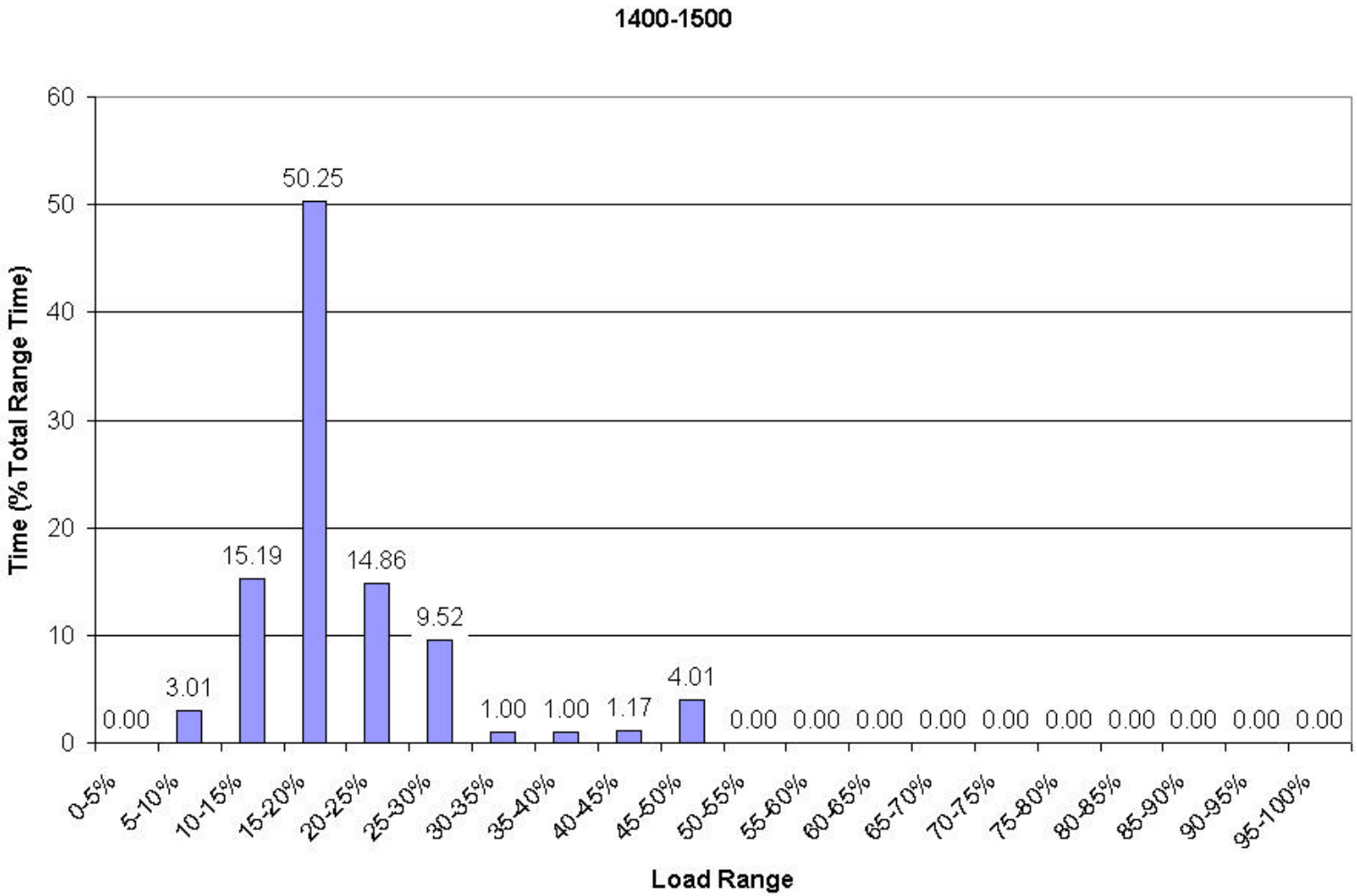
Percent Load vs. Percent Total Rated Speed Time for the John Deere 6059 Loader Engine



