

ABSTRACT

LEWIS, MICHAEL PHIL. Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles. (Under the direction of William Rasdorf.)

This dissertation presents a methodology for estimating weighted-average fuel use rates and emission rates NO_x , HC, CO, and PM of construction equipment performing representative duty cycles based on field data collected from 34 items of construction equipment. An engine modal analysis determined the variation of fuel use and emission rates with respect to 10 individual engine modes representing increasing engine loads. Multiple linear regression models estimated the fuel use rate of engine modes 2 – 10; an average fuel use rate was used to estimate the idling fuel use rate. Efforts to develop linear regression models for modal emission rates proved ineffective due to low R^2 values and unacceptable p-values for variable coefficients, thus, average modal emission rates of each pollutant based on the field data were used. The modal fuel use rates were weighted by the fraction of time spent in each engine mode to estimate a weighted-average mass per time fuel use rate for the representative duty cycle. The modal emission rates for each pollutant were weighted by the fraction of fuel used in each engine mode to estimate a weighted-average mass per fuel used emission rate for the representative duty cycle. The weighted-average emission rate for each pollutant was multiplied by the weighted-average fuel use rate to determine the mass per time emission rate for the duty cycle. Based on response plots of the actual versus estimated values, the methodology reliably estimated fuel use rates and emission rates of NO_x , CO, and PM.

Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment
Performing Representative Duty Cycles

by
Michael Phil Lewis

A dissertation submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Civil Engineering

Raleigh, North Carolina

2009

APPROVED BY:

William Rasdorf, PhD
Committee Chair

H. Christopher Frey, PhD

David W. Johnston, PhD

Michael Leming, PhD

William Hunt, PhD

BIOGRAPHY

Michael Phil Lewis is a graduate of Bunn High School in Franklin County, North Carolina. He received a Bachelors of Science in Civil Engineering in 1990 from North Carolina State University and a Masters of Science in Management, also from N.C. State, in 1999. Phil began working on his Doctor of Philosophy in Civil Engineering at N.C. State in 2005 and he anticipates completion in 2009.

Before seeking a PhD, Phil worked professionally for 14 years, including five years with the North Carolina Department of Transportation and nine years with Steel Dynamics, Inc. He is a licensed Professional Engineer in North Carolina and a member of numerous academic and professional organizations, including the American Society of Civil Engineers and Chi Epsilon National Civil Engineering Honor Society.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation through Grant No. 0327731 and also by the North Carolina Department of Transportation through Research Project No. HWY - 2006 – 08. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of NSF or NCDOT.

Valuable assistance with data analysis was provided by Saeed Abolhassani, M.S.C.E., Kangwook Kim, Ph.D., and Shih-Hao Pang, Ph.D. H. Christopher Frey, Ph.D. provided excellent technical advice regarding this work and William Rasdorf supported this work with his guidance and leadership.

TABLE OF CONTENTS

LIST OF TABLES	viii
LIST OF FIGURES	x
1.0 INTRODUCTION.....	1
1.1 Background.....	4
1.2 Purpose.....	6
1.3 Utility.....	7
1.4 Scope.....	9
2.0 LITERATURE REVIEW	11
2.1 Related Studies	11
2.2 Models for Estimating Nonroad Emissions.....	13
2.2.1 NONROAD Model.....	13
2.2.2 OFFROAD Model	14
2.2.3 URBEMIS Model.....	16
2.2.4 Road Construction Emissions Model	17
3.0 FUEL USE AND EMISSIONS FIELD MEASUREMENTS.....	19
3.1 Study Design	19
3.1.1 Equipment Selection.....	20
3.1.2 Equipment Activity.....	22
3.1.3 Equipment Location	23
3.1.4 Equipment Scheduling.....	24
3.2 Instrumentation.....	25
3.2.1 PEMS.....	25
3.2.2 Laptop Computer.....	27
3.2.3 GPS.....	28
3.2.4 Video Camera	28
3.3 Field Data.....	29
3.3.1 Fuel Use and Emissions Data	29
3.3.2 Visual Data	30
3.3.3 Construction Site and Activity Data	31
3.3.4 Equipment Data	32

3.4	Field Data Collection Problems	35
3.4.1	Unsuitable Weather	35
3.4.2	Difficult Operating Conditions	36
3.4.3	Scheduling Challenges	36
3.5	Data Quality Assurance.....	37
3.6	Results of Field Data Collection.....	38
4.0	ANALYSIS AND METHODOLOGY.....	40
4.1	Equipment Attributes Affecting Fuel Use and Emissions	42
4.1.1	Equipment Type	43
4.1.2	Engine Size.....	43
4.1.3	Engine Age.....	43
4.1.4	Engine Tier.....	44
4.1.5	Engine Load.....	44
4.2	Modal Analyses for Fuel Use and Emission Rates.....	47
4.2.1	Activity Modal Analysis.....	47
4.2.2	Engine Modal Analysis	48
4.3	Fuel Use and Emission Rates of Engine Modes	49
4.3.1	Exploratory Analysis of Engine Modal Data.....	50
4.3.2	Average Fuel Use and Emission Rates of Each Engine Mode	50
4.3.3	Models for Fuel Use and Emission Rates of Each Engine Mode	51
4.4	Representative Duty Cycles of Construction Equipment	53
4.4.1	Representative Duty Cycles.....	55
4.4.2	Engine Mode Distribution of Duty Cycles	55
4.5	Weighted-Average Fuel Use and Emission Rates for Equipment Duty Cycles	56
4.5.1	Weighted-Average Fuel Use Rates.....	57
4.5.2	Weighted-Average Emission Rates	57
4.5.3	Summary and Evaluation of Methodology	58
5.0	RESULTS AND DISCUSSION	60
5.1	Equipment Attributes Affecting Fuel Use and Emission Rates.....	60
5.1.1	Equipment Type	60
5.1.2	Engine Size.....	61
5.1.3	Engine Age.....	62
5.1.4	Engine Tier.....	62
5.1.5	Engine Load.....	63
5.2	Modal Analyses of Fuel Use and Emission Rates	63
5.2.1	Activity Modal Analysis.....	63
5.2.2	Engine Modal Analysis	68

5.3	Fuel Use and Emission Rates of Engine Modes	72
5.3.1	Exploratory Analysis of Engine Modal Data.....	72
5.3.2	Average Fuel Use and Emission Rates of Each Engine Mode	74
5.3.3	Models of Fuel Use and Emission Rates for Each Engine Mode	75
5.4	Representative Duty Cycles of Construction Equipment	79
5.4.1	Representative Duty Cycles.....	79
5.4.2	Engine Mode Distribution of Duty Cycles	80
5.5	Weighted-Average Fuel Use and Emission Rates for Equipment Duty Cycles	82
5.5.1	Weighted-Average Fuel Use Rates.....	82
5.5.2	Weighted-Average Emission Rates	85
5.5.3	Summary and Evaluation of Methodology	90
6.0	CONCLUSIONS	97
6.1	Construction Fuel Use and Emissions	97
6.2	Equipment Attributes	98
6.3	Modal Analyses.....	100
6.4	Regression Models for Engine Modal Fuel Use and Emission Rates.....	101
6.5	Representative Duty Cycles.....	102
6.6	Weighted-Average Fuel Use and Emission Rates.....	102
6.7	Performance and Use of Methodology	103
7.0	RECOMMENDATIONS.....	105
7.1	Construction Fuel Use and Emissions	105
7.2	Equipment Attributes	107
7.3	Modal Analyses.....	108
7.4	Regression Models for Engine Modal Fuel Use and Emission Rates.....	109
7.5	Representative Duty Cycles.....	110
7.6	Weighted-Average Fuel Use and Emission Rates.....	111
7.7	Performance and Use of Methodology	112

8.0	REFERENCES.....	114
9.0	APPENDICES.....	117
9.1	Appendix A: Activity Modal Analyses of Fuel Use and Emission Rates for Three Off-Road Trucks	118
9.2	Appendix B: Engine Modal Analyses of Fuel Use and Emission Rates for Three Off-Road Trucks	124
9.3	Appendix C: Datasets of Equipment Attributes, Fuel Use Rates, and Emission Rates for Engine Modes 1 through 10 for Each Item of Equipment.....	130
9.4	Appendix D: Boxplots for Fuel Use and Emission Rates Field Data	142
9.5	Appendix E: Residual Plots for Regression Models Used for Estimating the Fuel Use Rate of Engine Modes	153
9.6	Appendix F: Fraction of Time and Fuel Use per Engine Mode for Representative Duty Cycles	159
9.7	Appendix G: Residual Plots for Fuel Use and Emission Rates Response Plots	169

LIST OF TABLES

Table 1.1	Estimated 2008 Diesel Emissions of Nonroad Equipment Based on Equipment Classification.....	2
Table 1.2	Estimated 2008 Diesel Emissions of Construction and Mining Equipment Based on Equipment Type.....	3
Table 3.1	Comparison of Contribution and National Rankings of NO _x , CO, and PM ₁₀ for Selected Equipment	21
Table 3.2	Activity Modes for Construction Equipment.....	23
Table 3.3	Construction Site and Activity Data for a Motor Grader.....	32
Table 3.4	Equipment Data for Six Motor Graders.....	34
Table 3.5	Summary of Data Collection Results for Each Item of Equipment.....	39
Table 4.1	EPA Engine Tier Classifications and Specifications	46
Table 5.1	Summary of Equipment Types	61
Table 5.2	Summary of Horsepower and Displacement Ranges for Each Equipment Type ..	61
Table 5.3	Summary of Engine Model Year for Each Equipment Type.....	62
Table 5.4	Summary of Engine Tier Classifications for Each Equipment Type.....	62
Table 5.5	Average Fuel Use and Emission Rates per Engine Mode	75
Table 5.6	R ² Values for Models of Fuel Use and Emission Rates per Engine Mode.....	76
Table 5.7	Fuel Use Rate Models for Each Engine Mode	77
Table 5.8	Modal Fraction of Time and Fuel Used for Backhoe Load Truck Duty Cycle	81
Table 5.9	Equipment Attributes for Numerical Example	82
Table 5.10	Summary of Weighted Fuel Use Rates for Two Representative Duty Cycles of a Wheel Loader	85
Table 5.11	Summary of Weighted NO _x Emission Rates for Two Representative Duty Cycles of a Wheel Loader	87
Table 5.12	Summary of Weighted HC Emission Rates for Two Representative Duty Cycles of a Wheel Loader	88
Table 5.13	Summary of Weighted CO Emission Rates for Two Representative Duty Cycles of a Wheel Loader	88
Table 5.14	Summary of Weighted PM Emission Rates for Two Representative Duty Cycles of a Wheel Loader	89
Table 5.15	Summary of Weighted-Average Emission Rates for Two Representative Duty Cycles of a Wheel Loader	89
Table 5.16	Summary of Actual and Estimated Fuel Use and Emission Rates	92
Table 5.17	Summary of R ² , Slope, and Intercept for Response Plots	96
Table 9.1	Equipment Attributes and Duty Cycles for Each Item of Equipment	131
Table 9.2	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 1....	132
Table 9.3	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 2....	133
Table 9.4	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 3....	134
Table 9.5	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 4....	135
Table 9.6	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 5....	136

Table 9.7	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 6....	137
Table 9.8	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 7....	138
Table 9.9	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 8....	139
Table 9.10	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 9..	140
Table 9.11	Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 10	141
Table 9.12	Fraction of Time and Fuel Use per Mode for Backhoe "Load Truck" Duty Cycle	160
Table 9.13	Fraction of Time and Fuel Use per Mode for Backhoe "Move Soil" Duty Cycle	160
Table 9.14	Fraction of Time and Fuel Use per Mode for Backhoe "Move Material" Duty Cycle.....	161
Table 9.15	Fraction of Time and Fuel Use per Mode for Bulldozer "Rough Grade" Duty Cycle.....	161
Table 9.16	Fraction of Time and Fuel Use per Mode for Bulldozer "Fine Grade" Duty Cycle	162
Table 9.17	Fraction of Time and Fuel Use per Mode for Bulldozer "Stockpile" Duty Cycle	162
Table 9.18	Fraction of Time and Fuel Use per Mode for Excavator "Clear and Grub" Duty Cycle.....	163
Table 9.19	Fraction of Time and Fuel Use per Mode for Excavator "Move Rock" Duty Cycle.....	163
Table 9.20	Fraction of Time and Fuel Use per Mode for Excavator "Excavate Soil" Duty Cycle.....	164
Table 9.21	Fraction of Time and Fuel Use per Mode for Motor Grader "Resurface" Duty Cycle.....	164
Table 9.22	Fraction of Time and Fuel Use per Mode for Motor Grader "Shoulder" Duty Cycle.....	165
Table 9.23	Fraction of Time and Fuel Use per Mode for Off-Road Tuck "Haul Soil" Duty Cycle.....	165
Table 9.24	Fraction of Time and Fuel Use per Mode for Track Loader "Fine Grade" Duty Cycle.....	166
Table 9.25	Fration of Time and Fuel Use per Mode for Track Loader "Move Material" Duty Cycle.....	166
Table 9.26	Fraction of Time and Fuel Use per Mode for Track Loader "Stockpile" Duty Cycle.....	167
Table 9.27	Fraction of Time and Fuel Use per Mode for Wheel Loader "Move Soil" Duty Cycle.....	167
Table 9.28	Fraction of Time and Fuel Use per Mode for Wheel Loader "Load Truck" Duty Cycle.....	168

LIST OF FIGURES

Figure 1.1	Production of Equipment Emissions	5
Figure 3.1	Montana System by CATI, Inc.....	26
Figure 3.2	PEMS Installed on Bulldozer	29
Figure 3.3	Overview of Data Quality Assurance Procedures	38
Figure 4.1	Conceptual Diagram for Estimating Weighted-Average Fuel Use and Emission Rates	42
Figure 5.1	Activity Modal Analysis of Fuel Use for Off-Road Truck 1	64
Figure 5.2	Activity Modal Analysis of NO _x for Off-Road Truck 1.....	66
Figure 5.3	Activity Modal Analysis of HC for Off-Road Truck 1	66
Figure 5.4	Activity Modal Analysis of CO for Off-Road Truck 1	67
Figure 5.5	Activity Modal Analysis for CO ₂ for Off-Road Truck 1	67
Figure 5.6	Activity Modal Analysis of PM for Off-Road Truck 1	68
Figure 5.7	Engine Modal Analysis of Fuel Use for Off-Road Truck 1	69
Figure 5.8	Engine Modal Analysis of NO _x for Off-Road Truck 1	70
Figure 5.9	Engine Modal Analysis of HC for Off-Road Truck 1	70
Figure 5.10	Engine Modal Analysis of CO for Off-Road Truck 1	71
Figure 5.11	Engine Modal Analysis of CO ₂ for Off-Road Truck 1.....	71
Figure 5.12	Engine Modal Analysis of PM for Off-Road Truck 1.....	72
Figure 5.13	Response Surface for Fuel Use vs. HP and Engine Mode for Engine Tier 0.....	78
Figure 5.14	Response Surface for Fuel Use vs. HP and Engine Mode for Engine Tiers 1, 2, and 3	78
Figure 5.15	Response Plot for Fuel Use Rate	91
Figure 5.16	Response Plot for NO _x Emission Rate	94
Figure 5.17	Response Plot for HC Emission Rate	94
Figure 5.18	Response Plot for CO Emission Rate	95
Figure 5.19	Response Plot for PM Emission Rate.....	95
Figure 9.1	Activity Modal Analysis of Fuel Use for Three Off-Road Trucks	119
Figure 9.2	Fuel-Based Activity Modal Analysis of NO for Three Off-Road Trucks.....	120
Figure 9.3	Fuel-Based Activity Modal Analysis of HC for Three Off-Road Trucks	121
Figure 9.4	Fuel-Based Activity Modal Analysis of CO for Three Off-Road Trucks	122
Figure 9.5	Fuel-Based Activity Modal Analysis of PM for Three Off-Road Trucks.....	123
Figure 9.6	Engine Modal Analysis of Fuel Use for Three Off-Road Trucks	125
Figure 9.7	Fuel-Based Engine Modal Analysis of NO for Three Off-Road Trucks.....	126
Figure 9.8	Fuel-Based Engine Modal Analysis of HC for Three Off-Road Trucks.....	127
Figure 9.9	Fuel-Based Engine Modal Analysis of CO for Three Off-Road Trucks.....	128
Figure 9.10	Fuel-Based Engine Modal Analysis of PM for Three Off-Road Trucks.....	129
Figure 9.11	Boxplots for Mode 1 Fuel Use and Emission Rates.....	143
Figure 9.12	Boxplots for Mode 2 Fuel Use and Emission Rates.....	143
Figure 9.13	Boxplots for Mode 3 Fuel Use and Emission Rates.....	144
Figure 9.14	Boxplots for Mode 4 Fuel Use and Emission Rates.....	144

Figure 9.15	Boxplots for Mode 5 Fuel Use and Emission Rates.....	145
Figure 9.16	Boxplots for Mode 6 Fuel Use and Emission Rates.....	145
Figure 9.17	Boxplots for Mode 7 Fuel Use and Emission Rates.....	146
Figure 9.18	Boxplots for Mode 8 Fuel Use and Emission Rates.....	146
Figure 9.19	Boxplots for Mode 9 Fuel Use and Emission Rates.....	147
Figure 9.20	Boxplots for Mode 10 Fuel Use and Emission Rates.....	147
Figure 9.21	Boxplot for Mode 1 CO ₂	148
Figure 9.22	Boxplot for Mode 2 CO ₂	148
Figure 9.23	Boxplot for Mode 3 CO ₂	149
Figure 9.24	Boxplot for Mode 4 CO ₂	149
Figure 9.25	Boxplot for Mode 5 CO ₂	150
Figure 9.26	Boxplot for Mode 6 CO ₂	150
Figure 9.27	Boxplot for Mode 7 CO ₂	151
Figure 9.28	Boxplot for Mode 8 CO ₂	151
Figure 9.29	Boxplot for Mode 9 CO ₂	152
Figure 9.30	Boxplot for Mode 10 CO ₂	152
Figure 9.31	Residual Plots for Mode 1 Fuel Use.....	154
Figure 9.32	Residual Plots for Mode 2 Fuel Use.....	154
Figure 9.33	Residual Plots for Mode 3 Fuel Use.....	155
Figure 9.34	Residual Plots for Mode 4 Fuel Use.....	155
Figure 9.35	Residual Plots for Mode 5 Fuel Use.....	156
Figure 9.36	Residual Plots for Mode 6 Fuel Use.....	156
Figure 9.37	Residual Plots for Mode 7 Fuel Use.....	157
Figure 9.38	Residual Plots for Mode 8 Fuel Use.....	157
Figure 9.39	Residual Plots for Mode 9 Fuel Use.....	158
Figure 9.40	Residual Plots for Mode 10 Fuel Use.....	158
Figure 9.41	Residual Plots for Fuel Use Response Plot	170
Figure 9.42	Residual Plots for NO _x Response Plot.....	170
Figure 9.43	Residual Plots for HC Response Plot	171
Figure 9.44	Residual Plots for CO Response Plot	171
Figure 9.45	Residual Plots for PM Response Plot.....	172

1.0 INTRODUCTION

According to the United States Environmental Protection Agency (EPA), there are over two million items of construction and mining equipment in the United States that consumes almost 6 billion gallons of diesel fuel per year [EPA, 2005]. Nonroad diesel engines produce air pollutant emissions through the consumption of diesel fuel. The pollutants of primary concern are nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM). Carbon dioxide (CO_2) is a greenhouse gas that is produced by the burning of fossil fuels, including diesel fuel. Nonroad equipment not only includes equipment used in the construction and mining industries, but it also includes equipment used in other industries as well, such as agriculture, airports, and railroad presents the estimated 2008 annual diesel emissions of NO_x , HC, CO, CO_2 , and PM for all classifications of nonroad equipment based on the EPA NONROAD model [EPA, 2005]. Construction and mining equipment is the highest producer of these pollutants, emitting between 45% and 48% of the total diesel emissions of each pollutant among all types of nonroad equipment classifications.

This dissertation is focused on backhoes, bulldozers, excavators, motor graders, off-road trucks, track loaders, and wheel loaders. The estimated 2008 annual diesel emissions of NO_x , HC, CO, CO_2 , and PM_{10} of these equipment types are shown in Table 1.2. Note that track loaders and bulldozers are combined in the “Crawler Tractor/Dozers” equipment type. These seven equipment types produced approximately 56% of all construction and mining equipment emissions of NO_x , 50% of HC, 52% of CO, 54% of CO_2 , and 52% of PM.

Table 1.1 Estimated 2008 Diesel Emissions of Nonroad Equipment Based on Equipment Classification

Equipment Classification	NO_x Emissions		HC Emissions		CO Emissions		CO₂ Emissions		PM Emissions	
	tons/yr	% Total	tons/yr	% Total	tons/yr	% Total	tons/yr	% Total	tons/yr	% Total
Agricultural	466,306	33	43,589	32	242,770	34	43,832,188	30	48,734	36
Airport	9,673	1	676	1	4,222	1	1,071,741	1	768	1
Commercial	77,322	5	10,610	8	45,588	6	7,535,435	5	8,637	6
<i>Construction & Mining</i>	<i>642,939</i>	<i>45</i>	<i>62,702</i>	<i>47</i>	<i>339,312</i>	<i>47</i>	<i>70,669,186</i>	<i>48</i>	<i>60,464</i>	<i>45</i>
Industrial	120,727	9	10,170	8	57,459	8	14,501,504	10	10,649	8
Lawn & Garden (Com.)	32,467	2	3,566	3	15,149	2	3,183,751	2	3,027	2
Logging	14,403	1	1,004	1	5,211	1	1,929,276	1	1,143	1
Pleasure Craft	45,219	3	1,560	1	7,508	1	3,725,885	3	1,273	1
Railroad	2,953	< 1	497	< 1	2,262	< 1	260,995	< 1	399	< 1
Recreational	1,602	< 1	417	< 1	1,702	< 1	148,471	< 1	259	< 1
	1,413,611	100%	134,791	100%	721,183	100%	146,858,430	100%	135,353	100%

Table 1.2 Estimated 2008 Diesel Emissions of Construction and Mining Equipment Based on Equipment Type

Equipment Type	NO _x Emissions		HC Emissions		CO Emissions		CO ₂ Emissions		PM Emissions	
	tons/yr	% Total	tons/yr	% Total	tons/yr	% Total	tons/yr	% Total	tons/yr	% Total
Bore/Drill Rigs	12,547	2	999	2	4,444	1	1,013,100	1	906	1
Cement & Mortar Mixers	483	< 1	51	< 1	221	< 1	39,565	< 1	43	< 1
Concrete/Industrial Saws	721	< 1	76	< 1	528	< 1	83,326	< 1	92	< 1
Cranes	22,181	3	1,419	2	5,587	2	2,297,124	3	1,296	2
<i>Crawler Tractor/Dozers</i>	<i>87,740</i>	<i>14</i>	<i>5,643</i>	<i>9</i>	<i>35,864</i>	<i>11</i>	<i>10,022,925</i>	<i>14</i>	<i>6,450</i>	<i>11</i>
Crushing/Proc.	4,047	1	284	< 1	1,349	< 1	405,963	1	272	< 1
Dumpers/Tenders	149	< 1	41	< 1	169	< 1	13,995	< 1	29	< 1
<i>Excavators</i>	<i>78,973</i>	<i>12</i>	<i>5,535</i>	<i>9</i>	<i>30,508</i>	<i>9</i>	<i>10,062,764</i>	<i>14</i>	<i>6,387</i>	<i>11</i>
<i>Motor Graders</i>	<i>19,853</i>	<i>3</i>	<i>1,385</i>	<i>2</i>	<i>6,774</i>	<i>2</i>	<i>2,504,428</i>	<i>4</i>	<i>1,536</i>	<i>3</i>
Off-Highway Tractors	11,212	2	717	1	5,152	2	1,078,389	2	771	1
<i>Off-highway Trucks</i>	<i>77,139</i>	<i>12</i>	<i>4,035</i>	<i>6</i>	<i>25,336</i>	<i>7</i>	<i>8,605,788</i>	<i>12</i>	<i>4,474</i>	<i>7</i>
Other Construction	10,769	2	748	1	5,284	2	1,032,914	1	841	1
Other Mining	3,129	< 1	618	1	2,729	1	264,551	< 1	431	1
Pavers	8,278	1	645	1	3,727	1	991,720	1	741	1
Paving Equipment	1,341	< 1	118	< 1	708	< 1	149,004	< 1	131	< 1
Plate Compactors	292	< 1	43	< 1	198	< 1	26,621	< 1	35	< 1
Rollers	21,193	3	1,754	3	11,057	3	2,482,551	4	2,059	3
Rough Terrain Forklifts	28,490	4	2,668	4	17,785	5	3,219,898	5	3,148	5
<i>Rubber Tire Loaders</i>	<i>102,456</i>	<i>16</i>	<i>6,918</i>	<i>11</i>	<i>42,506</i>	<i>13</i>	<i>10,953,165</i>	<i>15</i>	<i>7,745</i>	<i>13</i>
Scrapers	23,407	4	1,265	2	10,083	3	2,700,674	4	1,605	3
Signal Boards/Light Plants	2,657	< 1	359	1	1,448	< 1	274,003	< 1	276	< 1
Skid Steer Loaders	46,224	7	12,600	20	55,966	16	4,542,756	6	9,143	15
Surfacing Equipment	952	< 1	79	< 1	557	< 1	91,616	< 1	89	< 1
Tampers/Rammers	19	< 1	3	< 1	13	< 1	3,973	< 1	2	< 1
<i>Tractors/Loaders/Backhoes</i>	<i>68,103</i>	<i>11</i>	<i>13,667</i>	<i>22</i>	<i>64,326</i>	<i>19</i>	<i>6,631,815</i>	<i>9</i>	<i>10,746</i>	<i>18</i>
Trenchers	10,585	2	1,032	2	6,993	2	1,176,558	2	1,219	2
	642,939	100%	62,702	100%	339,312	100%	70,669,186	100%	60,464	100%

1.1 Background

As fuel is consumed by an engine, tailpipe air pollutant emissions are produced. There are factors that influence the quantities of fuel that is used and the emissions that are produced, such as the task that the equipment is performing and the various equipment and engine activities that are occurring while the task is being performed.

Figure 1.1 shows that fuel is consumed by a wheel loader while it completes the task of loading soil into a dump truck. To complete this task, the wheel loader must perform the duty cycle components of *scooping* soil from a pile with its bucket, *traveling* with its bucket *loaded* to the truck, *dumping* the soil into the truck, and *returning* to the soil pile with its bucket *empty*. The wheel loader must repeat this duty cycle many times until the desired amount of soil has been moved.

While this duty cycle is being performed by the wheel loader, there are specific equipment activities and engine parameters that are measurable. These equipment activities, known as activity modes, include *idling*, *moving* with the bucket empty, and moving with the bucket loaded which begins with *scooping* the soil and ends with *dumping* the soil. The duration of each activity mode is measured in seconds. As the wheel loader performs the activity modes, specific engine activities can be monitored. The monitored engine activities include revolutions per minute (RPM), manifold absolute pressure (MAP), and intake air temperature (IAT). For any task with a particular duty cycle, activity modes and engine activity can be measured to determine their relationship to emissions.

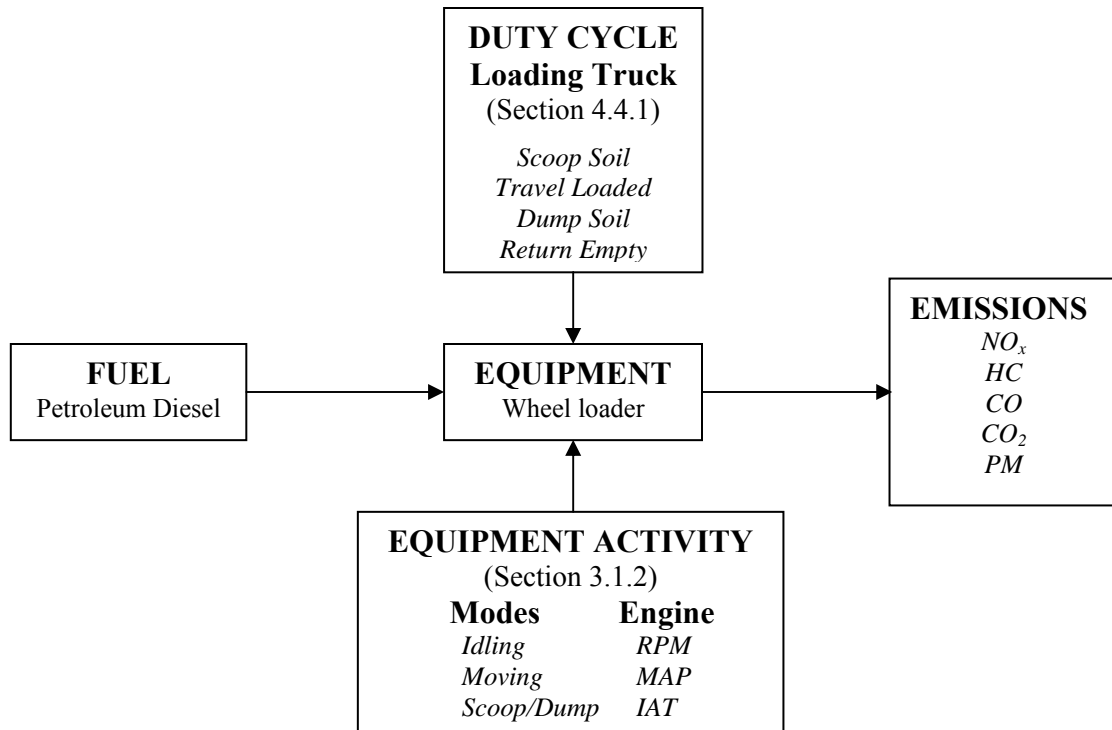


Figure 1.1 Production of Equipment Emissions

This relationship is expressed in terms of an emission factor, or emission rate. An emission factor is the rate at which pollutants are emitted into the atmosphere. Emission rates may be based on mass per time or mass per fuel used, such as grams per second (g/s). Likewise, emission rates may be expressed as the mass of pollutant in grams that is emitted per unit of fuel consumed in gallons (g/gal).

With respect to Figure 1.1, a concern is determining what is known and what is unknown. If emissions and time are both measured, then emissions can be related directly to time (g/s). If the fuel flow rate or the exhaust flow rate is measured, then emissions can be indirectly estimated on a mass per time basis (g/s). Emissions can also be related to fuel

(g/gal) based on a carbon balance. If equipment activity is measured, then emissions can be related to activity modes and engine activity. Trends in emissions based on time and fuel use can be correlated with engine performance. If the equipment duty cycle is monitored, then emissions can be related to the individual equipment tasks.

1.2 Purpose

In order to determine the environmental impacts of pollutants from construction equipment, it is necessary to quantify the amounts of fuel used and emissions generated by construction activities. Fuel use and emissions estimates from nonroad construction equipment are typically quantified based on steady-state engine dynamometer tests using uninstalled stationary engines. However, these tests do not represent in-use equipment activity. Thus, there is a need to determine the fuel use and emission rates of construction equipment based on in-use measurement methods to assess their true level of contribution. Field data can be used to quantify real-world construction activity and the influence of equipment duty cycles on fuel use and emissions.

Although it is possible to obtain field data by directly measuring the quantities of fuel used and pollutants emitted by nonroad equipment, it is not always practical to do so. A scientifically developed methodology is needed to reliably estimate fuel use and emissions for construction projects in the same manner that other common construction metrics are estimated.

1.3 Utility

All construction projects, regardless of size or type, have an energy use and emissions footprint. Even small commercial projects may have numerous vehicles and equipment on site at any given time or over time. Thus, there are many benefits of being able to accurately estimate construction activity fuel use and emissions. These benefits may be financial, environmental, or regulatory in nature and are of interest to many groups in the construction industry, including equipment manufacturers, equipment owners, fleet managers, general contractors, and project owners. A construction project's impact on air quality is of particular interest to environmentalists and policy makers concerned with the safety, health, and welfare of the public.

Just as most Americans feel burdened by increasing gas prices, construction equipment owners are particularly burdened by the demand of diesel fuel that this equipment requires. Fuel, along with tires, tracks, maintenance, and repairs are quantifiable components of construction equipment operating costs [CAT, 2004]. Equipment hourly operating costs are most sensitive to fuel use based on the price of the fuel and the fuel consumption rate of the equipment.

For example, based on a price of \$1.25 per gallon, the diesel fuel expense of a track-type tractor is approximately 28% of the total hourly operating costs. However, if the fuel price increases to \$2.50 per gallon and the other operating expenses remain constant, the fuel expense of the same item of equipment is approximately 44% of the total hourly operating costs. For a tractor that consumes 4.5 gallons of fuel per hour and operates for eight hours per day, this price increase results in an increased fuel expense of approximately \$50 per day

for this one item of equipment alone. Thus, for a fleet owner with many items of equipment, a change in fuel prices can have a significant impact on the fleet operating expense budget.

Equipment owners must accurately assess the fuel requirements for a particular project in order to accurately estimate project costs. These costs are the basis for the bid price that the equipment owner gives to the general contractor and the bid price that the general contractor subsequently gives to the project owner.

Air pollutant emissions from the consumption of diesel fuel have an environmental impact. These emissions, including NO_x, HC, CO, and PM, pose serious health threats to humans and animals including cardiovascular and respiratory problems. These pollutants can reduce visibility, cause smog, and damage plants and materials. Also, CO₂ is a greenhouse gas that contributes to global warming and climate change. It is necessary to quantify these emissions to appropriately manage them.

Environmentalists can use the methodology proposed herein to estimate the levels of pollutants from construction equipment for a proposed construction project to analyze the effect on air quality for that region, particularly if the project is located in an environmentally sensitive zone, such as an area of nonattainment with the current National Ambient Air Quality Standards (NAAQS) [CFR, 2007]. Although construction projects are not specifically required to meet NAAQS requirements, construction equipment produces emissions that are specified as NAAQS criteria pollutants, including NO₂, SO₂, CO, PM, and HC. HC is not a criteria pollutant itself but it is a precursor to ozone, which is a NAAQS criteria pollutant. NO_x is also a precursor to ozone.

Most federal regulations, such as the EPA Engine Tier Classifications and Standards [EPA (1), 2004], have required equipment engine manufacturers to make them responsible for lowering emissions. However, new regulations are now focusing on equipment owners as well. For example, the state departments of transportation for Connecticut, Massachusetts, and New York have included language in their contract specifications that requires emissions reduction strategies, such as installing retrofit engine technology, using ultra-low sulfur diesel fuel (to allow the use of other post-combustion controls), and limiting idle time [Northeast Diesel Collaborative, 2007].

With regard to fleet management, the Fraser Basin Council [2008], a nonprofit organization in Canada that focuses on sustainability, implemented the E3 Fleet Rating system which rates commercial equipment fleets based on fleet management practices, energy performance, and emissions performance. This type of program could be and likely will be extended geographically and can include any type of equipment fleet. The methodology presented here provides a way for engine manufacturers, equipment owners, and fleet managers to evaluate the effects of engine technology and fleet management practices on fuel use and emission rates of construction equipment duty cycles with respect to governmental regulations.

1.4 Scope

The overall objective of this dissertation is to provide a methodology for improved estimates of fuel use and emission rates of nonroad diesel construction equipment used for

construction activities. This objective was accomplished by completing the following set of tasks:

- Summarize field data collected in research conducted at North Carolina State University from two studies related to fuel use and emissions of 35 items of nonroad diesel construction equipment of eight different types that performed various activity modes and duty cycles.
- Evaluate engine parameters that affect fuel use and emission rates.
- Perform an engine-based modal analysis including classification of fuel use and emissions field data by engine modes and duty cycles.
- Develop statistically valid models for each engine mode based on equipment attributes to estimate fuel use and emission rates for that particular mode.
- Determine representative duty cycles for each equipment type examined under actual field operating conditions.
- Determine the percentage of time spent in each engine mode for each duty cycle and the percentage of fuel used in each engine mode.
- Determine the weighted-average fuel use and emission rates for each duty cycle.

2.0 LITERATURE REVIEW

This section reviews studies that have been done in the area of nonroad diesel equipment emissions, including construction equipment emissions, emissions regulations, and construction equipment fleet management with respect to emissions. Models used for estimating nonroad diesel emissions of construction equipment are discussed.

2.1 Related Studies

Much of the work related to construction equipment fuel use and emissions has been performed by researchers at North Carolina State University. Two projects were completed in 2007 that quantified the fuel use and emissions of construction equipment as they performed duty cycles in the field. One project addressed the life cycle inventory and impact analysis of nonroad diesel construction equipment by collecting field data from eight different types of equipment [Frey et al (1), 2007]. The other project focused on the effects of duty cycles on equipment fuel use and emissions for a publicly-owned fleet of backhoes, motor graders, and wheel loaders [Frey et al (2), 2007]. This project also compared the results of petroleum diesel emissions to biodiesel emissions.

These projects have served as a foundation to many publications related to the fuel use and emissions of construction equipment. Abolhassani et al [2007] evaluated the fuel use and emissions of excavators in the field. Frey et al (1) [2008] performed a comparison of petroleum diesel versus B20 biodiesel emissions from backhoes, motor graders, and wheel loaders performing field activities. Also, Frey et al (2) [2008] characterized the field activity,

fuel use, and emissions of selected motor graders fueled with petroleum diesel and B20 biodiesel.

The results of these projects have also been used to assess emissions regulations, compare data sources, evaluate fleet management decisions, and develop techniques for fuel use and emissions field data collection. Lewis et al (1) [2008] examined requirements and incentives for reducing emissions from construction equipment and also advocated the use of field emissions data versus emissions data obtained from engine dynamometer tests. Lewis et al (2) [2008] discussed the development and use of an emissions inventory for a fleet of backhoes, front-end loaders, and motor graders to make fleet management decisions related to replacing older equipment with newer equipment. Rasdorf et al [2008] proposed a field methodology for collecting fuel-use and emissions data from nonroad equipment as they perform construction activities.

Frey et al (3) [2008] assessed emission factors of NO_x and PM for heavy-duty diesel trucks based on field data. Although they are highway vehicles, heavy-duty diesel trucks are heavily involved in construction activities. Thus, this information can be used to evaluate total construction project emissions. Frey and Bammi [2003] evaluated probabilistic nonroad mobile source emission factors of NO_x and HC for construction, agricultural, and industrial engines, including both gasoline and diesel engines. This work used quantitative methods to characterize variability and uncertainty for these emission rates and can serve as a case study for other emission rate analyses.

2.2 Models for Estimating Nonroad Emissions

This section describes models that are used to estimate emissions from nonroad diesel equipment, including the NONROAD model, OFFROAD model, URBEMIS model, and the Road Construction Emissions model. The NONROAD and OFFROAD models are emission inventory models and URBEMIS and Road Construction Emission models are used to estimate emissions of construction projects.

2.2.1 NONROAD Model

The Environmental Protection Agency's NONROAD model [EPA, 2005] predicts emissions of nonroad equipment based on fleet average emission rates. The model includes over 260 specific equipment items classified by equipment type and horsepower rating. The model can estimate emissions for different fuel types including gasoline, diesel, compressed natural gas, and liquid petroleum gas. Emissions include NO_x, HC, CO, CO₂, PM, and sulfur oxides (SO_x).

The NONROAD model estimates emissions on several geographic levels including national, state, county, and, in some cases, sub-county. It can also forecast emissions through 2050 or backcast emissions to 1970 using growth and scrappage rates for equipment. Emissions can be estimated on a yearly, seasonal, or monthly basis.

The NONROAD model estimates emissions in tons per year for specific equipment types based on the following input estimates:

- Equipment population distributed by age, power, fuel type, and application
- Average engine load factor (fraction of maximum power)

- Available horsepower (hp)
- Equipment activity (hours per year)
- Emission factor based on deterioration or new standards (grams per hp-hr)

One of the key input estimates that must be provided is the engine load factor, which is the fraction of the maximum rated engine power that is available [EPA (2), 2004]. Nonroad engines operate at a variety of speeds and loads and operation at full load is rare. Load factors vary widely depending on how the equipment is operated. The NONROAD model uses an average load factor that takes into account equipment operation including idling and partial loads. For construction equipment, the load factors used include 0.21 for backhoes and 0.59 for bulldozers, excavators, motor graders, off-road trucks, track loaders, and wheel loaders. Thus, the NONROAD model estimates emissions based on an average load factor for a certain type of equipment, depending on site conditions.

2.2.2 OFFROAD Model

The OFFROAD model [OFFROAD, 2007] was developed by the California Air Resources Board (CARB) to estimate emissions of nonroad equipment in the state of California. Emissions inventories are produced for each county, air basin, engine type, fuel type, equipment group, and horsepower group. The OFFROAD model takes into account the effects of regulations, technology types, and seasonal conditions on emissions.

There are three primary components of the OFFROAD model including equipment population, equipment activity, and emission factors. Emissions in units of tons per year are estimated by multiplying the following parameters:

- Emission factor in grams per brake horsepower-hour (g/bhp-hr)
- Population of each item of equipment
- Maximum average rated horsepower (hp)
- Load factor (fraction of maximum power)
- Annual activity in hours per year (hr/yr)

The population component of the OFFROAD model contains growth and scrappage factors that account for the addition of new equipment and the retirement of older equipment. These factors are used to derive population distributions of equipment for specified calendar years from 1970 to 2040. Thus, the model is able to forecast emissions for future years or estimate emissions for past years.

The activity component of the OFFROAD model contains information such as annual average use hours, engine load factors, brake-specific fuel consumption, and starts per year for each equipment type by fuel, engine type, and horsepower group. The activity component takes into account seasonal and temporal effects on emissions based on monthly, weekly, and daily usage patterns of each equipment type. Overall, there are 94 equipment types classified within 17 categories.

The emissions component uses emission factors based on model year for NO_x, HC, CO, PM, and CO₂. The emission factors are engine specific and vary according to fuel type, horsepower group, and model year. The equipment-specific emission factors are adjusted according to the duty cycle of the equipment. The emission factors are also adjusted

according to an estimated deterioration rate of the engine which results in increased emissions as the equipment is used.

There are many similarities between the EPA NONROAD model and the CARB OFFROAD model, particularly with respect to the methodology that is used to estimate emissions. However, the NONROAD model provides emissions inventories on a nationwide level whereas the OFFROAD model is not recommended for use outside of California.

2.2.3 URBEMIS Model

URBEMIS2007 is a comprehensive model that was developed by the Sacramento Metropolitan Air Quality Management District (SMAQMD) to estimate the emissions of air pollutants from land development projects [URBEMIS, 2007]. This model allows the user to estimate construction emissions of NO_x, CO, PM₁₀, PM_{2.5}, CO₂, reactive organic gases (ROG), and sulfur oxides (SO_x). Emissions may be estimated in units of pounds per day (lb/day) or tons per year (ton/yr). URBEMIS2007 uses seven project phases:

1. Demolition
2. Fine Site Grading
3. Mass Site Grading
4. Trenching
5. Building Construction
6. Architectural Coating
7. Paving

URBEMIS2007 estimates construction emissions based on project size, the equipment that is used on the project, and emission factors of the equipment. The project size is measured in acres and the model assumes that heavy construction takes place on approximately 25% of the project at one time. The model also uses a default list of equipment with various horsepower ranges and load factors; however, if the actual equipment to be used on the project is known, then that equipment may be used instead. The model uses OFFROAD emission factors for nonroad emissions and EMFAC emission factors for highway emissions. EMFAC is a separate model used by the California Air Resources Board used to estimate emissions from highway vehicles.

2.2.4 Road Construction Emissions Model

Another emissions estimating model developed by SMAQMD is the Road Construction Emissions Model, Version 6.3.1 [RCM, 2007]. This model is similar to URBEMIS2007 but it focuses on linear projects such as roadways; it can also be used for projects such as bikeways or levee repair. This model estimates emissions for four project phases including grubbing/land clearing, grading/excavation, drainage/utilities/sub-grade, and paving.