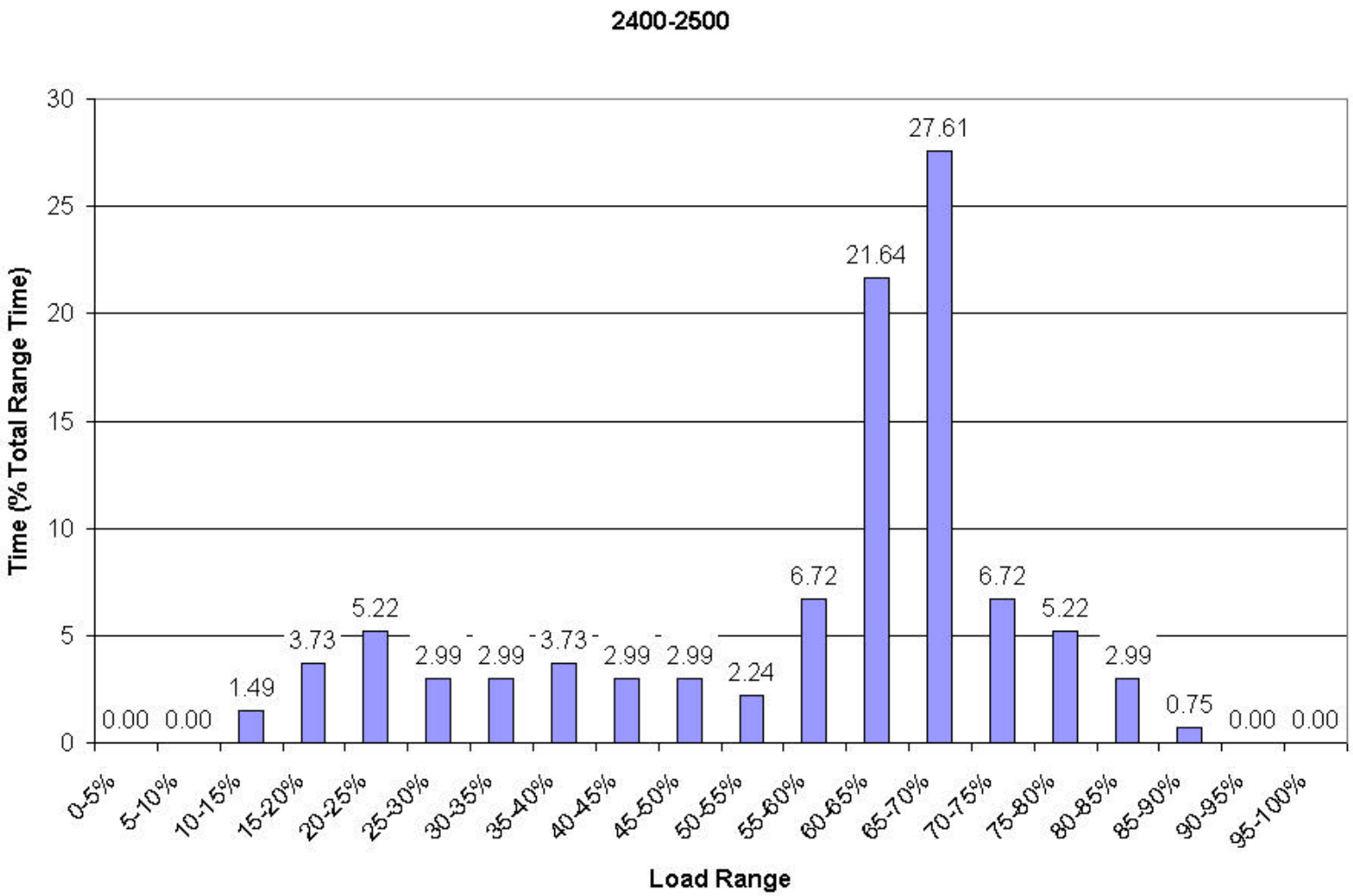
Percentage of Total Cycle Time Spent in Each Speed Range for the John Deere 4039T Street Sweeper Engine



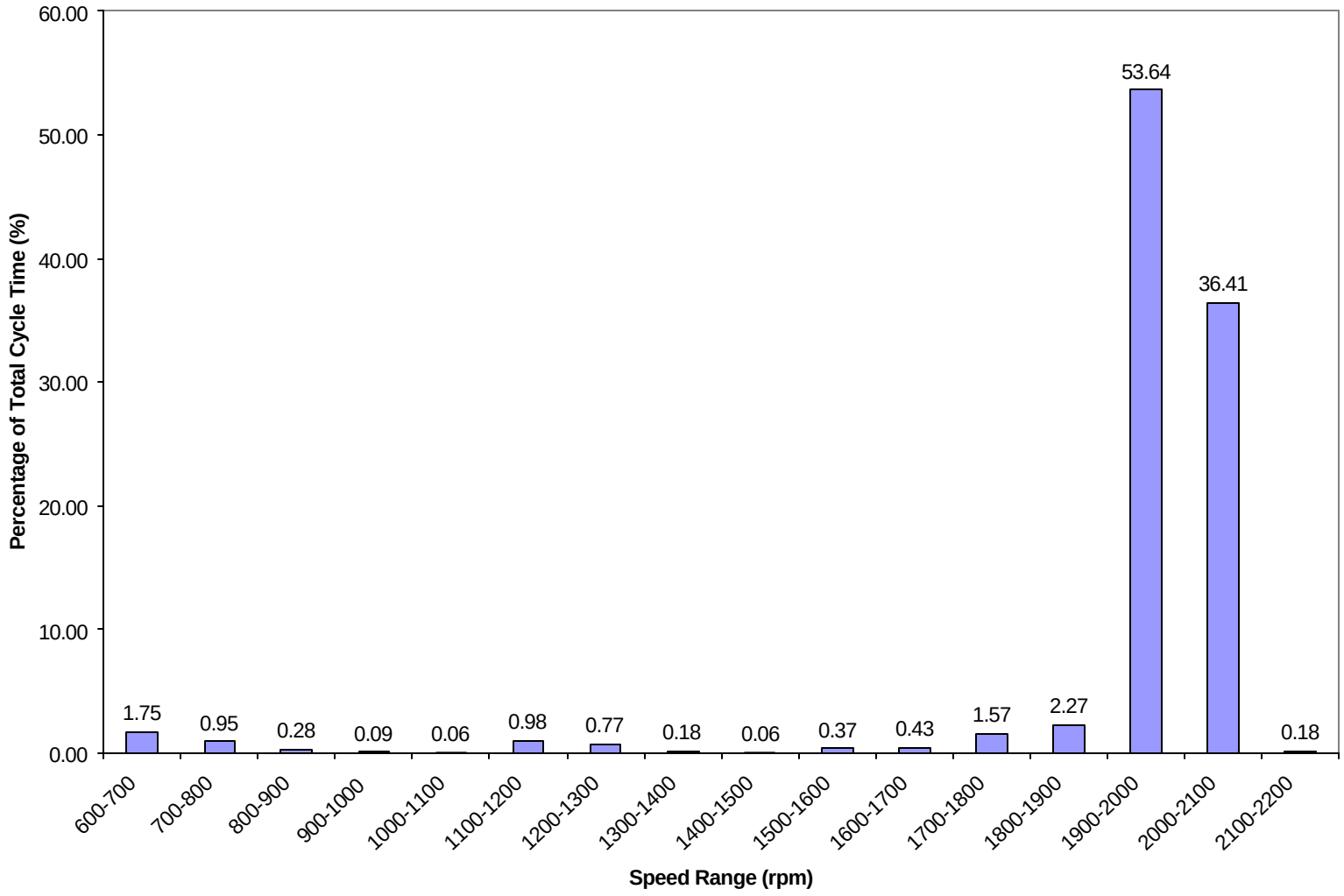
Percent Load vs. Percent Total Intermediate Speed Time for the John Deere 4039T Street Sweeper Engine



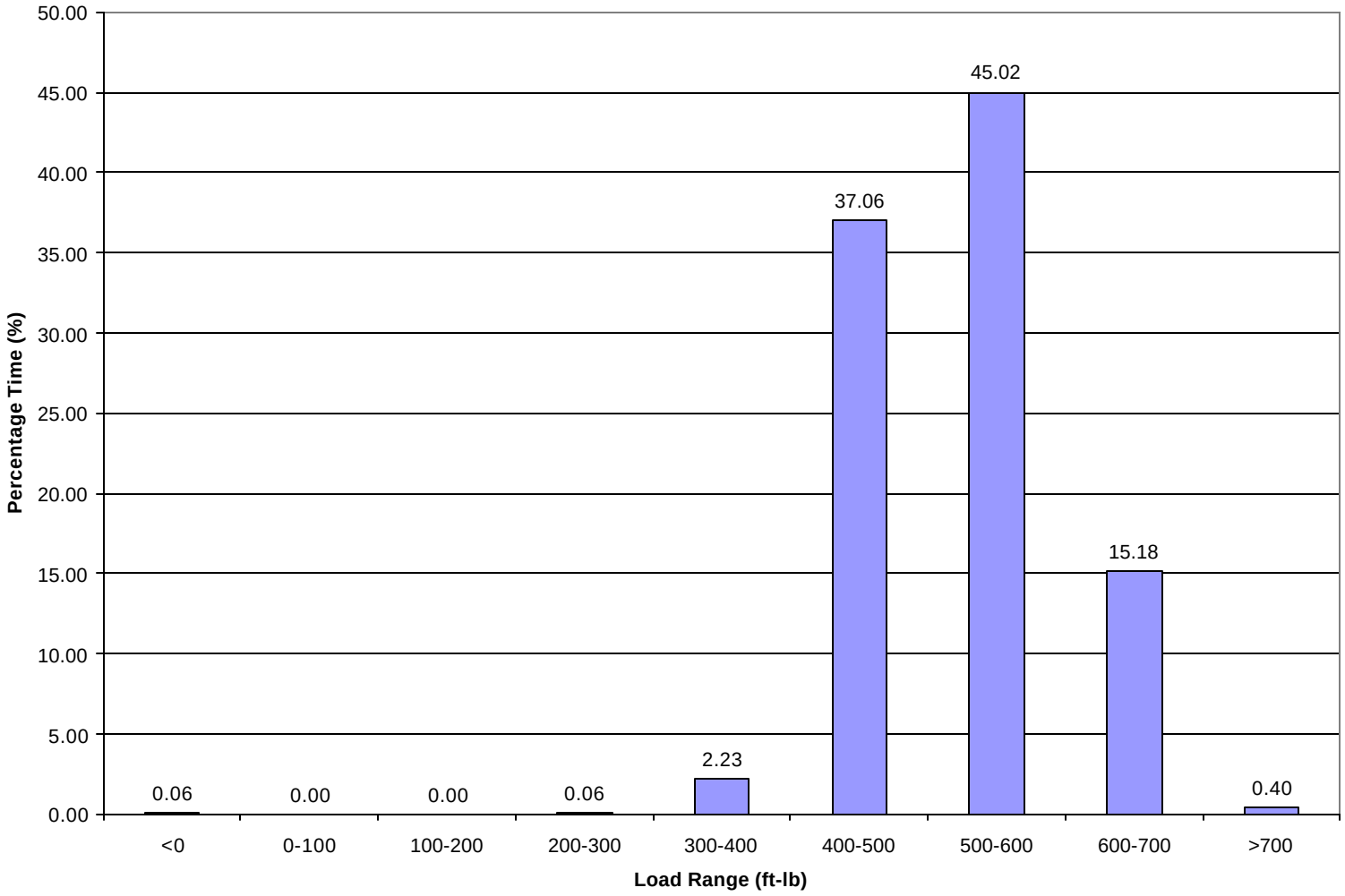
Percent Load vs. Percent Total Rated Speed Time for the John Deere 4039T Street Sweeper Engine