The user is given the option of using a default list of equipment or inputting a list of equipment that will actually be used. The model also can estimate emissions for calendar years between 2005 and 2025. Other required model inputs include project type (new road construction, road widening, or bridge/overpass construction), construction time (months), predominant soil type (sand gravel, weathered rock-earth, or blasted rock), project length

(miles), project area (acres), maximum area disturbed per day (acres), amount of soil imported per day (cubic yards), amount of soil exported per day (cubic yards), and average truck capacity (cubic yards).

URBEMIS2007 and the Road Construction Emissions Model are recommended for use only in the state of California since they use EMFAC emission factors for highway emissions and OFFROAD emission factors for nonroad emissions. However, this model and URBEMIS2007 could be easily modified to estimate construction emissions on a nationwide basis.

3.0 FUEL USE AND EMISSIONS FIELD MEASUREMENTS

The research that supports the fuel use and emissions model involved collecting and analyzing fuel use and emissions data from different types of construction equipment as they performed field activities [Frey et al (1), 2007; Frey et al (2), 2007]. The primary objectives of the research reported herein were to measure in-use duty cycles, fuel use, and emissions of this equipment, develop recommended duty cycles and emissions estimates to be used for operational evaluation, and examine how field emissions data can be used to develop an emissions inventory for construction equipment.

The basis of the field data collection effort was an on-board portable emissions monitoring system (PEMS) that was used to gather fuel use and emissions data directly from in-use construction equipment. A brief description of the field data collection efforts are presented here but a more detailed assessment of these procedures are presented by Rasdorf et al [2008]. This section includes a discussion on the research study design, the instrumentation that was used to collect the field data, the type of field data that was collected, data collection problems, and data quality assurance procedures. A summary of the equipment that were tested and the amount of data that was collected is presented.

3.1 Study Design

The key elements of the study design that was used to collect fuel use and emissions field data included evaluating and selecting the types of equipment to test, determining which equipment activities to test, locating subject equipment for testing, and scheduling data collection testing with owners. This section describes each of these tasks.

3.1.1 Equipment Selection

The types of construction equipment selected for data collection were prioritized based on analyses using the EPA NONROAD model [EPA, 2005]. NONROAD was used to rank construction equipment based on their respective contribution of NO_x, CO, and PM. Essentially, the equipment that produced the highest quantities of these emissions (as determined by NONROAD) was selected for the study. The selected equipment included backhoes, bulldozers, excavators, generators, motor graders, off-road trucks, skid-steer loaders, track loaders, and wheel loaders.

The equipment that was selected for this research was estimated to contribute over 70 percent of all NO_x, CO, and PM from construction equipment in the United States. Table 3.1 summarizes the 2005 emissions data that were estimated using the NONROAD ranking of this equipment and equipment based on their contribution of NO_x, CO, and PM [EPA, 2005]. For example, wheel loaders contributed 14.5% of all NO_x produced by construction equipment, which made them the most significant contributor of NO_x, however, they were the third highest contributor of CO and PM, producing 11.5% and 11.2% of these emissions respectively. Note that Table 1.2 presents data obtained from the NONROAD model for the year 2008, thus the results presented in Table 1.2 and Table 3.1 are similar in magnitude but not equal.

Although motor graders did not rank in the top 10 for emissions of NO_x, CO, or PM, they are often used for highway construction and maintenance operations as well as general grading for all types of construction projects. They were included in the analysis because of their frequent use.

Even though generators did rank in the top 10 for emissions of these pollutants, they were not included in the dataset for the fuel use and emissions estimating methodology because of dissimilar duty cycles with the other items. Generators are stationary items of equipment that remain in one place while in use. The other items are mobile and move around the job site while in use. Thus, only mobile equipment was included in the fuel use and emissions model.

Table 3.1 Comparison of Contribution and National Rankings of NO_x, CO, and PM₁₀ for Selected Equipment for 2005

Equipment	NO _x		CO		PM ₁₀	
	Contribution (%)	National Ranking	Contribution (%)	National Ranking	Contribution (%)	National Ranking
Wheel Loaders	14.5	1	11.5	3	11.2	3
Bulldozers/Track Loaders	12.5	2	9.3	4	9.1	4
Excavators	11.4	3	7.4	5	8.6	5
Off-Highway Trucks	11.0	4	7.3	6	6.6	6
Backhoes	9.2	5	16.0	1	15.1	1
Skid-Steer Loaders	6.2	6	14.5	2	13.6	2
Generators	4.7	7	5.1	7	6.0	7
Motor Graders	2.9	12	1.7	14	2.1	13
	72.4		72.8		72.3	

Skid-steer loaders were also excluded from the dataset for the fuel use and emissions methodology. Field data were collected for only one skid-steer loader; the horsepower rating and displacement of the engine was much lower for this equipment than the other equipment in the dataset. Thus, the one skid-steer loader was not included in the dataset because its engine size was much smaller than those of the other equipment.

3.1.2 Equipment Activity

The type of task and related duty cycle being performed by equipment can influence the engine load of the equipment. For example, a wheel loader moving with its bucket loaded imposes a higher load on the engine than a wheel loader moving with the bucket empty. Typically, emissions from the equipment increase as the engine load of the equipment increases. Engine load was monitored by measuring MAP.

Activity modes were observed to relate the engine load to the activity that was being performed. Similar to duty cycle components, activity modes are a set of specific actions that equipment performs to accomplish a specific task. The difference is that activity modes were observed for the specific purpose of determining how particular actions of the equipment affect the emissions of the equipment. In general, the equipment is considered to be working during the execution of activity modes. Idling was an observed activity mode but it is not usually considered to be a duty cycle component because it is time that the equipment spends with the engine on but not working. Activity modes are based on the timeline of each specific activity of the equipment rather than on the overall task to be completed. Activity modes for each type of equipment are shown in Table 3.2.

Table 3.2 Activity Modes for Construction Equipment

Equipment	Activity Mode
Backhoe	Idling Moving Scoop/Dump Front Bucket Scoop/Dump Rear Bucket
Bulldozer	Idling Forward Reverse Blade
Excavator	Idling Moving Scoop/Dump Cycle
Motor Grader	Idling Moving Blade
Off-Road Truck	Idling Moving Hauling Dumping
Track Loader	Idling Moving Scoop/Dump
Wheel Loader	Idling Moving Scoop/Dump

3.1.3 Equipment Location

The primary location for the data collection efforts was on or near the campus of North Carolina State University in Raleigh. N.C. State has had a high volume of construction activity and there have been numerous construction sites on campus. There were many construction projects within a 50 mile radius of Raleigh which had the selected types of construction equipment available for monitoring. The construction projects

consisted of a wide variety of types, including institutional, commercial, utility, and general highway maintenance projects.

3.1.4 Equipment Scheduling

Prior to data collection, permission to monitor the equipment was obtained from the equipment owner, the project supervisor, and the equipment operator. Permission was also obtained to interact with the operator and the equipment during the data collection process. These individuals were assured of the following:

- The data collection process would not interfere with nor interrupt the productivity of the equipment.
- The PEMS used to collect emissions and engine data from the construction equipment would neither temporarily nor permanently affect engine operation.
- The research team would maintain a safe distance from all construction activities.

Scheduling equipment data collection with the owners took varying amounts of time. For instance, some owners were responsive and would provide an answer within 48 hours. Some owners were non-responsive and other owners had to be contacted. When an owner agreed to participate in the study, data collection could be scheduled for the next opportunity that the particular item of equipment would be used.

Most of the equipment that was tested was privately owned by construction contractors. However, some of the equipment was publicly owned by the North Carolina Department of Transportation (NCDOT). Although some private equipment owners did not

wish to participate in the study, many were willing to cooperate. The testing for the publicly owned equipment was coordinated with NCDOT county maintenance engineers.

3.2 Instrumentation

Several instruments were required to collect field data from construction equipment. These instruments included a portable emissions measurement system (PEMS) for gathering fuel use and emissions data, a laptop computer for recording activity modes of the equipment, a global positioning system (GPS) for documenting the equipment's location on the project site, and a video camera for recording visual data related to the equipment and the project site.

3.2.1 PEMS

The PEMS was installed on the construction equipment and connected to the equipment's engine and it gathered air pollutant emissions data using a sample probe inserted into the tailpipe while the equipment performed construction activities. The PEMS also collected engine information such as MAP, IAT, and RPM using sensors temporarily installed on the engine. The air pollutant emissions data and the engine data were used to estimate emission rates. Additionally, the PEMS estimated the fuel use of the equipment on a mass per time basis based on the emissions of CO₂.

The PEMS that was used for data collection was the Montana System (CATI, 2003) manufactured by Clean Air Technologies International, Inc. as shown in Figure 3.1 Montana System by CATI, Inc.. This particular PEMS used non-dispersive infrared (NDIR) detection to measure CO₂, CO, and HC, and used electrochemical cells to measure NO and oxygen

(O₂). PM was measured using a light scattering laser photometer detection method. A detailed assessment of the precision and accuracy of the PEMS is reported by Battelle [2003].



Figure 3.1 Montana System by CATI, Inc.

There are two ways that the PEMS collects engine parameter data. One is through the use of an electronic control unit (ECU) that is part of the engine itself. The ECU collects and reports engine parameters and diagnostic data. An engine scanner may be connected to the ECU to record engine parameter data from the equipment. The PEMS is capable of being connected to the scanner and obtaining the engine data directly. The ECU is often available on nonroad construction equipment but it is proprietary to the equipment manufacturer and usually requires licensed software and additional hardware to download and decode the data. There is no standardization for this process among equipment manufacturers. The second way that the PEMS collects engine data is through a sensor array that connects to the equipment's engine to obtain engine data. The variables that were measured were IAT, MAP, and RPM. The engine activity data for this research was collected by using the sensor array.

The PEMS measures data accurately for NO, CO, and CO₂. The HC data tend to be biased low because NDIR responds more accurately to straight chain HC than to aromatic compounds [Stephens and Cadle, 1991]. The HC emission rates reported here may be low by a factor of two. The PM detection method is analogous to opacity. Based on previous comparisons of the opacity-based measurements to other PM data, the absolute values inferred from the opacity-based measurements could be low by an order of magnitude. The HC and PM measurements presented here may be used for relative comparisons of emission rates from different sources, but not for characterization of the actual magnitude.

3.2.2 Laptop Computer

A laptop computer was used to record data regarding the activity modes of the equipment. A Visual Basic program in Microsoft Excel was developed to record a second-by-second timeline of the equipment activity modes. A member of the research team would follow the equipment from a safe distance and press a key on the laptop computer's numeric keypad each time the equipment changed activity modes, thus recording the amount of time spent in that particular mode.

Although the laptop computer was not physically connected to the PEMS, the internal clock of the laptop computer was synchronized with the internal clock of the PEMS. When the data collection session had ended, the activity mode data from the laptop computer was merged with the fuel use and emissions data from the PEMS in order to obtain a second-by-second timeline of equipment fuel use and emissions with respect to activity modes.

3.2.3 GPS

A GPS was used to determine the construction equipment's position by triangulating distances from satellites. The GPS receiver was typically installed on the roof of the equipment in order to receive the best signal from the satellites. The GPS unit was connected to the PEMS, thus the equipment's location defined by latitude and longitude was provided on a second-by-second basis. Since the laptop computer was synchronized with the PEMS, the equipment's location information was also linked to the activity modes of the equipment. It was possible to have a second-by-second timeline of fuel use and emissions according to the equipment's location and activity mode. Although the GPS data was not used for the fuel use and emissions model, this data was archived for future analysis if necessary. The GPS data was used in some cases to help quantify the amount of work that had been performed, such as linear miles of a dirt road that had been scraped by a motor grader.

3.2.4 Video Camera

A video camera was used to record the activity pattern of the construction equipment that was being monitored. The video camera was placed a safe distance from the equipment work area and a member of the research team recorded visual data related to the equipment work activities. The video camera was not used for the entire duration of the data collection session; only a few minutes of visual data was collected in order to record the representative duty cycles and activity modes of the equipment as well as a general view of the work area. The video data was archived on both a digital video disc (DVD) and another computer for future use.

3.3 Field Data

There were four primary types of field data that were collected. This data included fuel use and emissions data, visual data, construction site and equipment activity data, and equipment data. This section discusses each of these types of data.

3.3.1 Fuel Use and Emissions Data

When the PEMS had been installed, as seen in Figure 3.2, and the equipment began operation, the research team was able to begin collecting fuel use and emissions data from the equipment as it performed construction activities. This was done through the combined use of the PEMS and the laptop computer. The PEMS was used to collect fuel use and emissions data, engine parameter data, and location data. The laptop computer was used to collect equipment activity mode data.



Figure 3.2 PEMS Installed on Bulldozer

Recording activity mode duration was accomplished by using the numeric keypad of the laptop computer. Each activity mode of the equipment was classified by a keypad number. For example, the activity modes and their corresponding number for a wheel loader were:

1. Scoop/Dump
2. Moving
3. Idling

Each time the wheel loader began one of these activity modes, the corresponding number was pressed on the numeric keypad. Since the time was recorded for each keystroke, the duration of each recorded activity mode could be determined.

3.3.2 Visual Data

A video camera was used to record visual data related to the equipment at the construction site. The video camera recorded the following information:

- The task and duty cycles being performed by the equipment at the site
- The typical activity modes of the equipment
- The site characteristics, including terrain and weather

In general, a panoramic view of the construction site was recorded to show the working environment of the equipment. Essentially, the video enabled the research team to gather a form of visual data regarding the site, the equipment, and the work being performed by the equipment. This was done to allow a visual analysis in case questions arose in the data that might be explained by an unusual or unanticipated duty cycle or operator activity.

3.3.3 Construction Site and Activity Data

A necessary part of the overall data collection process was to assess the field conditions at the construction site where the equipment was working and to record the nature of the equipment activity. There were three types of data that were collected: General, Work Activity, and Modal Description. *General* data included basic information such as the project name and location, the date and time of the data collection session, and the weather, terrain and type of soil encountered at the project site. *Work Activity* information included a description of the task and duty cycles being performed by the equipment as well as any quantities and units of production that could be measured. *Modal Description* information included a listing and description of the equipment activity modes that were observed. All of this data was collected on paper worksheets in the field and then transferred to an electronic spreadsheet for archiving. Table 3.3 is an example of the construction site and activity data that was collected for a motor grader.

This type of information was important for comparisons of fuel use and emissions data among equipment activity. For example, the emissions data for a wheel loader that was being used to move soil at a particular location could be compared to the emissions data for a similar wheel loader that was being used to move rock at another location. Assessing and recording the field conditions and equipment activity enabled the analysis of fuel use and emissions data with respect to tasks and activity modes for each item of equipment.

Table 3.3 Construction Site and Activity Data for a Motor Grader

General	Project ID	NCDOT MG1 PD
	Project	Dirt Road Maintenance
	Location	Garner and Fuquay-Varina
	Date	2/01/06
	Time	9:00 AM - 3:30 PM
	Weather	48 F, 43% Humidity
	Terrain	Level
	Soils	Sandy Topsoil
Work Activity	Activity	Scraping Dirt Road
	Unit	Miles of road scraped
	Quantity	13.2
	Procedure	1. Lowers blade 2. Moves forward, scraping top surface of road 3. Continues until entire road is scraped
Modal Description	Modes	1. Idling 2. Moving 3. Blade
	Description	All three modes observed

3.3.4 Equipment Data

Another necessary part of the overall data collection process was to collect and record information related to the specific item of equipment that was being tested. This information included data for the identification, chassis, engine, and owner of the equipment. *Identification* data included the owner's identification number for the equipment as well as the manufacturer's Vehicle Identification Number (VIN). *Chassis* data included information about the equipment itself, such as the manufacturer, model number, model year, and gross vehicle weight (GVW). *Engine* data included information about the equipment's engine, such as the manufacturer, model number, model year, aspiration, displacement, number of

cylinders, horsepower, and hours of use. *Owner* data included contact information for the party responsible for the equipment, such as name and telephone numbers. All of this data was recorded on paper worksheets in the field and transferred to an electronic spreadsheet for archiving. Table 3.4 is an example of the equipment data that was collected for six motor graders.

This type of information was important for comparisons of fuel use and emissions data based on the equipment's engine and the equipment type. For example, emissions data for five wheel loaders could be compared to determine how emissions changed as the horsepower rating changed. Also, emissions data from wheel loaders could be compared and contrasted to emissions data for track loaders to evaluate emissions based on the type of equipment that is being used.

Table 3.4 Equipment Data for Six Motor Graders

Identification	Project ID	NCDOT MG 1	NCDOT MG 2	NCDOT MG 3	NCDOT MG 4	NCDOT MG 5	NCDOT MG 6
	Owner ID	955-0515	955-0606	955-0516	948-6647	955-0277	955-0633
	VIN	X033353X	X036740X	X033355X	G580001U1020178	720A187156823583	VCE06930P00040736
Chassis	Manufacturer	VOLVO	VOLVO	VOLVO	DRESSER	CHAMPION	VOLVO
	Model	G720VHP	G720B	G720VHP	850	G720	G930
	Year	2001	2004	2001	1990	1993	2007
	GVW (lbs)	37,000	37,000	37,000	37,000	37,000	37,000
	Blade Length (yd)	4	4	4	4	4	4
Engine	Manufacturer	Cummins	Volvo	Cummins	Dresser	Cummins	Volvo
	Model	6C8.3	D7DGBE2	6C8.3	D505T	6C8.3	D7
	Year	2001	2004	2001	1990	1993	2007
	Aspiration	Turbocharged	Turbocharged	Turbocharged	Turbocharged	Turbocharged	Turbocharged
	Displacement	8.27	7.1	8.27	8.27	8.27	7.2
	Cylinders	6	6	6	6	6	6
	Horsepower	195	195	195	167	160	198
	RPM	2,200	2,200	2,200	2,500	2,200	2,100
	Hours	4,367	841	3,044	440	4,554	3
	Fuel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
User	Company	NCDOT Wake	NCDOT Nash	NCDOT Wake.	NCDOT Wake	NCDOT Nash	NCDOT Wake
	Contact	Jason Holmes	Terry Ellis	Jason Holmes	Jason Holmes	Terry Ellis	Bobby Robbins

3.4 Field Data Collection Problems

Field emissions data collection from nonroad construction equipment occurs in the challenging and difficult environment of a construction work site. Several problems were encountered with regard to the collection of field data, including unsuitable weather, difficult operating conditions, and scheduling challenges.

3.4.1 Unsuitable Weather

The PEMS is a sensitive electro-mechanical instrument that was designed for use in a controlled and moderate environment; it is not a “ruggedized” instrument. Thus, construction sites posed significant challenges when using the PEMS, particularly with regard to temperature and moisture.

Data collection could not occur during a rain or snow event because the PEMS was typically installed on an external surface of the equipment. However, it could be used under these conditions if it was installed in a conditioned-space cab, such as an off-road truck. Additionally, if the temperature dropped below freezing (32°F), data collection could not occur because moisture in the sample line would freeze. Likewise, if the ambient temperature exceeded 90°F and if the PEMS was installed externally on the equipment, data collection could not occur because the PEMS is susceptible to overheating and would shut down at high temperatures. The research team only collected data for nonroad equipment on non-precipitation days and only when the temperature was between 32°F and 90°F. The actual range of temperatures for the collected data was 35°F to 87°F.

3.4.2 Difficult Operating Conditions

The PEMS is sensitive to vibration transmitted from the equipment as well as to dust and mud that are typically found on construction sites. Vibration, dust, and mud were frequently responsible for causing the PEMS to malfunction. When these demanding conditions caused a malfunction, it was necessary to return the instrument to the manufacturer for repairs. These repairs required between several weeks and several months to complete, resulting in critical and substantial lost time for data collection.

These problems were solved by various methods. For instance, to minimize the effects of vibration on the PEMS, three layers of one inch foam padding were placed between the surface of the PEMS and the surface of the equipment. To prevent dust from entering the PEMS, a dust cover was fabricated using a fine mesh material. The cover acted as a filter that prevented dust from entering the PEMS but allowed adequate air flow around it. A reflective sun cover was placed over the PEMS to prevent it from overheating due to sun exposure. The research team checked the PEMS at approximately 30 minute intervals during the data collection process to ensure that it was still functioning properly. The PEMS was cleaned internally between data collection sessions.

3.4.3 Scheduling Challenges

When the owners allowed their equipment to be tested, data collection had to be scheduled to accommodate the production schedule. This was difficult because owners would sometimes change their work schedule without notifying the research team ahead of time and a data collection day would be lost. Also, the data collection schedule sometimes

changed due to the weather as well as to other unforeseeable events, such as a equipment malfunction or operator absence. Ultimately, the data collection schedule was dependent upon a combination of the construction schedule, equipment availability, and site conditions.

3.5 Data Quality Assurance

A minimum of three hours of second-by-second data were targeted to be collected from each item of equipment that was tested. When it had been collected, this field data underwent a quality assurance process to determine whether any errors or problems existed in the data [Frey et al (2), 2007]. If any errors were found, they were corrected when possible. If the errors could not be corrected, then the invalid data were removed. The purpose of the quality assurance process was to produce a valid dataset of average fuel use and emission rates for each item of equipment. Only the data that could not be corrected were excluded from the dataset. The data quality assurance procedures were completed for each item of equipment that was tested.

One of the primary concerns of the data quality assurance procedures was to check the synchronization of data streams from the sensor array and exhaust gas analyzers within the PEMS, as well as communication between the sensor array and the PEMS. Typical data errors included unusual IAT, MAP, and RPM values and negative emissions values. When such data were found, they were corrected and allowed to remain in the dataset. If they could not be corrected, these data were removed from the dataset. An overview of the data quality assurance procedures is shown in Figure 3.3. A complete discussion of the data quality assurance procedures are provided in the appendices of the report by Frey et al (2) [2007].

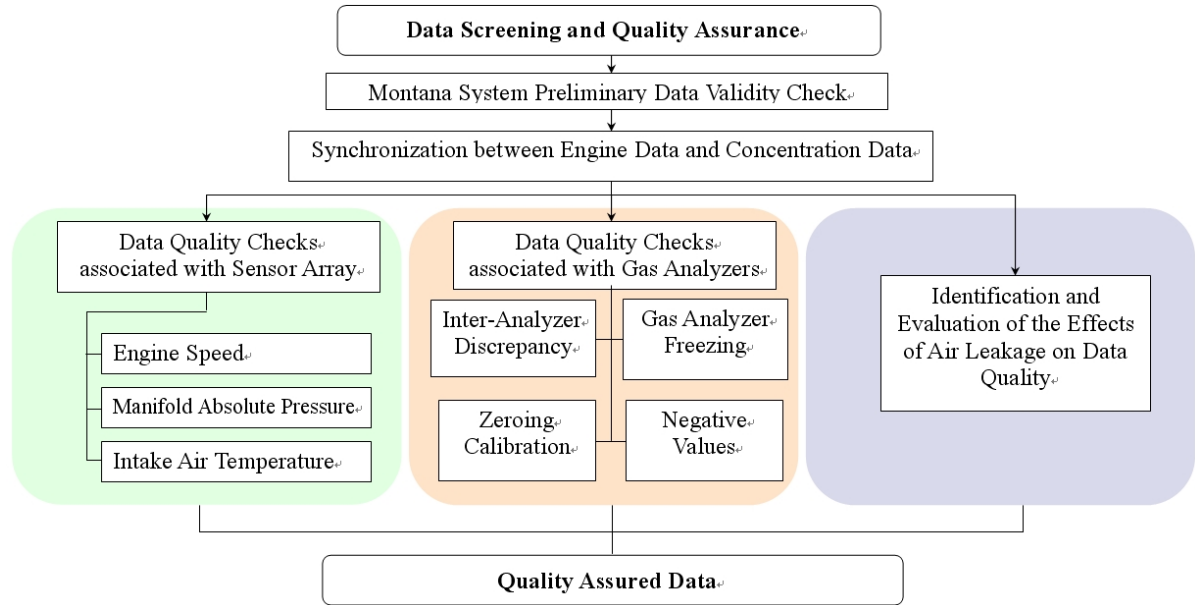


Figure 3.3 Overview of Data Quality Assurance Procedures [Frey et al (2), 2007]

3.6 Results of Field Data Collection

At the completion of the field data measurement effort, 39 items of equipment had been tested. These included eight backhoes, six motor graders, three excavators, four generators, six motor graders, three off-road trucks, one skid-steer loader, three track loaders, and five wheel loaders. After eliminating the generators and the skid-steer loader for the reasons mentioned previously, 34 items included in the dataset for the fuel use and emissions estimation methodology. Quality assured data is the total number of seconds that remained after all invalid data was removed. On average, approximately 9% of the field data was removed during the quality assurance process because it was considered to be invalid. This massive database included over 550,000 seconds (153 hours) of data collected in the field, of

which approximately 500,000 seconds (139 hours) were quality assured and available for data.

Table 3.5 Summary of Data Collection Results for Each Item of Equipment

Equipment Item	Data Collection Results		
	Field (seconds)	Quality Assured (seconds)	Invalid (%)
Backhoe 1	9,335	8,898	5
Backhoe 2	20,415	13,407	34
Backhoe 3	10390	9854	5
Backhoe 4	9,226	8,297	10
Backhoe 5	11,567	10,551	9
Backhoe 6	18,237	16,407	10
Backhoe 7	8,647	8,354	3
Backhoe 8	9,105	8,555	6
Bulldozer 1	29,180	28,690	2
Bulldozer 2	41,931	40,691	3
Bulldozer 3	18,412	18,147	1
Bulldozer 4	13,533	12,698	6
Bulldozer 5	11,352	11,309	0
Bulldozer 6	10,542	5,161	51
Excavator 1	54,848	53,487	2
Excavator 2	20,044	19,697	2
Excavator 3	20,644	18,326	11
Motor Grader 1	16,348	15,727	4
Motor Grader 2	12,205	11,704	4
Motor Grader 3	7,860	7,663	3
Motor Grader 4	11,500	10,040	13
Motor Grader 5	10,602	9,789	8
Motor Grader 6	9,262	8,687	6
Off-Road Truck 1	27,100	21,746	20
Off-Road Truck 2	5,574	5,084	9
Off-Road Truck 3	13,588	8,464	38
Track Loader 1	7,198	5,516	23
Track Loader 2	14,184	10,502	26
Track Loader 3	13,205	9,921	25
Wheel Loader 1	17,908	17,785	1
Wheel Loader 2	20,217	19,064	6
Wheel Loader 3	12,974	12,876	1
Wheel Loader 4	10,950	10,667	3
Wheel Loader 5	10,774	10,434	3
	550,758	499,859	9

4.0 ANALYSIS AND METHODOLOGY

This chapter describes the methodology that was used to estimate the weighted-average fuel use and emission rates of construction equipment duty cycles. This methodology was based on the field data measurements described in Chapter 3.0. The following steps were taken to estimate the fuel use and emission rates of construction equipment duty cycles:

1. Identify and quantify equipment attributes based on equipment type, engine size, engine age, engine tier, and engine load that affect equipment fuel use and emission rates.
2. Conduct an engine modal analysis for each item of equipment to stratify the range of engine load into 10 engine modes.
3. Develop engine modal fuel use and emission rates for each engine mode based on statistical analysis, including multiple linear regression models and modal averages.
4. Establish representative duty cycles for each item of equipment and determine the fraction of time spent in each engine mode of the duty cycle and the fraction of fuel used in each engine mode of the duty cycle.
5. Determine the weighted-average fuel use rate of the representative duty cycle by multiplying the modal fuel use rate for each engine mode by the fraction of time spent in each engine mode and then totaling the products of each engine mode.
6. Determine the weighted-average emission rate of the representative duty cycle for each pollutant by multiplying the modal emission rate for each engine mode by the

fraction of fuel used in each engine mode and then totaling the products of each engine mode.

7. Convert the mass per fuel used weighted-average emission rate to a mass per time weighted-average emission rate by multiplying the mass per fuel used weighted-average emission rate times the mass per time weighted-average fuel use rate.

Figure 4.1 shows a conceptual diagram of the methodology used to estimate the weighted-average fuel use and emission rates of construction vehicles performing representative duty cycles. According to this figure, duty cycle modal information for representative duty cycles is stored in a database. This information includes the fraction of time spent in each engine mode and the fraction of fuel used in each engine mode. The modal fraction of time for the duty cycle is used as an input to weight the modal fuel use rate. The total of the weighted fuel use rates is the weighted-average fuel use rate for the particular duty cycle. The same process is used to estimate the weighted-average emission rate for each pollutant, except the modal fraction of fuel used in each engine mode is used to weight the modal emission rates of each pollutant. The weighted-average emission rates are converted to a mass per time basis by multiplying the mass per fuel used emission rate by the weighted-average fuel use rate.

4.1 Equipment Attributes Affecting Fuel Use and Emissions

This section discusses the attributes that were considered for the fuel use and emissions estimation methodology, including equipment type, engine age, engine size, engine tier, and engine load.

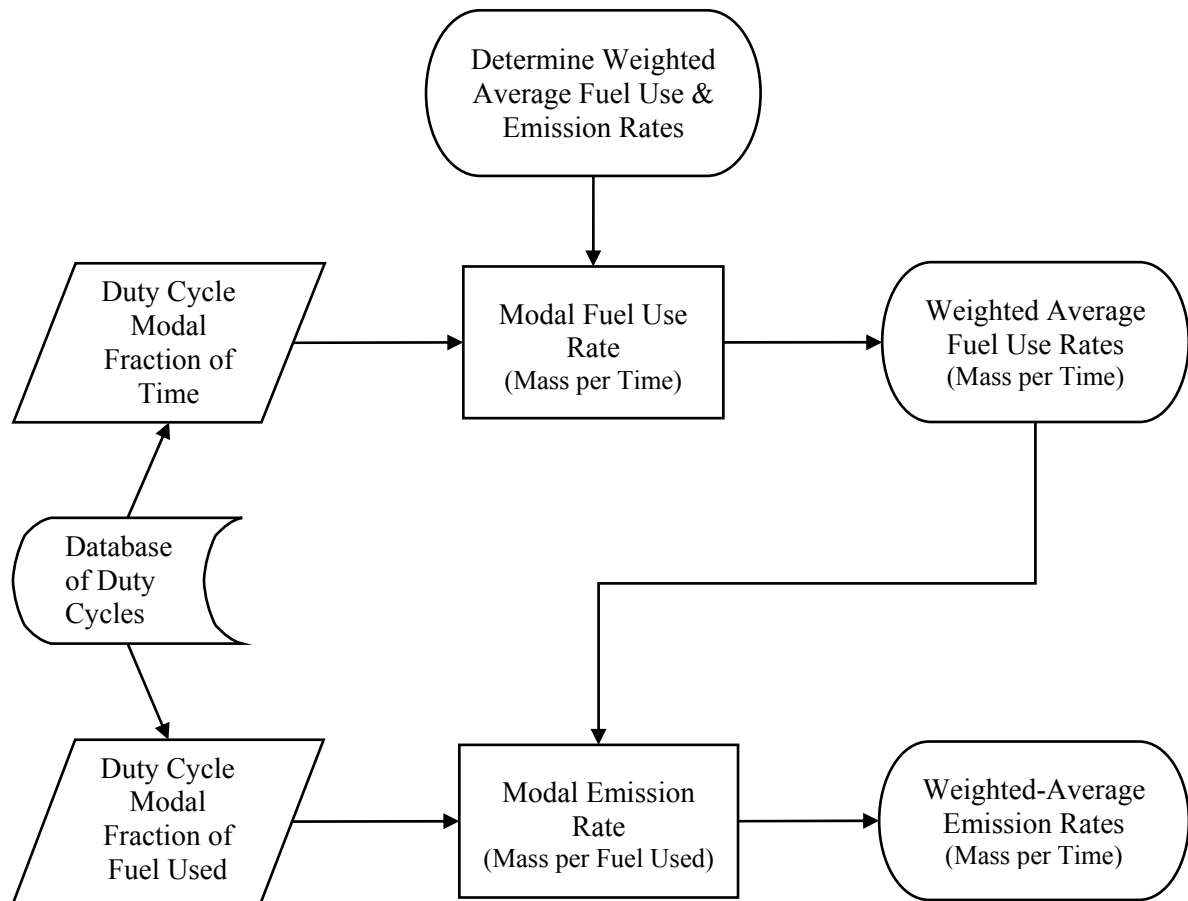


Figure 4.1 Conceptual Diagram for Estimating Weighted-Average Fuel Use and Emission Rates

4.1.1 Equipment Type

There are many types of construction equipment, including multi-purpose equipment that is capable of performing many tasks and specialty equipment that is designed for one or only a few distinct tasks. The types of equipment included in the fuel use and emissions estimation methodology were multi-purpose equipment commonly used for earthmoving activities and related tasks. For example, a backhoe combines the hauling capabilities of a wheel loader with the digging capabilities of a small excavator. Thus, a backhoe is a versatile, multi-purpose equipment item that is useful for many construction activities.

4.1.2 Engine Size

The size of the equipment's engine affects its fuel use and emission rates. Typically, larger engines consume more fuel and thus produce more emissions. For this methodology, engine size was represented by the engine's rated horsepower and the engine displacement.

4.1.3 Engine Age

Equipment engines tend to become less efficient as they are used over time. The deterioration in the efficiency of the equipment's engine depends on how it was used and maintained. As equipment engines are used, they may use more fuel at a partial load than they would have at full load [Nichols and Day, 2005]. Thus, engine age has an impact on the fuel use of construction equipment. For this methodology, engine age was represented by the engine model year.

The engine model year is the year in which the engine was manufactured, thus engines with a lower model year represent older engines. Engine hours of use are another attribute that can be used to measure engine age. However, insufficient data was collected for engine hours for it to be included in this analysis.

4.1.4 Engine Tier

Engine tier is a hybrid attribute based on engine age and engine size. Tier classifications are based on the horsepower rating and the model year of the equipment's engine. Engine tiers are emission standards adopted by the EPA in 1994 for all new nonroad diesel engines [EPA (1), 2004]. Diesel engines manufactured after a specified date must meet the performance levels specified in that standard. The EPA engine tier classifications include successive Tier 1, Tier 2, Tier 3, Tier 4 Transitional, and Tier 4 Final, which are effective in reducing emissions in a phased sequence from 1996 to 2013. The EPA engine tier classifications and specifications are found in Table 4.1.

4.1.5 Engine Load

Construction equipment rarely works continuously at full engine load because individual activities impose different loads on the equipment's engine. For example, a wheel loader operates under a higher engine load while it is moving with a full bucket or ascending a steep grade than it does while it is moving with an empty bucket or descending a steep grade. Most equipment is subject to significant amounts of idle time at a low engine load.

The average engine load for most construction activities are between approximately 25% and 75% of the maximum [Nichols and Day, 2005].

For this research project, engine load was determined by actually measuring the manifold absolute pressure (MAP) of the engine. For engines that are turbocharged, the MAP increases as air is forced into the engine intake at pressures higher than the atmosphere to produce more power. MAP has been consistently identified as being highly correlated with fuel use and emission rates [Frey et al (2), 2007]. Thus, MAP may be used as a surrogate for engine load.

Table 4.1 EPA Engine Tier Classifications and Specifications

Engine Horsepower (HP)	Model Years	Regulation	Emission Standards (g/hp-hr)				
			HC ¹	NMHC + NO _x	CO	NO _x	PM
50 ≤ HP < 75	1998 – 2003	Tier 1	NS	NS	NS	6.9	NS
	2004 – 2007	Tier 2	NS	5.6	3.7	NS	0.30
	2008 – 2012	Tier 3	NS	3.5	3.7	NS	0.22
	2008 – 2012	Tier 4 Transitional ²	NS	3.5	3.7	NS	0.22
	2013 +	Tier 4 Final ²	NS	3.5	3.7	NS	0.02
75 ≤ HP < 100	1998 – 2003	Tier 1	NS	NS	NS	6.9	NS
	2004 – 2007	Tier 2	NS	5.6	3.7	NS	0.30
	2008 – 2011	Tier 3	NS	3.5	3.7	NS	0.30
	2012 – 2013	Tier 4 Transitional ³	0.14 (50%)	NS	3.7	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	3.7	0.30	0.01
100 ≤ HP < 175	1997 – 2002	Tier 1	NS	NS	NS	6.9	NS
	2003 – 2006	Tier 2	NS	4.9	3.7	NS	0.22
	2007 – 2011	Tier 3	NS	3.0	3.7	NS	0.22
	2012 – 2013	Tier 4 Transitional ³	0.14 (50%)	NS	3.7	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	3.7	0.30	0.01
175 ≤ HP < 300	1996 – 2002	Tier 1	1.0	NS	8.5	6.9	0.40
	2003 – 2005	Tier 2	NS	4.9	2.6	NS	0.15
	2006 – 2010	Tier 3	NS	3.0	2.6	NS	0.15
	2011 – 2013	Tier 4 Transitional ³	0.14 (50%)	NS	2.6	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	2.6	0.30	0.01
300 ≤ HP < 600	1996 – 2000	Tier 1	1.0	NS	8.5	6.9	0.40
	2001 – 2005	Tier 2	NS	4.8	2.6	NS	0.15
	2006 – 2010	Tier 3	NS	3.0	2.6	NS	0.15
	2011 – 2013	Tier 4 Transitional ³	0.14 (50%)	NS	2.6	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	2.6	0.30	0.01
600 ≤ HP < 750	1996 – 2001	Tier 1	1.0	NS	8.5	6.9	0.40
	2002 – 2005	Tier 2	NS	4.8	2.6	NS	0.15
	2006 – 2010	Tier 3	NS	3.0	2.6	NS	0.15
	2011 – 2013	Tier 4 Transitional ³	0.14 (50%)	NS	2.6	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	2.6	0.30	0.01
750 ≤ HP (except generators)	2000 – 2005	Tier 1	1.0	NS	8.5	6.9	0.40
	2006 – 2010	Tier 2	NS	4.8	2.6	NS	0.15
	2011 – 2014	Tier 4 Transitional	0.30	NS	2.6	2.6	0.075
	2015 +	Tier 4 Final	0.14	NS	2.6	2.6	0.03

NS = No Standard

¹ Tier 4 standards are in the form of non-methane hydrocarbons (NMHC).

² The Tier 3 NO_x standard of 3.5 g/hp-hr was implemented beginning in 2008. The Tier 4 Transitional standard also begins in 2008, leaving the Tier 3 NO_x standard unchanged but adding a 0.22 g/hp-hr PM standard.

³ Percentages are model year sales fractions required to comply with the indicated NO_x and NMHC standards for model years where less than 100% is required.

4.2 Modal Analyses for Fuel Use and Emission Rates

In order to determine the impact of equipment and engine activity on the fuel use and emission rates of construction equipment, it is necessary to analyze the field data associated with equipment and engine activity. This was accomplished by performing an activity modal analysis and engine modal analysis. The activity modal analysis focused on what the equipment was doing, such as idling or working, and the engine modal analysis focused on the range of engine loads that were imposed on the engine. This section describes these analyses in detail.

4.2.1 Activity Modal Analysis

In activity modal analysis, the fuel use and emission rates of the equipment's activity modes were quantified. This was done by stratifying the second-by-second data into activity mode categories and then calculating the average fuel use and emission rates for each activity mode. The average fuel use rate is expressed on a mass per time basis of grams of fuel consumed per second (g/s). The results of activity modal analyses for three off-road trucks are presented in Appendix A and discussed in Section 5.2.1.

The average emission rates may be expressed on a similar mass per time basis (g/s) or on a mass per fuel used basis of grams per gallon of fuel used (g/gal). On a fuel basis, emission rates are sensitive to idling and working (non-idling) modes. However, fuel-based emission rates are less sensitive to engine loads imposed by working modes than time-based emission rates. Fuel-based emission rates tend to be more robust for estimating purposes and are used in the activity modal analysis.

4.2.2 Engine Modal Analysis

As discussed in Section 4.1.5, MAP was measured as an indicator of engine load. Since most equipment has various ranges of MAP values, a method was needed to normalize these values in order to compare them on a consistent basis with MAP values from other equipment. The actual recorded MAP values for a specific item of equipment were normalized according to the following equation:

$$\text{MAP}_{\text{nor}} = \frac{\text{MAP} - \text{MAP}_{\text{min}}}{\text{MAP}_{\text{max}} - \text{MAP}_{\text{min}}} \quad \text{Equation 1}$$

where,

MAP_{nor} = Normalized MAP for a measured MAP for a specific item of equipment

MAP_{max} = Maximum MAP for a specific item of equipment

MAP_{min} = Minimum MAP for a specific item of equipment

MAP = Measured MAP for a specific item of equipment

The overall normalized MAP values range from 0 to 1, thus representing a percentage of engine loads. This range was further categorized into bins defined as 0.0 to 0.1, 0.1 to 0.2, 0.2 to 0.3, 0.3 to 0.4, 0.4 to 0.5, 0.5 to 0.6, 0.6 to 0.7, 0.7 to 0.8, 0.8 to 0.9, and 0.9 to 1.0. For the purposes of this methodology, these bins are referred to as engine modes. Each engine mode is referenced by the integers 1 to 10 inclusively for the corresponding normalized MAP bin. For example, engine mode 1 refers to the normalized MAP bin of $0.0 \leq \text{Mode 1} < 0.1$ and engine mode 10 refers to the normalized MAP bin of $0.9 \leq \text{Mode 10} < 1.0$. Engine mode 1 represents the minimum load imposed on the engine and engine mode

10 represents the maximum load imposed on the engine. Engine mode 1 corresponds to the idling activity mode and engine modes 2 – 10 correspond to working (non-idling) modes.

In the engine modal analysis, the fuel use and emission rates of the equipment's engine modes were quantified. This was done by stratifying the second-by-second data into engine mode categories and then calculating the average fuel use and emission rates for each engine mode. The average fuel use rate was expressed in terms of grams of fuel consumed per second (g/s). The results of engine modal analyses for three off-road trucks are presented in Appendix B and discussed in Section 5.2.2.

The average emission rates may be expressed on a similar mass per time basis (g/s) or on a mass per fuel used basis of grams per gallon of fuel used (g/gal). On a fuel basis, emission rates are sensitive to each engine mode. Fuel-based emission rates tend to be more robust for estimating purposes and are used in the engine modal analysis.

4.3 Fuel Use and Emission Rates of Engine Modes

After completing the engine modal analysis, it was necessary to determine the fuel use and emission rate of each pollutant for each engine mode. The fuel use and emission rates for each engine mode were determined by using either the average fuel use and emission rate for each mode or by developing a predictive model for each engine mode using multiple linear regression (MLR) based on the equipment attribute data. This section addresses the methods that were used to estimate the fuel use and emission rates for each engine mode, including the exploratory analysis of the engine modal data, calculating the

average fuel use and emission rates for each engine mode, and developing predictive models for each mode based on MLR.

4.3.1 Exploratory Analysis of Engine Modal Data

The engine modal data was reviewed to determine if there were any missing or unusual data and if there were any outliers in the data that could unduly influence analyses. Outliers were determined from boxplots of the data that were created by Minitab statistical software (Minitab, 2007). Minitab defines outliers as observations that are greater than 1.5 times the inter-quartile range (quartile 3 minus quartile 1). Individual observations that met this criterion in the engine modal fuel use and emissions data were identified as outliers. The boxplots generated by Minitab are provided in Appendix D.

The outliers were investigated to determine if they were the result of a data entry error, an issue related to data collection, a missing factor that affected data collection, or a random error. If the cause of the outlier could not be satisfactorily determined, then the data was analyzed with the outliers and also without the outliers.

4.3.2 Average Fuel Use and Emission Rates of Each Engine Mode

Based on the engine modal analysis, the average fuel use rate and emission rate of each pollutant were calculated for each engine mode. These averages were based on the 34 observed items of equipment. The averages were calculated with the outliers included in the data and also with the outliers excluded from the data. The percent difference between the two averages for each engine mode was determined for comparison.