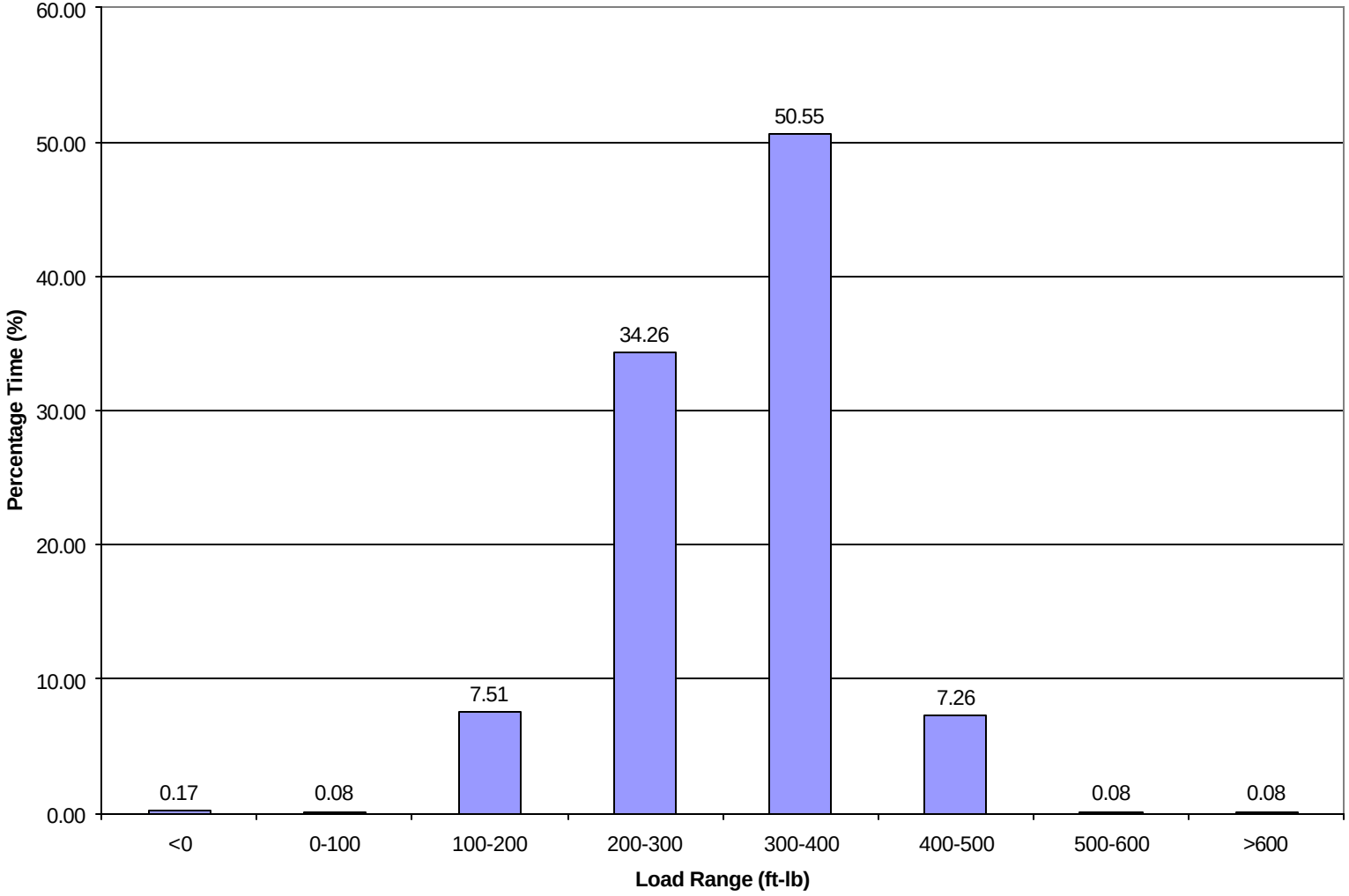
Speed Range Characterization for the Komatsu S6D125-1 Engine: Excavator Cycle 1 (Digging)



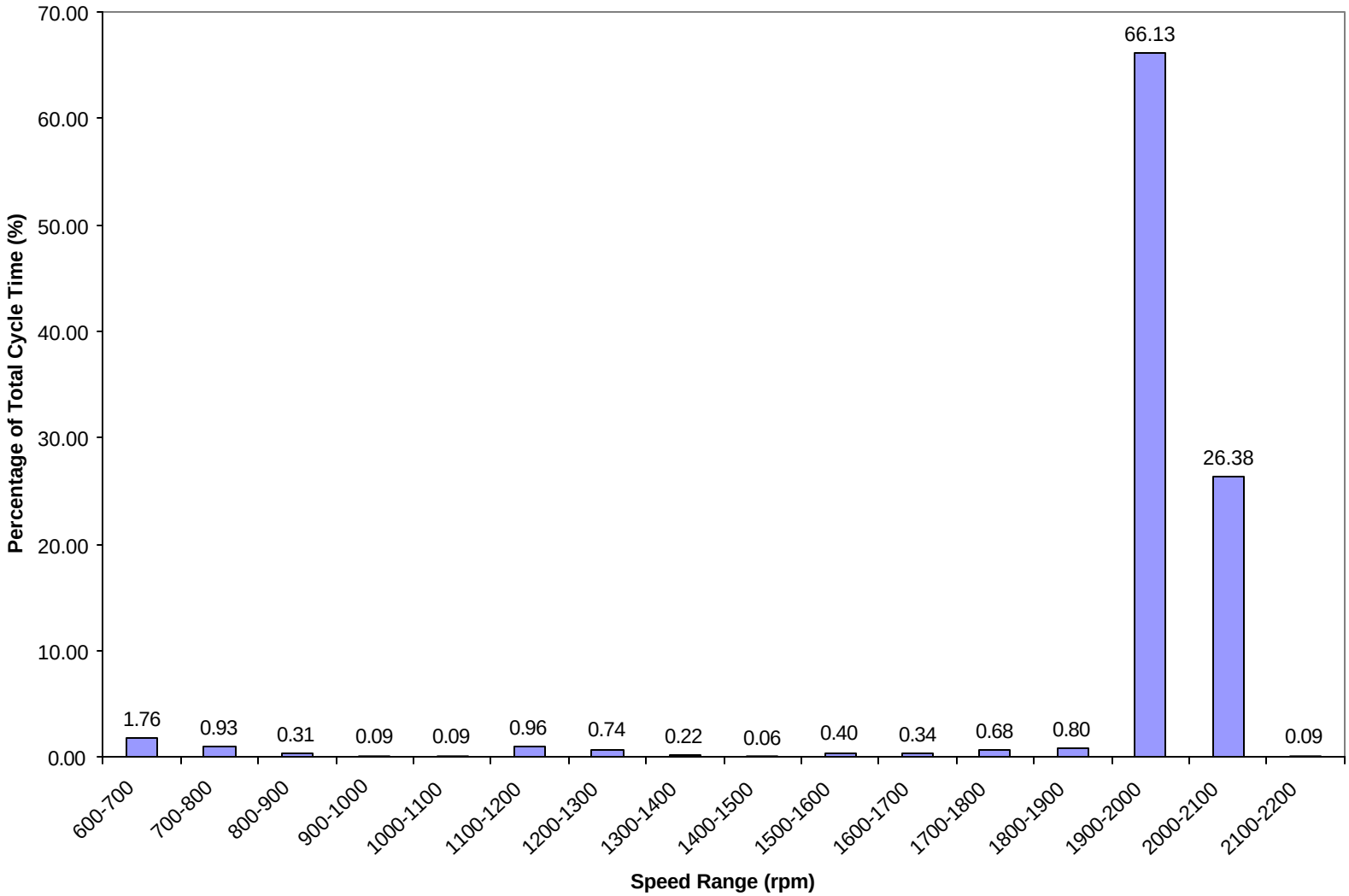
Load Range Characterization for 1900-2000 rpm Speed Range for Komatsu S6D125-1 Engine: Excavator Cycle 1 (Digging)



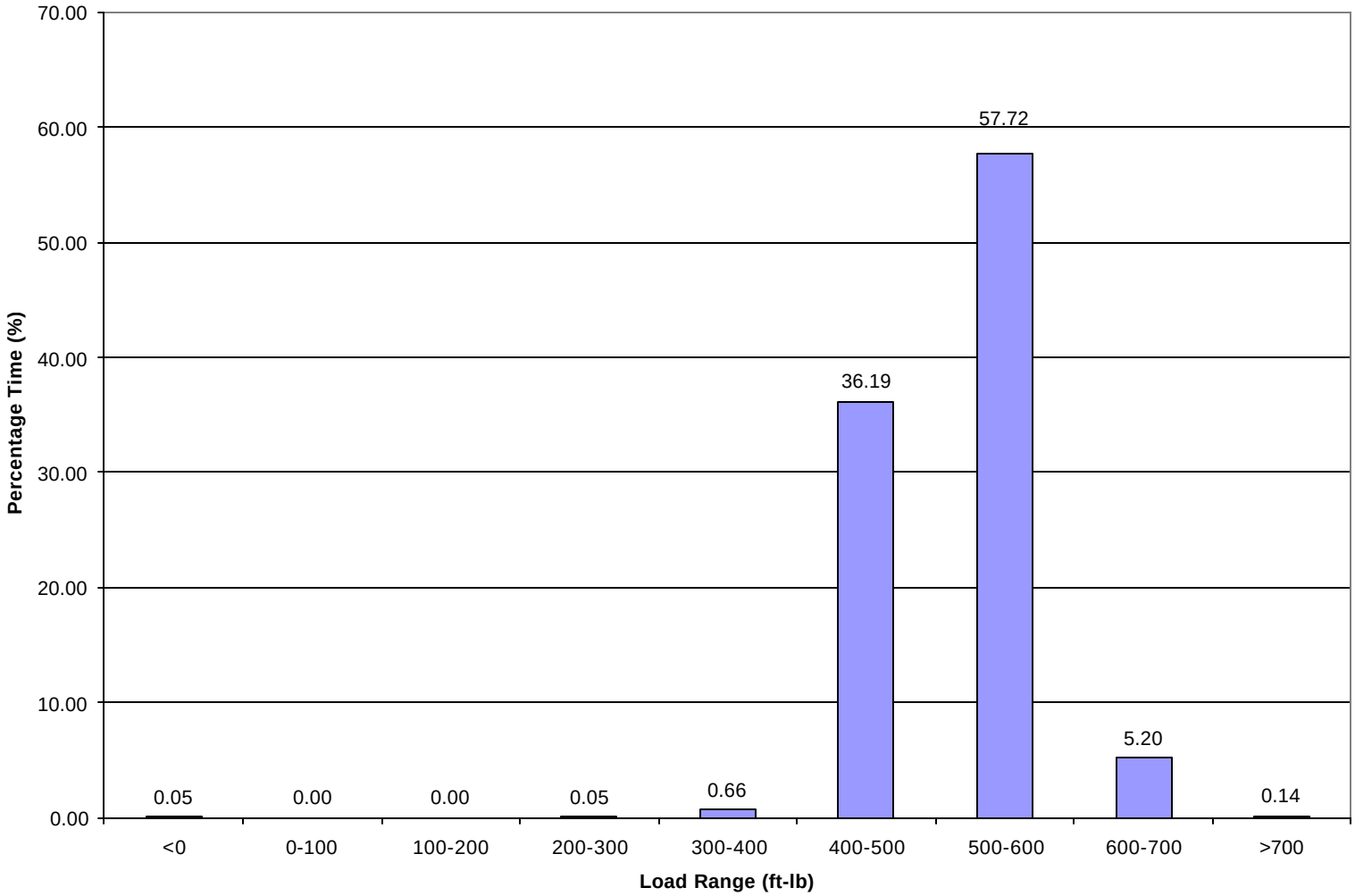
Load Range Characterization for 2000-2100 rpm Speed Range for Komatsu S6D125-1 Engine: Excavator Cycle 1 (Digging)