4.3.3 Models for Fuel Use and Emission Rates of Each Engine Mode

The purpose of the models was to find a relationship between the equipment's attributes and its fuel use and emission rates and then develop a model that describes this relationship. These models were based on the fuel use and emission rates of 34 nonroad diesel construction equipment items. The dataset of equipment attributes and fuel use rates for each item of equipment and each engine mode is provided in Appendix C; there are 10 engine mode datasets with 34 items of equipment in each along with their related attributes and fuel use and emission rates.

The fuel use rates (g/s) and the fuel-based emission rates (g/gal) of NO_x, HC, CO, and PM were predicted based on equipment attribute data including horsepower (HP), displacement (Disp), model year (MY), equipment type (BH, BD, EX, MG, OT, TL, and WL), and engine tier (Tier 0, Tier 1, Tier 2, and Tier 3). CO₂ emission rates are approximately constant on a fuel basis because over 99% of the carbon in the fuel is typically converted to CO₂ and very little of the carbon in the fuel is converted to CO, HC, or PM; therefore, a model was not needed for CO₂ emissions. Engine load was accounted for in the fuel use and emissions models by developing a model for individual engine modes.

Multicollinearity among predictor variables was evaluated by Minitab through the use of the Variance Inflation Factor (VIF). A VIF value equal to 1 indicates that the variables are not correlated; a value between 1 and 5 indicates that the variables are moderately correlated; and a value between 5 and 10 indicates that the variables are highly correlated. VIF values greater than ten indicate that multicollinearity may be unduly influencing the results of the analysis and unimportant predictor variables should be removed from the model.

Standard stepwise regression using forward selection was used to develop the models for each engine mode. In order to be included in the model, a coefficient's p-value had to be less than 0.05 to ensure that the coefficient was significantly different from zero. Coefficients that had p-values greater than 0.05 were excluded from the model. The forward selection process was used with the dataset that included the outliers and also with the dataset that excluded the outliers; thus, two sets of models for each engine mode were produced.

The coefficient of determination, R^2 and R^2 -adjusted, were used to assess the fit of the MLR model [Rumsey, 2007]. R^2 represents the percentage of the variability in the response variable values that is explained by the model, thus values close to 1.0 suggest that the model performs well for predicting the response variable. R^2 -adjusted is the value of R^2 that has been adjusted downward to account for the number of variables in the model. A high value of R^2 -adjusted indicates that the model fits the data very well. An estimate of the standard deviation of the error term in each model is provided and is represented by the symbol "S." In general, a better model will have higher values for R^2 and R^2 -adjusted and a smaller values for S.

The conditions of the multiple linear regression models were checked using residual plots. Minitab provides a four-in-one residual plot that includes the following graphs:

- Normal probability plot of the residuals
- Residuals versus the fitted values
- Histogram of the residuals
- Residuals versus the order of the data

The normal probability plot determines if the residuals have a normal distribution. If the residuals are in a straight line, then normal distribution can be assumed. The residuals versus the fitted values plot determine if the residuals have a mean of zero. There should be no distinct patterns in the residuals that would indicate a bias in the model. The histogram of the residuals is also used to check for normal distribution. The histogram should be approximately symmetric and look like a bell-shaped curve. The residuals versus the order of the data in the sample determine if interdependence exists among the residuals. For the interdependence condition to be met, the residuals should not affect one another. Thus, there should be no distinct pattern or trend in the residuals versus the order of data [Rumsey, 2007].

In summary, predictive models for engine modal fuel use rates were developed for engine modes 1 – 10 inclusive for the dataset that included the outliers and also for the dataset that excluded the outliers for a total of 20 fuel use rate prediction models. Predictive models for the emission rates of NO_x, HC, CO, and PM were developed for engine modes 1 – 10 inclusive for the dataset that included the outliers and also for the dataset that excluded the outliers for a total of 20 emission rate prediction models for each pollutant. These engine mode models are used with the engine mode distribution of duty cycle values to determine the weighted-average fuel use rate and the weighted-average emission rate of each pollutant for a particular duty cycle.

4.4 Representative Duty Cycles of Construction Equipment

The equipment types that are used primarily for earthmoving and material handling activities work in intermittent cycles [Nichols and Day, 2005]. This equipment typically has

a bucket or body that is loaded, moved, dumped, and returned to the loading point. One complete set of these operations is called a duty cycle. For example, an off-road truck has a large bed that is loaded with material at a loading point. The truck moves the load to a dumping point and dumps the material. The truck then returns to the loading point with an empty bed to begin the process again.

Not only is the duty cycle a key element for estimating production of construction equipment, duty cycles are a key element for estimating fuel use and emission rates. Just as the haul and return distance can impact the production rate of the equipment, the amount of time spent hauling and returning in their respective engine modes can impact the fuel use rate for that particular duty cycle. Likewise, the amount of fuel used hauling and returning in their respective engine modes can impact the fuel-based emission rates for that particular duty cycle. Just as the quantity of material moved can be estimated by multiplying the hauling capacity of the equipment by the number of duty cycles completed, the quantity of fuel use and emissions can be estimated by multiplying the fuel use and emissions per duty cycle by the total number of duty cycles completed. This relationship allows fuel use and emissions to be estimated on an equipment level, activity level, and project level.

This section addresses the representative duty cycles of the equipment that was included in this study. Representative duty cycles for each equipment type are discussed, as well as the fraction of time spent in each engine mode and the fraction of fuel used in each engine mode of a particular duty cycle.

4.4.1 Representative Duty Cycles

Construction equipment is capable of performing many tasks and therefore has many possible duty cycles. There are many factors that affect duty cycles, such as the activity being performed, job-site conditions, and operator skill. The activity and job site information was collected and was used to develop a representative duty cycle description for the operation that the equipment was performing.

The purpose of establishing representative duty cycles for each equipment type is to determine how common duty cycles affect the fuel use and emission rates of the equipment. This allows the fuel use and emission rates to be compared for different duty cycles for each equipment type. The fuel use and emission rates of equipment types that share common representative duty cycles can be compared based on equipment type. For example, the fuel use and emission rates of three representative duty cycles of a wheel loader can be compared to determine which duty cycles has the highest fuel use and emission rates for a wheel loader. The fuel use and emission rates of a wheel loader that is being used to move soil can be compared to the fuel use and emission rates of a track loader that is being used to move soil to determine which equipment has the highest fuel use and emission rates for that duty cycle.

4.4.2 Engine Mode Distribution of Duty Cycles

The fraction of time that is spent in each engine mode is needed to calculate the weighted-average fuel use rate for a particular duty cycle and the fraction of fuel used in each engine mode is needed to calculate the weighted-average fuel-based emission rates for a particular duty cycle. The amount of time spent in each engine mode and the amount of fuel

used in each engine mode for a particular duty cycle was determined from the field data. The field data was stratified according to engine mode and the amount of time and the amount of fuel used was totaled for each engine mode. This was done for each item of equipment that was observed and the duty cycle being performed by the equipment was recorded. Thus, the fraction of time that an item of equipment spent in each engine mode and the fraction of fuel used by an item of equipment in each engine mode was estimated based on the overall total time and fuel used for the duty cycle.

When one equipment type was observed performing a particular duty cycle on numerous occasions, an aggregate engine mode distribution of the duty cycle was estimated. In this case, the time spent in each engine mode was combined from each observation of the duty cycle to calculate the aggregate total time spent in each engine mode. Likewise, the fuel used in each engine mode was combined from each observation of the duty cycle to calculate the aggregate total fuel used in each engine mode. From these totals, the aggregate fraction of time spent in each engine mode and the aggregate fraction of fuel used in each engine mode was calculated for a particular duty cycle performed by specific equipment type.

4.5 Weighted-Average Fuel Use and Emission Rates for Equipment Duty Cycles

This section discusses the weighted-average fuel use rates and weighted-average emission rates for common construction equipment duty cycles. The general form of the equations used to estimate the weighted-average fuel use and emission rates are given. A discussion on the methods used to assess and evaluate the overall methodology for estimating the weighted-average fuel use and emission rates of construction equipment is provided.

4.5.1 Weighted-Average Fuel Use Rates

The weighted-average fuel use rate for an equipment duty cycle is based on the total of the predicted fuel use rates for each engine mode that has been weighted by the fraction of time that the equipment spends in each engine mode. The weighted-average fuel use rate for a duty cycle with n engine modes is calculated by the following equation:

$$\text{Fuel}_{\text{wt. avg.}} = \sum_{i=1}^n F_{\text{time}(i)} \times A_i \times \text{CF} \quad \text{Equation 2}$$

where,

$\text{Fuel}_{\text{wt. avg.}}$ = weighted-average fuel use rate (gal/hr) for a duty cycle with n engine modes

$F_{\text{time}(i)}$ = fraction of time spent in engine mode i

A_i = estimated fuel use rate (g/s) for mode i (g/s)

CF = conversion factor (1.132) to convert g/s to gal/hr

The fraction of time spent in each engine mode (F_{time}) is determined from the field data for each duty cycle. The fuel use rate for mode 1 (A_1) is the average fuel use rate for engine mode 1 and the fuel use rate for engine mode 2 through engine mode 10 ($A_2 - A_{10}$) are based on the fuel use regression models for the respective mode. The conversion factor is based on 3,600 seconds per hour, 454 grams per pound, and 7.0 pounds of diesel fuel per gallon.

4.5.2 Weighted-Average Emission Rates

The weighted-average emission rates of NO_x , HC, CO, and PM for an equipment duty cycle is determined by multiplying the duty cycle's weighted-average fuel use rate by the

total of the particular pollutant's predicted emission rates for each engine mode that has been weighted by the fraction of the fuel used by the equipment in each engine mode. The weighted-average emission rate of pollutant j for a duty cycle with n engine modes is calculated by the following equation:

$$E_{j \text{ wt. avg.}} = \text{Fuel}_{\text{wt. avg.}} \times \sum_{i=1}^n F_{\text{fuel}(i)} \times B_{ij} \quad \text{Equation 3}$$

where,

$E_{j \text{ wt. avg.}}$ = weighted-average emission rate (g/hr) of pollutant j for a duty cycle with n engine modes

$\text{Fuel}_{\text{wt. avg.}}$ = weighted-average fuel use rate (gal/hr) for a duty cycle with n engine modes

$F_{\text{fuel}(i)}$ = fraction of fuel used in engine mode i

B_{ij} = emission rate (g/gal) for pollutant j and engine mode i

The fraction of fuel used in each engine mode (f_i) is determined from the field data for each duty cycle. The emission rate of pollutant j for mode i (B_{ij}) is the average emission rate of that pollutant for that particular engine mode. Modal averages are used because satisfactory models for each pollutant and each engine mode could not be achieved by multiple linear regression.

4.5.3 Summary and Evaluation of Methodology

The methodology used to estimate the weighted-average fuel use and emission rates of the construction equipment that was observed during field data collection. These results

were compared to the actual fuel use and emission rates determined from the field data for each item of equipment. This estimating methodology was evaluated by reviewing response plots of the fuel use and emission rates. Response plots of the actual versus the estimated data values were developed for the fuel use rates and emission rates of NO_x, HC, CO, and PM. The goodness-of-fit (R^2) for the fuel use rate and emission rate of each pollutant was calculated to assess the precision of the methodology and the slope of the regression line was determined to assess the accuracy of the methodology. The residual diagnostic plots, including the normal probability plot, the residuals versus the fitted values, the histogram of residuals, and the residuals versus the order of data, were checked for verification of the conditions of multiple linear regression.

5.0 RESULTS AND DISCUSSION

This chapter presents the results of the methodology that was discussed in Chapter 4.

Results are presented for the following:

- Equipment attributes affecting fuel use and emission rates
- Modal analyses for fuel use and emission rates
- Methods for estimating fuel use and emission rates of engine modes
- Representative duty cycles of construction equipment
- Weighted-average fuel use and emission rates of construction equipment

5.1 Equipment Attributes Affecting Fuel Use and Emission Rates

This section presents the results of the field data collection efforts for obtaining information about equipment attributes that affect fuel use and emission rates. Results are included for equipment types, engine size, engine age, engine tier, and engine load.

5.1.1 Equipment Type

Table 5.1 summarizes the equipment type and mounting for each item of equipment that was tested. Of the 34 items of equipment that were tested, there were seven types as described in Section 4.1.1.

Table 5.1 Summary of Equipment Types

Equipment Type	Equipment Tested
Backhoe	8
Bulldozer	6
Excavator	3
Motor Grader	6
Off-Road Truck	3
Track Loader	3
Wheel Loader	5

5.1.2 Engine Size

Table 5.2 summarizes the horsepower rating and displacement of the engines for each item of equipment that was tested. The range of horsepower and displacement for each equipment type is indicated by the minimum and maximum values in the Horsepower and Displacement columns. The horsepower ratings of the tested ranged from 70 to 306 hp. The engine displacement of the tested equipment ranged from 3.9 to 14.2 liters.

Table 5.2 Summary of Horsepower and Displacement Ranges for Each Equipment Type

Equipment Type	Number Tested	Horsepower (HP)		Displacement (liters)	
		Minimum	Maximum	Minimum	Maximum
Backhoe	8	88	99	3.9	4.5
Bulldozer	6	89	285	3.9	14.2
Excavator	3	93	254	3.9	8.3
Motor Grader	6	160	198	7.1	8.3
Off-Road Truck	3	285	306	9.6	10.3
Track Loader	3	70	149	4.5	7.2
Wheel Loader	5	88	133	4.0	6.0

5.1.3 Engine Age

Table 5.3 summarizes the engine model year information for each equipment type. The range of model years is indicated by the minimum and maximum values in the Model Year column. The overall range of model years for the tested equipment was 1988 to 2007.

Table 5.3 Summary of Engine Model Year for Each Equipment Type

Equipment Type	Number Tested	Model Year	
		Minimum	Maximum
Backhoe	8	1997	2004
Bulldozer	6	1988	2005
Excavator	3	1998	2003
Motor Grader	6	1990	2007
Off-Road Truck	3	1998	2005
Track Loader	3	1997	2006
Wheel Loader	5	2002	2006

5.1.4 Engine Tier

Table 5.4 summarizes the engine tier classifications that were tested for each equipment type. The number of equipment items that were tested in each engine tier is shown in the Tier classification columns. Note that Tier 4 engines have not been phased in at the time of this writing, thus no Tier 4 engines were tested.

Table 5.4 Summary of Engine Tier Classifications for Each Equipment Type

Equipment Type	Number Tested	Engine Tier Classification			
		Tier 0	Tier 1	Tier 2	Tier 3
Backhoe	8	1	4	3	0
Bulldozer	6	2	3	1	0
Excavator	3	0	2	1	0
Motor Grader	6	2	2	1	1
Off-Road Truck	3	0	2	1	0
Track Loader	3	1	0	2	0
Wheel Loader	5	0	1	2	0

5.1.5 Engine Load

MAP values typically range from approximately 100 kPa (atmospheric pressure) to over 250 kPa. MAP ranges vary among equipment types and even among individual equipment within equipment types. Thus, it is necessary to normalize the MAP data for each individual item of equipment for comparison with other equipment. Normalized MAP values were discussed in Section 4.2.2.

5.2 Modal Analyses of Fuel Use and Emission Rates

This section presents the results of the activity modal analysis and the engine modal analysis of fuel use and emission rates. Sample results for one off-road truck are included in this section. The results of a complete activity modal analysis of fuel use and emission rates for three off-road trucks are included in Appendix A. The results of a complete engine modal analysis of fuel use and emission rates for three off-road trucks are included in Appendix B.

5.2.1 Activity Modal Analysis

Appendix A presents an activity modal analysis of fuel use for three off-road trucks. The fuel use rates are similar in magnitude for moving, hauling, and dumping (working modes) but they are significantly higher than those for the idling mode. However, the average fuel use rates for the working modes represent an average over the range of engine loads experienced during each working mode; an engine-based modal analysis is needed to evaluate the influence of engine loads for each working mode.

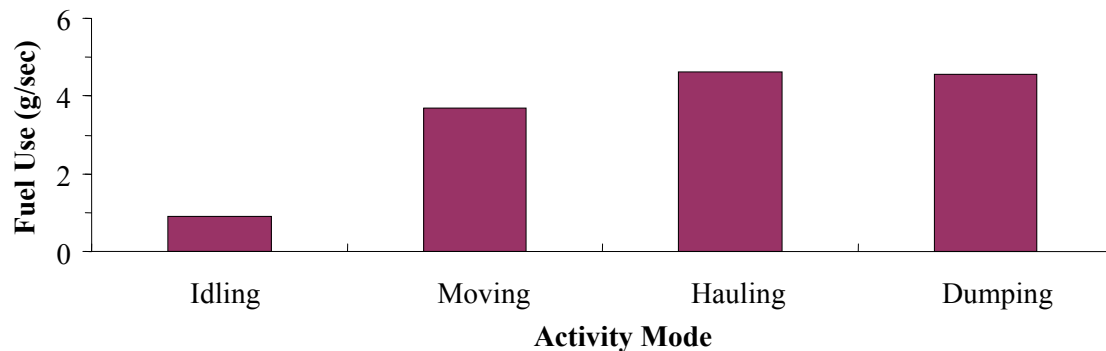


Figure 5.1 Activity Modal Analysis of Fuel Use for Off-Road Truck 1

An activity modal analysis of fuel-based emission rates of NO_x , HC, CO, CO_2 , and PM for an off-road truck are shown in Figure 5.2 through Figure 5.6. These figures indicate the sensitivity of fuel-based emission rates for each pollutant based on activity modes. There are three observations based on the activity modal analysis for Off-Road Truck 1.

The first observation is that NO_x and HC fuel-based emission rates are sensitive to idling and working engine modes. For example, the idling activity mode has higher emission rates of NO_x (Figure 5.2) and HC (Figure 5.3) than the working (non-idle) activity modes. Each of the working activity modes is similar in magnitude and they are also significantly lower than the idling activity mode. Thus, it is only necessary to assess the working activity modes collectively as non-idle activity modes.

The second observation is that fuel-based CO (Figure 5.4) and PM (Figure 5.6) emission rates are also sensitive to idling and working activity modes. However, the emission rates for CO and PM are lower for the idling activity mode than they are for the

working activity modes, whereas the emission rates of NO_x and HC were higher for the idling activity mode than they were for the working activity modes.

The third observation is that CO_2 emissions are constant regardless of activity mode. Most of the carbon in diesel fuel is emitted as CO_2 , thus CO_2 emissions are highly correlated with fuel use. It is not necessary to perform an activity modal analysis for CO_2 because approximately 10 kg of CO_2 are emitted for each gallon of diesel fuel that is consumed, regardless of the activity mode.

The observations of the activity modal analysis for Off-Road Truck 1 are typical of the observations for the equipment that was tested. In general, fuel-based emission rates are collectively most sensitive to idling activity modes and working activity modes. Thus, it is not necessary to evaluate the individual working modes, such as moving, hauling, and dumping; an analysis that evaluates only idle and non-idle modes will typically suffice. However, there are exceptions, such as the emission rate of CO for the dumping activity shown in Figure 5.4, in which a non-idle activity mode may have a high emission rate.

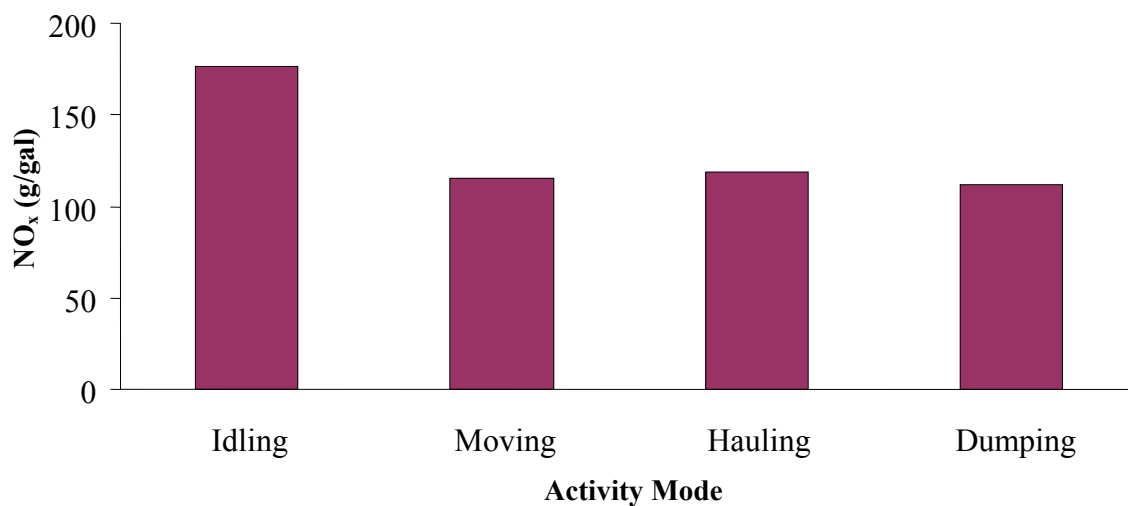


Figure 5.2 Activity Modal Analysis of NO_x for Off-Road Truck 1

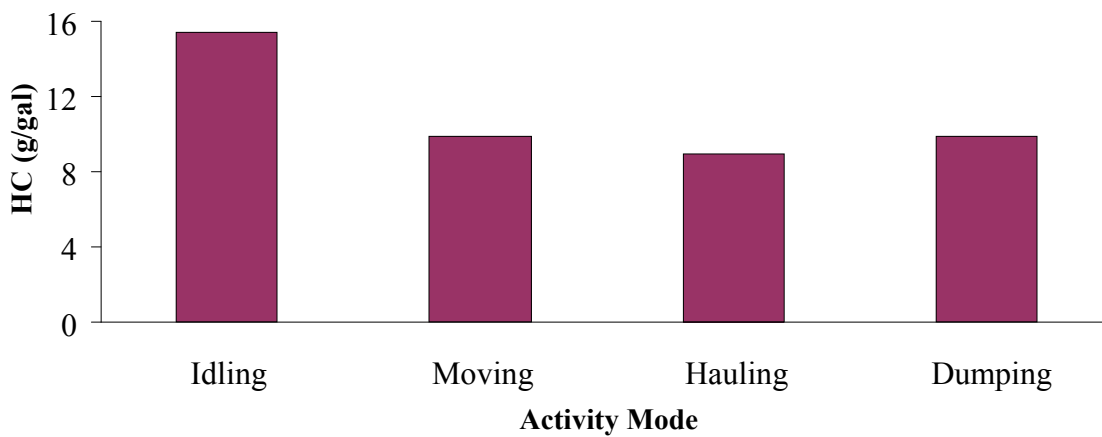


Figure 5.3 Activity Modal Analysis of HC for Off-Road Truck 1

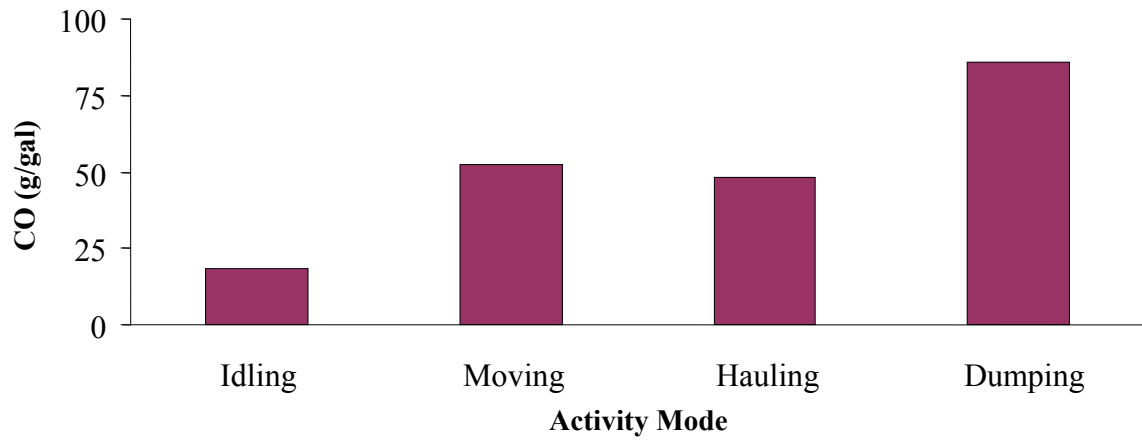


Figure 5.4 Activity Modal Analysis of CO for Off-Road Truck 1

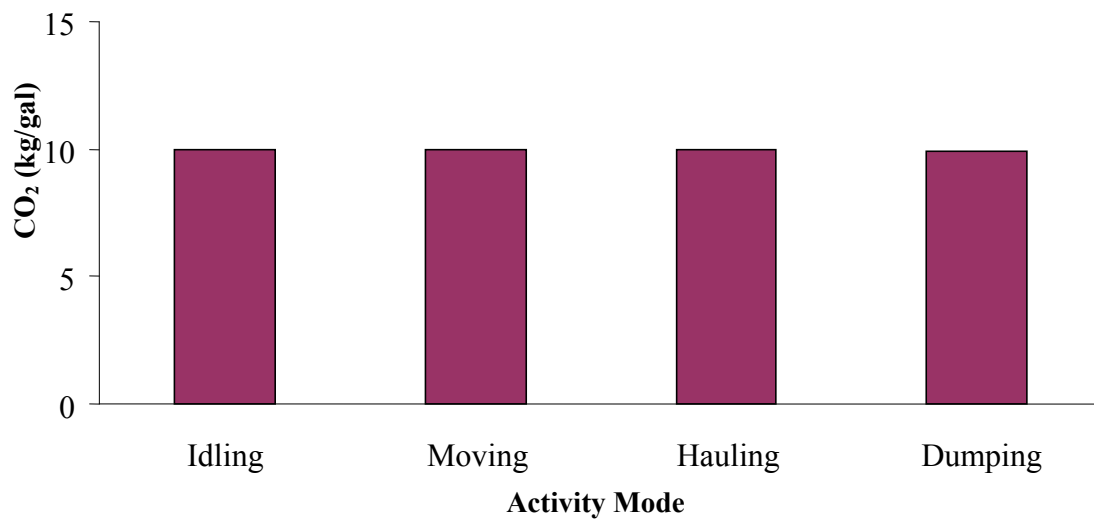


Figure 5.5 Activity Modal Analysis for CO₂ for Off-Road Truck 1

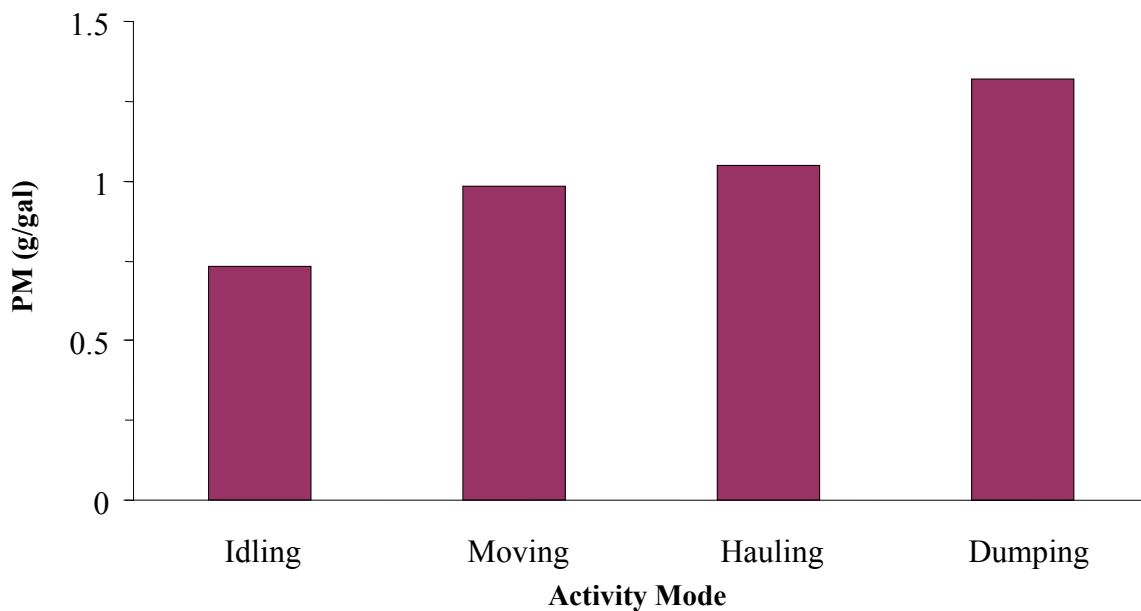


Figure 5.6 Activity Modal Analysis of PM for Off-Road Truck 1

5.2.2 Engine Modal Analysis

Figure 5.7 shows an engine modal analysis of fuel use for an off-road truck. From this figure, it is clear that fuel use rates are sensitive to each engine mode. As engine mode increases, the fuel use rate increases as well. This is typically true for the equipment that was observed, however, there is variability in the amount of the increase between engine modes. Thus, it is necessary to analyze fuel use rates for each engine mode for the fuel use estimation methodology.

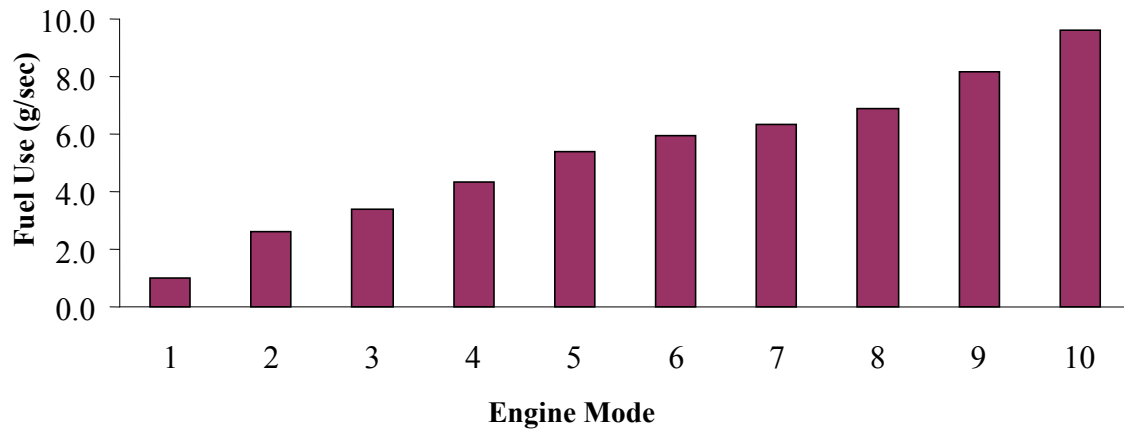


Figure 5.7 Engine Modal Analysis of Fuel Use for Off-Road Truck 1

Figure 5.8 through Figure 5.12 show the engine modal analysis of emission rates of NO_x, HC, CO, CO₂, and PM. These figures indicate the sensitivity of fuel-based emission rates for each pollutant based on engine modes, particularly for NO_x, HC, CO, and PM. The modal emission rates of CO₂ are approximately constant and not sensitive to engine modes.

Based on the modal analysis shown in Figure 5.8 through Figure 5.12, it is apparent that there is variability among the modal emission rates of NO_x, HC, CO, and PM. In general, the most variability is among idling and non-idling modes but there is also variability among the individual working modes (modes 2 - 10). Not shown in these figures but otherwise established in this work, there is also variability among individual items of equipment. This variability makes it difficult to predict modal emission rates, particularly with multiple linear regression. Thus, modal average emission rates for each pollutant were used.

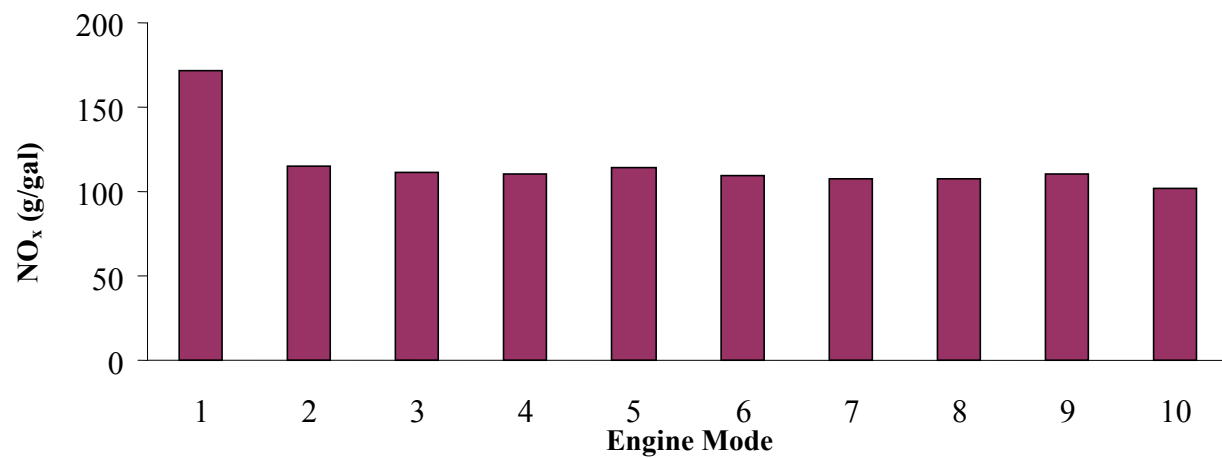


Figure 5.8 Engine Modal Analysis of NO_x for Off-Road Truck 1

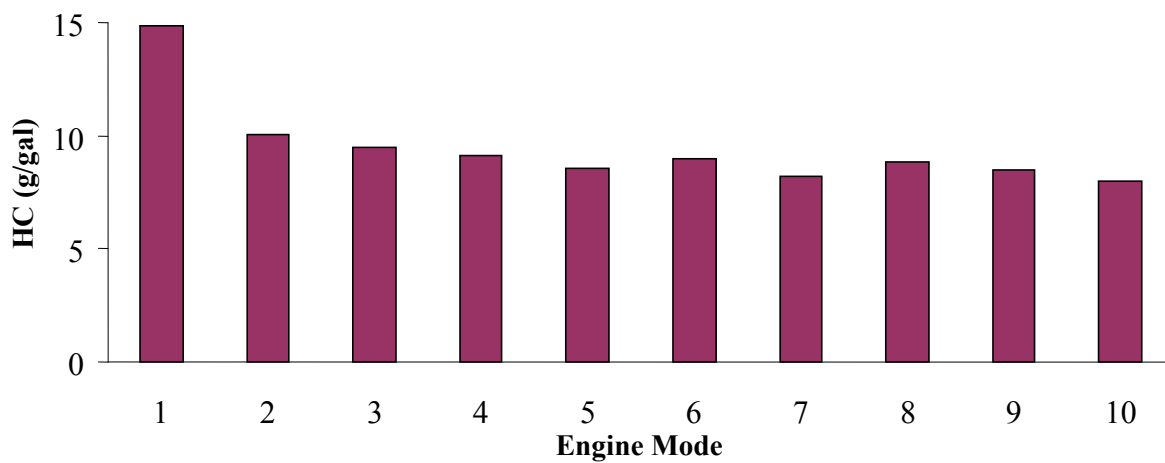


Figure 5.9 Engine Modal Analysis of HC for Off-Road Truck 1

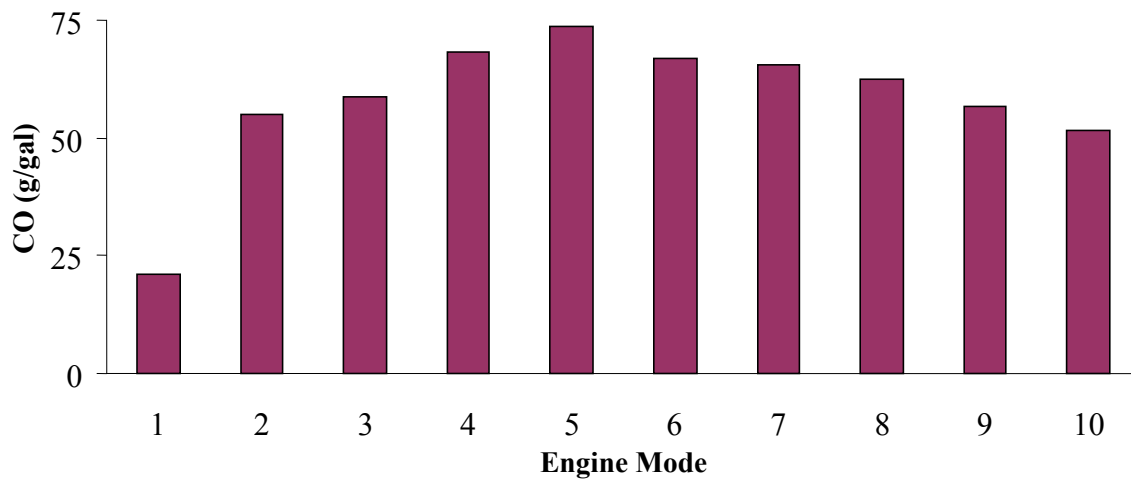


Figure 5.10 Engine Modal Analysis of CO for Off-Road Truck 1

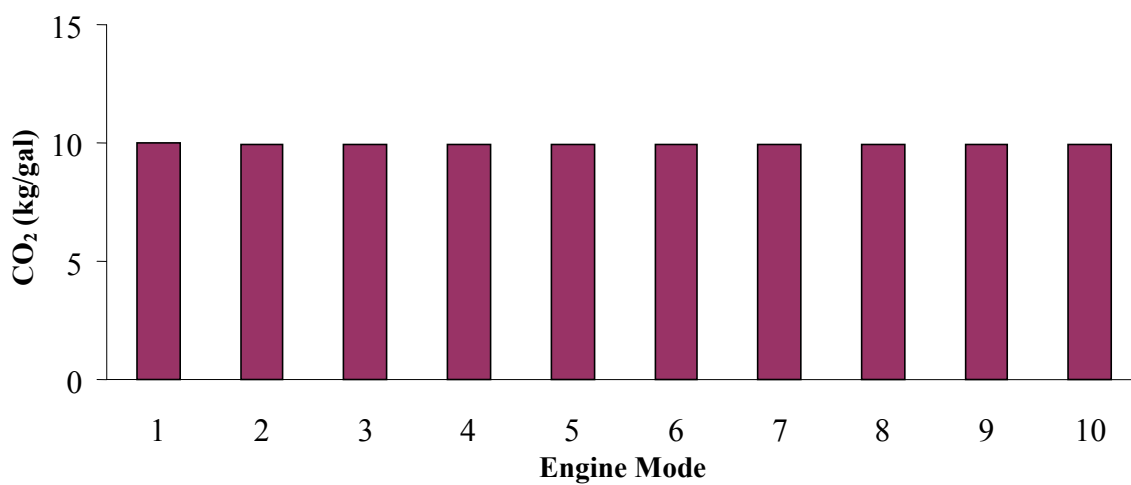


Figure 5.11 Engine Modal Analysis of CO₂ for Off-Road Truck 1

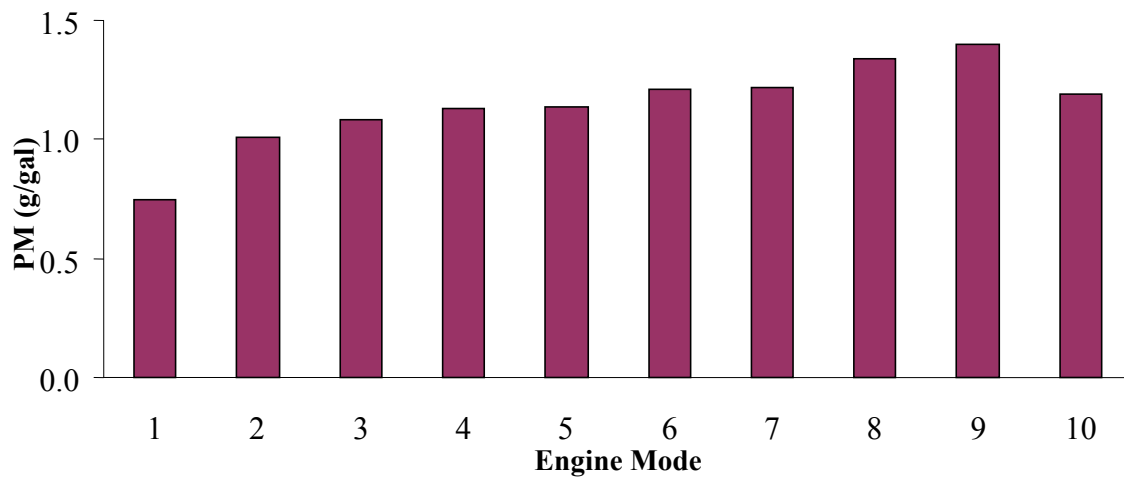


Figure 5.12 Engine Modal Analysis of PM for Off-Road Truck 1

5.3 Fuel Use and Emission Rates of Engine Modes

This section presents the results of the exploratory analysis of the engine modal data, the average fuel use and emission rates for each engine mode, and the predictive models for used to estimate the fuel use and emission rates for each engine mode. Summary tables of these results are included in this section and results for the supporting analyses are included in the appendices.

5.3.1 Exploratory Analysis of Engine Modal Data

The exploratory analysis of the engine modal data revealed that Bulldozer 5 had missing PM values for each engine mode and Motor Grader 3 had unusual CO values for each engine mode. There was a malfunction with the PEMS that prevented collection of PM data for Bulldozer 5, thus PM data is not available for this item of equipment. The quality

assured field data for Motor Grader 3 reported a negative CO value for each engine mode. Negative values were not always removed from the field data because the negative values may not be statistically different from zero. However, there were enough negative values in the CO data that a negative average emission rate was produced for each engine mode. The negative average CO emission rates were removed from each engine mode.

Outliers in the fuel use and emission rates engine modal data were identified using boxplots created by Minitab. For modes 1 – 10, there were 16 outliers identified for fuel use, 14 for NO_x, 19 for HC, 25 for CO, 33 for CO₂, and 21 for PM. Overall, there were 128 data points identified as outliers out of approximately 2,040 data points, or approximately 6%. The following items of equipment were prominent outliers: Bulldozer 5 Fuel Use (modes 2 – 10), Bulldozer 4 NO_x (modes 2 – 9), Motor Grader 3 HC (modes 1 – 10), Bulldozer 3 CO (modes 2 – 10), Backhoe 7 CO₂ (modes 2 – 10), Bulldozer 3 CO₂ (modes 3 – 10), Backhoe 3 PM (modes 2 – 10).

Most of the outliers could not be determined to be the result of a data entry error, an issue related to data collection, a missing factor that affected data collection, or a random error. Thus, the datasets were analyzed both with and without the outliers to determine their influence. Although analytical results are presented for both datasets, the data that included the outliers were used to determine the weighted-average fuel use and emission rates because there was no obvious reason to omit the outliers.

However, there was one data point that was particularly intriguing. The fuel use rate of 5.0 g/s for Bulldozer 4 Mode 1 (idling) was much higher than any other modal fuel use rate for that item of equipment, including Mode 10 which was only 1.9 g/s. The Mode 1

value is not physically plausible and may represent an error in data collection, such as recording an activity mode mistakenly as idling when it may have actually been a non-idling activity. Thus, the Mode 1 fuel use value for Bulldozer 4 was excluded from the analyses.

5.3.2 Average Fuel Use and Emission Rates of Each Engine Mode

Table 5.5 shows the average fuel use rates and the average emission rates of NO_x, HC, CO, CO₂, and PM for each engine mode. The average for each engine mode was calculated both with the outliers and without the outliers. The percentage difference between the two modal averages is presented for comparison to quantify the influence of the outliers. This percentage represents the impact on the modal averages of removing the outliers from the dataset versus calculating the modal averages with the outliers included.

With the exception of CO₂, the modal average fuel use and emission rates are lower for the dataset with the outliers excluded than the dataset with the outliers included; the outliers have no noticeable effect on the modal average emission rates of CO₂. Removing the outliers from the original dataset decreased the modal averages by 5 – 23% for fuel use; 0 – 6% for NO_x; 12 – 42% for HC; 14 – 34% for CO; and 3 – 18% for PM.

Table 5.5 also indicates trends in the modal averages. The modal average fuel use rate increases as the engine mode increases. The modal average emission rates of NO_x, HC and CO generally decrease as the engine mode increases. The modal average emission rates of CO₂ and PM are essentially constant and show very little sensitivity to engine mode.