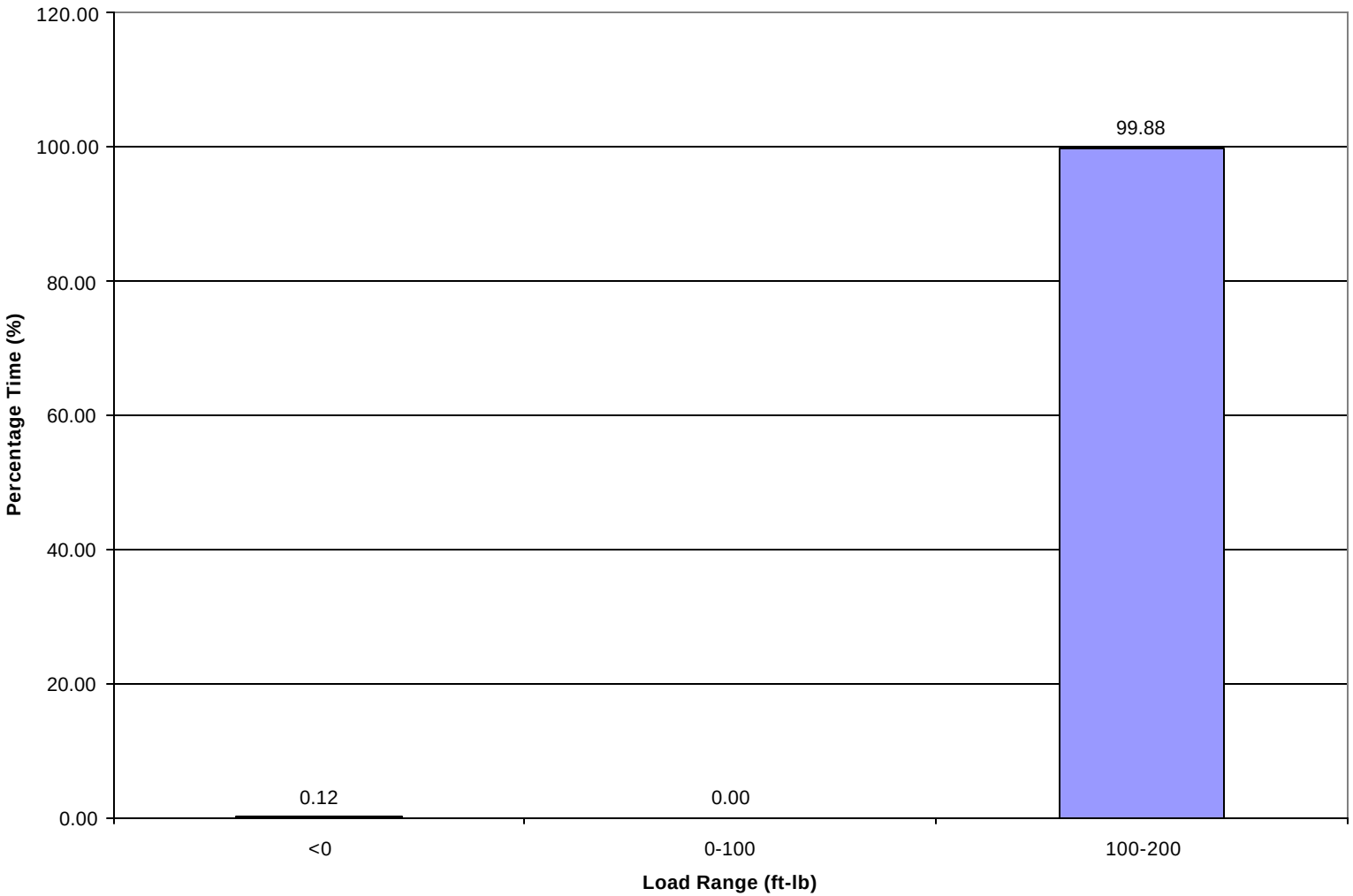
Speed Range Characterization for Komatsu S6D125-1 Engine: Excavator Cycle 2 (Hauling)



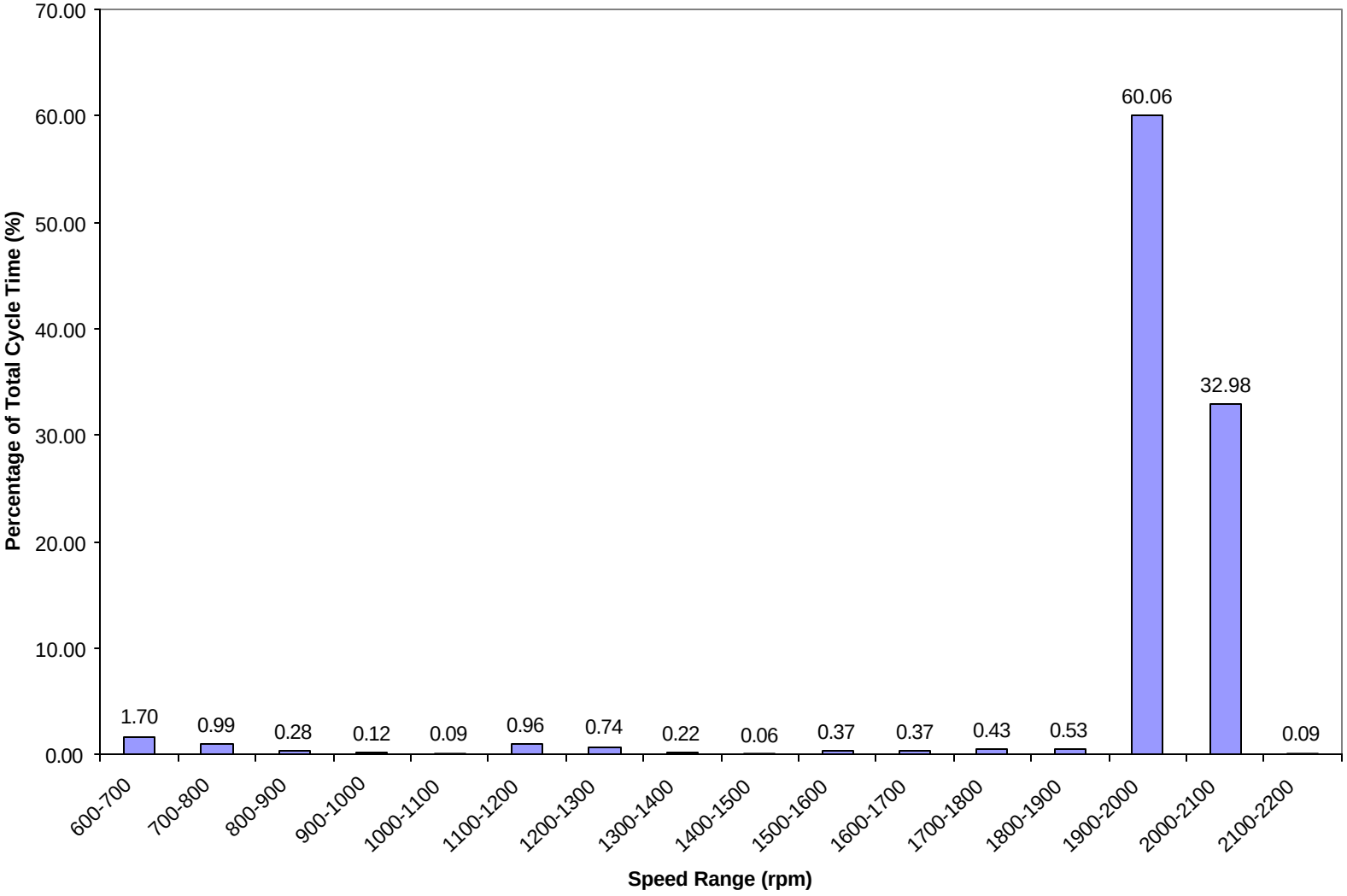
Load Range Characterization for 1900-2000 rpm Speed Range for Komatsu S6D125-1 Engine: Excavator Cycle 2 (Hauling)