5.3.3 Models of Fuel Use and Emission Rates for Each Engine Mode

Table 5.6 presents the coefficient of determination (R^2) values for the MLR models that were developed to predict fuel use and emission rates for each engine mode. The R^2 values are shown for the models that were developed using the dataset with the outliers included and the dataset with the outliers excluded. Models were not developed for CO₂ because CO₂ emissions are essentially constant on a mass per fuel used basis.

Table 5.5 Average Fuel Use and Emission Rates per Engine Mode

		Engine Mode									
		1	2	3	4	5	6	7	8	9	10
Fuel Use (g/s)	With Outliers	0.63	1.39	1.99	2.54	2.98	3.45	3.96	4.49	5.08	5.63
	Without Outliers	0.63	1.31	1.66	2.11	2.65	2.65	3.74	4.23	4.78	5.31
	% Difference	0	5	17	17	11	23	6	6	6	6
NO_x (g/gal)	With Outliers	156	137	125	118	114	113	109	111	111	113
	Without Outliers	156	129	121	113	109	109	103	105	104	106
	% Difference	0	6	3	4	4	3	6	6	6	6
HC (g/gal)	With Outliers	27	24	20	15	13	12	12	11	11	9
	Without Outliers	22	14	12	13	11	10	10	9	9	8
	% Difference	17	42	37	18	12	12	18	15	18	13
CO (g/gal)	With Outliers	53	54	48	40	37	35	32	31	30	28
	Without Outliers	45	46	33	30	28	27	23	21	20	19
	% Difference	14	14	31	25	24	25	29	34	34	33
CO₂ (kg/gal)	With Outliers	9.9	9.9	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
	Without Outliers	9.9	9.9	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
	% Difference	0	0	0	0	0	0	0	0	0	0
PM (g/gal)	With Outliers	0.99	1.03	1.00	0.96	0.99	1.07	1.04	1.11	1.02	1.09
	Without Outliers	0.82	0.97	0.94	0.92	0.96	1.02	0.96	1.00	0.90	0.90
	% Difference	18	6	6	3	3	5	8	10	13	17

Table 5.6 R² Values for Models of Fuel Use and Emission Rates per Engine Mode

		Engine Mode									
		1	2	3	4	5	6	7	8	9	10
Fuel Use (g/s)	With Outliers	35	76	77	76	77	77	78	78	80	81
	Without Outliers	17	77	60	59	66	71	77	76	78	83
NO_x (g/gal)	With Outliers	34	48	42	36	38	37	40	39	44	49
	Without Outliers	34	37	50	51	49	44	42	43	49	45
HC (g/gal)	With Outliers	32	NA	NA	14	20	30	26	25	NA	14
	Without Outliers	NA	NA	40	NA	NA	NA	14	NA	NA	19
CO (g/gal)	With Outliers	41	13	NA	12	13	44	NA	NA	NA	NA
	Without Outliers	29	14	45	14	NA	NA	NA	15	NA	13
PM (g/gal)	With Outliers	31	19	NA	NA	NA	13	13	15	NA	14
	Without Outliers	NA	24	13	NA	NA	13	NA	NA	NA	NA

NA = Not Applicable; no model was produced based on the model selection criteria

The engine modal MLR models for fuel use rates accounted for 76 – 81% of the variability in the data with the outliers included for engine modes 2 – 10 and 35% of the variability for engine mode 1. The models accounted for 59 – 83% of the variability in the data with the outliers excluded for engine modes 2 – 10 and 17% of the variability for engine mode 1. In general, the models for predicting fuel use rates performed better for the dataset with the outliers included than the dataset with the outliers excluded. Thus, the MLR models are used for modes 2 – 10 to estimate the modal fuel use rates of construction equipment. However, the modal average fuel use rate discussed in Section 5.3.2 was used for mode 1 because of the low R² value for that particular model. The conditions of multiple linear regression are met as indicated by the residual plots found in Appendix E.

The results of the MLR fuel use models for modes 2 – 10 are presented in Table 5.7. These models are based on horsepower and engine tier. All that is needed to estimate the fuel use rate for engine modes 2 – 10 is the horsepower rating of the engine and the engine tier classification.

Table 5.7 Fuel Use Rate Models for Each Engine Mode

Mode	Model	S	R ²	R ² -adj
1	fuel[g/s] = 0.6 ¹	NA	NA	NA
2	fuel[g/s] = - 0.364 + 0.0112 HP + 0.565 TIER_0	0.5	76	75
3	fuel[g/s] = - 0.620 + 0.0166 HP + 0.876 TIER_0	0.7	77	75
4	fuel[g/s] = - 0.882 + 0.0216 HP + 1.29 TIER_0	0.9	76	74
5	fuel[g/s] = - 0.908 + 0.0244 HP + 1.56 TIER_0	1.0	77	76
6	fuel[g/s] = - 1.05 + 0.0283 HP + 1.81 TIER_0	1.1	77	76
7	fuel[g/s] = - 1.30 + 0.0332 HP + 2.03 TIER_0	1.3	78	76
8	fuel[g/s] = - 1.39 + 0.0368 HP + 2.47 TIER_0	1.4	78	77
9	fuel[g/s] = - 1.68 + 0.0422 HP + 2.93 TIER_0	1.6	80	78
10	fuel[g/s] = - 1.66 + 0.0458 HP + 2.93 TIER_0	1.6	81	80

¹ Average Fuel Use Rate for Mode 1 (See Table 5.5)

Note that the variable “Tier_0” serves as an indicator variable in the model with a value of either zero or one. If the engine tier classification is Tier 0, then the coefficient is multiplied by one. If the engine tier classification is Tier 1, Tier 2, or Tier 3, then the coefficient is multiplied by zero, thus having no effect on the model. A mode 1 fuel use value of 0.6 g/s is used for all equipment types because of the low R² (35%) value associated with the MLR mode 1 model.

Figure 5.13 and Figure 5.14 are response surface plots for mode 2 – 10 fuel use based on horsepower and engine mode for equipment with engine Tier 0 and engine Tier 1 – 3 classifications, respectively. A response surface is a three-dimensional representation of the relationship between a response variable and two predictor variables. Response surfaces are

used to graphically display the best-fitting model and to observe any trends or patterns in the responses [Quinn and Keough, 2007]. These figures clearly show that fuel use increases as horsepower and engine mode increase. However, fuel use is more sensitive to engine mode than horsepower.

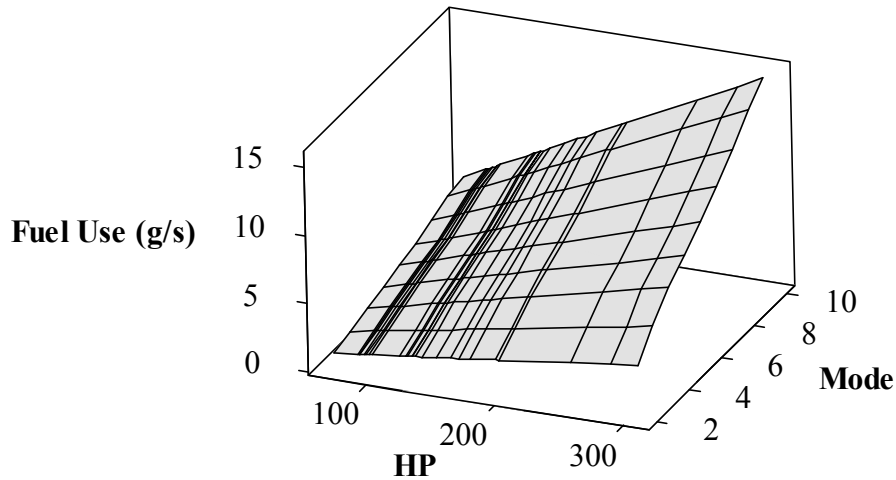


Figure 5.13 Response Surface for Fuel Use vs. HP and Engine Mode for Engine Tier 0

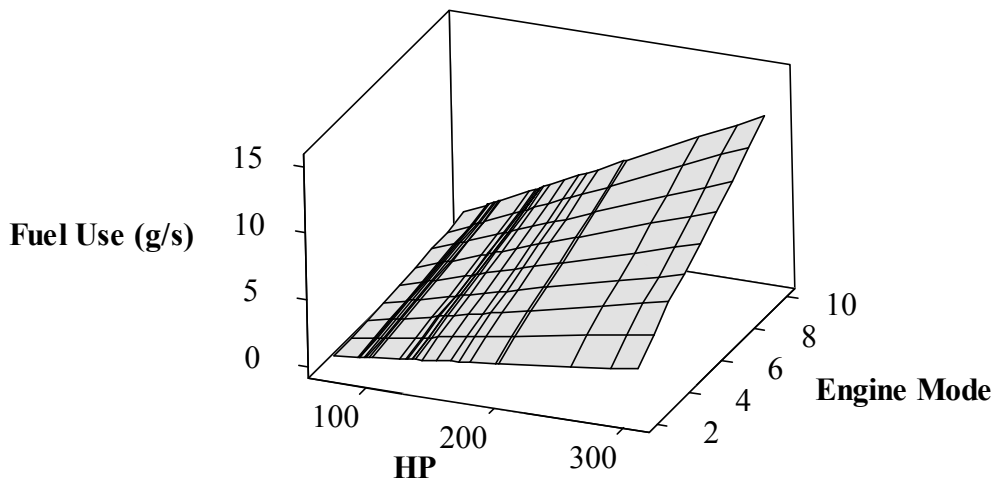


Figure 5.14 Response Surface for Fuel Use vs. HP and Engine Mode for Engine Tiers 1, 2, and 3

The models for estimating the modal emission rates of NO_x, HC, CO, and PM shown in Table 5.6 did not perform as well as the models used for estimating the modal fuel use rates. The NO_x modal emission models have R² values in the range of 34 – 49% with the outliers and 34 – 51% without the outliers. With regard to HC, CO, and PM, Minitab was unable to generate MLR models for several modes based on the selection criteria. The models that were developed for these pollutants had low R² values, in the range of 12 – 41% for the models with the outliers and 13 – 45% for the models without the outliers. Thus, the average modal emission rates for each pollutant are used to estimate the emission rates per engine mode and the inclusion or exclusion of outliers appears to have little affect on the results.

5.4 Representative Duty Cycles of Construction Equipment

This section presents results related to the duty cycles of the construction equipment that was observed during data collection. A summary table of representative duty cycles for each item of equipment is provided in Appendix C. Sample results of an engine mode distribution of duty cycles for a backhoe are presented in this section. A complete set of engine mode distribution of duty cycles showing the fraction of time spent in each engine mode and the fraction of fuel used in each engine mode are provided in Appendix F.

5.4.1 Representative Duty Cycles

A representative duty cycles for each item of equipment that was monitored during field data collection was defined. Although it is possible to describe the equipment's duty

cycle in great detail, these representative duty cycles are intended to only provide the general nature of the duty cycle. The weighted-average fuel use and emission rates of equipment duty cycles are based on these representative duty cycles. The representative duty cycle that was observed for each item of equipment is listed in Table 9.1 in Appendix C.

Each equipment type was observed performing multiple duty cycles. For example, three representative duty cycles were observed for backhoes. Backhoes 1, 5, and 6 were observed performing a “Load Truck” duty cycle, Backhoes 3, 4, 7, and 8 were observed performing a “Move Soil” duty cycle, and Backhoe 2 was observed performing a “Move Material” duty cycle. Overall, there were 17 different duty cycles observed for eight different equipment types.

Most of the representative duty cycles are classified based on normal working conditions. However, the “Stockpile” duty cycle that was performed by two bulldozers and one track loader involved the equipment working on a steep slope, which may affect the fuel use and emission rates. The “Haul Soil” duty cycle observed for Off-Road Truck 2 and Off-Road Truck 3 involved hauling soil for a short distance of approximately 300 feet up a steep slope, which may also affect the fuel use and emission rates. Otherwise, no other adverse conditions were observed.

5.4.2 Engine Mode Distribution of Duty Cycles

The engine modes of the representative duty cycles were distributed by the amount of time spent in each engine mode and the amount of fuel used in each engine mode. It was necessary to distribute the engine modes by time in order to properly weight the mass per

time fuel use rates for the weighted-average fuel use calculations. It was necessary to distribute the engine modes by fuel use in order to properly weight the mass per fuel used emission rates for the weighted-average fuel use calculations.

Table 5.8 Modal Fraction of Time and Fuel Used for Backhoe Load Truck Duty Cycle

Mode	BH 1		BH 5		BH 6		Aggregate			
	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{time} (%)	Fuel (g)	F _{fuel} (%)
1	7,865	2,660	3,169	901	3,668	1,158	14,702	42%	4,719	11%
2	471	408	2,939	3,040	2,214	2,174	5,624	16%	5,622	13%
3	181	202	1,529	2,041	3,565	5,045	5,275	15%	7,288	16%
4	82	108	534	891	2,859	4,778	3,475	10%	5,777	13%
5	61	91	326	711	1,037	2,082	1,424	4%	2,884	6%
6	28	46	405	1,071	281	4,957	714	2%	6,075	14%
7	20	43	552	1,627	422	1,180	994	3%	2,850	6%
8	22	52	307	1,004	1,002	3,327	1,331	4%	4,383	10%
9	37	103	270	968	752	2,863	1,059	3%	3,934	9%
10	13	40	75	289	206	921	294	1%	1,250	3%
	8,780	3,752	10,106	12,543	16,006	28,485	34,892	100%	44,781	100%

Table 5.8 shows the modal amount of time in seconds (s) and the modal amount of fuel used in grams (g) for three backhoes performing a “Load Truck” duty cycle. The table also shows the aggregate total amount of time and fuel used for each engine mode for the three backhoes. From this total, the fraction of time (F_{time}) and the fraction of fuel used (F_{fuel}) for each engine mode is determined. For example, a backhoe is estimated to spend 42% of the duty cycle time in mode 1, which corresponds to idling; and 41% of the duty cycle time is spent in modes 2 – 4. Thus, 83% of the duty cycle time is spent in engine modes 1 – 4. However, only 53% of the duty cycle fuel use occurs in engine modes 1 – 4. Therefore, fuel is consumed at a much higher rate for the upper modes due to higher engine loads.

5.5 Weighted-Average Fuel Use and Emission Rates for Equipment Duty Cycles

This section presents results of the methodology used to determine the weighted-average fuel use and emission rates of construction equipment performing representative duty cycles. A summary table of the weighted-average fuel use and emission rates of the observed construction equipment and duty cycles is provided. The response plots of the fuel use rates and emission rates of each pollutant are discussed.

Table 5.9 Equipment Attributes for Numerical Example

Attribute	Variable
Equipment Type	Wheel Loader
Engine Horsepower	140
Engine Displacement	6.0
Engine Model Year	2004
Engine Tier	2

A numerical example is provided to illustrate how this methodology is used. In this example, a wheel loader with the attributes shown in Table 5.9 is used to perform a “Load Truck” duty cycle and a “Move Soil” duty cycle. The results of the duty cycles are compared to determine the effects of the duty cycle on the equipment’s fuel use and emission rates.

5.5.1 Weighted-Average Fuel Use Rates

Table 5.10 summarizes the results of the weighted-average fuel use calculations for the wheel loader in the numerical example. The following steps were taken to estimate the weighted-average fuel use rate for each duty cycle:

1. Using the equipment attributes in Table 5.9, compute the predicted fuel use rate for each engine mode based on the models shown in Table 5.7. The predicted modal fuel use rates for this numerical example are shown in column B of Table 5.10. The following sample calculation shows how the predicted modal fuel use rates were calculated for Mode 2 of the wheel loader used in this numerical example:

$$\begin{aligned}\text{Mode 2 fuel[g/s]} &= -0.364 + 0.0112 \text{ HP} + 0.565 \text{ TIER_0} \\ &= -0.364 + 0.0112 (140) + 0.565 (0) \\ &= 1.2 \text{ g/s}\end{aligned}$$

2. Multiply the predicted fuel use rate (g/s) by the duty cycle fraction of time spent in each engine mode selected from the appropriate modal fraction of time and fuel used tables in Appendix F. The modal fraction of time for the “Move Soil” and “Load Truck” duty cycles are shown in columns C and D respectively of Table 5.10. The weighted modal fuel use rates for each engine mode are shown in column E for the “Move Soil” duty cycle and column F for the “Load Truck” duty cycle. The weighted modal fuel use rates for the “Move Soil” duty cycle found in column E are obtained by multiplying column B by column C for each mode. The weighted modal fuel use rates for the “Load Truck” duty cycle found in column F are obtained by multiplying column B by column D for each engine mode. The weighted modal fuel use rate for Mode 3 for each duty cycle is estimated by the following sample calculations:

$$\text{“Move Soil” Mode 3 Weighted Fuel Use} = 1.7 \text{ g/s} \times 0.06 = 0.10 \text{ g/s}$$

$$\text{“Load Truck” Mode 3 Weighted Fuel Use} = 1.7 \text{ g/s} \times 0.12 = 0.20 \text{ g/s}$$

3. Total the weighted fuel use rates for each engine mode to obtain the weighted-average fuel use rate (Fuel_{wt. avg.}) for each duty cycle. The weighted-average fuel use rate for the “Move Soil” duty cycle is shown at the bottom of column E in Table 5.10 and the weighted-average fuel use rate for the “Load Truck” duty cycle is shown at the bottom of Column F.
4. Convert the weighted-average fuel use rate (g/s) for each duty cycle to gallons per hour (gal/hr). To obtain gallons per hour, multiply grams per second by the conversion factor of 1.132 as described in Section 4.5.1. The following sample calculations show the conversions for each duty cycle:

$$\text{“Move Soil” Fuel}_{\text{wt. avg.}} = 1.0 \text{ g/s} \times 1.132 = 1.13 \text{ gal/hr}$$

$$\text{“Load Truck” Fuel}_{\text{wt. avg.}} = 1.4 \text{ g/s} \times 1.132 = 1.58 \text{ gal/hr}$$

Based on the results shown in Table 5.10, the fuel use rate for the “Move Soil” duty cycle is approximately 1.0 g/s (1.13 gal/hr) and approximately 1.4 g/s (1.58 gal/hr) for the “Load Truck” duty cycle; thus, the “Load Truck” duty cycle has a fuel use rate that is approximately 40% higher than the “Move Soil” duty cycle. This is attributed to the fact that wheel loaders spend more time in higher engine modes while performing a “Load Truck” duty cycle than they do while performing a “Move Soil” duty cycle.

It is important to convert the weighted-average fuel use rates from grams per second to gallons per hour because construction activity durations are often measured in units of days, which are easily converted to hours. For example, a construction project schedule may indicate that a “Move Soil” duty cycle will take two days, or 16 hours, to complete. Thus, the total fuel used for this activity will be approximately 18 gallons (1.13 gal/hr x 16 hr). If

the current price for diesel fuel is \$2.50 per gallon, then the fuel expense for this activity is approximately \$45. The total project fuel expense can be estimated in a similar manner by totaling the fuel expense for each item of equipment that is used for each activity.

Table 5.10 Summary of Weighted Fuel Use Rates for Two Representative Duty Cycles of a Wheel Loader

(A) Engine Mode	(B) Modal Fuel Use (g/s)	Modal Fraction of Time		Weighted Fuel Use	
		(C) Move Soil	(D) Load Truck	(E) Move Soil (g/s)	(F) Load Truck (g/s)
1	0.6	0.67	0.50	0.40	0.30
2	1.2	0.13	0.13	0.16	0.16
3	1.7	0.06	0.12	0.10	0.20
4	2.1	0.04	0.08	0.08	0.17
5	2.5	0.03	0.06	0.08	0.15
6	2.9	0.02	0.04	0.06	0.12
7	3.4	0.01	0.03	0.03	0.10
8	3.8	0.01	0.02	0.04	0.08
9	4.2	0.01	0.01	0.04	0.04
10	4.8	0.01	0.01	0.05	0.05
			Fuel wt. avg.	1.0 g/s (1.13 gal/hr)	1.4 g/s (1.58 gal/hr)

5.5.2 Weighted-Average Emission Rates

Table 5.11 through Table 5.14 summarizes the results of the weighted emission rates of each pollutant. The following steps were taken to estimate the emission rates of NO_x, HC, CO, and PM for each duty cycle of the wheel loader used in this numerical example:

1. Select the average modal emission rates (g/gal) of NO_x, HC, CO, and PM for each engine mode from Table 5.5. The average modal emission rates for each pollutant are shown in column B of Table 5.11 through Table 5.14.
2. Multiply the modal emission rates by the duty cycle fraction of fuel used in each engine mode selected from the appropriate modal fraction of time and fuel used tables in Appendix F. The modal fraction of fuel used for the “Move Soil” and “Load Truck” duty cycles for each pollutant are shown in columns C and D respectively of Table 5.11 through Table 5.14. The weighted modal emission rates for the “Move Soil” duty cycle found in column E are obtained by multiplying column B by column C for each mode. The weighted modal emission rates for the “Load Truck” duty cycle found in column F are obtained by multiplying column B by column D for each engine mode. For example, the weighted modal emission rate of NO_x for Mode 3 for each duty cycle is estimated by the following sample calculations:

$$\text{“Move Soil” Mode 3 Weighted NO}_x \text{ Rate} = 125 \text{ g/gal} \times 0.09 = 11 \text{ g/gal}$$

$$\text{“Load Truck” Mode 3 Weighted NO}_x \text{ Rate} = 125 \text{ g/s} \times 0.16 = 20 \text{ g/gal}$$

3. Total the weighted emission rates of each pollutant for each engine mode to obtain the weighted-average emission rate (Pollutant_{wt. avg.}) for each duty cycle. The weighted-average emission rate for the “Move Soil” duty cycle is shown at the bottom of column E in Table 5.11 through Table 5.14 and the weighted-average emission rate for the “Load Truck” duty cycle is shown at the bottom of Column F.
4. Multiply the weighted-average emission rate of each pollutant (g/gal) by the weighted-average fuel use rate (gal/hr) to obtain the weighted-average emission rate

of each pollutant in units of grams per hour (g/hr). For example, the weighted-average emission rate of NO_x for a wheel loader performing a “Move Soil” duty cycle is computed by multiplying the weighted-average emission rate from Table 5.11 (133 g/gal) by the weighted-average fuel use rate from Table 5.10 (1.13 gal/hr) for a result of 150 g/hr. Table 5.15 summarizes the weighted-average emission rate of each pollutant.

Table 5.11 Summary of Weighted NO_x Emission Rates for Two Representative Duty Cycles of a Wheel Loader

(A) Engine Mode	(B) Modal Emissions (g/gal)	Modal Fraction of Fuel Use		Weighted Emission Rate	
		(C) Move Soil	(D) Load Truck	(E) Move Soil (g/gal)	(F) Load Truck (g/gal)
1	156	0.34	0.19	54	30
2	137	0.15	0.12	21	16
3	125	0.09	0.16	11	20
4	118	0.08	0.14	10	16
5	114	0.07	0.13	8	15
6	113	0.06	0.08	7	9
7	109	0.04	0.07	4	8
8	111	0.05	0.06	6	7
9	111	0.05	0.04	6	4
10	113	0.05	0.02	6	2
NO_x wt. avg.				133 g/gal	126 g/gal

Table 5.12 Summary of Weighted HC Emission Rates for Two Representative Duty Cycles of a Wheel Loader

		Modal Fraction of Fuel Use		Weighted Emission Rate	
(A) Engine Mode	(B) Modal Emissions (g/gal)	(C) Move Soil	(D) Load Truck	(E) Move Soil (g/gal)	(F) Load Truck (g/gal)
1	27	0.34	0.19	9	5
2	24	0.15	0.12	4	3
3	20	0.09	0.16	2	3
4	15	0.08	0.14	1	2
5	13	0.07	0.13	1	2
6	12	0.06	0.08	1	1
7	12	0.04	0.07	0	1
8	11	0.05	0.06	1	1
9	11	0.05	0.04	1	0
10	9	0.05	0.02	0	0
			HC wt. avg•	20 g/gal	18 g/gal

Table 5.13 Summary of Weighted CO Emission Rates for Two Representative Duty Cycles of a Wheel Loader

		Modal Fraction of Fuel Use		Weighted Emission Rate	
(A) Engine Mode	(B) Modal Emissions (g/gal)	(C) Move Soil	(D) Load Truck	(E) Move Soil (g/gal)	(F) Load Truck (g/gal)
1	53	0.34	0.19	18	10
2	54	0.15	0.12	8	6
3	48	0.09	0.16	4	8
4	40	0.08	0.14	3	5
5	37	0.07	0.13	3	5
6	35	0.06	0.08	2	3
7	32	0.04	0.07	1	2
8	31	0.05	0.06	2	2
9	30	0.05	0.04	2	1
10	28	0.05	0.02	1	1
			CO wt. avg•	45 g/gal	43 g/gal

Table 5.14 Summary of Weighted PM Emission Rates for Two Representative Duty Cycles of a Wheel Loader

(A) Engine Mode	(B) Modal Emissions (g/gal)	Modal Fraction of Fuel Use		Weighted Emission Rate	
		(C) Move Soil	(D) Load Truck	(E) Move Soil (g/gal)	(F) Load Truck (g/gal)
1	1.0	0.34	0.19	0.34	0.19
2	1.0	0.15	0.12	0.15	0.12
3	1.0	0.09	0.16	0.09	0.16
4	1.0	0.08	0.14	0.08	0.14
5	1.0	0.07	0.13	0.07	0.13
6	1.1	0.06	0.08	0.07	0.09
7	1.0	0.04	0.07	0.04	0.07
8	1.1	0.05	0.06	0.06	0.07
9	1.0	0.05	0.04	0.05	0.04
10	1.1	0.05	0.02	0.06	0.02
PM_{wt. avg.}				1.02 g/gal	1.02 g/gal

Table 5.15 Summary of Weighted-Average Emission Rates for Two Representative Duty Cycles of a Wheel Loader

Pollutant	Duty Cycle	
	Move Soil (g/hr)	Load Truck (g/hr)
NO _x	150	199
HC	23	28
CO	51	68
PM	1.2	1.6

Based on Table 5.15, the mass per time weighted-average-emission rates for the “Load Truck” duty cycle are higher than those for the “Move Soil” duty cycle. This is in contrast to the mass per fuel used weighted-average emission rates for each pollutant shown in Table 5.11 through Table 5.14. However, the “Load Truck” duty cycle has a higher

weighted-average fuel use rate than the “Move Soil” duty cycle. Thus, the “Load Truck” duty cycle produces higher emissions than the “Move Soil” duty cycle because of a higher fuel use rate. This relationship establishes a link between fuel use and emissions and it also implies that the type of duty cycle being performed by the equipment has an impact on the levels of emitted pollutants.

A construction project schedule may indicate that a “Move Soil” duty cycle will take two days, or 16 hours, to complete. Thus, the total NO_x emissions for this activity will be approximately 2,400 grams (150 g/hr x 16 hr), or 5.3 pounds. The total project emissions of each pollutant can be estimated in a similar manner by totaling the emissions of each pollutant for each item of equipment that is used for each activity.

5.5.3 Summary and Evaluation of Methodology

Table 5.16 is a summary of the actual and estimated fuel use rates and emission rates for each item of equipment and its respective duty cycle. The actual rates were determined from the field data collection results and the estimated rates were calculated from the weighted-average fuel use and emission rates methodology presented here. Based on the results in Table 5.16, response plots were created for the fuel use rate and the emission rates of NO_x, HC, CO, and PM.

Figure 5.15 through Figure 5.19 are the response plots for the fuel use rate and the emission rates of NO_x, HC, CO, and PM, respectively. The R² of the regression line in each plot relates to the precision of the estimating methodology and the slope of the regression

line relates to the accuracy of the estimating methodology. The intercept of the regression line equation shown on each plot relates to the bias of the particular model.

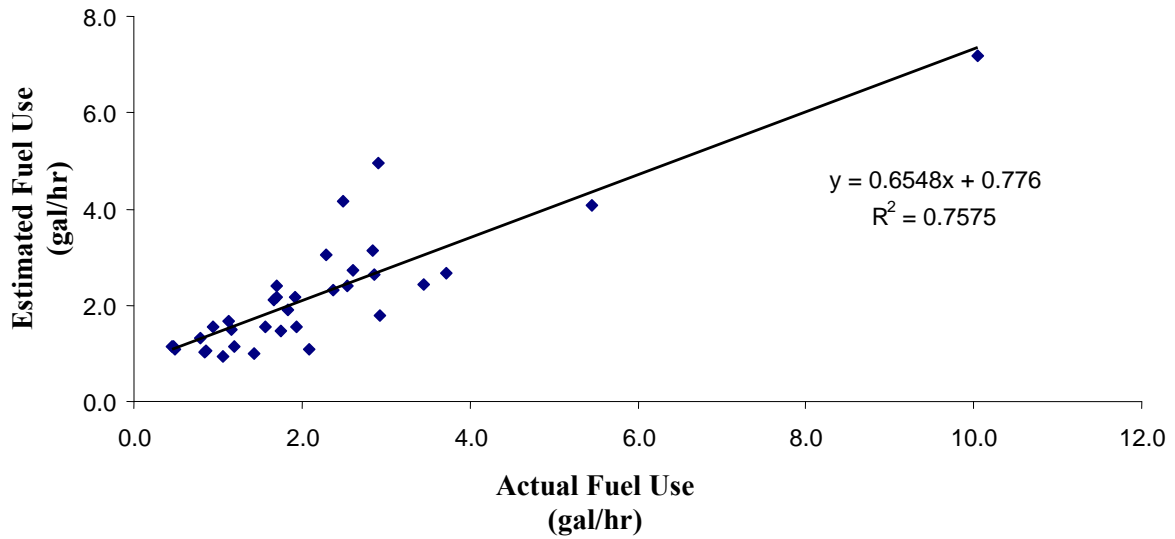


Figure 5.15 Response Plot for Fuel Use Rate

Table 5.16 Summary of Actual and Estimated Fuel Use and Emission Rates

Equipment	Duty Cycle	Fuel Use		NOx		HC		CO		PM	
		Actual (gal/hr)	Estimated (gal/hr)	Actual (g/hr)	Estimated (g/hr)	Actual (g/hr)	Estimated (g/hr)	Actual (g/hr)	Estimated (g/hr)	Actual (g/hr)	Estimated (g/hr)
BH 1	Load Truck	0.5	1.1	60	131	14	18	25	44	0.1	1.1
BH 2	Move Material	1.1	0.9	112	122	9	19	35	44	1.1	0.9
BH 3	Move Soil	0.8	1.0	73	136	7	20	15	46	1.3	1.0
BH 4	Move Soil	0.5	1.1	64	150	6	22	5	51	0.3	1.1
BH 5	Load Truck	1.8	1.9	231	234	27	31	179	78	2.3	2.0
BH 6	Load Truck	2.1	1.1	178	134	19	18	64	45	2.1	1.1
BH 7	Move Soil	1.2	1.2	111	153	42	22	105	52	1.6	1.2
BH 8	Move Soil	0.5	1.1	69	150	6	22	10	51	0.4	1.1
BD 1	Rough Grade	1.7	2.1	252	305	16	49	63	102	2.3	2.1
BD 2	Fine Grade	0.9	1.0	92	145	14	23	28	49	0.7	1.1
BD 3	Fine Grade	1.4	1.0	228	139	18	22	91	47	2.3	1.0
BD 4	Rough Grade	3.4	2.4	613	354	39	57	131	118	2.9	2.5
BD 5	Stockpile	10.1	7.2	1913	829	33	86	240	236	NA	7.6
BD 6	Stockpile	1.1	1.7	104	193	24	20	44	55	0.9	1.8
EX 1	Clear & Grub	2.8	3.1	319	377	13	47	37	119	3.2	3.2
EX 2	Move Rock	2.3	3.1	175	351	18	40	71	110	1.7	3.2
EX 3	Excavate Soil	1.9	1.5	214	176	20	20	27	54	1.5	1.6
MG 1	Resurface	5.5	4.1	643	473	53	54	67	145	4.9	4.2
MG 2	Shoulder	1.7	2.4	192	295	50	39	48	96	1.0	2.5
MG 3	Shoulder	2.5	2.4	275	295	152	39	NA	96	2.8	2.5
MG 4	Resurface	2.9	4.9	596	573	95	65	141	176	2.3	5.1
MG 5	Shoulder	2.6	2.7	423	334	26	44	134	109	1.9	2.8
MG 6	Resurface	2.5	4.2	163	482	21	55	17	148	1.8	4.3

Table 5.16 continued, Summary of Actual and Estimated Fuel Use and Emission Rates

Equipment	Duty Cycle	Fuel Use		NO _x		HC		CO		PM	
		Actual (gal/hr)	Estimated (gal/hr)	Actual (g/hr)	Estimated (g/hr)	Actual (g/hr)	Estimated (g/hr)	Actual (g/hr)	Estimated (g/hr)	Actual (g/hr)	Estimated (g/hr)
OT 1	Haul Soil	2.4	2.3	298	307	22	45	121	102	2.2	2.3
OT 2	Haul Soil	1.7	2.2	246	290	15	42	41	96	1.5	2.2
OT 3	Haul Soil	1.9	2.2	268	290	17	42	59	96	1.6	2.2
TL 1	Fine Grade	2.9	1.8	169	228	29	30	67	73	2.3	1.8
TL 2	Move Material	2.9	2.7	514	309	22	34	38	92	2.1	2.8
TL 3	Stockpile	3.7	2.7	216	306	7	31	58	86	2.2	2.8
WL 1	Move Soil	1.7	1.5	179	193	19	28	73	65	1.5	1.5
WL 2	Load Truck	1.6	1.5	195	194	33	27	38	66	1.5	1.6
WL 3	Load Truck	0.9	1.5	131	194	8	27	18	66	0.4	1.6
WL 4	Load Truck	1.2	1.5	156	188	15	26	12	64	1.1	1.5
WL 5	Move Soil	0.8	1.3	78	177	8	26	23	60	0.5	1.4

Key

BH = Backhoe

BD = Bulldozer

EX = Excavator

MG = Motor Grader

OT = Off-Road Truck

TL = Track Loader

WL = Wheel Loader

NA = Data Not Available

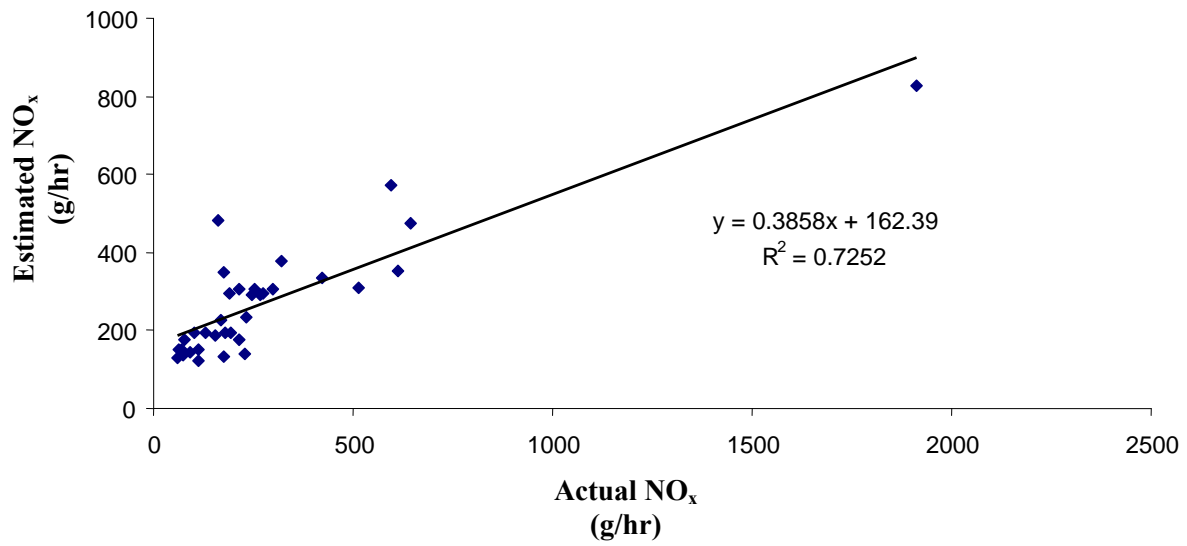


Figure 5.16 Response Plot for NO_x Emission Rate

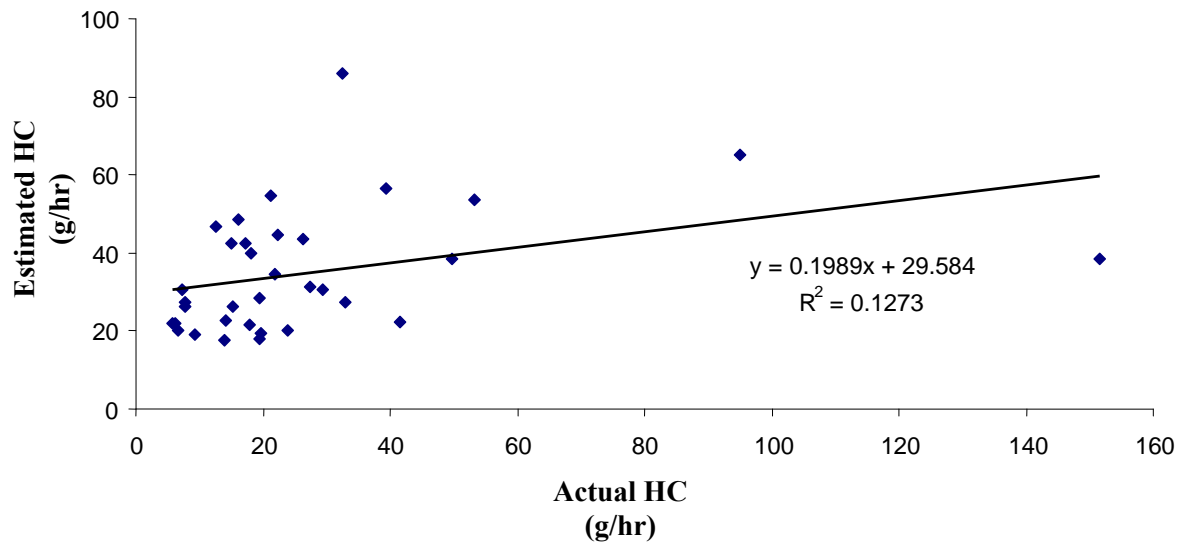


Figure 5.17 Response Plot for HC Emission Rate

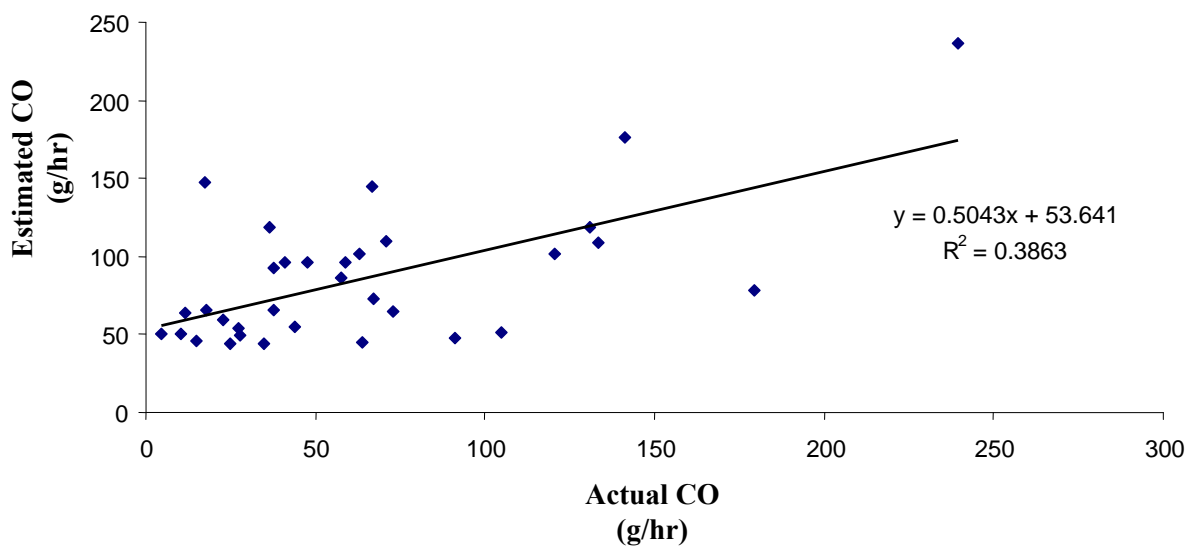


Figure 5.18 Response Plot for CO Emission Rate

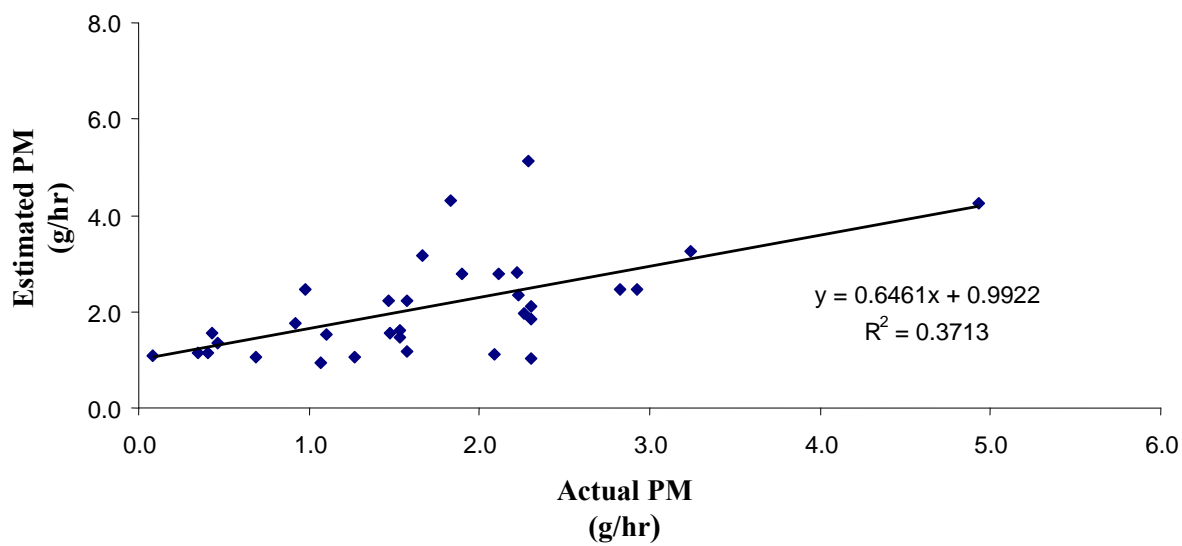


Figure 5.19 Response Plot for PM Emission Rate

Table 5.17 summarizes the R^2 , slope, and intercept for each response plot. Based on these results, the models for fuel use and NO_x performed well with R^2 values (precision) over 76% and 73%, respectively. Thus, these models are considered to be precise. The accuracy (slope) of the fuel use model is good with a slope of 65%; however, the accuracy of the NO_x model is lower with a slope of 39%. The precision (R^2) of the models for CO and PM was moderate with R^2 values of 39% and 37%, respectively; however, the accuracy was better with slopes of 50% and 65%, respectively. The model for HC had a low precision and low accuracy with an R^2 value of 13% and a slope of 20%, not surprising considering that the PEMS typically recorded HC values that were low by a factor of two.

The residual plots for each response are included in Appendix G. Based on these plots, the conditions of linear regression are met. The normal probability plot of the residuals is approximately a straight line; there is no pattern or “fanning out” of the data in the residuals versus the fitted values plot; the histogram of residuals is approximately normal; and there is no pattern in the residuals versus the order of data plot. These conditions are true for each of the fuel use and emission rates response plots.

Table 5.17 Summary of R^2 , Slope, and Intercept for Response Plots

Response Plot	R^2 (%)	Slope (%)	Intercept (g/hr)
Fuel Use	76	65	0.78 ¹
NO_x	73	39	162
HC	13	20	30
CO	39	50	54
PM	37	65	1.0

¹ Fuel Use is in units of gal/hr.