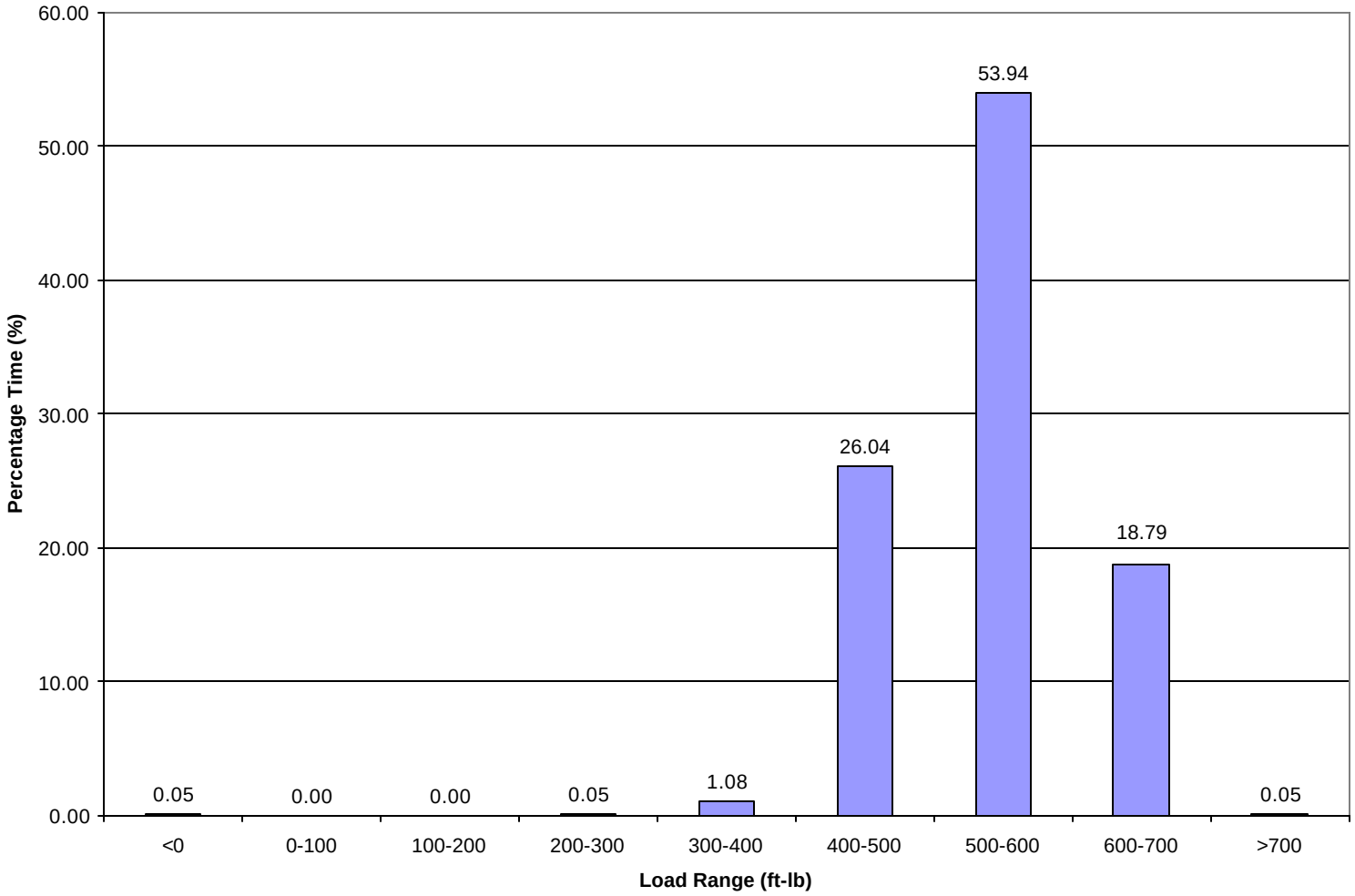
Load Range Characterization for 2000-2100 rpm Speed Range for Komatsu S6D125-1 Engine: Excavator Cycle 2 (Hauling)



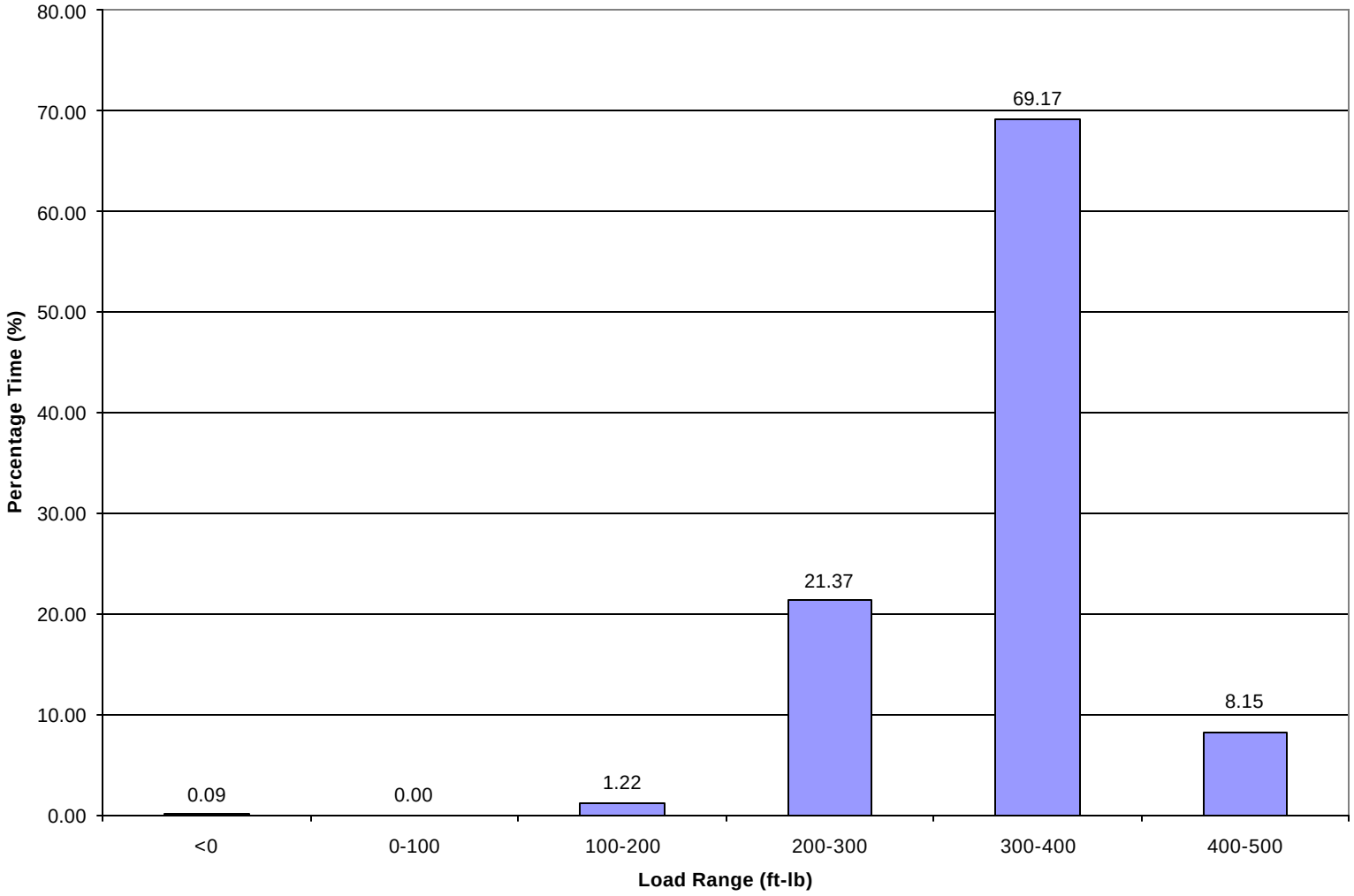
Speed Range Characterization for Komatsu S6D125-1 Engine: Excavator Cycle 3 (Trenching)



Load Range Characterization for 1900-2000 rpm Speed Range for Komatsu S6D125-1 Engine: Excavator Cycle 3 (Trenching)



Load Range Characterization for 2000-2100 rpm Speed Range for Komatsu S6D125-1 Engine: Excavator Cycle 3 (Trenching)



Conclusions

- Brake-specific 8-mode emissions results were much higher than transient test results and are not an accurate indication of in-use vehicle emissions
- Cycle nature has a considerably larger effect on emissions results than an accurate recreation of the infield cycle
- For cycle development, refinement of dynamometer setpoints has little effect on full-cycle integrated results but the differences could be large on second-by-second or other discrete cycle section
- On-board testing in the field would be more representative of actual performance than steady-state testing on the vehicles tested in a test cell

Recommendations for Future Research

- Continued assessment of new, up-coming technologies
- Investigate the use of manufacturer-supplied $BSCO_2$ data for a direct power prediction from infield data
- Investigate the use of the MEMS system for the infield testing of electronically-controlled equipment
- Incorporate the use of a miniature, real-time particulate matter measurement device for collection of infield PM
- Investigate fuel-specific data presentation to eliminate the need to quantify torque in the field
- Adopt very strict acceptance criteria for portable emissions measurement systems--more so than laboratory-grade instruments.

Acknowledgements

- California Air Resources Board

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