6.0 CONCLUSIONS

This chapter presents the findings and conclusions that resulted from this work. The conclusions are categorized by field data measurements, equipment attributes, modal analyses, models for engine modal fuel use and emission rates, representative duty cycles, weighted-average fuel use and emission rates, and performance and use of the methodology.

6.1 Construction Fuel Use and Emissions

Construction equipment consumes diesel fuel and produces air pollutant emissions, including NO_x, HC, CO, CO₂, and PM, which pose a serious threat to human health and the environment. The construction industry has an obligation to reduce fuel use and lower construction equipment emissions and to assume a leadership role in developing methods and searching for innovative ways to reduce air pollutant emissions.

Data are needed to properly understand the emissions problem and determine its scope in order for the construction industry to responsibly manage its equipment assets. Much of the construction equipment emissions data that is currently available is based on steady-state conditions used for engine dynamometer tests. These tests do not take into account the episodic nature of most construction equipment or the effects of the activity that is being performed by the equipment. Thus, field data based on construction equipment that is performing duty cycles is needed to help establish an accurate baseline from fuel use and emissions of in-use construction equipment.

The PEMS used for the field data collection measured accurate emission rates for NO_x, CO, and CO₂, however, the HC emission rates may be low by a factor of two and the

PM emission rates may be low by an order of magnitude. Thus, the HC and PM emission rates observed during the field data measurements may be used for comparisons of emission rates from different sources but not for characterization of the actual magnitude of these emission rates.

There is less variability for fuel-based emission rates than for time-based emission rates. Fuel-based emission rates are a more robust basis for emission analyses than time-based emission rates. Therefore, using fuel-based emission rates helps to reduce the overall variability in the emission rates estimation methodology. Fuel-based emission rates are also useful because there are often multiple sources of fuel use information in addition to the estimating methodology presented here, including manufacturer specifications and historical data for the particular item of equipment.

Fuel use and emissions field data collection of construction equipment on project sites takes place in a challenging environment. This environment caused problems for the PEMS that stemmed from dust, vibration, and precipitation. Although precautions were taken to mitigate these problems, they often caused a malfunction of the PEMS which resulted in lengthy delays and valuable lost data collection time. A more reliable method of collecting fuel use and emissions data under field conditions is needed.

6.2 Equipment Attributes

The field data that was collected for this work is based on seven types of construction equipment. A minimum of three and a maximum of eight items of equipment of each type were observed. However, many other types of equipment are frequently used for

construction activities and each equipment type has a wide range of attributes, such as engine size, engine age, engine tier, and engine load. Thus, the field data presented here is limited to only seven equipment types with limited equipment attributes within each type.

The equipment attributes presented here were used as predictor variables in the modal fuel use and emission rates prediction models and are based on a limited range of values. For example, the range of horsepower ratings for the equipment that was tested was between 70 and 306 hp and the range of model years was between 1988 and 2007. Most of the equipment tested had a Tier 0, Tier 1, or Tier 2 engine and only one item of equipment had a Tier 3 engine. Thus, additional Tier 3 engines are needed for this research and Tier 4 Final engines will be phased in beginning in 2013 and field testing will be needed for those engines.

The fuel use and emission rates analyses that were conducted here are based on a limited number of equipment attributes related to equipment type, engine size, engine age, engine tier and engine load. However, many other equipment attributes exist that can be used to examine fuel use and emission rates, such as gross machine weight, engine speed, other measures of engine load, and engine operating hours.

The analyses performed in this study were based on all 34 equipment items that were observed; these items were not classified into groups for further evaluation. For example, it is possible to categorize the data by equipment type, engine size, engine tier, and engine age to further refine the analysis.

6.3 Modal Analyses

Activity modal analysis is based on the activity modes of a specific item of equipment. However, the activity modes do not always correspond to the duty cycle components of the equipment. For example, the activity modes of a wheel loader include idling, moving, and scoop/dump; the duty cycle components include load, haul, dump, and return. Thus, activity modal analysis does not directly account for the variation in engine load for each activity mode.

The activity modal analysis revealed that the highest amount of variability in the fuel use and emission rates are between the idle and non-idle modes; there is little variability among non-idle engine modes for fuel use and emission rates. The non-idle fuel use rates are higher than the idle fuel use rates on a mass per time basis. The non-idle emission rates are typically lower than the idle emission rates on a mass per fuel used basis.

The engine modal analysis revealed that mass per time fuel use rates are sensitive to 10 increments of engine load. The lowest fuel use rate was for engine mode 1 and the highest fuel use rate was for engine mode 10; the fuel use rates increased steadily between engine mode 1 and engine mode 10. Engine mode 1 corresponds to an idling mode and engine mode 10 corresponds to the highest possible engine load.

The engine modal analysis revealed that the highest variability of mass per fuel used emission rates are between the idling engine mode (mode 1) and the non-idling engine modes (modes 2 – 10). There is less variability in the modal emission rates of modes 2 – 10 for each pollutant.

6.4 Regression Models for Engine Modal Fuel Use and Emission Rates

The regression models for engine modal fuel use and emission rates are a key component for estimating the weighted-average fuel use and emission rates of representative duty cycles for construction equipment. Thus, it is necessary to reduce the amount of variability in these models as much as possible. Mass per fuel used emission rates were used to develop the predictive models for engine modal emission rates since fuel-based emission rates have less variability than time-based emission rates. Time-based fuel use rates were the only option available for developing the predictive models for the engine modal fuel use rates.

The regression models for engine modal fuel use rates performed well for engine modes 2 - 10. These models had an R^2 of approximately 76% – 81% and the regression coefficients for each model were statistically significant with p-values less than 0.05. The R^2 for the engine mode 1 model was approximately 35%. Due to the low R^2 of this model, an average modal fuel use rate was used for mode 1 since no reliable model could be developed for this engine mode.

An attempt was made to generate regression models for the emission rates of each pollutant based on a model selection criterion that all model coefficients have a p-value less than 0.05. In many cases, a model could not be generated based on this criterion for the emission rates of HC, CO, and PM. For the models that were generated, the R^2 values were between 12% and 41%. For the emission rates of NO_x , models were generated for each engine mode with R^2 values between 34% and 49%. Based on the low R^2 values regression models could not be used, therefore, average modal emission rates of each pollutant calculated directly from the field data were used instead.

6.5 Representative Duty Cycles

Defining a representative duty cycle is a key component to estimating the weighted-average fuel use and emission rates of representative duty cycles of construction equipment. In total, 17 duty cycles were observed for seven different types of equipment. In many cases, multiple items of the same equipment type were observed performing the same duty cycle. Thus, it was possible to estimate an average of the time spent and the fuel used in each engine mode for a particular equipment type and a particular duty cycle.

The fraction of time that is spent in each engine mode can be determined from the field data. This is crucial for weighting the average fuel use and rate in order to estimate the weighted-average fuel use rate of a representative duty cycle. The fraction of fuel used can also be determined from the field data. This is crucial for weighting the modal emission rate in order to estimate the weighted-average emission rate of each pollutant for the representative duty cycle.

6.6 Weighted-Average Fuel Use and Emission Rates

Weighted-average fuel use rates make it possible to estimate the total fuel consumption requirements of construction equipment performing a representative duty cycle. The total fuel requirements can be used to estimate the fuel expense of the duty cycle. The total fuel requirements and fuel expense can be estimated at the duty cycle level, the project activity level, and the overall project level.

Weighted-average emission rates make it possible to estimate the total emissions of each pollutant of construction equipment performing a representative duty cycle. The total

emissions of each pollutant can be estimated at the duty cycle level, the project activity level, and the overall project level.

The weighted-average fuel use rate is translated into emissions by multiplying it by the fuel-weighted emission rate, which means that emission rates of NO_x, HC, CO, and PM increase as the fuel use rate increases. Reducing fuel use not only saves money but it also reduces emissions. This methodology provides a means for estimating the fuel use and emission rates of construction equipment which can then be used to quantify the financial and environmental impacts related to construction equipment.

The weighted-average fuel use rate measured in gallons per hour can be linked to common production rates of construction equipment measured in units of production per hour; likewise, the weighted-average emission rate measured in grams per hour can be linked to the same production rates. By dividing the production rate by the weighted-average fuel use rate, it is possible to estimate the equipment fuel efficiency in units of production per gallon of fuel used, such as cubic yards per gallon. By dividing the weighted-average emission rate by the production rate, it is possible to estimate total emissions of each pollutant based on units of production, such as grams per cubic yard.

6.7 Performance and Use of Methodology

The methodology performed well for estimating fuel use rates for construction equipment when comparing the actual values to the estimated values. The overall R² (precision) of the methodology is 76% and the slope (accuracy) of the regression line is 65%.

This methodology proves useful for estimating fuel use rates of construction equipment with attributes in the range of those of the observed equipment presented here.

The methodology also performed well for estimating NO_x emission rates for construction equipment when comparing the actual values to the estimated values. The overall R^2 of the model is 73% and the slope of the regression line is 39%. The methodology performed reasonably for CO and PM emission rates, with R^2 values of 39% and 37%, respectively. The methodology had the lowest R^2 value for HC at 13%. Thus, the methodology reliably estimates emission rates of NO_x and it can also be useful for estimating emission rates of CO, and PM.

Validation tests are needed to further evaluate and calibrate the model developed in this methodology; however, there is no additional data available from this study to do so. Although the estimated fuel use and emission rates were compared to the actual fuel use and emission rates gathered from the field data, it is desirable to have additional data from other sources to compare with the results of the model.

This methodology is a mathematical model that may be used in many ways. The methodology may be used as a stand-alone model that is implemented by a spreadsheet to estimate fuel use and emission rates. This methodology may be used with more comprehensive models, such as URBEMIS or the Road Construction Emissions model to improve their fuel use and emissions estimates. This methodology may also be used in conjunction with construction estimating and scheduling methodologies used to estimate production and durations of construction activities in order to estimate the fuel use and emissions associated with these activities.

7.0 RECOMMENDATIONS

This chapter presents recommendations based on the conclusions presented in Chapter 6.0. The recommendations are categorized by field data measurement, equipment attributes, modal analyses, predictive models for engine modal fuel use and emission rates, representative duty cycles, and weighted-average fuel use and emission rates.

7.1 Construction Fuel Use and Emissions

The construction industry must raise its level of awareness with respect to air pollutant emissions of nonroad diesel construction equipment. In particular, there are a number of specific activities that could be undertaken by the construction industry including:

1. Contribute to finding ways to reduce the air pollutant emissions of construction equipment to improve air quality.
2. Determine the effects on emissions of alternative fuels, such as biodiesel, when used in construction equipment.
3. Modify construction equipment operating procedures, such as reducing idling time in order to decrease fuel use and reduce air pollutant emissions.
4. Investigate technological controls for construction equipment that will reduce air pollutant emissions, such as selective catalytic reduction, diesel oxidation catalysts, diesel particulate filters, closed crankcase ventilation systems, and exhaust gas recirculation.

5. Develop green fleet certification programs that take into account measured real-world factors that prevent or reduce emissions, and that encourage verification of the effectiveness of such programs in reducing emissions based on field data.

The construction industry should begin to acquire and use field data to verify and evaluate equipment emissions under actual operating conditions. In doing so, it would establish an accurate baseline assessment of current emissions. This assessment may be used in many ways, such as to determine the benefits of replacing older equipment with newer equipment or to evaluate rebuilding or replacing older engines without replacing the equipment itself. Air pollutant emissions inventories based on accurate emission rates for construction equipment should be developed. These air pollutant emission inventories should be used to develop air pollutant emissions projections for new projects based on typical construction planning metrics such as plans, specifications, contract documents, estimates, and work breakdown structure.

Other data sources for HC and PM emission rates should be considered for the analyses that are presented in this work since the field emission measurements tend to report low values for the magnitude of these pollutants. For example, the EPA NONROAD model may be used to provide emission rates of HC and PM. However, the emission rates of HC and PM presented here are still effective at showing trends in emission data with respect to their sources.

Fuel-based emission rates should be used for emission analyses because they have less variability than time-based emission rates. The fuel-based emission rates should be used

for the modal fuel use and emission rates regression models and also for developing emissions inventories of construction equipment.

Researchers should investigate new methods of collecting fuel use and emissions field data. For example, in-use engine information such as RPM and fuel use rates are available via electronic control units (ECU) and Vehicle Information Management Systems (VIMS) that are available on many newer items of equipment. Other PEMS should be investigated to determine which ones are best suited for nonroad construction equipment. Furthermore, these should be standardized by equipment manufacturers so that both data collection and dissemination are facilitated.

7.2 Equipment Attributes

The field data collection efforts should be expanded to include other types of construction equipment, such as compactors, cranes, and scrapers. Additional equipment within the seven types that have already been observed should be targeted for more tests in order to increase and refine the equipment attribute data that has already been collected. By expanding the database of field data for construction equipment, more comprehensive analyses can be conducted with regard to fuel use and emissions on construction projects.

Care should be taken when using the models herein to assess construction equipment that has attributes outside the ranges of values that were included in this work. This methodology should not be used to extrapolate predictions of fuel use and emission rates for equipment that has attributes outside of the ranges of those that are presented here.

Equipment attributes other than the ones presented here should be considered when evaluating fuel use and emission rates analyses of construction equipment. For example, other attributes may include gross machine weight, engine speed, alternative methods of measuring engine load, and hours of engine operation. Hours of engine operation is considered to be the best indicator of engine age; thus, this data should especially be collected.

Additional groupings of equipment attribute data should be considered for evaluation, such as equipment within a specified horsepower range. For example, the data used for this work could be refined into equipment groups with engines less than 100 horsepower, between 100 and 200 horsepower, and over 200 horsepower. Other possible groupings that should be evaluated include equipment type, engine tiers, and equipment with tires versus equipment with tracks. Evaluating groupings within the data may reveal trends within those particular classifications.

7.3 Modal Analyses

Activity modal analyses of fuel use and emission rates should be based on the duty cycle components that are used to estimate equipment productivity. The average engine load for each duty cycle component should be measured as well. This will help to provide a link for analyzing fuel use and emission rates with respect to productivity of the equipment.

For simplified activity modal analysis of fuel use and emission rates, it is only necessary to observe idle and non-idle modes. Thus, data related to when the equipment is idling and data related to when the equipment is doing work and not idling is all that needs to

be evaluated. However, when performing more complex analyses, such as determining the average fuel use and emission rates for each activity mode, it is necessary to measure all applicable activity modes.

The engine modal analysis for fuel use should be used to help evaluate fuel consumption of construction equipment. Operational analyses of equipment should be conducted to determine how to reduce the fraction of the duty cycle that is spent in higher engine modes in order to reduce the amount of fuel that is consumed. Likewise, evaluating methods of reducing idling time will also lead to a reduction in fuel use.

With respect to engine modal analyses, stratifying the engine load data into different increments may help refine the engine modal emission rates. It may be helpful to stratify the data in smaller increments or organize the data in other groupings, such as the corresponding activity mode or duty cycle component. For example, performing an engine modal analysis for each activity mode of an off-road truck (hauling, dumping, moving, and idle) would help to refine the estimates of the fuel use and emission rates for each activity mode. Determining the average emission rate for each pollutant based on the average engine load for each duty cycle component will help to estimate the average emission rates of duty cycles with unusual cycle times.

7.4 Regression Models for Engine Modal Fuel Use and Emission Rates

Fuel-based emission rates should be used for developing the regression models for engine modal emission rates since they have less variability than time-based emission rates.

These predictive models should be used to estimate the weighted-average fuel use and emission rates of construction equipment performing representative duty cycles.

The regression models for the engine modal fuel use rates can be used to estimate the weighted-average fuel use rate of representative duty cycles for construction equipment. However, other equipment attributes that may affect the equipment's fuel use rate should be investigated. These attributes include gross machine weight, engine speed, other measures of engine load, and engine operating hours. Other statistical approaches to modeling emission rates should be investigated, such as nonlinear and multivariate analysis.

A linear regression modeling approach proved to be ineffective for estimating modal emission rates, particularly for HC, CO, and PM. Thus, average modal emission rates calculated directly from the field data were used to estimate the weighted-average emission rates of each pollutant. Other engine attributes that may affect the emission rate (such as those mentioned above) should be investigated. Other statistical approaches to modeling, such as nonlinear methods and multivariate analysis, should be considered.

7.5 Representative Duty Cycles

Determination and definition of representative duty cycles should continue. The field measurements that have already been collected should be analyzed to determine additional representative duty cycles. Additional equipment types should be observed to expand the database of representative duty cycles for construction equipment.

Additional field data measurements should be collected for estimating the fraction of time spent in each engine mode and the fraction of fuel used in each engine mode. These

fractions should then be matched to the corresponding duty cycle component that is used to estimate construction equipment productivity. Thus, it would be possible to perform an engine modal analysis for each duty cycle component.

Engine mode distributions of time and fuel should be used to compare and evaluate the engine loads for various duty cycles. These comparisons can be used to help determine the equipment type that is best suited to accomplish a certain duty cycle.

7.6 Weighted-Average Fuel Use and Emission Rates

Weighted-average fuel rates should be used to estimate the total fuel consumption requirements and fuel expense for construction equipment performing representative duty cycles. The fuel requirements for equipment that is used for each project activity should be totaled to determine the fuel requirements for the overall project. The overall project fuel requirements should be multiplied by the current fuel price to determine the fuel expense for the overall project.

Weighted-average emission rates should be used to estimate the total emissions of each pollutant for construction equipment performing representative duty cycles. The total emissions of equipment that is used for each project activity should be totaled to estimate the total emissions of each pollutant for the overall project. These emissions estimates should be used by fleet managers to effectively manage their diesel-powered equipment with respect to emissions.

The weighted-average fuel use and emission rates should be linked to construction equipment production rates in order to provide another means for estimating fuel use and

emissions of construction projects. Thus, fuel use and emission rates can be based on activity quantities in lieu of activity durations.

Additional research should be performed to determine productivity-based fuel use and emission rates since production data exists for most of the observed equipment. Average productivity-based fuel use and emission factors should be determined for each representative duty cycle when the data to do so is available. When the data is not available, additional equipment testing is required, controlled experiments may be needed to focus more closely on precisely measuring the production of the representative duty cycle.

7.7 Performance and Use of Methodology

The methodology and model derived herein is recommended for estimating fuel use rates and NO_x emission rates for construction equipment with attributes in the range of the equipment that were observed performing representative duty cycles. Although more variability exists in the methodology for estimating emission rates of HC, CO, and PM, it still can be used to compare trends in these emission rates among different equipment types and duty cycles.

Additional research is recommended to collect fuel use and emissions data that can be used to validate and calibrate the model presented in this methodology. This data may come from others or it may be collected from additional field studies. Data should also be collected to analyze a case study for this methodology. For example, fuel use and emissions data should be collected for a typical construction project, such as a shopping plaza. This

field data can then be compared to the estimated fuel use and emissions data produced by this model for validation and calibration.

This methodology should be developed for implementation by using spreadsheets for user inputs and calculations and databases for duty cycle modal information. The model should then be made available for users interested in estimating fuel use and emission rates of representative duty cycles, such as equipment manufacturers, fleet owners, contractors, engineers, and regulators. Additional research should be performed to determine how this methodology can be used with construction estimating and scheduling software to estimate the fuel use and emissions of common construction activities and construction projects.

8.0 REFERENCES

- Abolhasani, S., C. Frey, K. Kim, S. Pang, W. Rasdorf, and P. Lewis, (2008). Real-World In-Use Activity, Fuel Use, and Emissions for Nonroad Construction Vehicles: A Case Study for Excavators, *Journal of the Air & Waste Management Association*, Vol. 58, No. 8.
- Battelle (2003). Environmental Technology Verification Report: Clean Air Technologies International, Inc. REMOTE On-Board Emissions Monitor, Prepared by Battelle for the U.S. Environmental Protection Agency, Columbus, OH.
- CAT (2004). *Caterpillar Performance Handbook, Edition 35*, Caterpillar, Inc., Peoria, Ill.
- CATI (2003). *OEM-2100 Montana System Operation Manual*, Clean Air Technologies International, Inc., Buffalo, New York.
- CFR (2007). *Title 40 – Protection of Environment, Part 50 – National Primary and Secondary Ambient Air Quality Standards*, Code of Federal Regulations, Vol. 2, pp. 5 – 127. Available at www.access.gpo.gov/nara/cfr/waisidx_07/40cfr50_07.html.
- EPA (1) (2004). “Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling - Compression-Ignition,” EPA420-P-04-009, NR-009c, U.S. Environmental Protection Agency, Washington, D.C.
- EPA (2) (2004). “Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling,” EPA420-P-04-005, NR-005c, U.S. Environmental Protection Agency, Office of Transportation and Air Quality, Ann Arbor, MI.
- EPA (2005). “User’s Guide for the Final NONROAD2005 Model,” EPA-420-R-05-013, U.S. Environmental Protection Agency, Office of Transportation and Air Quality, Ann Arbor, MI.
- Fraser Basin Council (2008). “E3 Fleet Greening Canada’s Fleets,” www.e3fleet.com/mc/page.do, Information viewed on April 9, 2008.
- Frey, C. and S. Bammi (2003). Probabilistic Nonroad Mobile Source Emission Factors, *Journal of Environmental Engineering*, Vol. 129, No. 2, pp. 162-168.
- Frey, C. (1), W. Rasdorf, K. Kim, S. Pang, P. Lewis, and S. Abolhassani (2007). “Life Cycle Inventory and Impact Analysis Framework for Nonroad Construction Vehicles and Equipment (TSE03-L),” Research Project for National Science Foundation, Arlington, Va.

- Frey, C. (2), W. Rasdorf, K. Kim, S. Pang, P. Lewis, and S. Abolhassani (2007). “Real-World Duty Cycles and Utilization for Construction Equipment in North Carolina,” Final Report for Research Project No. HWY - 2006 – 08, North Carolina Department of Transportation, Raleigh, NC.
- Frey, C. (1), W. Rasdorf, K. Kim, S. Pang, and P. Lewis (2008). Comparison of Real World Emissions of Backhoes, Front-End Loaders, and Motor Graders for B20 Biodiesel vs. Petroleum Diesel and for Selected Engine Tiers, *Transportation Research Record*, No. 2058, pp. 33-42.
- Frey, C. (2), K. Kim, W. Rasdorf, S. Pang, and P. Lewis (2008). Characterization of Real-World Activity, Fuel Use, and Emissions of Selected Motor Graders Fueled with Petroleum Diesel and B20 Biodiesel, *Journal of the Air & Waste Management Association*, Vol. 58, No. 10.
- Frey, C. (3), N. Rouphail, and H. Zhai (2008). Link-Based Emission Factors for Heavy-Duty Diesel Trucks Based on Real-World Data, *Transportation Research Record*, No. 2058, pp. 23 – 32.
- Lewis, P. (1), W. Rasdorf, C. Frey, K. Kim, and S. Pang (2008). Requirements and Incentives for Reducing Construction Vehicle Emissions and Comparison of Nonroad Diesel Engine Emissions Data Sources, *Journal of Construction Engineering and Management*, (Accepted for Publication).
- Lewis, P. (2), C. Frey, and W. Rasdorf (2008). Development and Use of Emissions Inventories for Construction Vehicles, *Transportation Research Record*, Journal of the Transportation Research Board, (Accepted for Publication).
- Minitab (2007). Minitab 15, Version 15.1.30.0, Minitab, Inc., State College, PA.
- Nichols, H. and D. Day (2005). *Moving the Earth: The Workbook of Excavation*, The McGraw-Hill Companies, Inc., New York, NY.
- Northeast Diesel Collaborative (2007). “Construction,” www.northeastdiesel.org/construction, Information viewed on December 13, 2007.
- OFFROAD (2007). OFFROAD 2007, Version 2.0.1.2, California Air Resources Board, Sacramento, Ca.
- Quinn, G. and M. Keough (2007). *Experimental Design and Data Analysis for Biologists*, Cambridge University Press, Cambridge, UK.

- Rasdorf, W., C. Frey, P. Lewis, K. Kim S. Pang, and S. Abolhassani (2008). "Procedures for Real-World Measurements of Emissions from Diesel Construction Vehicles," *Journal of Infrastructure Systems*, Submitted October 2008.
- RCEM (2007). Road Construction Emissions Model, Version 6.3.1, Prepared by Sacramento Metropolitan Air Quality Management District, Sacramento, CA. Available for download at www.airquality.org/ceqa/index.shtml.
- Rumsey, Deborah (2007). *Intermediate Statistics for Dummies*, Wiley Publishing, Inc., Indianapolis, IN.
- Stephens, R. and S. Cadle (1991). Remote Sensing Measurements of Carbon Monoxide Emissions from On-Road Vehicles, *Journal of Air & Waste Management Association*, Vol. 41, 39 - 46.
- URBEMIS (2007). "Software User's Guide: URBEMIS2007 for Windows," Prepared by Jones and Stokes Associates, Sacramento, CA.

9.0 APPENDICES

9.1 Appendix A: Activity Modal Analyses of Fuel Use and Emission Rates for Three Off-Road Trucks

This appendix provides a complete activity modal analysis for three off-road trucks. Figure 9.1 is a mass per time (grams per second) analysis of fuel use for each observed activity mode for each off-road truck. Figure 9.2 through Figure 9.5 are fuel-based (grams per gallon) analyses of emissions of NO_x, HC, CO, and PM for each activity mode for each off-road truck. The emissions of CO₂ are approximately constant for each activity mode; therefore, they are not shown in this analysis.

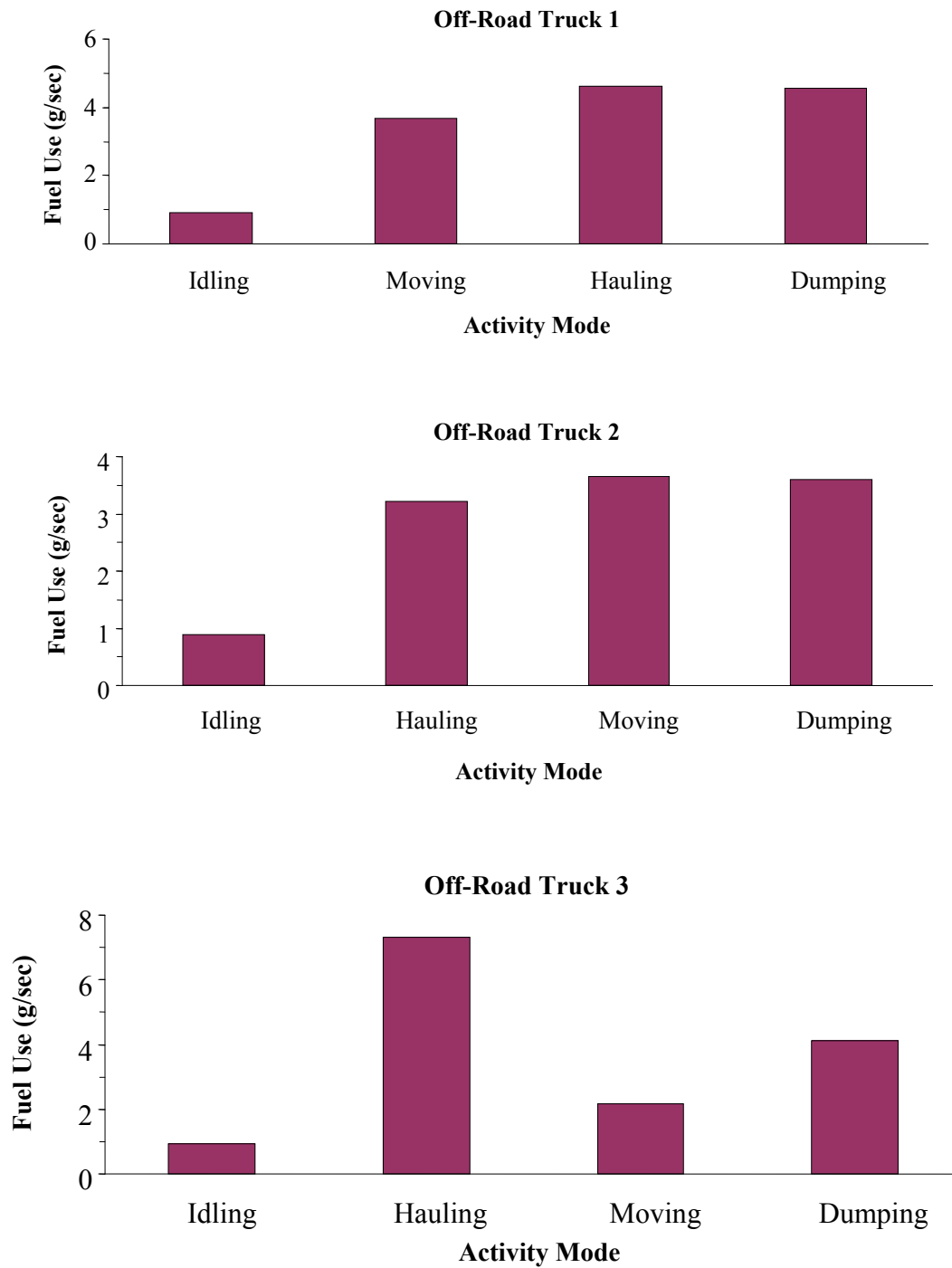


Figure 9.1 Activity Modal Analysis of Fuel Use for Three Off-Road Trucks

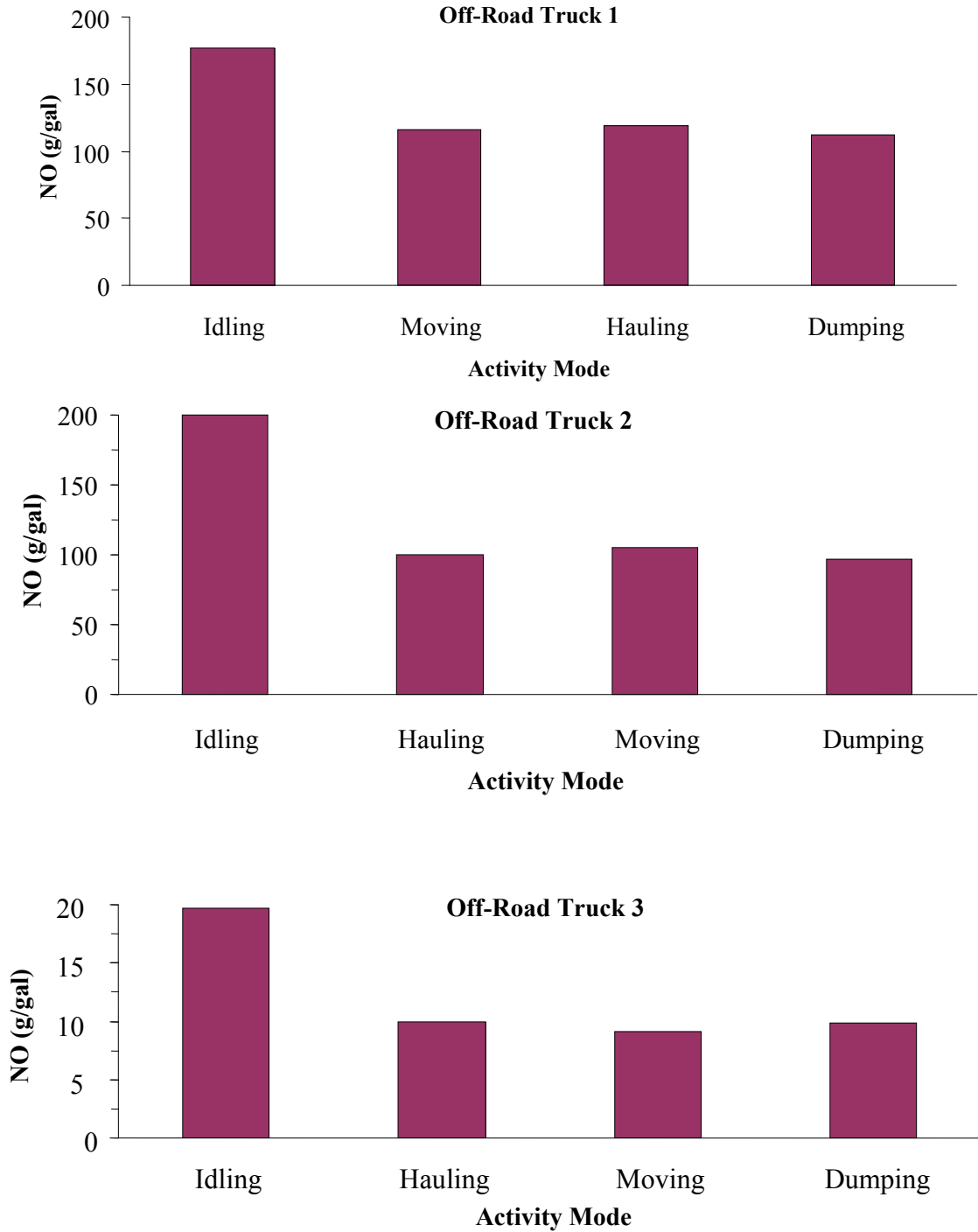


Figure 9.2 Fuel-Based Activity Modal Analysis of NO for Three Off-Road Trucks

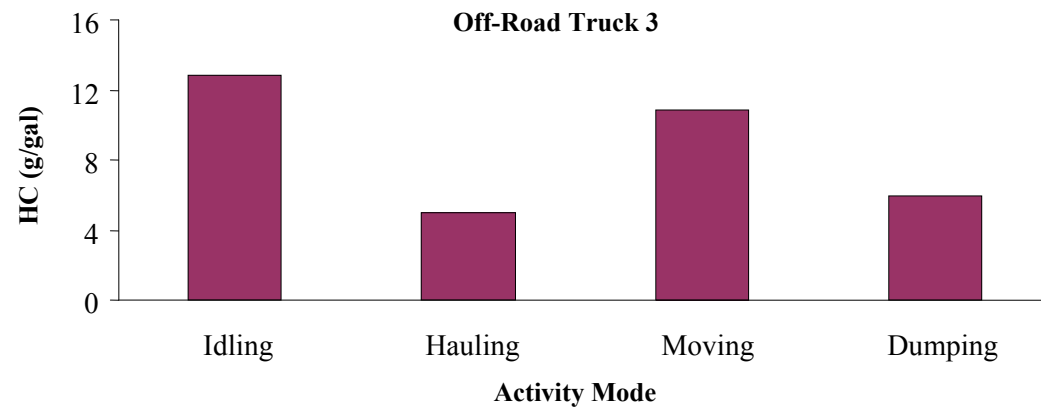
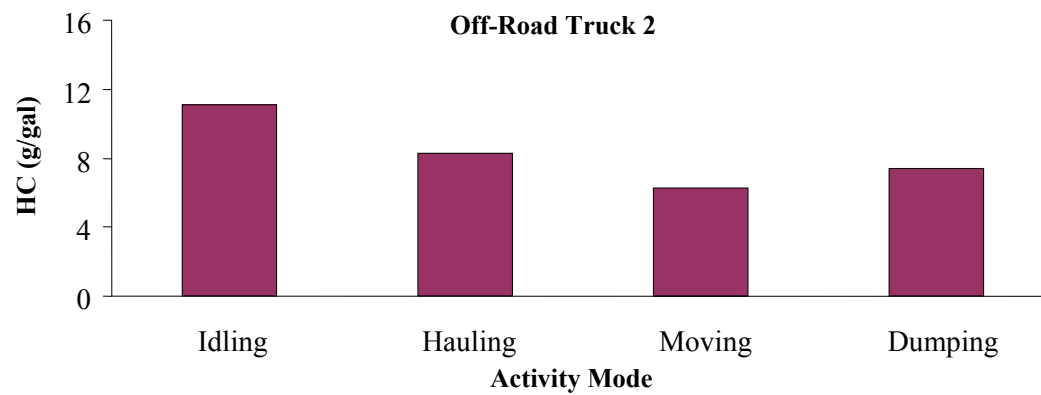
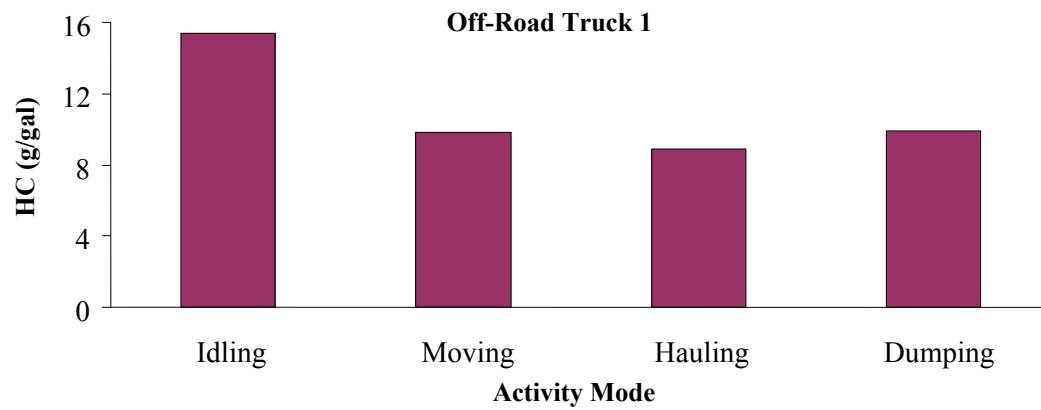


Figure 9.3 Fuel-Based Activity Modal Analysis of HC for Three Off-Road Trucks

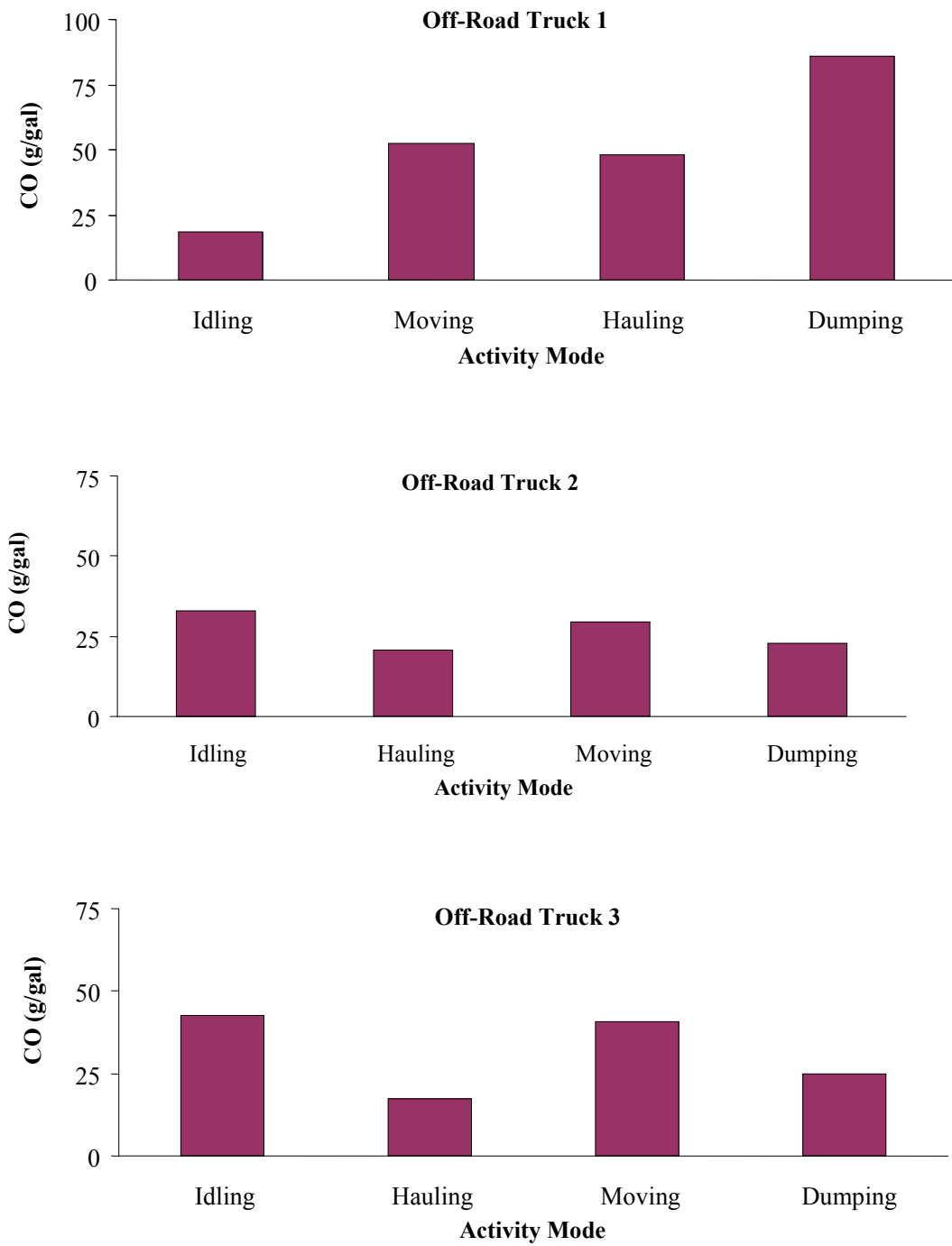


Figure 9.4 Fuel-Based Activity Modal Analysis of CO for Three Off-Road Trucks

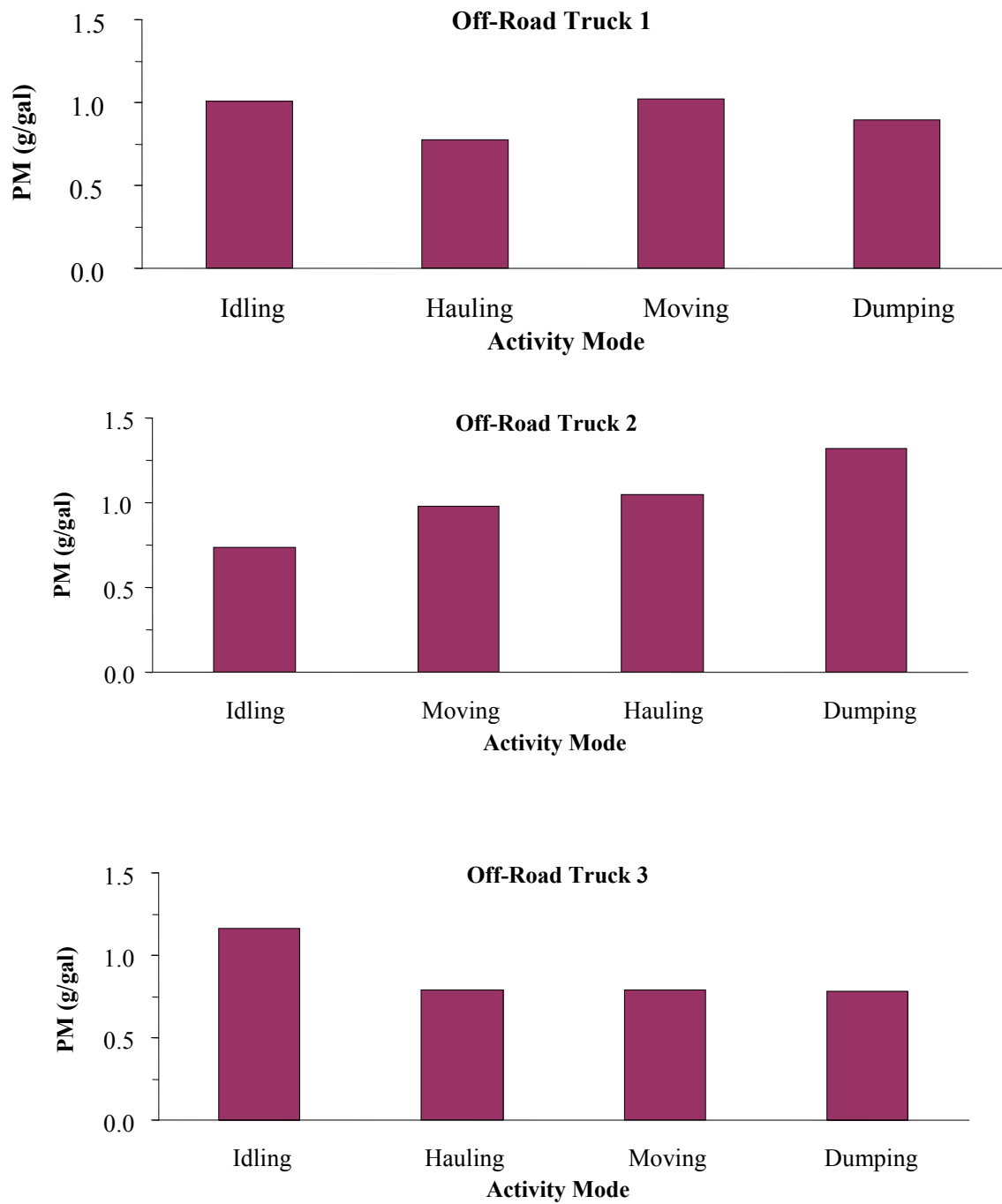


Figure 9.5 Fuel-Based Activity Modal Analysis of PM for Three Off-Road Trucks

9.2 Appendix B: Engine Modal Analyses of Fuel Use and Emission Rates for Three Off-Road Trucks

This appendix provides a complete engine modal analysis for three off-road trucks. Figure 9.6 is a mass per time (grams per second) analysis of fuel use for each engine mode for each off-road truck. Figure 9.7 through Figure 9.10 are fuel-based (grams per gallon) analyses of emissions of NO_x, HC, CO, and PM for each activity mode for each off-road truck. The emissions of CO₂ are approximately constant for each activity mode and are not shown in this analysis.

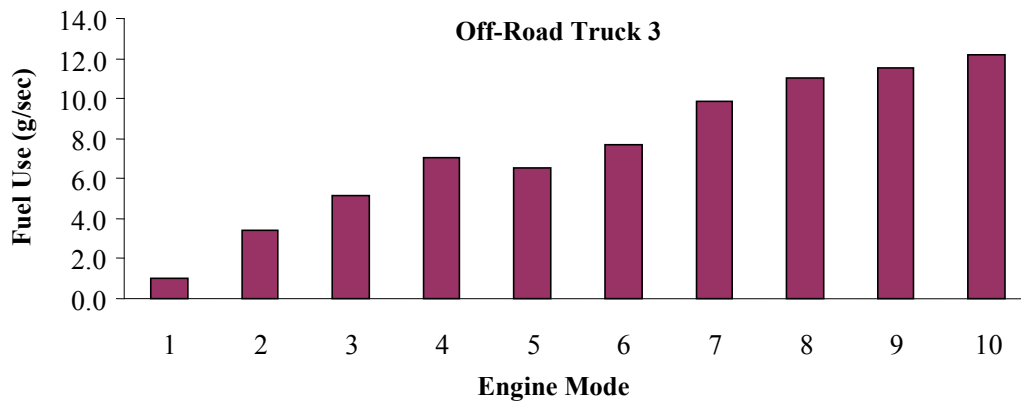
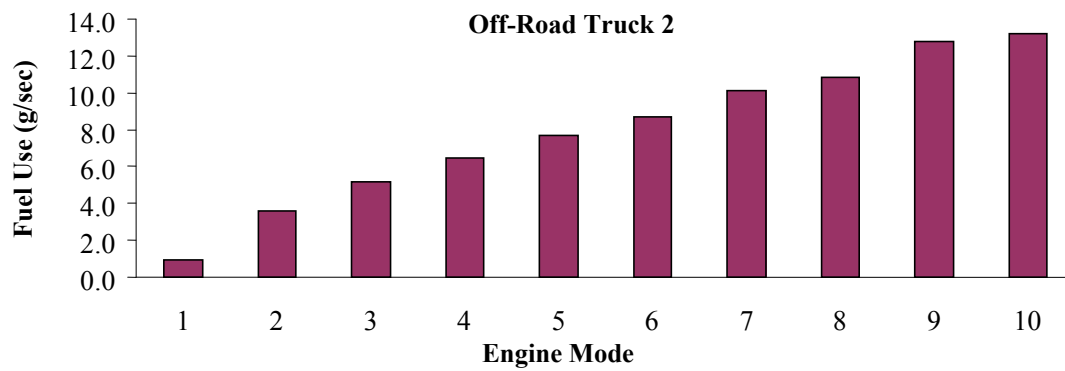
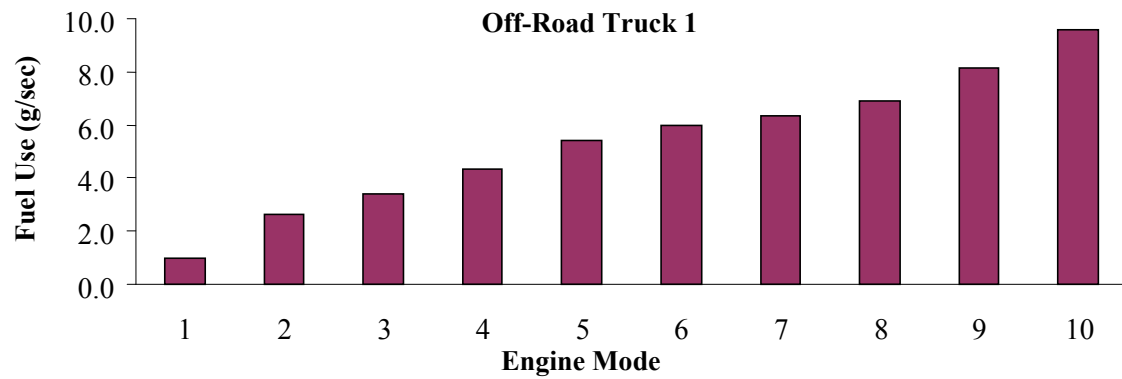


Figure 9.6 Engine Modal Analysis of Fuel Use for Three Off-Road Trucks

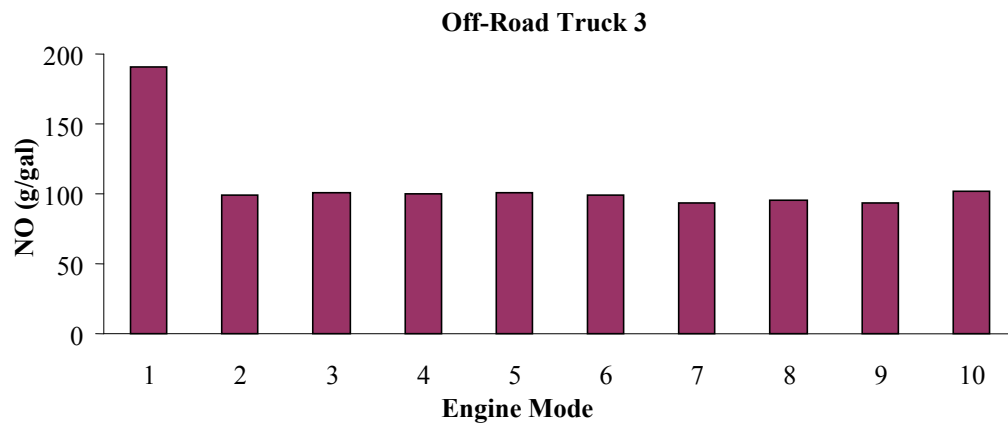
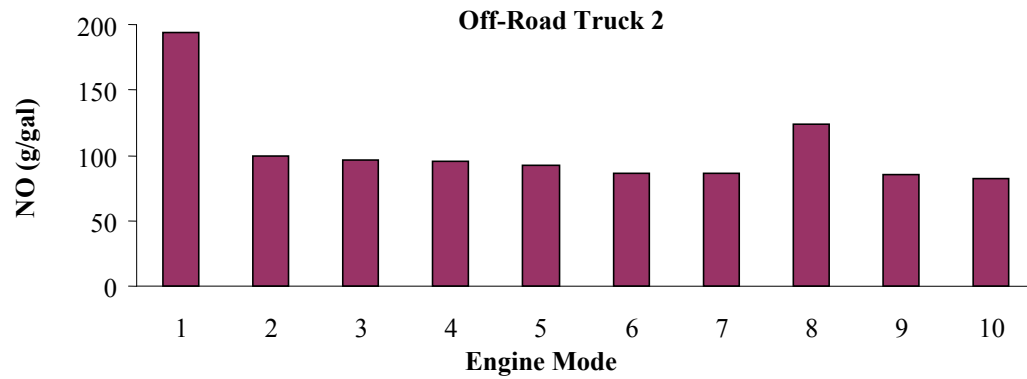
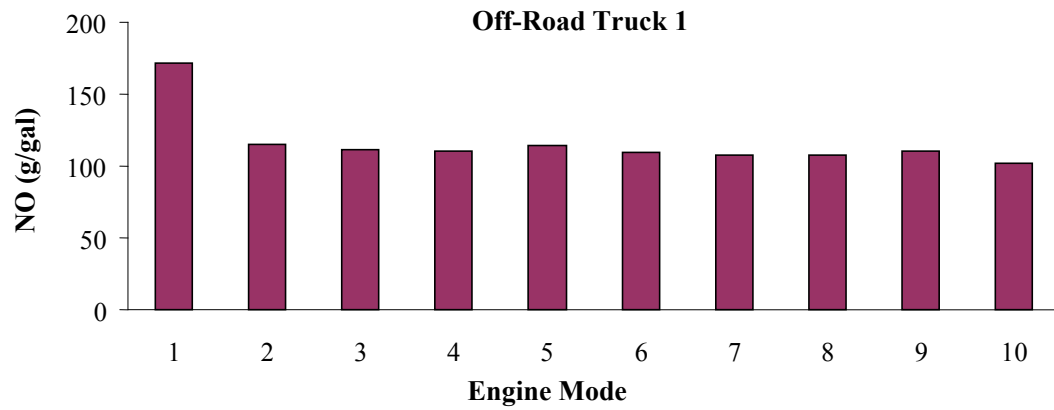


Figure 9.7 Fuel-Based Engine Modal Analysis of NO for Three Off-Road Trucks

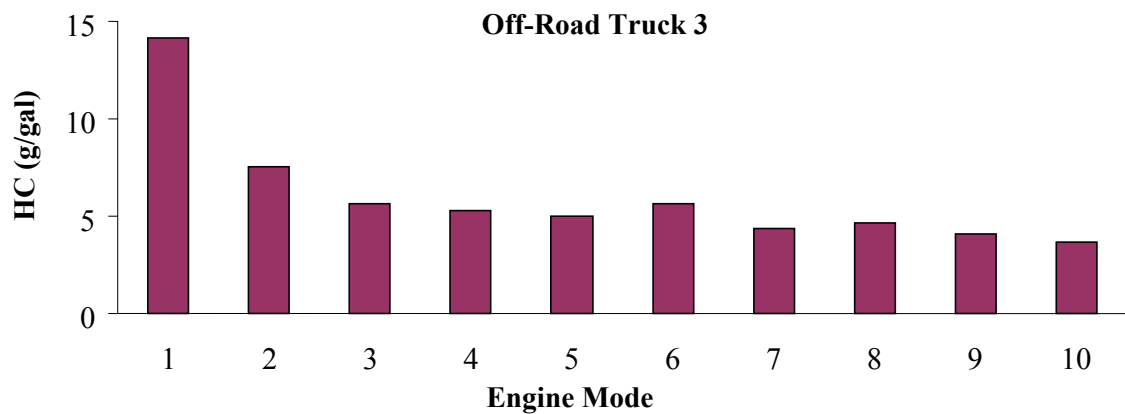
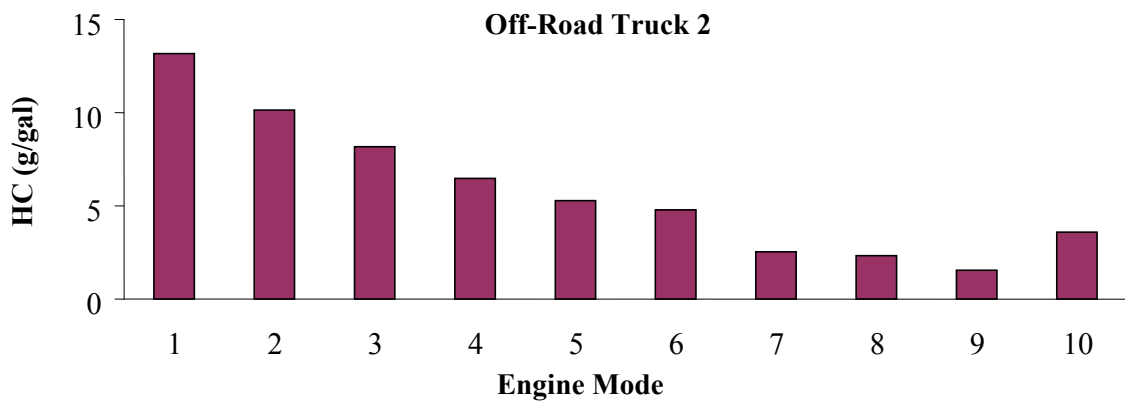
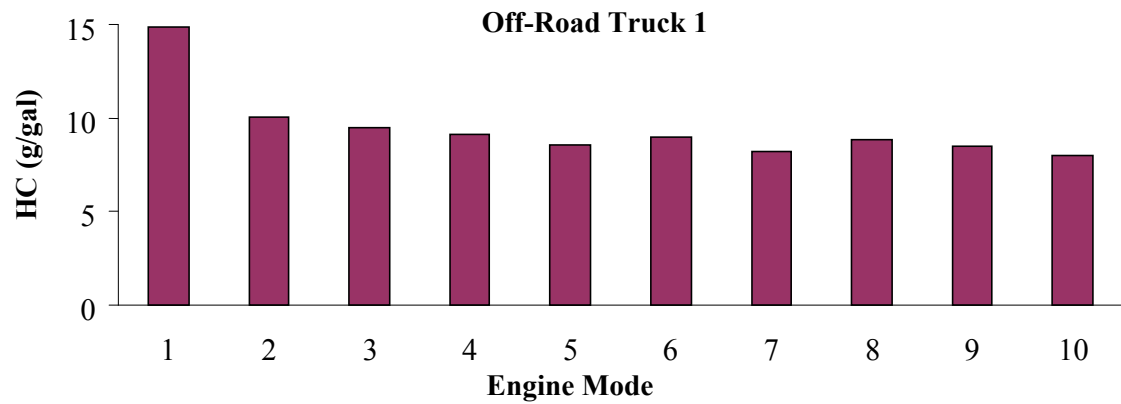


Figure 9.8 Fuel-Based Engine Modal Analysis of HC for Three Off-Road Trucks

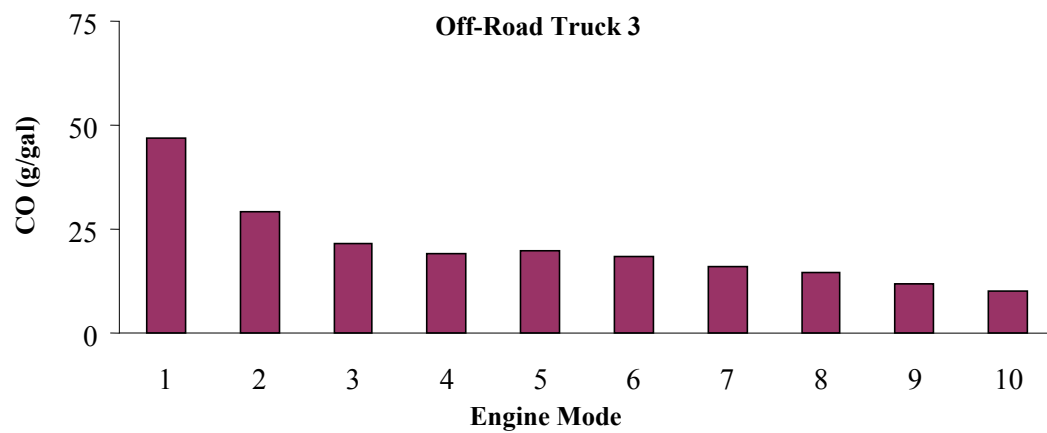
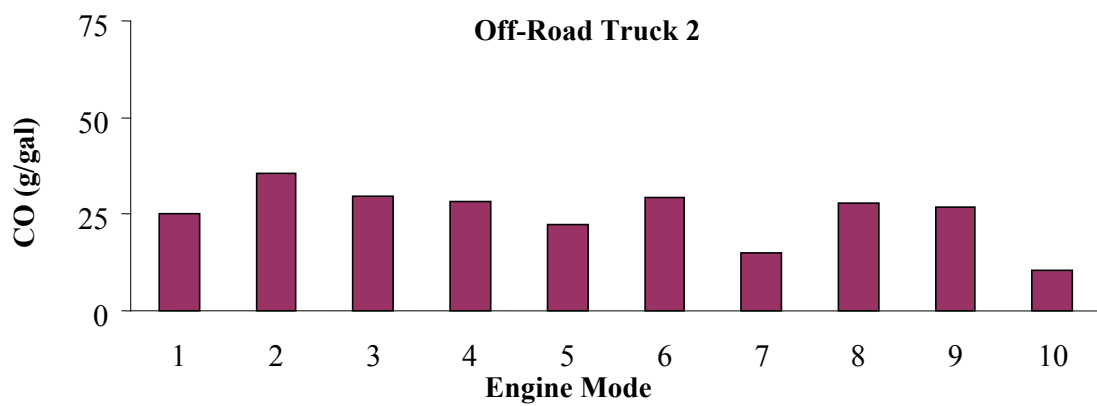
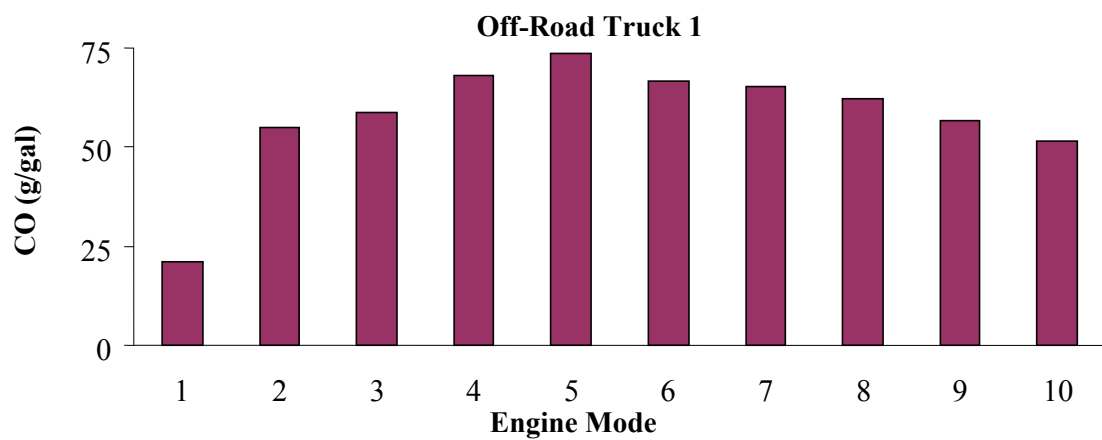


Figure 9.9 Fuel-Based Engine Modal Analysis of CO for Three Off-Road Trucks

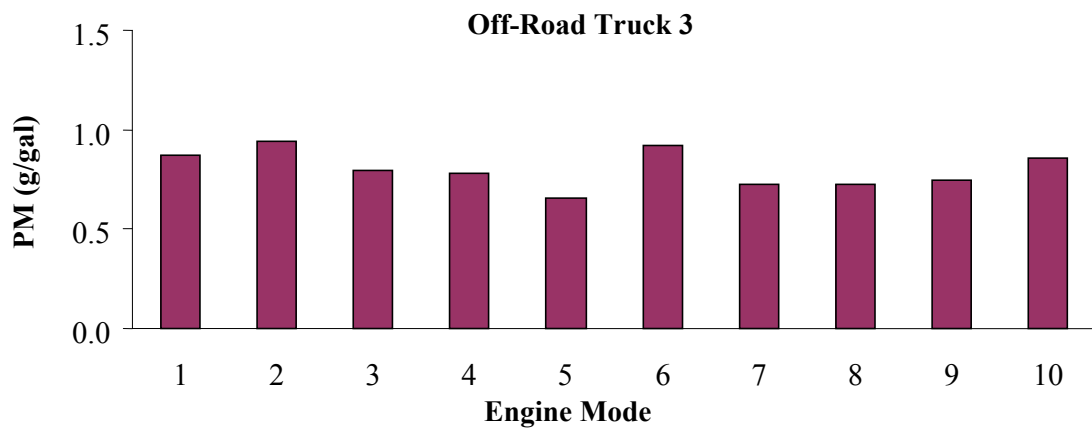
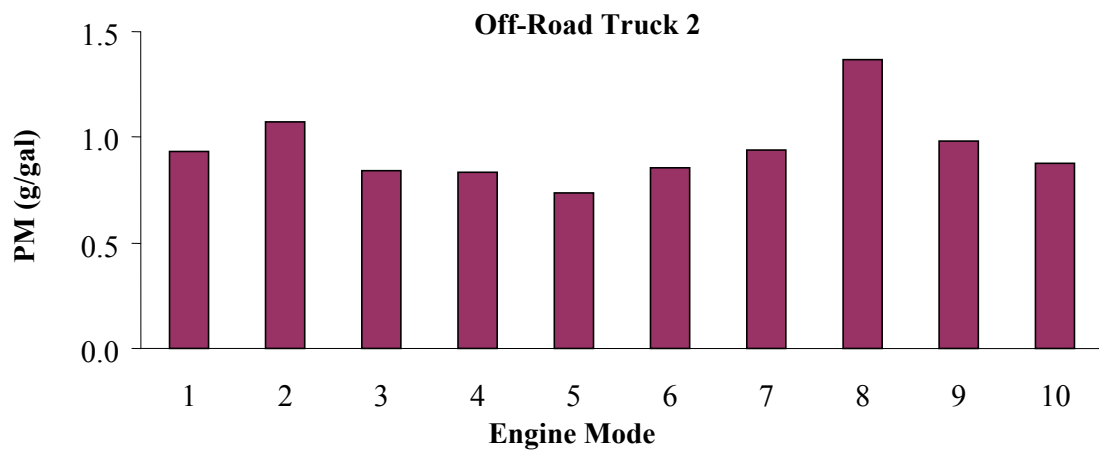
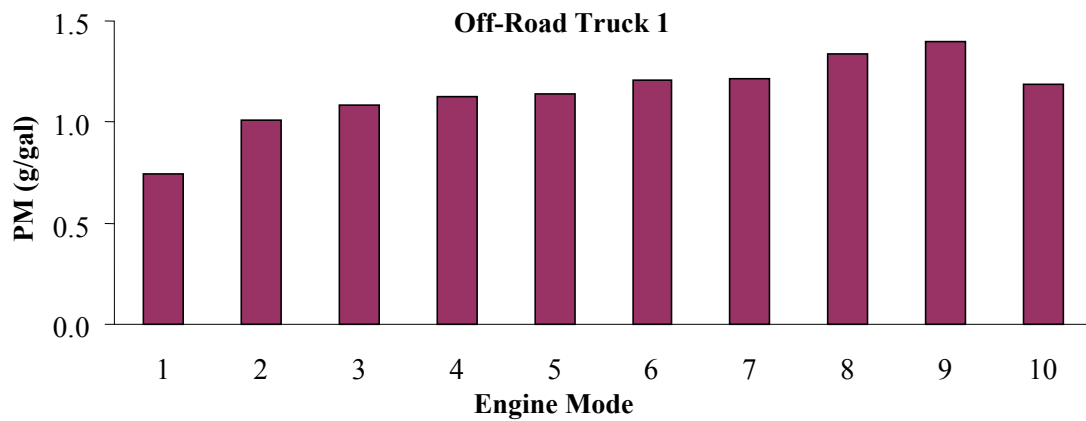


Figure 9.10 Fuel-Based Engine Modal Analysis of PM for Three Off-Road Trucks

9.3 Appendix C: Datasets of Equipment Attributes, Fuel Use Rates, and Emission Rates for Engine Modes 1 through 10 for Each Item of Equipment

This appendix presents the field data that was collected from each item of equipment and was used for developing the multiple linear regression predictive models for estimating fuel use and emission rates for each engine mode. Table 9.1 provides the equipment attributes and duty cycles for each item that was tested. Table 9.2 through Table 9.11 provide the average normalized MAP, time-based fuel use rates, time-based emission rates of each pollutant, and fuel-based emission rates of each pollutant for each item of equipment and each engine mode. Missing values indicate that valid data was not available for that variable. Values shown as 0.0 indicate that the value is less than 0.05.

Table 9.1 Equipment Attributes and Duty Cycles for Each Item of Equipment

Equipment Item	Mount	Horsepower (HP)	Displacement (Liters)	Model Year	Engine Tier	Duty Cycle
Backhoe 1	Wheel	88	4.0	2004	2	Load Truck
Backhoe 2	Wheel	88	4.2	1999	1	Move Material
Backhoe 3	Wheel	88	4.2	2000	1	Move Soil
Backhoe 4	Wheel	97	3.9	2004	2	Move Soil
Backhoe 5	Wheel	90	4.2	1997	0	Load Truck
Backhoe 6	Wheel	90	4.2	2001	1	Load Truck
Backhoe 7	Wheel	99	4.5	1999	1	Move Soil
Backhoe 8	Wheel	97	4.5	2004	2	Move Soil
Bulldozer 1	Track	89	5.0	1988	0	Rough Grade
Bulldozer 2	Track	95	3.9	2002	1	Fine Grade
Bulldozer 3	Track	90	5.0	2003	1	Fine Grade
Bulldozer 4	Track	175	10.5	1998	1	Rough Grade
Bulldozer 5	Track	285	14.2	1995	0	Stockpile
Bulldozer 6	Track	99	4.2	2005	2	Stockpile
Excavator 1	Track	254	8.3	2001	1	Clear & Grub
Excavator 2	Track	138	6.4	2003	2	Move Rock
Excavator 3	Track	93	3.9	1998	1	Excavate Soil
Motor Grader 1	Wheel	195	8.3	2001	1	Resurface
Motor Grader 2	Wheel	195	7.1	2004	2	Shoulder
Motor Grader 3	Wheel	195	8.3	2001	1	Shoulder
Motor Grader 4	Wheel	167	8.3	1990	0	Resurface
Motor Grader 5	Wheel	160	8.3	1993	0	Shoulder
Motor Grader 6	Wheel	198	7.2	2007	3	Resurface
Off-Road Truck 1	Wheel	306	9.6	2005	2	Haul Soil
Off-Road Truck 2	Wheel	285	10.3	1998	1	Haul Soil
Off-Road Truck 3	Wheel	285	10.3	1998	1	Haul Soil
Track Loader 1	Track	121	7.2	1998	1	Fine Grade
Track Loader 2	Track	70	4.5	1997	0	Move Material
Track Loader 3	Track	127	7.2	2006	2	Stockpile
Wheel Loader 1	Wheel	149	5.9	2004	2	Move Soil
Wheel Loader 2	Wheel	130	5.9	2002	1	Load Truck
Wheel Loader 3	Wheel	130	5.9	2002	1	Load Truck
Wheel Loader 4	Wheel	126	5.9	2002	1	Load Truck
Wheel Loader 5	Wheel	133	6.0	2005	2	Move Soil

Table 9.2 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 1

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	1	0.02	0.3	14	4	7	1	0.0	124	36	70	9,854	0.2
Backhoe 2	1	0.06	0.4	11	2	5	1	0.2	87	16	43	9,951	1.3
Backhoe 3	1	0.07	1.1	31	2	5	3	0.4	94	8	18	10,104	1.5
Backhoe 4	1	0.05	0.1	8	1	0	0	0.0	232	15	11	10,035	0.7
Backhoe 5	1	0.03	0.3	4	4	5	1	0.4	42	49	65	9,822	4.2
Backhoe 6	1	0.05	0.3	12	2	4	1	0.2	122	22	43	9,819	2.3
Backhoe 7	1	0.05	0.3	17	1	4	1	0.1	174	13	43	9,746	1.0
Backhoe 8	1	0.05	0.2	10	1	2	0	0.0	200	24	38	9,974	1.0
Bulldozer 1	1	0.04	0.4	26	3	10	1	0.1	199	24	78	9,871	0.9
Bulldozer 2	1	0.02	0.3	12	3	7	1	0.0	117	24	52	9,908	0.5
Bulldozer 3	1	0.04	1.9	93	6	24	6	1.0	163	16	78	9,903	1.7
Bulldozer 4	1	0.04	5.0	265	15	57	16	1.3	191	13	51	10,066	1.0
Bulldozer 5	1	0.01	1.1	76	6	36	3		229	20	110	9,955	
Bulldozer 6	1	0.07	0.7	21	7	11	2	0.1	102	36	52	9,876	0.6
Excavator 1	1	0.01	0.6	31	2	5	2	0.2	174	12	30	9,986	0.9
Excavator 2	1	0.06	1.0	41	6	27	3	0.2	135	19	87	9,878	0.8
Excavator 3	1	0.04	0.3	15	2	4	1	0.1	188	28	49	9,906	0.8
Motor Grader 1	1	0.03	0.8	46	8	8	3	0.2	182	42	36	9,884	0.9
Motor Grader 2	1	0.01	0.6	29	9	5	2	0.1	165	50	27	9,875	0.5
Motor Grader 3	1	0.03	0.3	20	11		1	0.1	203	113		9,735	1.0
Motor Grader 4	1	0.06	0.8	61	17	34	2	0.1	239	83	167	9,550	0.5
Motor Grader 5	1	0.03	0.6	38	4	32	2	0.1	191	20	169	9,740	0.7
Motor Grader 6	1	0.03	0.4	19	1	2	1	0.1	156	9	11	10,021	0.6
Off-Road Truck 1	1	0.03	1.0	51	4	7	3	0.2	172	15	21	9,990	0.7
Off-Road Truck 2	1	0.01	0.9	55	3	7	3	0.3	194	13	25	10,102	0.9
Off-Road Truck 3	1	0.01	1.0	56	4	13	3	0.3	190	14	47	9,944	0.9
Track Loader 1	1	0.04	1.8	36	5	12	6	0.4	79	17	30	9,969	0.7
Track Loader 2	1	0.04	0.6	24	3	5	2	0.2	131	16	26	9,982	1.5
Track Loader 3	1	0.01	0.5	14	1	7	2	0.1	94	8	43	9,980	0.9
Wheel Loader 1	1	0.04	0.8	29	3	11	2	0.2	125	17	45	9,953	0.7
Wheel Loader 2	1	0.04	0.6	24	7	11	2	0.1	137	41	66	9,842	0.8
Wheel Loader 3	1	0.04	0.3	16	1	4	1	0.0	199	17	53	9,712	0.3
Wheel Loader 4	1	0.05	0.3	17	4	2	1	0.1	157	45	21	9,897	1.0
Wheel Loader 5	1	0.04	0.5	15	2	6	1	0.1	104	14	40	9,965	0.6

Table 9.3 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 2

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	2	0.15	0.9	38	4	5	3	0.0	142	16	20	9,987	0.1
Backhoe 2	2	0.16	1.1	40	3	13	3	0.3	112	9	40	9,976	0.9
Backhoe 3	2	0.14	0.4	7	1	2	1	0.3	66	9	20	10,111	2.9
Backhoe 4	2	0.16	0.4	20	2	1	1	0.1	167	16	12	9,998	0.7
Backhoe 5	2	0.16	1.0	28	6	12	3	0.4	92	19	40	9,952	1.3
Backhoe 6	2	0.14	1.0	36	4	9	3	0.4	117	12	30	9,887	1.3
Backhoe 7	2	0.15	0.9	36	76	61	3	0.4	132	206	168	8,952	1.6
Backhoe 8	2	0.16	0.5	22	1	3	2	0.1	151	10	18	10,010	0.8
Bulldozer 1	2	0.15	1.1	67	4	18	3	0.4	221	15	63	9,923	1.6
Bulldozer 2	2	0.16	1.0	36	5	6	3	0.2	122	20	60	9,911	0.5
Bulldozer 3	2	0.16	0.4	23	3	21	1	0.2	182	26	176	9,718	1.5
Bulldozer 4	2	0.14	0.6	50	4	11	2	0.2	281	23	60	10,023	1.1
Bulldozer 5	2	0.16	3.9	229	5	132	12		216	5	114	9,996	
Bulldozer 6	2	0.15	1.0	29	6	13	3	0.2	94	20	43	9,943	0.7
Excavator 1	2	0.16	2.1	57	5	17	7	0.7	88	8	26	10,000	1.1
Excavator 2	2	0.17	2.0	56	6	38	6	0.3	95	11	63	9,938	0.5
Excavator 3	2	0.15	0.8	29	2	28	2	0.2	125	9	120	9,843	1.1
Motor Grader 1	2	0.14	2.0	95	7	12	6	0.7	160	13	20	9,997	1.3
Motor Grader 2	2	0.15	2.2	79	23	49	7	0.4	119	34	78	9,843	0.7
Motor Grader 3	2	0.15	1.0	44	24		3	0.4	162	136		9,700	1.8
Motor Grader 4	2	0.14	1.6	128	21	29	5	0.4	261	43	63	9,838	0.8
Motor Grader 5	2	0.15	2.0	114	8	42	6	0.5	189	13	72	9,913	0.8
Motor Grader 6	2	0.14	1.0	36	3	6	3	0.2	114	10	17	10,007	0.7
Off-Road Truck 1	2	0.15	2.6	92	8	48	8	0.8	115	10	55	9,950	1.0
Off-Road Truck 2	2	0.15	3.6	107	8	31	11	1.1	99	10	36	10,093	1.1
Off-Road Truck 3	2	0.14	3.4	107	8	30	11	0.9	99	8	29	9,997	0.9
Track Loader 1	2	0.14	0.9	18	6	32	3	0.3	69	22	107	9,837	1.2
Track Loader 2	2	0.15	1.3	59	7	10	4	0.3	144	16	25	9,982	0.8
Track Loader 3	2	0.16	1.2	24	0	32	4	0.4	64	0.3	82	9,920	1.0
Wheel Loader 1	2	0.15	1.5	49	5	21	5	0.5	106	11	45	9,970	1.1
Wheel Loader 2	2	0.16	1.4	64	9	8	4	0.4	145	20	18	9,978	1.0
Wheel Loader 3	2	0.14	0.8	39	2	5	3	0.1	159	11	22	9,766	0.8
Wheel Loader 4	2	0.16	0.8	37	3	2	3	0.2	148	12	10	10,014	0.8
Wheel Loader 5	2	0.14	1.0	36	2	6	3	0.2	114	7	20	10,014	0.5

Table 9.4 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 3

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	3	0.24	1.1	44	6	6	4	0.1	126	16	19	9,986	0.2
Backhoe 2	3	0.26	1.5	56	4	13	5	0.3	120	8	30	9,996	0.7
Backhoe 3	3	0.26	0.3	7	1	3	1	0.3	65	13	32	10,080	2.8
Backhoe 4	3	0.24	0.5	22	2	2	2	0.1	132	12	10	10,011	0.7
Backhoe 5	3	0.24	1.3	40	6	17	4	0.5	99	14	43	9,964	1.2
Backhoe 6	3	0.25	1.4	50	5	15	4	0.4	111	11	33	9,883	0.9
Backhoe 7	3	0.24	1.4	45	81	111	4	0.7	104	165	234	8,966	1.7
Backhoe 8	3	0.24	0.6	25	2	3	2	0.1	138	12	18	10,007	0.8
Bulldozer 1	3	0.25	1.6	90	5	22	5	0.8	212	13	56	9,940	2.1
Bulldozer 2	3	0.25	1.3	46	6	8	4	0.3	125	17	48	9,950	0.7
Bulldozer 3	3	0.24	0.4	24	3	26	1	0.2	170	23	188	9,709	1.3
Bulldozer 4	3	0.26	0.8	62	6	15	3	0.3	245	23	57	10,029	1.0
Bulldozer 5	3	0.26	5.9	312	6	133	18		180	4	75	10,066	
Bulldozer 6	3	0.26	1.3	38	8	14	4	0.4	89	19	34	9,959	0.9
Excavator 1	3	0.24	3.0	96	5	16	9	1.1	106	5	18	10,024	1.2
Excavator 2	3	0.25	2.7	67	7	31	8	0.4	81	8	38	9,987	0.5
Excavator 3	3	0.27	1.2	34	5	19	4	0.3	91	14	53	9,942	0.7
Motor Grader 1	3	0.25	2.8	117	11	15	9	0.9	136	13	18	10,000	1.1
Motor Grader 2	3	0.26	3.4	112	29	35	10	0.7	107	26	36	9,933	0.7
Motor Grader 3	3	0.25	1.5	62	34		5	0.5	131	78		9,845	1.2
Motor Grader 4	3	0.25	2.5	160	29	38	8	0.6	205	37	52	9,871	0.8
Motor Grader 5	3	0.25	2.9	157	9	43	9	0.7	174	11	50	9,955	0.8
Motor Grader 6	3	0.27	1.6	41	6	4	5	0.4	83	11	7	10,022	0.8
Off-Road Truck 1	3	0.25	3.4	114	9	65	11	1.1	111	9	59	9,946	1.1
Off-Road Truck 2	3	0.25	5.2	159	10	39	16	1.3	97	8	30	10,115	0.8
Off-Road Truck 3	3	0.25	5.2	165	9	35	16	1.3	101	6	22	10,017	0.8
Track Loader 1	3	0.23	1.6	18	8	82	5	0.6	35	15	161	9,763	1.3
Track Loader 2	3	0.25	1.7	84	7	10	5	0.4	157	13	20	9,999	0.8
Track Loader 3	3	0.26	1.9	41	2	17	6	0.7	71	3	31	10,010	1.3
Wheel Loader 1	3	0.25	2.0	63	7	28	6	0.5	103	12	45	9,967	0.9
Wheel Loader 2	3	0.25	1.9	77	10	8	6	0.6	133	18	15	9,989	1.0
Wheel Loader 3	3	0.25	1.3	58	2	6	4	0.2	153	11	15	9,802	1.0
Wheel Loader 4	3	0.24	1.1	48	3	3	3	0.3	146	11	9	10,020	0.9
Wheel Loader 5	3	0.25	1.5	47	3	9	5	0.2	98	6	20	10,014	0.5

Table 9.5 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 4

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	4	0.35	1.3	43	9	8	4	0.1	107	21	21	9,970	0.1
Backhoe 2	4	0.35	1.8	57	4	15	6	0.4	105	7	27	10,001	0.7
Backhoe 3	4	0.34	0.3	7	2	3	1	0.3	67	15	33	10,143	2.8
Backhoe 4	4	0.34	0.6	24	2	2	2	0.2	119	11	10	10,018	0.8
Backhoe 5	4	0.34	1.7	58	9	40	5	0.5	111	18	76	9,900	1.0
Backhoe 6	4	0.34	1.7	55	5	19	5	0.4	104	9	37	9,906	0.9
Backhoe 7	4	0.36	1.9	49	24	93	6	0.8	80	53	175	9,406	1.4
Backhoe 8	4	0.34	0.7	26	3	5	2	0.2	128	14	22	9,983	0.8
Bulldozer 1	4	0.36	2.3	107	6	24	7	1.1	156	9	37	9,981	1.6
Bulldozer 2	4	0.35	1.7	54	7	10	5	0.4	121	19	49	9,937	0.6
Bulldozer 3	4	0.34	0.6	25	4	37	2	0.2	144	24	213	9,665	1.1
Bulldozer 4	4	0.35	0.7	55	5	12	2	0.2	268	23	57	10,026	0.9
Bulldozer 5	4	0.35	7.5	405	7	107	24		179	3	47	10,107	
Bulldozer 6	4	0.34	1.2	32	6	9	4	0.4	86	14	23	9,991	1.2
Excavator 1	4	0.35	4.1	136	5	16	13	1.5	109	4	13	10,036	1.2
Excavator 2	4	0.35	3.3	78	7	29	10	0.6	76	7	28	10,004	0.6
Excavator 3	4	0.35	1.5	48	6	12	5	0.3	100	13	25	9,988	0.7
Motor Grader 1	4	0.35	3.3	132	12	15	10	1.0	129	12	15	10,007	1.0
Motor Grader 2	4	0.34	4.1	124	31	38	13	0.9	96	23	32	9,949	0.7
Motor Grader 3	4	0.35	1.9	73	39		6	0.7	119	66		9,883	1.1
Motor Grader 4	4	0.35	3.3	189	31	42	10	0.8	180	30	41	9,910	0.8
Motor Grader 5	4	0.35	3.8	195	11	46	12	0.9	161	10	40	9,976	0.8
Motor Grader 6	4	0.34	1.9	46	7	3	6	0.5	75	12	5	10,021	0.8
Off-Road Truck 1	4	0.35	4.3	145	11	98	13	1.4	110	9	68	9,932	1.1
Off-Road Truck 2	4	0.35	6.4	204	11	45	20	1.7	96	6	28	10,119	0.8
Off-Road Truck 3	4	0.40	7.1	222	12	42	22	1.7	100	5	19	10,019	0.8
Track Loader 1	4	0.35	2.3	37	12	31	7	0.7	51	16	43	9,951	1.0
Track Loader 2	4	0.35	2.5	131	9	12	8	0.6	164	12	16	10,010	0.8
Track Loader 3	4	0.35	2.9	49	2	19	9	0.7	53	2	22	10,028	0.8
Wheel Loader 1	4	0.35	2.5	77	8	34	8	0.6	100	11	44	9,970	0.9
Wheel Loader 2	4	0.35	2.3	87	12	10	7	0.7	121	16	14	9,994	1.0
Wheel Loader 3	4	0.35	1.6	66	3	6	5	0.2	158	8	14	9,795	1.4
Wheel Loader 4	4	0.34	1.4	60	4	4	4	0.4	141	10	9	10,020	0.8
Wheel Loader 5	4	0.35	2.0	59	3	11	6	0.3	93	5	18	10,019	0.6

Table 9.6 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 5

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	5	0.38	1.4	44	9	9	4	0.1	103	20	21	9,974	0.1
Backhoe 2	5	0.45	2.1	58	3	23	7	0.9	86	4	41	9,991	1.4
Backhoe 3	5	0.46	0.3	7	1	3	1	0.3	67	12	33	10,111	2.8
Backhoe 4	5	0.44	0.8	28	3	3	2	0.2	115	13	11	10,002	0.8
Backhoe 5	5	0.46	2.2	79	10	103	7	0.7	115	15	150	9,792	1.0
Backhoe 6	5	0.43	2.0	60	10	26	6	0.6	95	15	41	9,912	1.0
Backhoe 7	5	0.45	2.4	57	6	46	7	0.8	76	8	69	9,712	1.1
Backhoe 8	5	0.44	0.8	32	3	4	3	0.2	132	11	18	10,003	0.9
Bulldozer 1	5	0.46	2.8	124	6	25	9	1.3	144	8	32	9,993	1.5
Bulldozer 2	5	0.45	1.9	60	5	9	6	0.6	125	20	54	9,933	0.6
Bulldozer 3	5	0.45	0.6	27	4	34	2	0.3	151	23	194	9,700	1.5
Bulldozer 4	5	0.40	0.7	57	5	12	2	0.2	259	22	55	10,015	0.8
Bulldozer 5	5	0.45	8.6	480	9	106	27		181	3	44	10,113	
Bulldozer 6	5	0.45	0.9	22	2	5	3	0.4	77	7	16	10,019	1.5
Excavator 1	5	0.45	5.2	168	5	16	16	1.8	105	3	10	10,042	1.1
Excavator 2	5	0.45	3.8	85	8	27	12	0.8	72	6	23	10,015	0.7
Excavator 3	5	0.46	2.0	70	6	8	6	0.4	112	11	13	10,014	0.7
Motor Grader 1	5	0.46	4.0	149	15	15	13	1.2	117	12	13	10,012	1.0
Motor Grader 2	5	0.45	5.0	130	29	37	16	0.9	83	18	24	9,978	0.6
Motor Grader 3	5	0.45	2.3	73	44		7	0.8	100	61		9,892	1.1
Motor Grader 4	5	0.44	3.9	231	28	46	12	1.0	189	23	39	9,933	0.9
Motor Grader 5	5	0.45	4.7	216	13	48	15	1.2	145	9	33	9,989	0.8
Motor Grader 6	5	0.45	2.4	47	9	3	8	0.7	62	12	4	10,022	0.9
Off-Road Truck 1	5	0.45	5.4	191	13	136	17	1.8	114	9	74	9,924	1.1
Off-Road Truck 2	5	0.45	7.7	236	10	40	24	1.8	92	5	22	10,134	0.7
Off-Road Truck 3	5	0.35	6.5	208	10	40	21	1.3	101	5	20	10,018	0.7
Track Loader 1	5	0.47	2.9	49	11	25	9	0.8	53	12	27	9,988	0.8
Track Loader 2	5	0.46	2.7	147	7	12	9	0.6	160	8	14	10,023	0.8
Track Loader 3	5	0.45	3.5	59	2	22	11	0.8	53	2	20	10,033	0.7
Wheel Loader 1	5	0.45	2.9	87	9	37	9	0.8	97	11	41	9,976	0.9
Wheel Loader 2	5	0.45	2.8	102	13	11	9	0.8	117	15	13	9,999	1.0
Wheel Loader 3	5	0.44	1.9	74	3	7	6	0.3	147	7	15	9,820	1.8
Wheel Loader 4	5	0.45	1.6	66	5	4	5	0.5	132	10	9	10,023	1.0
Wheel Loader 5	5	0.45	2.4	64	4	13	8	0.4	86	6	17	10,021	0.6

Table 9.7 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 6

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	6	0.54	1.7	49	6	9	5	0.1	96	12	17	10,005	0.1
Backhoe 2	6	0.56	2.4	68	3	18	8	1.5	89	4	29	10,009	1.8
Backhoe 3	6	0.55	0.3	7	1	4	1	0.3	67	12	36	10,089	2.7
Backhoe 4	6	0.54	0.9	33	4	3	3	0.2	119	14	11	9,999	0.8
Backhoe 5	6	0.56	2.6	108	9	193	8	0.9	128	10	229	9,683	1.1
Backhoe 6	6	0.55	2.5	81	14	37	8	1.0	104	18	48	9,895	1.3
Backhoe 7	6	0.56	2.8	62	5	51	9	1.0	70	8	71	9,708	1.2
Backhoe 8	6	0.56	1.0	42	3	5	3	0.3	142	9	16	10,006	1.0
Bulldozer 1	6	0.55	3.3	140	7	27	10	1.4	133	7	26	10,005	1.4
Bulldozer 2	6	0.55	2.2	63	9	11	7	0.7	126	22	60	9,917	0.7
Bulldozer 3	6	0.55	0.6	33	3	22	2	0.2	177	18	118	9,834	1.3
Bulldozer 4	6	0.55	0.9	64	6	13	3	0.2	239	21	49	10,034	0.9
Bulldozer 5	6	0.55	9.9	543	9	94	31		178	3	32	10,133	
Bulldozer 6	6	0.57	1.0	24	1	7	3	0.5	78	3	22	10,030	1.5
Excavator 1	6	0.55	6.1	195	6	18	19	2.2	103	3	9	10,043	1.2
Excavator 2	6	0.55	4.3	93	8	27	14	1.0	68	6	20	10,021	0.7
Excavator 3	6	0.55	2.4	81	7	8	7	0.5	110	10	10	10,020	0.8
Motor Grader 1	6	0.55	4.6	165	16	17	14	1.4	112	12	12	10,014	1.0
Motor Grader 2	6	0.54	5.9	151	23	26	18	1.0	83	13	15	10,006	0.5
Motor Grader 3	6	0.56	2.8	85	51		9	1.0	97	58		9,900	1.2
Motor Grader 4	6	0.54	4.8	304	33	62	15	1.5	201	22	45	9,928	1.1
Motor Grader 5	6	0.56	5.8	257	15	51	18	1.3	141	8	29	9,998	0.7
Motor Grader 6	6	0.55	3.0	49	9	6	9	0.7	53	10	6	10,026	0.8
Off-Road Truck 1	6	0.55	6.0	201	15	132	19	2.1	109	9	67	9,933	1.2
Off-Road Truck 2	6	0.54	8.7	241	11	69	27	2.3	86	5	29	10,114	0.9
Off-Road Truck 3	6	0.45	7.7	239	14	44	24	2.2	99	6	18	10,019	0.9
Track Loader 1	6	0.55	3.4	57	12	24	11	0.9	53	11	22	9,999	0.9
Track Loader 2	6	0.56	2.5	122	7	10	8	0.7	148	8	13	10,025	1.2
Track Loader 3	6	0.55	4.2	69	3	23	13	0.9	52	2	18	10,036	0.7
Wheel Loader 1	6	0.55	3.3	95	11	39	10	0.9	93	11	38	9,982	0.9
Wheel Loader 2	6	0.55	3.2	114	15	12	10	1.0	113	15	12	10,003	1.0
Wheel Loader 3	6	0.55	2.2	82	4	7	7	0.4	151	17	17	9,742	2.2
Wheel Loader 4	6	0.55	1.9	73	6	5	6	0.6	126	10	9	10,024	1.1
Wheel Loader 5	6	0.55	2.7	74	5	16	8	0.5	88	6	19	10,020	0.7

Table 9.8 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 7

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	7	0.66	2.1	56	9	13	7	0.1	86	13	19	9,995	0.1
Backhoe 2	7	0.66	2.8	77	3	23	9	1.9	90	4	34	10,002	2.0
Backhoe 3	7	0.65	0.3	7	1	4	1	0.3	68	12	36	10,102	2.7
Backhoe 4	7	0.65	1.0	34	4	3	3	0.2	115	12	10	10,016	0.8
Backhoe 5	7	0.65	2.9	123	9	167	9	1.1	130	10	176	9,767	1.1
Backhoe 6	7	0.66	2.8	89	17	43	9	1.1	101	19	49	9,939	1.3
Backhoe 7	7	0.64	3.0	63	4	65	9	1.5	66	8	80	9,696	1.6
Backhoe 8	7	0.65	1.1	49	3	6	3	0.3	150	8	18	10,005	1.1
Bulldozer 1	7	0.64	3.7	147	7	30	12	1.7	125	6	27	10,007	1.5
Bulldozer 2	7	0.65	2.4	65	10	12	7	0.8	124	18	51	9,941	0.8
Bulldozer 3	7	0.66	0.7	32	3	25	2	0.2	158	17	122	9,829	0.8
Bulldozer 4	7	0.65	1.1	72	10	13	3	0.3	206	29	36	9,880	0.8
Bulldozer 5	7	0.65	11.2	629	11	91	35		182	3	27	10,141	
Bulldozer 6	7	0.66	1.1	23	2	4	3	0.5	68	7	11	10,032	1.7
Excavator 1	7	0.65	7.1	229	7	19	22	2.8	104	3	9	10,044	1.3
Excavator 2	7	0.65	4.8	101	8	27	15	1.2	67	6	18	10,025	0.8
Excavator 3	7	0.65	2.7	91	8	8	8	0.7	108	10	9	10,022	0.9
Motor Grader 1	7	0.65	5.5	195	17	20	17	1.6	110	10	11	10,021	1.0
Motor Grader 2	7	0.64	6.3	150	27	34	20	1.3	76	14	17	10,000	0.6
Motor Grader 3	7	0.64	3.3	101	61		10	1.1	98	60		9,901	1.1
Motor Grader 4	7	0.64	5.4	363	39	68	17	1.7	209	23	42	9,929	1.0
Motor Grader 5	7	0.64	6.7	314	14	40	21	1.5	149	7	19	10,019	0.7
Motor Grader 6	7	0.64	3.7	60	8	9	12	0.7	53	7	8	10,033	0.7
Off-Road Truck 1	7	0.65	6.3	207	15	137	20	2.2	107	8	65	9,938	1.2
Off-Road Truck 2	7	0.66	10.1	271	8	48	32	3.0	86	3	15	10,145	0.9
Off-Road Truck 3	7	0.66	9.9	289	14	49	31	2.3	93	4	16	10,028	0.7
Track Loader 1	7	0.64	4.0	68	13	22	13	0.9	54	10	18	10,006	0.7
Track Loader 2	7	0.65	2.9	137	6	12	9	0.8	143	6	13	10,031	1.1
Track Loader 3	7	0.65	4.6	74	3	23	14	0.9	52	2	16	10,038	0.7
Wheel Loader 1	7	0.65	3.7	103	12	43	11	1.1	91	11	38	9,981	1.0
Wheel Loader 2	7	0.65	3.7	126	16	14	12	1.2	108	14	12	10,005	1.0
Wheel Loader 3	7	0.65	2.6	91	6	9	8	0.4	125	13	14	9,782	1.0
Wheel Loader 4	7	0.65	2.1	77	6	5	7	0.7	120	10	8	10,023	1.1
Wheel Loader 5	7	0.65	3.2	87	5	15	10	0.6	88	5	15	10,029	0.6

Table 9.9 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 8

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	8	0.74	2.4	72	9	14	7	0.1	98	12	19	9,998	0.1
Backhoe 2	8	0.74	3.2	90	3	17	10	2.9	91	3	19	10,027	2.8
Backhoe 3	8	0.75	0.3	8	1	3	1	0.3	80	12	29	10,116	2.8
Backhoe 4	8	0.76	1.2	42	4	4	4	0.3	113	10	10	10,016	0.8
Backhoe 5	8	0.75	3.3	143	10	132	10	1.3	135	9	124	9,850	1.2
Backhoe 6	8	0.75	3.3	109	20	35	10	1.4	105	19	34	9,982	1.3
Backhoe 7	8	0.74	3.1	58	5	96	9	1.9	59	9	118	9,630	1.9
Backhoe 8	8	0.75	1.1	47	3	6	4	0.4	134	8	16	10,014	1.1
Bulldozer 1	8	0.74	4.2	163	7	37	13	2.2	123	5	28	10,004	1.6
Bulldozer 2	8	0.74	2.8	76	11	27	9	1.1	119	15	33	9,979	0.9
Bulldozer 3	8	0.75	0.6	27	3	32	2	0.1	141	17	166	9,763	0.6
Bulldozer 4	8	0.75	1.2	77	8	16	4	0.3	203	21	41	10,010	0.8
Bulldozer 5	8	0.76	13.0	714	11	87	41		177	3	22	10,149	
Bulldozer 6	8	0.73	1.1	24	3	4	4	0.6	68	8	11	10,030	1.8
Excavator 1	8	0.75	7.9	263	6	19	25	2.9	106	2	8	10,048	1.2
Excavator 2	8	0.75	5.3	107	9	28	17	1.5	65	5	17	10,027	0.9
Excavator 3	8	0.75	3.0	100	8	8	10	0.8	105	10	9	10,022	1.0
Motor Grader 1	8	0.75	6.2	224	17	22	20	1.8	113	9	11	10,023	1.0
Motor Grader 2	8	0.75	6.9	174	25	30	22	1.2	81	11	14	10,010	0.6
Motor Grader 3	8	0.74	4.0	133	77		12	1.3	106	64		9,900	1.1
Motor Grader 4	8	0.75	6.4	444	43	68	20	2.0	220	22	37	9,943	1.1
Motor Grader 5	8	0.74	7.4	372	15	43	23	1.6	160	6	19	10,019	0.7
Motor Grader 6	8	0.75	4.5	72	5	12	14	0.8	51	4	9	10,040	0.6
Off-Road Truck 1	8	0.75	6.9	223	18	140	22	2.5	108	9	62	9,941	1.3
Off-Road Truck 2	8	0.77	10.9	418	8	95	34	4.7	124	2	28	10,113	1.4
Off-Road Truck 3	8	0.75	11.0	327	16	52	35	2.6	95	5	15	10,029	0.7
Track Loader 1	8	0.74	4.5	79	14	23	14	1.0	55	10	16	10,013	0.7
Track Loader 2	8	0.76	3.9	225	7	13	12	0.8	178	5	11	10,038	0.8
Track Loader 3	8	0.75	5.1	80	4	24	16	1.0	50	2	15	10,039	0.6
Wheel Loader 1	8	0.75	4.2	117	13	48	13	1.3	90	11	38	9,982	1.1
Wheel Loader 2	8	0.75	4.2	136	18	16	13	1.6	103	14	12	10,005	1.2
Wheel Loader 3	8	0.74	3.0	104	7	10	9	0.5	125	17	12	9,797	1.4
Wheel Loader 4	8	0.76	2.5	89	7	6	8	0.8	115	9	8	10,025	1.1
Wheel Loader 5	8	0.76	3.9	102	5	19	12	0.8	84	4	16	10,030	0.6

Table 9.10 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 9

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	9	0.85	2.8	73	9	14	9	0.1	83	10	15	10,012	0.1
Backhoe 2	9	0.85	2.8	83	5	31	9	0.3	98	7	49	9,968	0.3
Backhoe 3	9	0.84	0.4	12	1	1	1	0.2	82	8	9	10,100	2.3
Backhoe 4	9	0.86	1.3	44	4	4	4	0.3	105	11	11	10,017	0.8
Backhoe 5	9	0.84	3.6	162	10	117	12	1.5	139	8	100	9,891	1.3
Backhoe 6	9	0.85	3.8	120	21	34	12	1.7	101	18	28	10,005	1.4
Backhoe 7	9	0.85	3.0	52	5	112	9	2.0	54	20	127	9,594	2.1
Backhoe 8	9	0.85	1.3	53	3	8	4	0.4	130	9	20	10,010	1.1
Bulldozer 1	9	0.85	4.8	185	8	41	15	2.4	124	5	27	10,009	1.6
Bulldozer 2	9	0.85	3.1	82	11	12	10	1.3	134	23	53	9,921	0.6
Bulldozer 3	9	0.84	0.6	25	3	32	2	0.1	143	17	178	9,744	0.7
Bulldozer 4	9	0.85	1.4	89	8	17	4	0.3	210	21	41	10,039	0.8
Bulldozer 5	9	0.85	15.0	888	11	73	47		191	2	16	10,160	
Bulldozer 6	9	0.88	1.3	27	3	6	4	1.1	65	7	15	10,030	2.5
Excavator 1	9	0.84	8.6	293	6	17	27	3.3	109	2	6	10,050	1.2
Excavator 2	9	0.85	5.8	114	9	29	18	1.8	63	5	16	10,029	1.0
Excavator 3	9	0.85	3.4	110	8	10	11	1.1	104	9	9	10,025	1.1
Motor Grader 1	9	0.85	7.7	283	20	28	24	2.1	116	9	12	10,025	0.9
Motor Grader 2	9	0.85	7.9	182	25	21	25	1.3	73	10	8	10,022	0.5
Motor Grader 3	9	0.85	4.5	158	83		14	1.6	112	60		9,910	1.2
Motor Grader 4	9	0.85	7.5	554	46	66	24	2.6	233	19	29	9,962	1.1
Motor Grader 5	9	0.85	8.3	434	13	43	26	1.8	166	5	16	10,027	0.7
Motor Grader 6	9	0.85	5.3	82	4	12	17	0.9	49	3	8	10,045	0.6
Off-Road Truck 1	9	0.85	8.1	268	19	148	25	3.1	110	8	57	9,951	1.4
Off-Road Truck 2	9	0.84	12.8	337	6	107	40	3.9	85	2	27	10,048	1.0
Off-Road Truck 3	9	0.84	11.5	340	15	44	36	2.8	94	4	12	10,034	0.7
Track Loader 1	9	0.85	5.2	96	17	22	16	1.2	58	10	13	10,015	0.7
Track Loader 2	9	0.85	4.7	297	8	15	15	1.0	197	5	10	10,039	0.8
Track Loader 3	9	0.86	5.8	99	3	22	18	1.0	55	2	12	10,046	0.6
Wheel Loader 1	9	0.85	4.7	130	14	51	15	1.6	88	10	35	9,988	1.1
Wheel Loader 2	9	0.84	4.7	147	20	15	15	1.7	100	14	11	10,008	1.2
Wheel Loader 3	9	0.84	3.6	124	6	10	11	0.6	113	6	9	9,812	0.6
Wheel Loader 4	9	0.84	3.0	109	6	6	9	0.9	116	7	7	10,035	1.0
Wheel Loader 5	9	0.85	4.4	109	5	22	14	1.0	80	4	16	10,030	0.7

Table 9.11 Average Normalized MAP, Fuel Use Rates, and Emission Rates for Mode 10

Equipment Item	Engine Mode	Avg. Norm. MAP	Fuel [g/s]	NO _x [g/s]	HC [g/s]	CO [g/s]	CO ₂ [g/s]	PM [mg/s]	NO _x [g/gal]	HC [g/gal]	CO [g/gal]	CO ₂ [g/gal]	PM [g/gal]
Backhoe 1	10	0.95	3.1	79	13	15	10	0.1	84	12	15	10,006	0.1
Backhoe 2	10	0.95	3.4	108	4	36	11	0.3	110	8	39	9,984	0.3
Backhoe 3	10	0.97	0.3	7	1	2	1	0.2	75	7	25	10,092	2.1
Backhoe 4	10	0.94	1.5	51	5	6	5	0.4	111	11	12	10,015	0.9
Backhoe 5	10	0.94	3.8	188	11	102	12	1.6	155	9	85	9,914	1.3
Backhoe 6	10	0.94	4.5	167	11	46	16	2.0	104	7	29	10,073	1.2
Backhoe 7	10	0.94	3.4	58	3	119	10	2.3	54	3	112	9,659	2.1
Backhoe 8	10	0.93	1.4	57	4	8	4	0.5	129	9	18	10,006	1.1
Bulldozer 1	10	0.96	5.1	194	9	39	16	2.5	120	5	24	10,014	1.6
Bulldozer 2	10	0.94	3.3	79	13	12	10	1.3	130	24	49	9,923	0.5
Bulldozer 3	10	0.94	0.5	27	4	29	2	0.2	156	21	170	9,743	1.1
Bulldozer 4	10	0.92	1.9	109	9	26	6	0.6	197	18	44	10,066	1.1
Bulldozer 5	10	0.93	16.3	1030	12	69	51		204	2	14	10,163	
Bulldozer 6	10	1.00	1.3	33	9	8	4	1.9	78	20	18	9,984	4.5
Excavator 1	10	0.93	9.3	321	6	16	29	3.8	110	2	6	10,052	1.3
Excavator 2	10	0.93	6.0	117	9	28	19	2.1	62	5	15	10,032	1.1
Excavator 3	10	0.93	3.7	122	7	11	12	1.1	105	8	10	10,028	1.1
Motor Grader 1	10	0.94	9.0	324	19	31	28	2.4	112	7	11	10,031	0.9
Motor Grader 2	10	0.95	8.7	217	24	18	28	1.6	79	9	7	10,029	0.6
Motor Grader 3	10	0.96	5.8	217	60		18	2.0	117	34		9,962	1.2
Motor Grader 4	10	0.93	7.8	575	47	75	24	2.7	232	19	31	9,959	1.1
Motor Grader 5	10	0.87	8.4	439	13	41	27	1.8	165	5	16	10,028	0.7
Motor Grader 6	10	0.94	6.1	110	4	20	19	1.2	57	2	10	10,043	0.6
Off-Road Truck 1	10	0.93	9.6	295	22	163	30	3.2	102	8	52	9,960	1.2
Off-Road Truck 2	10	0.95	13.2	340	15	43	42	3.6	83	4	10	10,129	0.9
Off-Road Truck 3	10	0.96	12.2	392	14	39	39	3.3	102	4	10	10,038	0.9
Track Loader 1	10	0.94	5.9	109	17	21	18	1.4	59	9	11	10,020	0.8
Track Loader 2	10	0.95	5.5	381	8	17	17	1.0	218	5	10	10,043	0.7
Track Loader 3	10	0.92	6.1	113	2	22	19	1.0	59	1	11	10,049	0.5
Wheel Loader 1	10	0.93	5.6	158	15	68	18	2.0	90	9	38	9,987	1.2
Wheel Loader 2	10	0.94	5.1	158	22	17	16	2.0	98	13	10	10,009	1.2
Wheel Loader 3	10	0.93	4.1	140	6	11	13	0.6	109	5	8	9,817	0.4
Wheel Loader 4	10	0.94	3.9	138	8	10	12	1.3	114	6	8	10,033	1.1
Wheel Loader 5	10	0.95	5.4	130	7	21	17	1.3	76	4	13	10,034	0.8

9.4 Appendix D: Boxplots for Fuel Use and Emission Rates Field Data

This appendix provides the boxplots that were used to determine outliers in the fuel use and emissions field data. Figure 9.11 through Figure 9.20 are the boxplots for the fuel use rate and emission rates of NO_x, HC, CO, and PM for each of the ten engine modes. Because the CO₂ emission rates are on a much higher scale than the other pollutants, the CO₂ boxplots for each engine mode are shown in Figure 9.21 through Figure 9.30. The outliers are indicated by an asterisk in the boxplots. Although identity of the outlier is not shown on the graph, it is easily determined from the Minitab software and shown in the data tables in Appendix C.

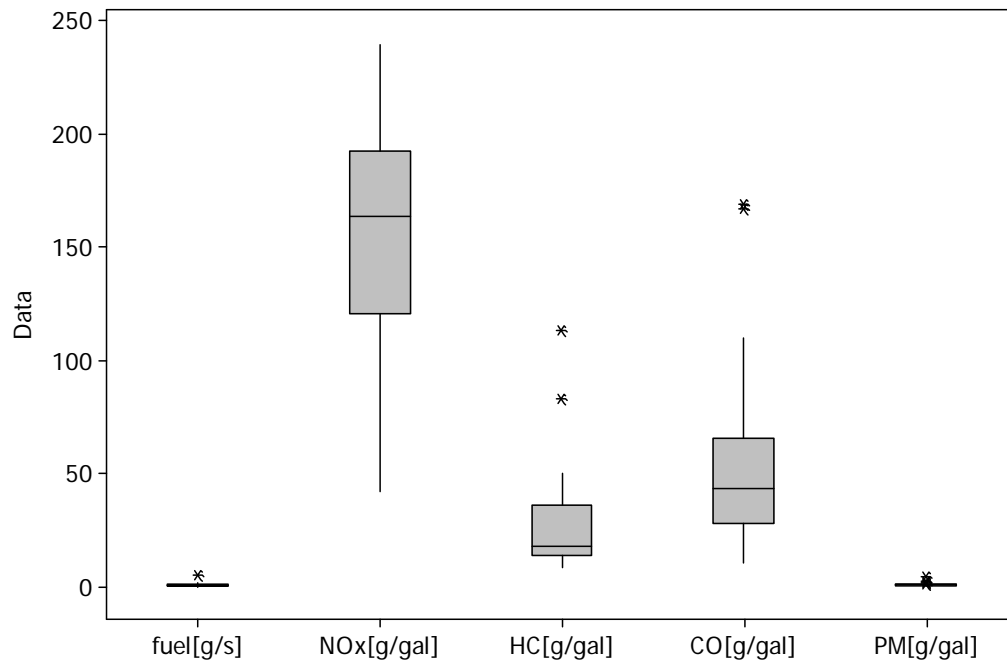


Figure 9.11 Boxplots for Mode 1 Fuel Use and Emission Rates

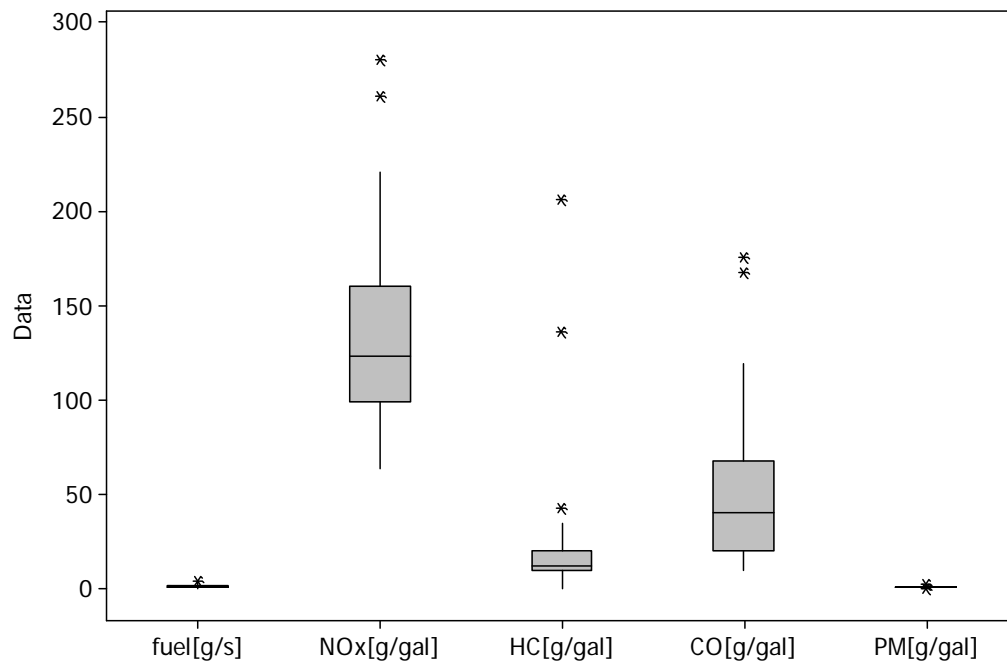


Figure 9.12 Boxplots for Mode 2 Fuel Use and Emission Rates

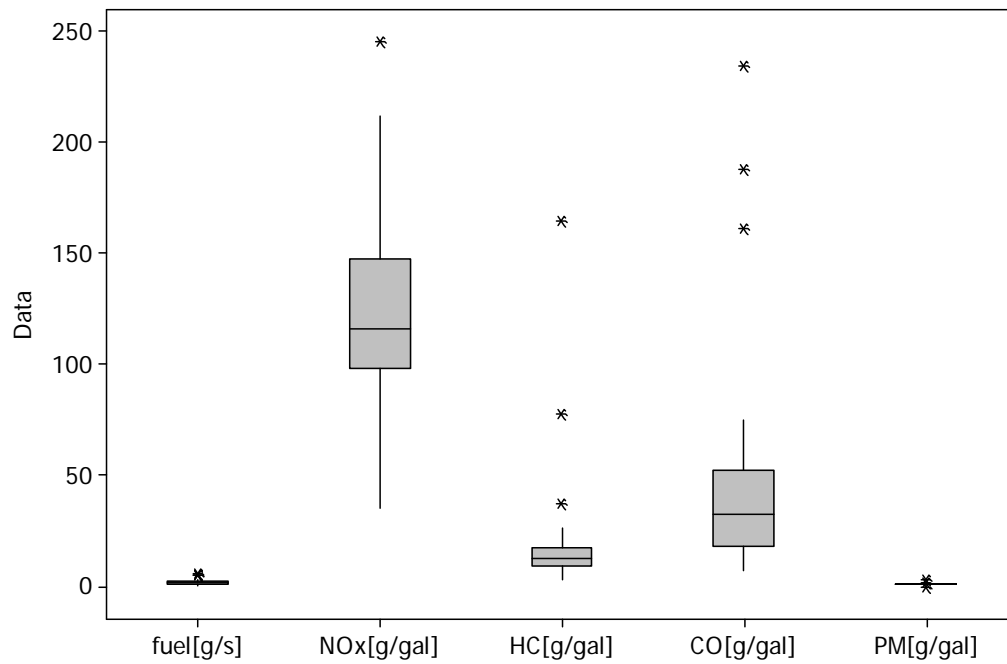


Figure 9.13 Boxplots for Mode 3 Fuel Use and Emission Rates

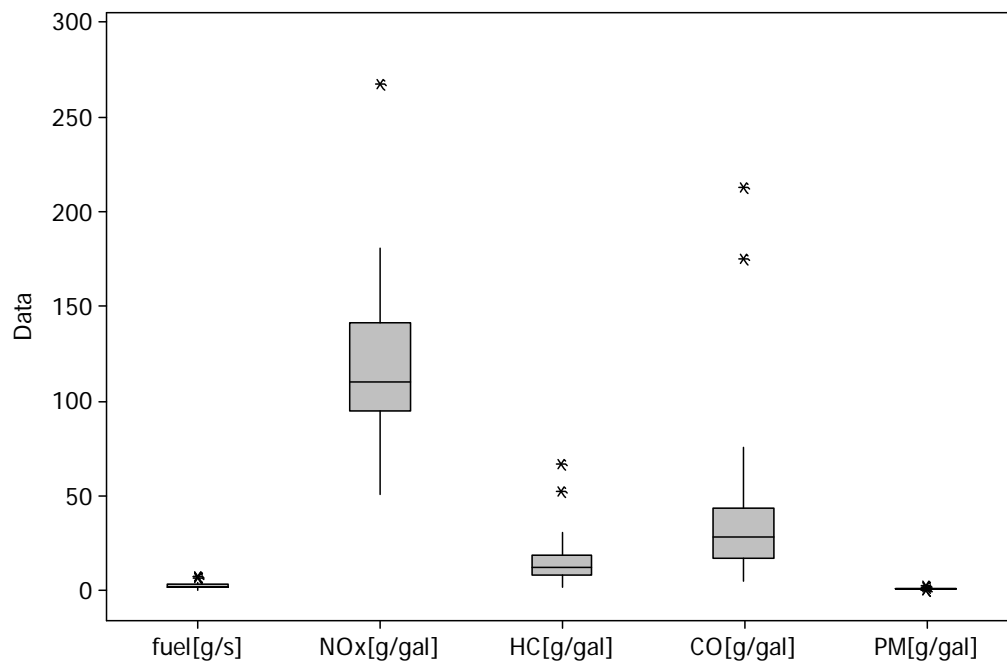


Figure 9.14 Boxplots for Mode 4 Fuel Use and Emission Rates

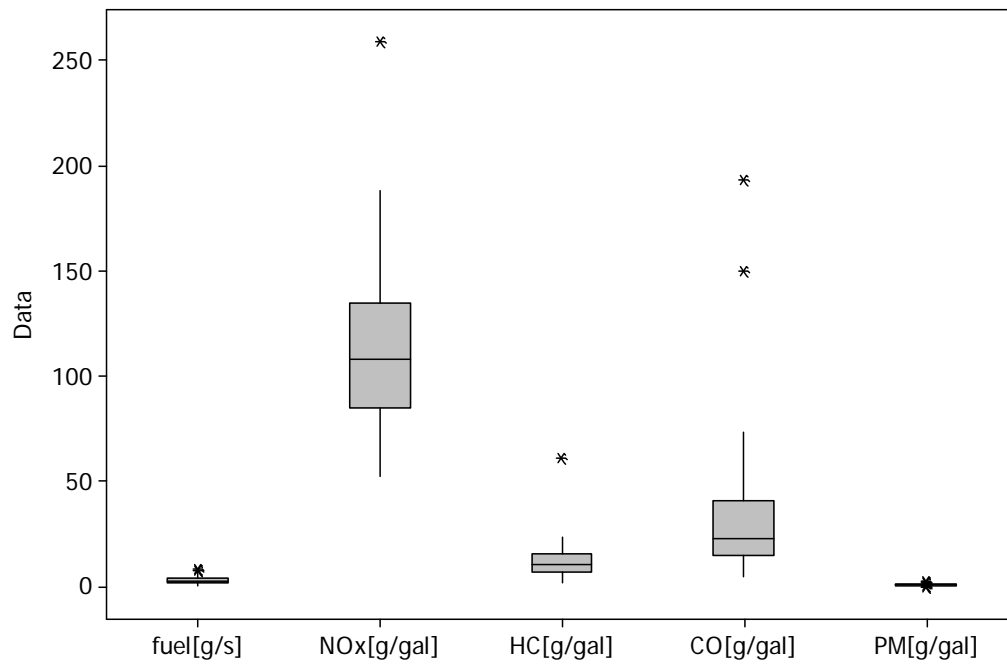


Figure 9.15 Boxplots for Mode 5 Fuel Use and Emission Rates

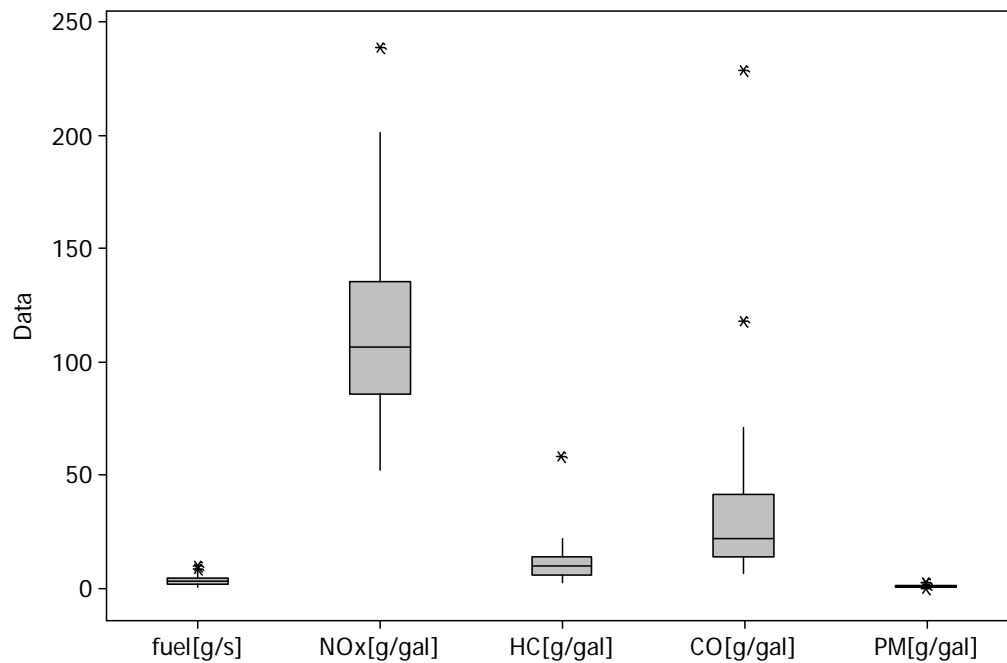


Figure 9.16 Boxplots for Mode 6 Fuel Use and Emission Rates

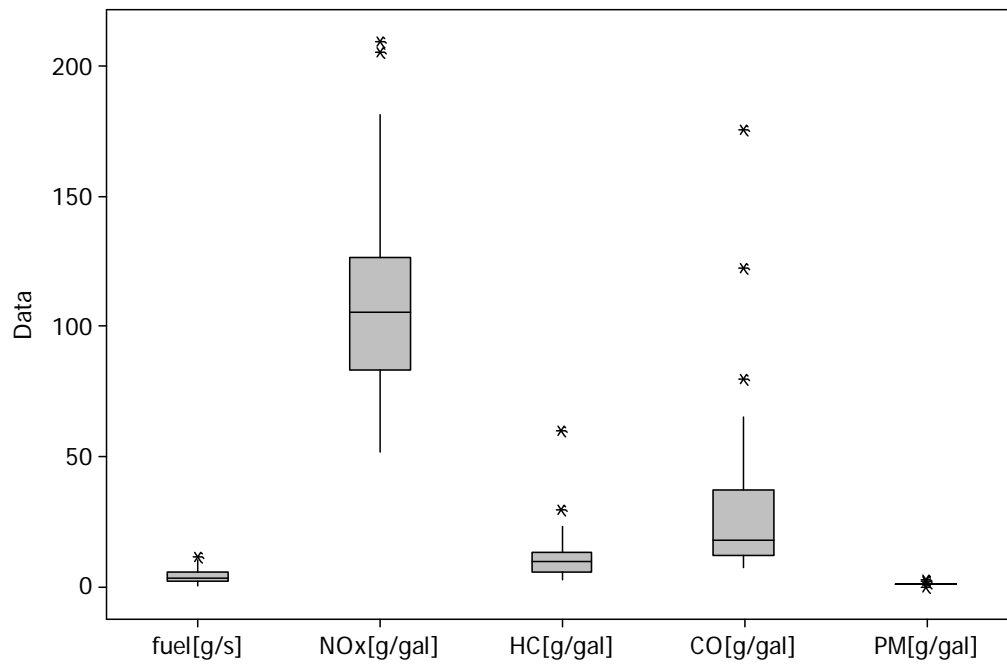


Figure 9.17 Boxplots for Mode 7 Fuel Use and Emission Rates

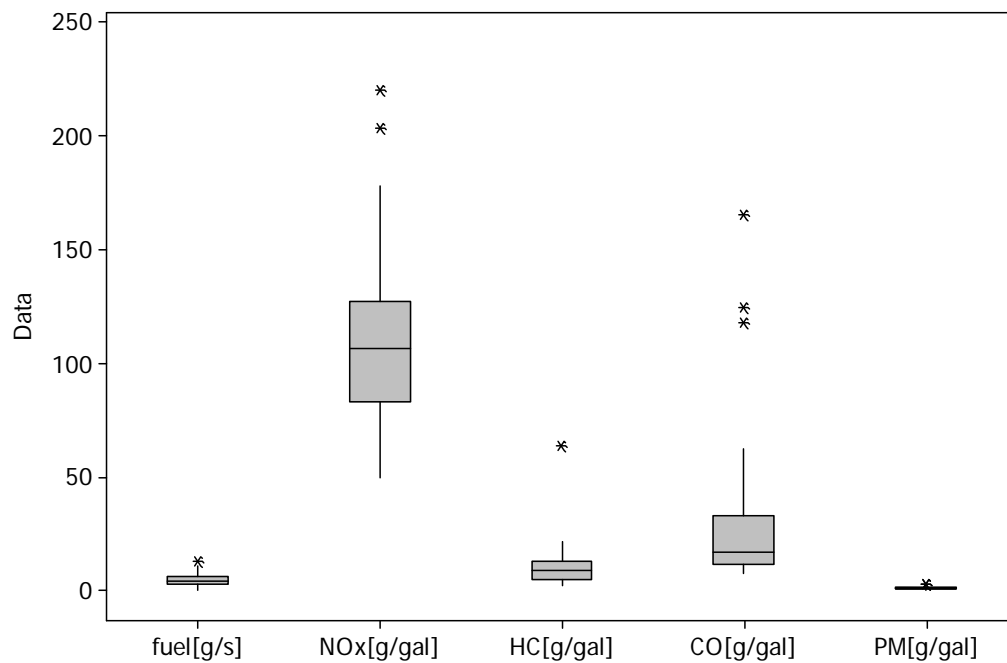


Figure 9.18 Boxplots for Mode 8 Fuel Use and Emission Rates

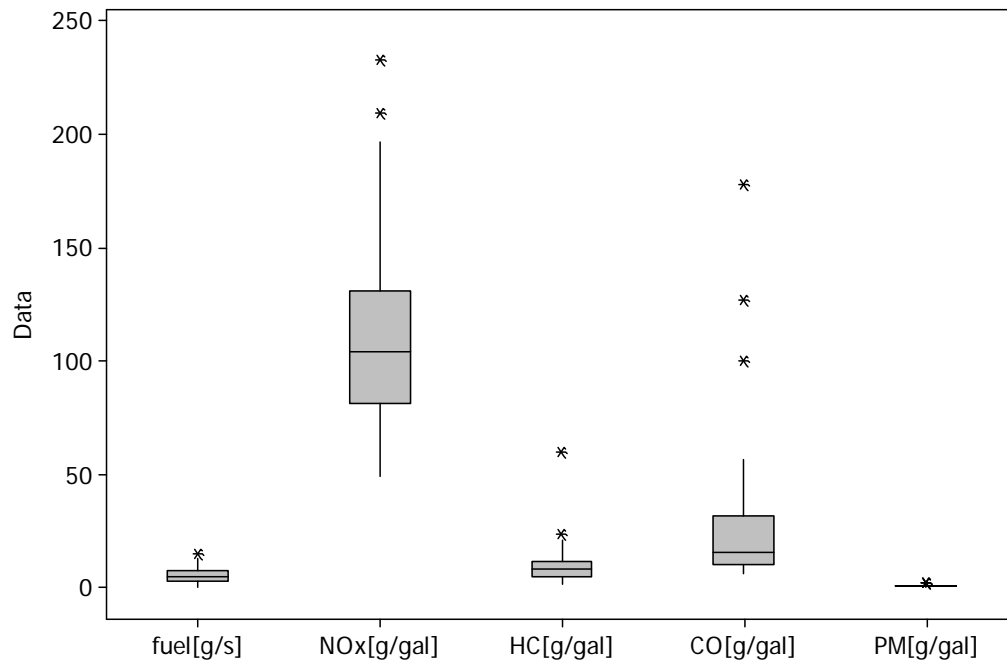


Figure 9.19 Boxplots for Mode 9 Fuel Use and Emission Rates

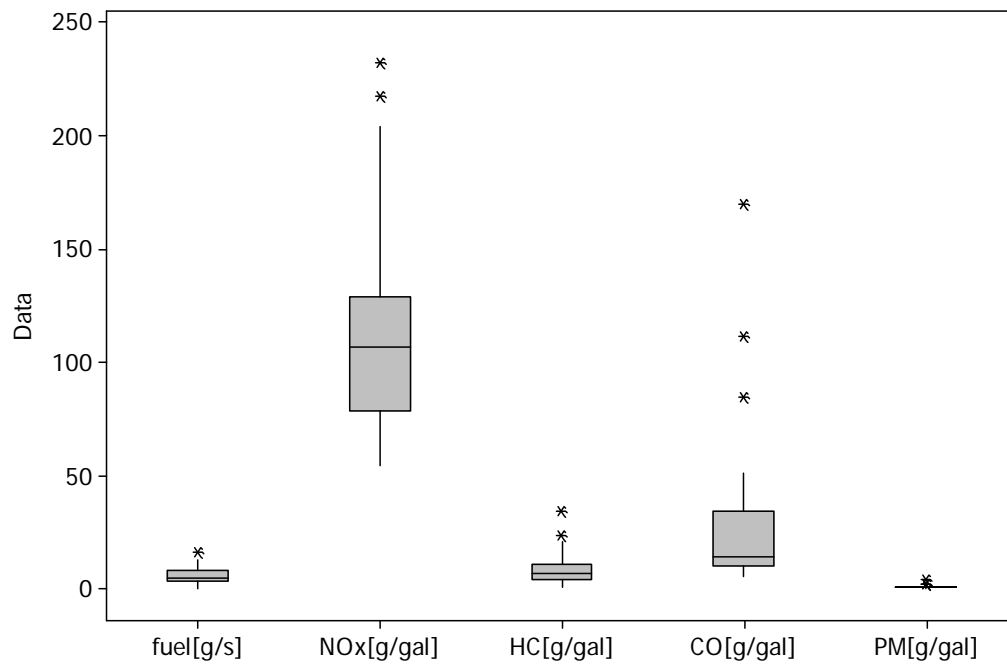


Figure 9.20 Boxplots for Mode 10 Fuel Use and Emission Rates

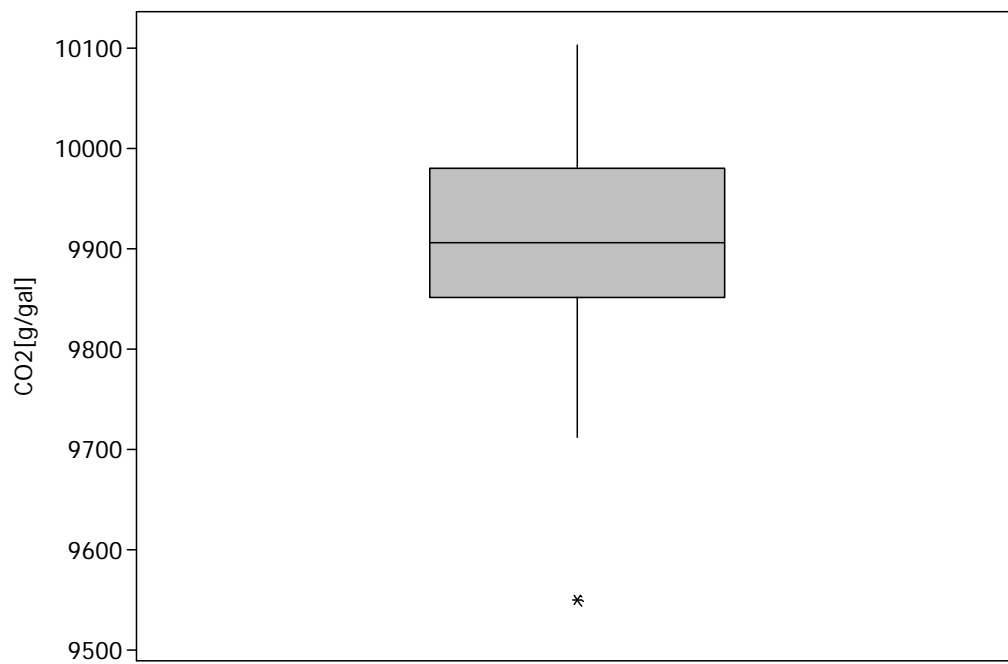


Figure 9.21 Boxplot for Mode 1 CO₂

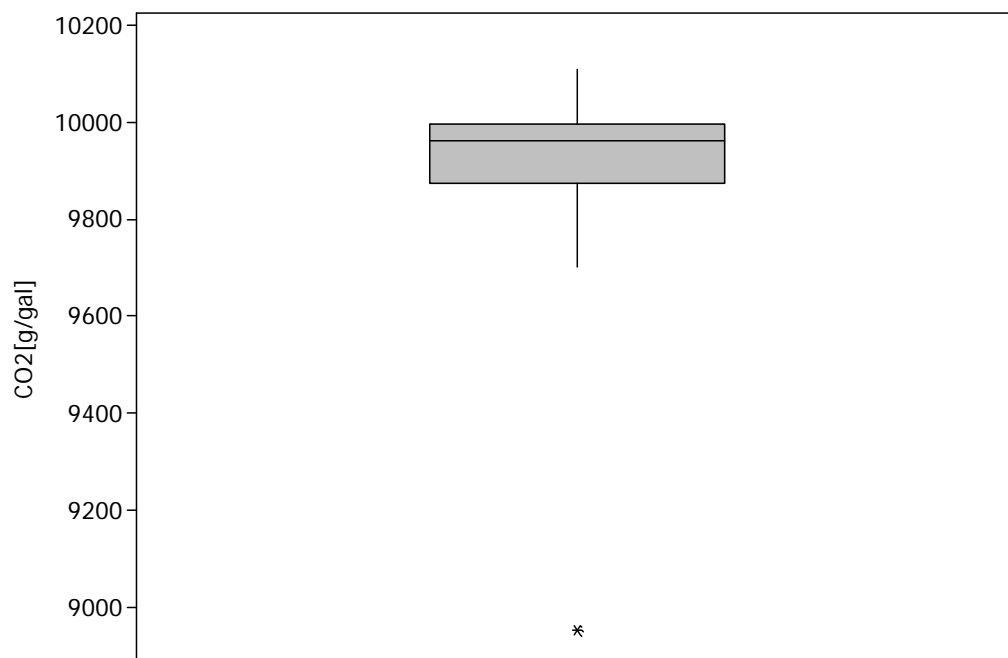


Figure 9.22 Boxplot for Mode 2 CO₂

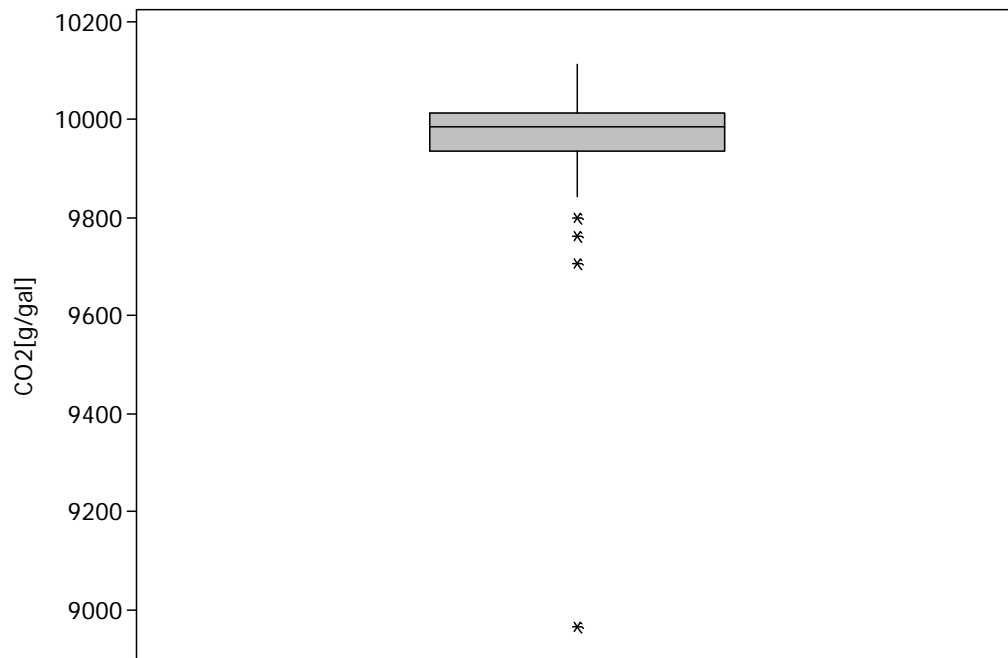


Figure 9.23 Boxplot for Mode 3 CO₂

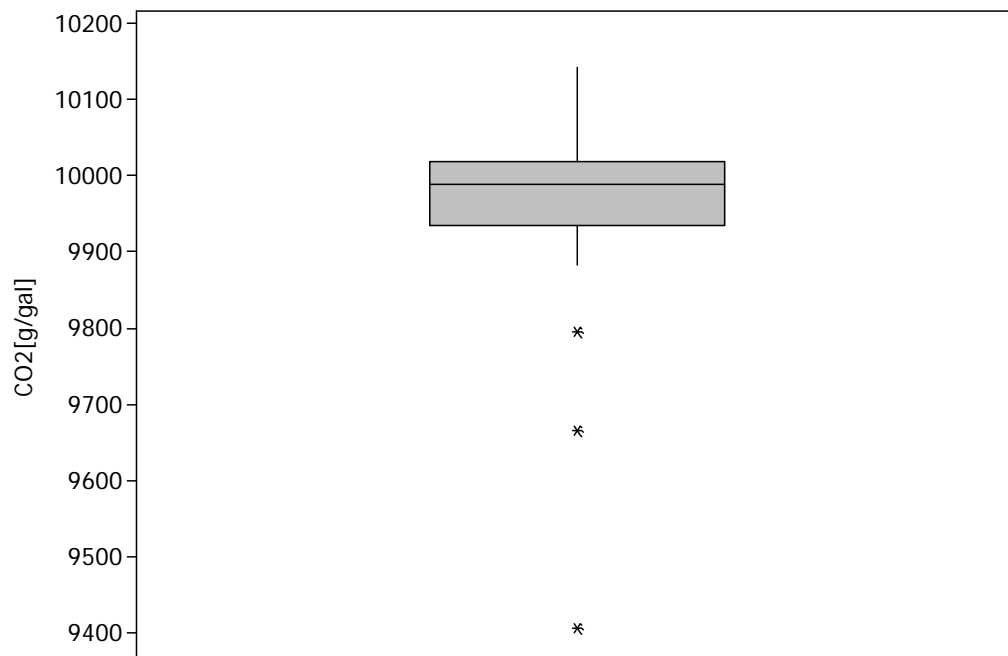


Figure 9.24 Boxplot for Mode 4 CO₂

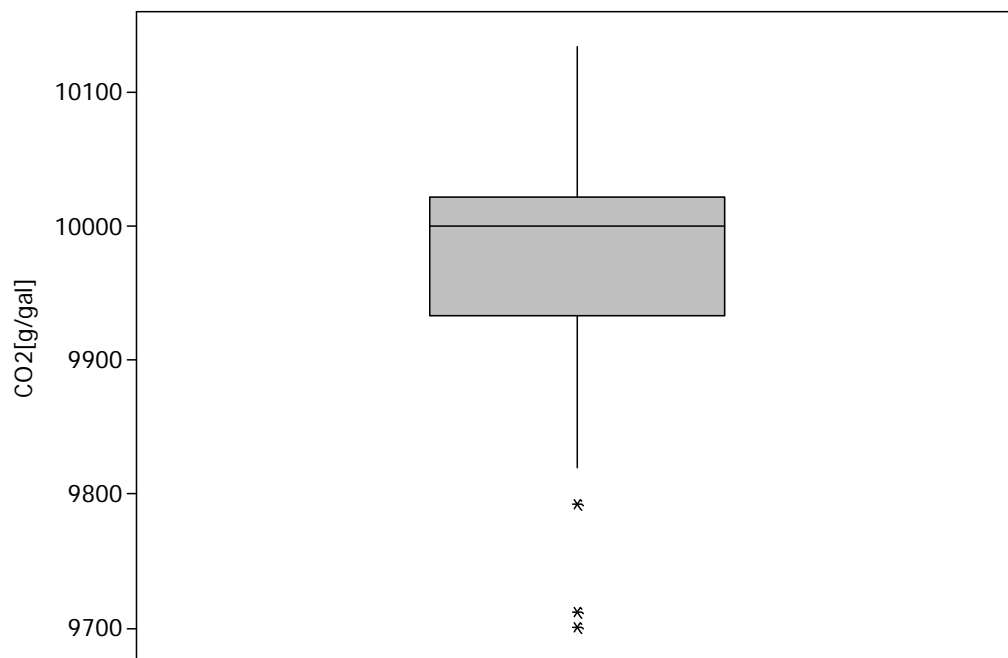


Figure 9.25 Boxplot for Mode 5 CO₂

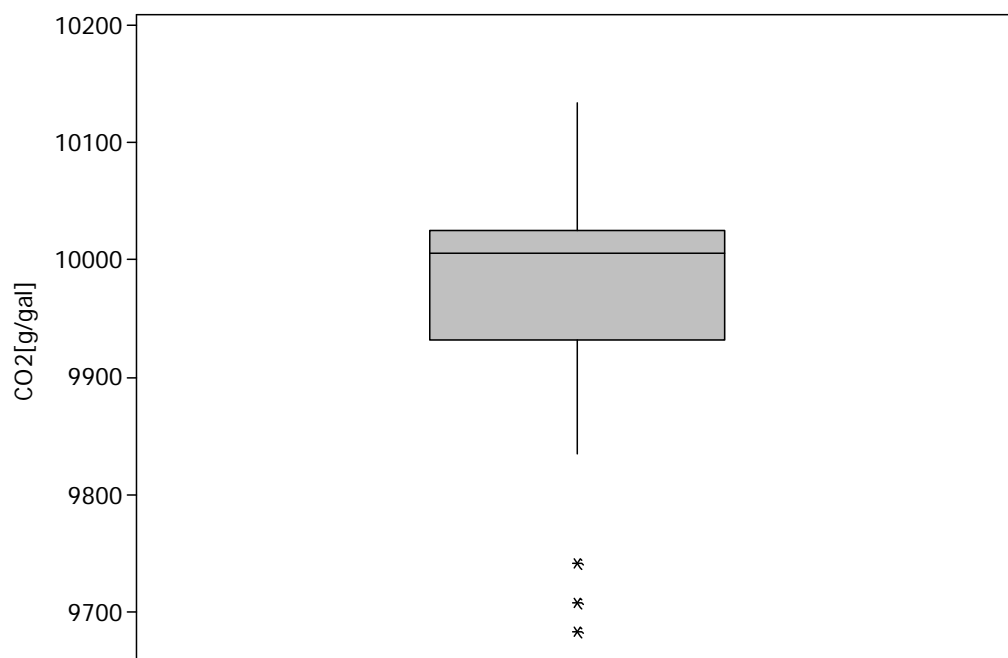


Figure 9.26 Boxplot for Mode 6 CO₂

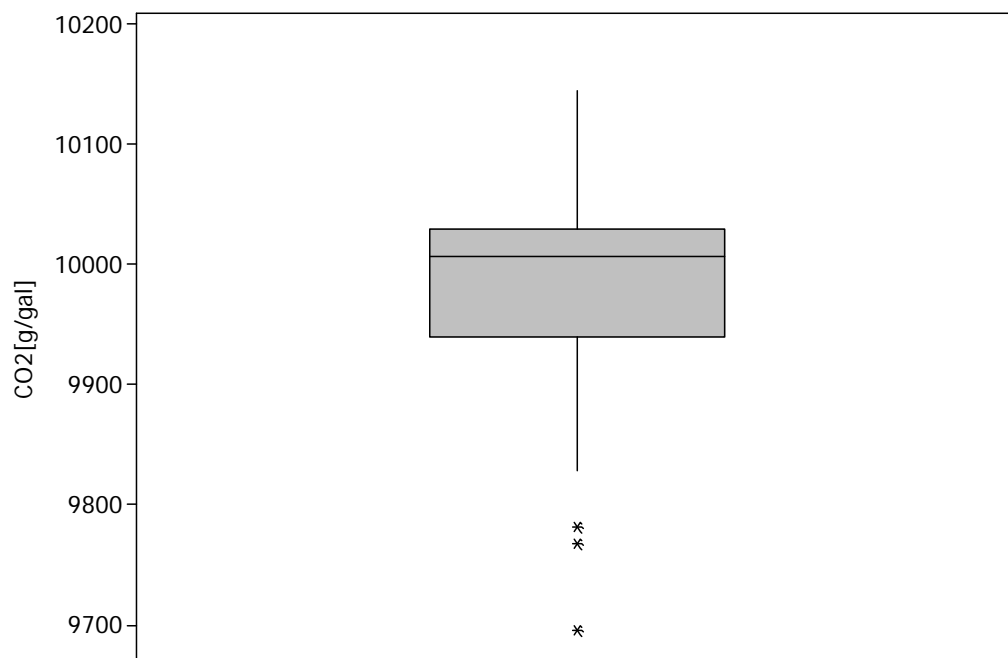


Figure 9.27 Boxplot for Mode 7 CO₂

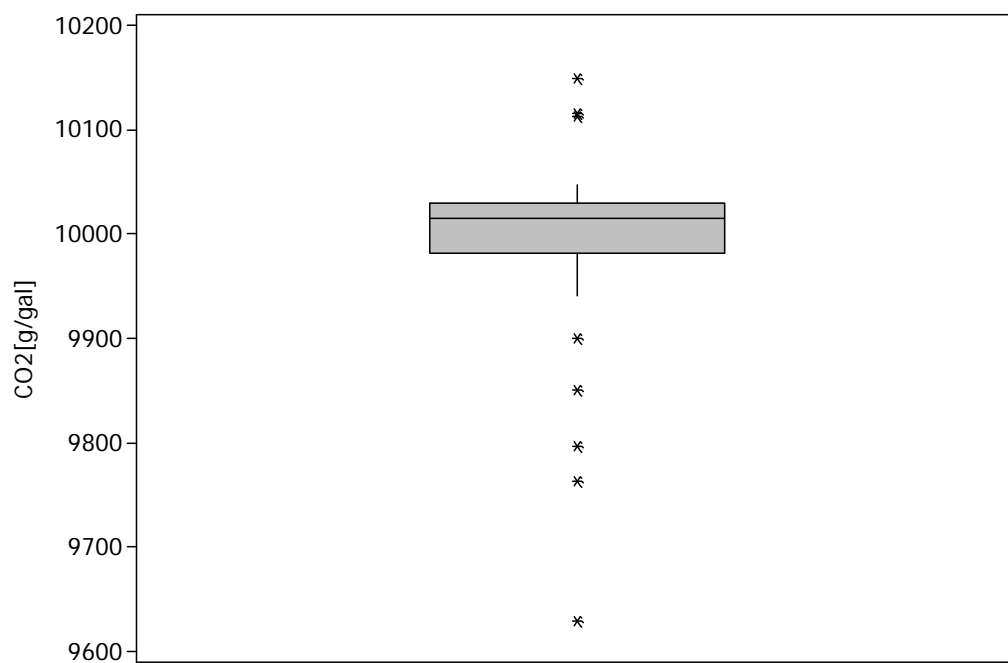


Figure 9.28 Boxplot for Mode 8 CO₂

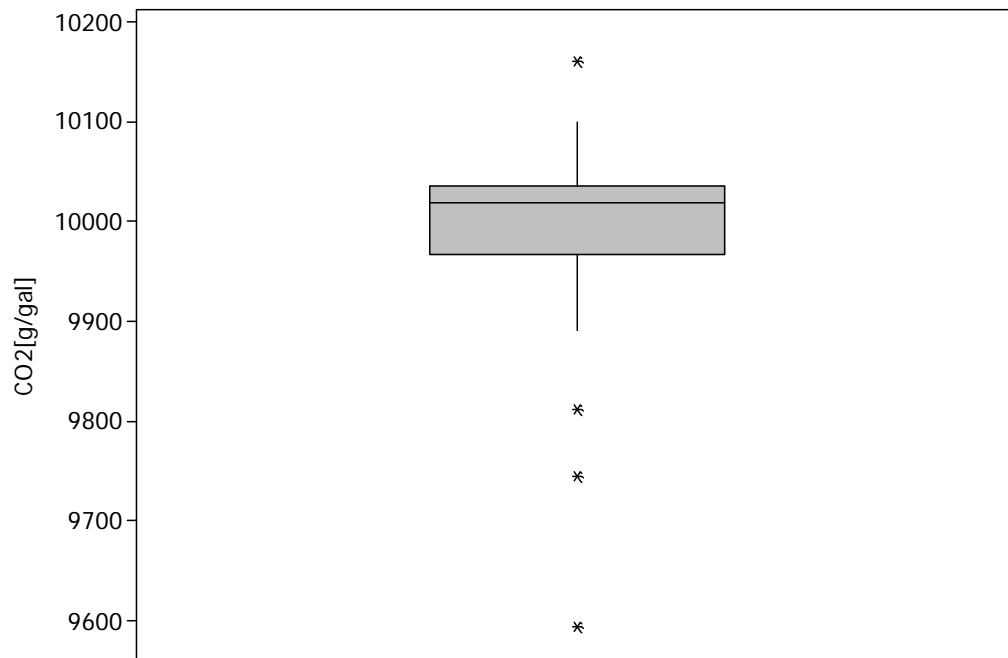


Figure 9.29 Boxplot for Mode 9 CO₂

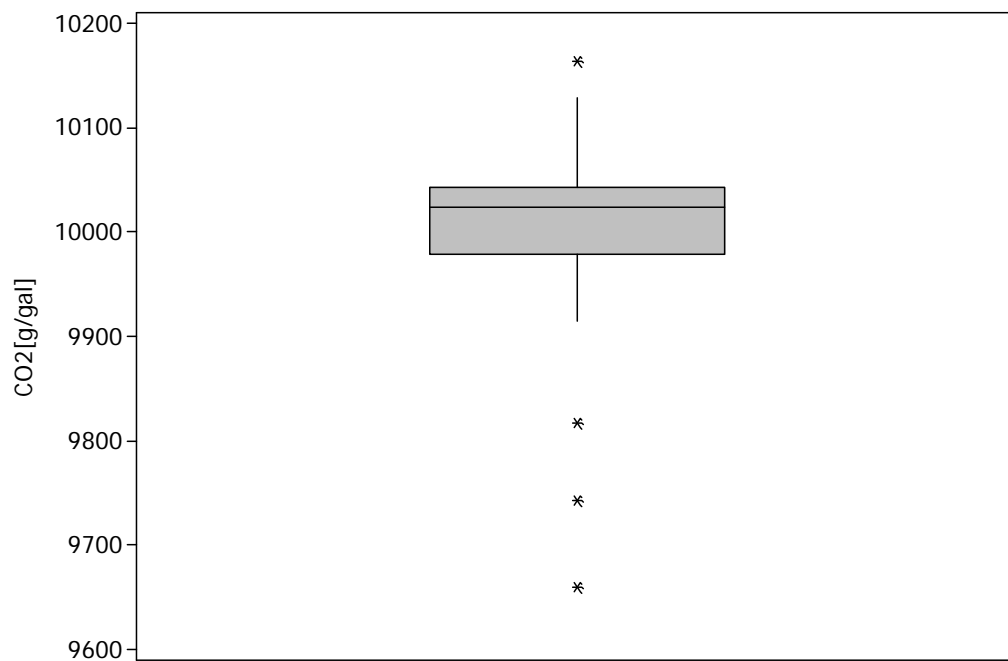


Figure 9.30 Boxplot for Mode 10 CO₂

9.5 Appendix E: Residual Plots for Regression Models Used for Estimating the Fuel Use Rate of Engine Modes

This appendix provides the residual plots used to check the conditions of multiple linear regression for the models that were used to estimate the fuel use rate for each of the ten engine modes. The residual plots include normal probability plots, residuals versus the fitted values, histogram of the residuals, and residuals versus the observation order. The residual plots were generated by Minitab.

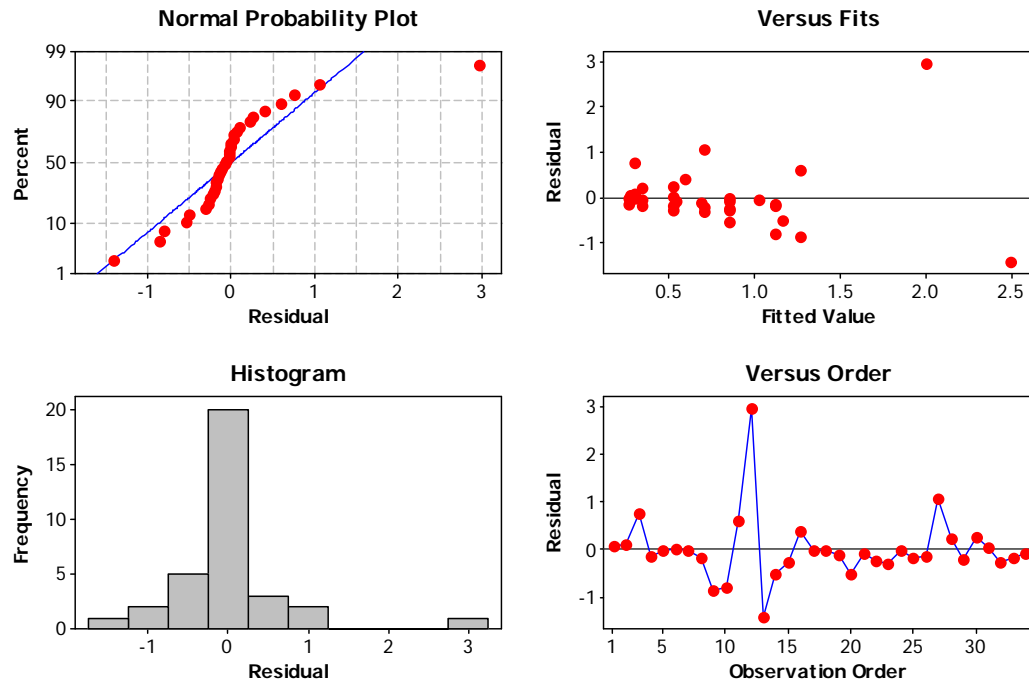


Figure 9.31 Residual Plots for Mode 1 Fuel Use

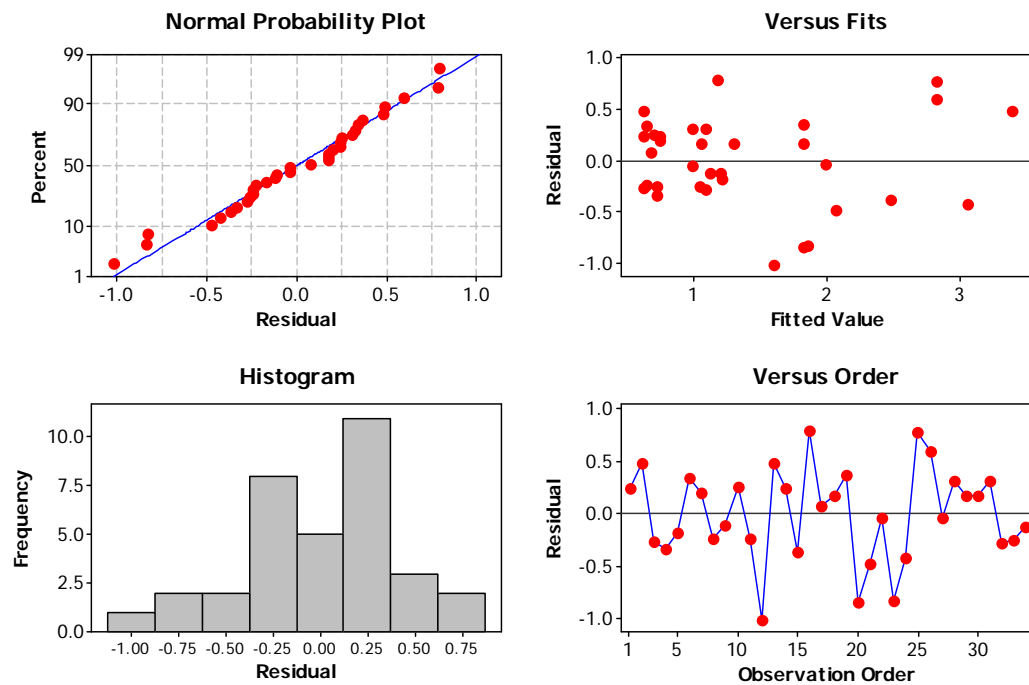


Figure 9.32 Residual Plots for Mode 2 Fuel Use

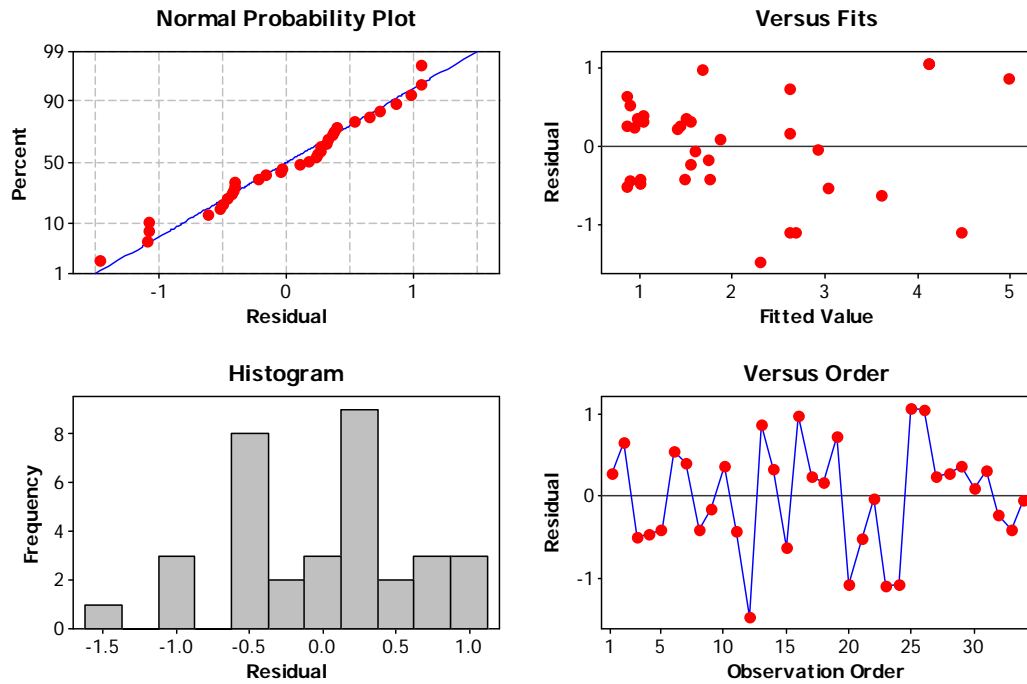


Figure 9.33 Residual Plots for Mode 3 Fuel Use

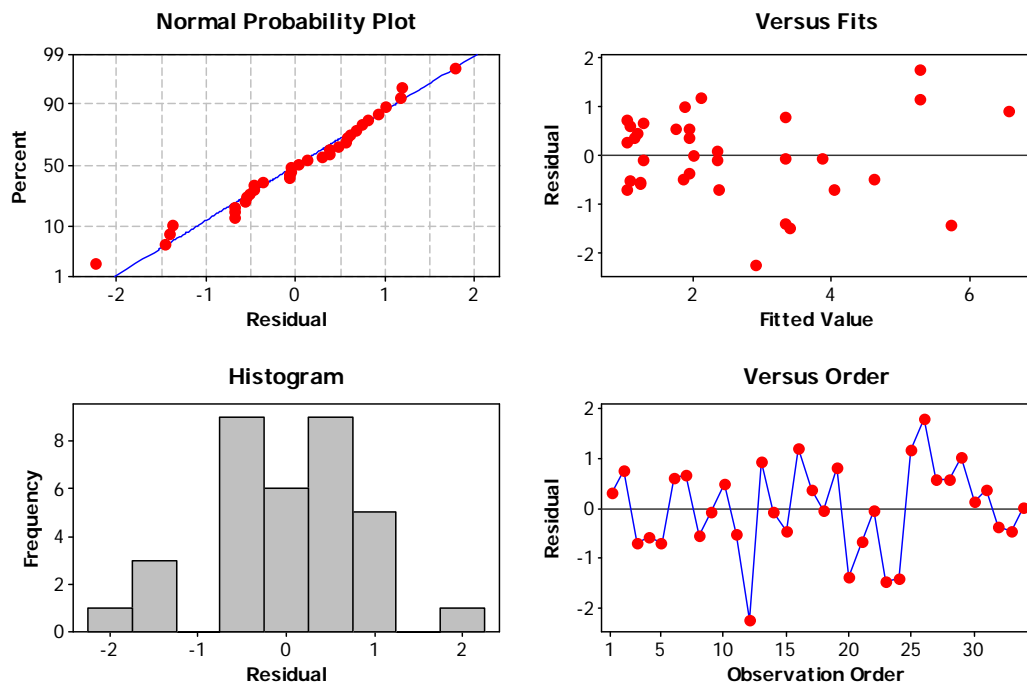


Figure 9.34 Residual Plots for Mode 4 Fuel Use

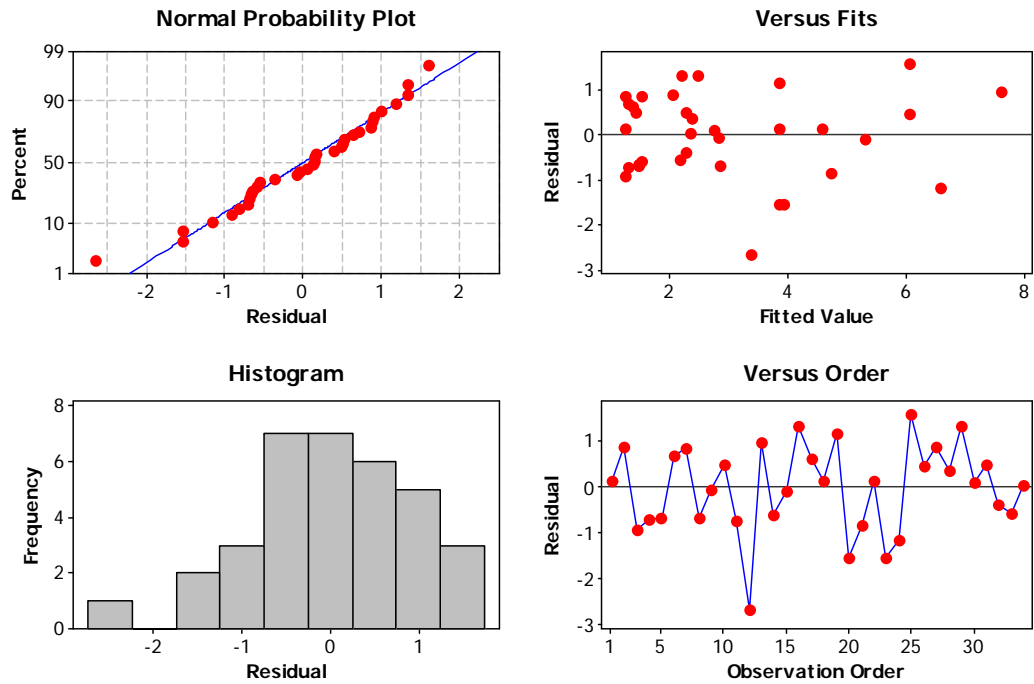


Figure 9.35 Residual Plots for Mode 5 Fuel Use

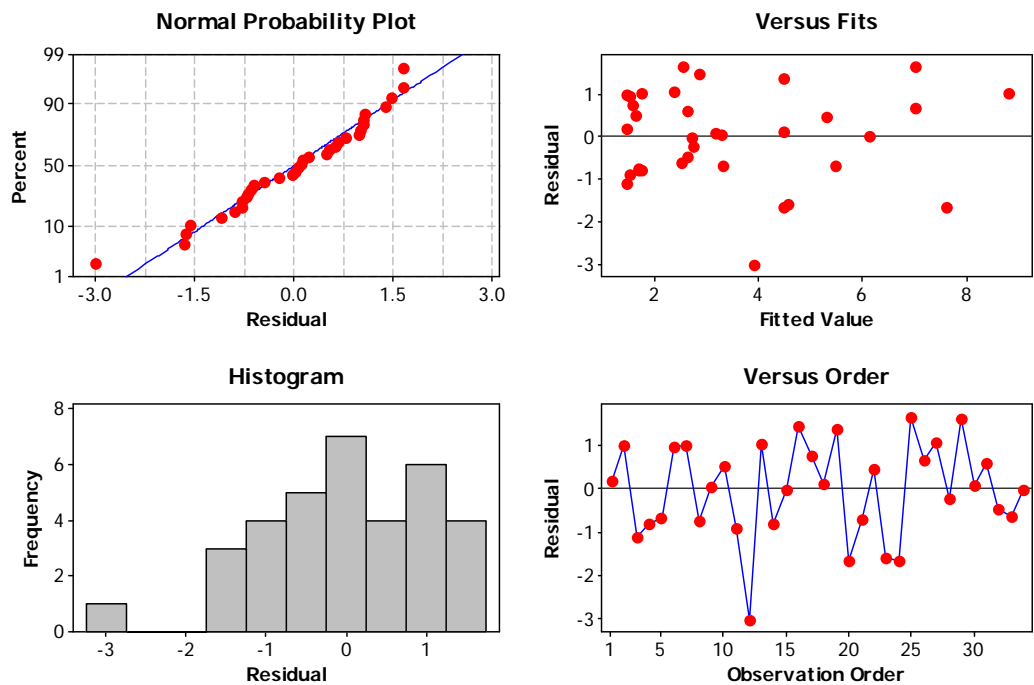


Figure 9.36 Residual Plots for Mode 6 Fuel Use

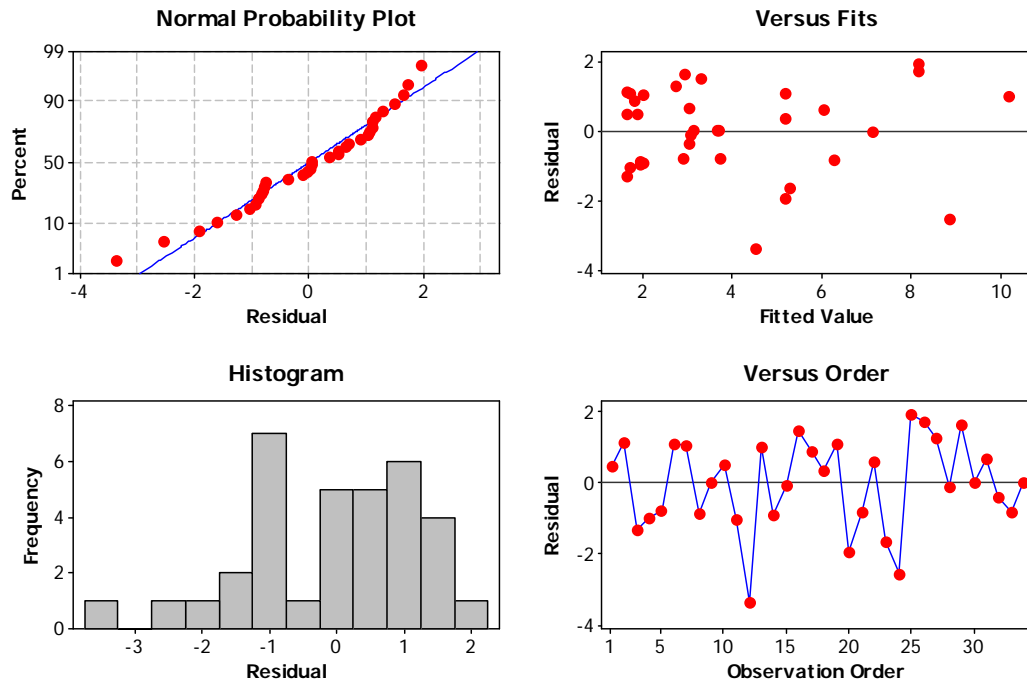


Figure 9.37 Residual Plots for Mode 7 Fuel Use

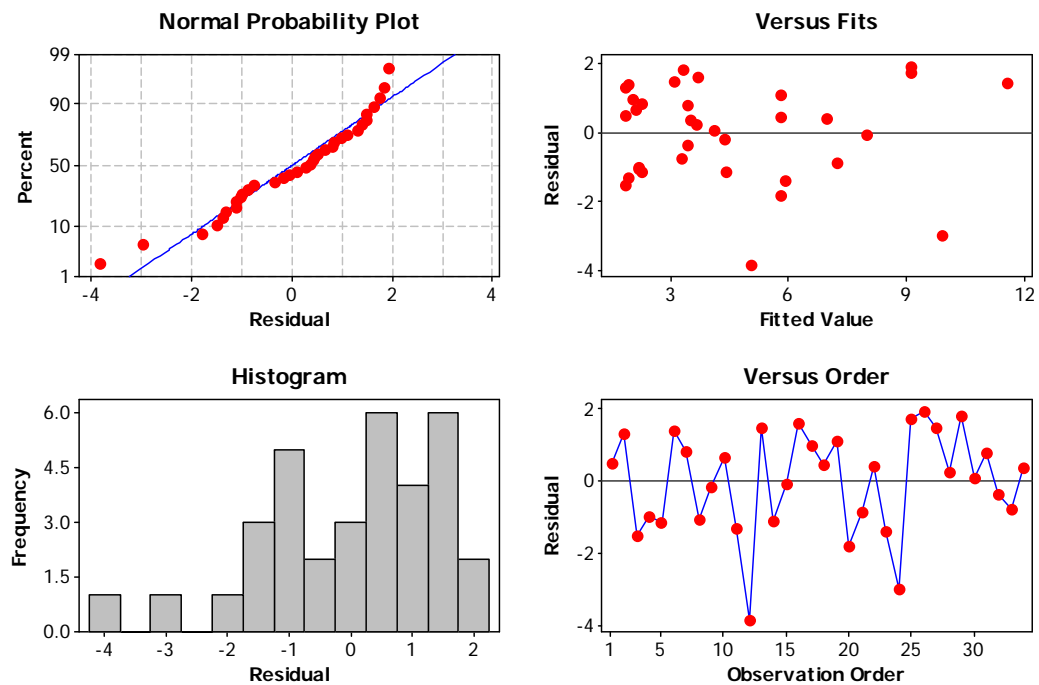


Figure 9.38 Residual Plots for Mode 8 Fuel Use

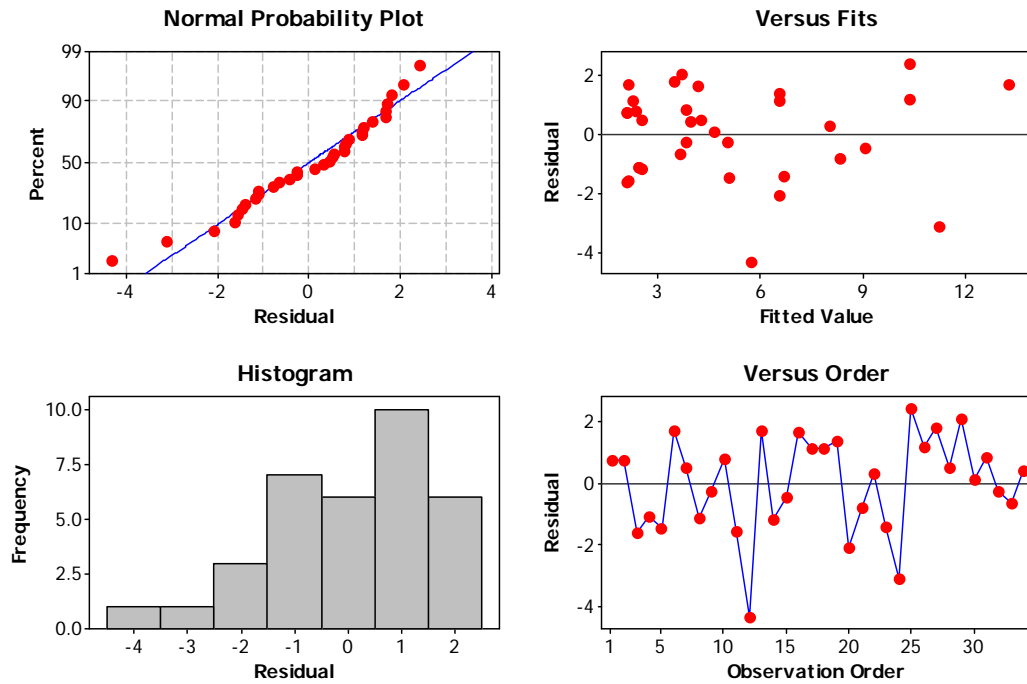


Figure 9.39 Residual Plots for Mode 9 Fuel Use

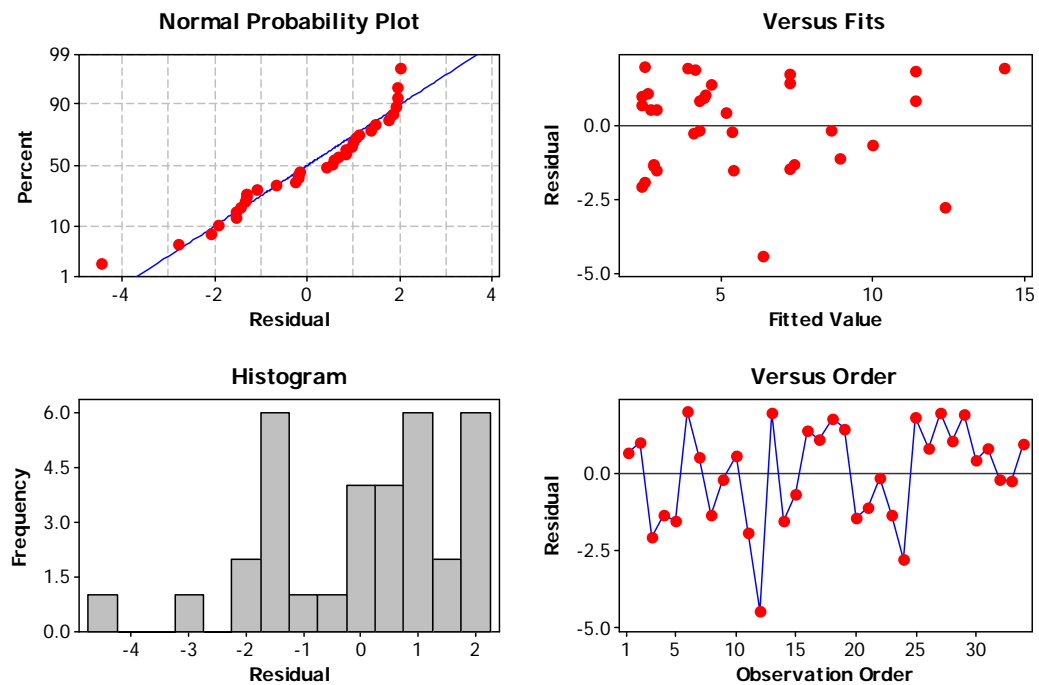


Figure 9.40 Residual Plots for Mode 10 Fuel Use

9.6 Appendix F: Fraction of Time and Fuel Use per Engine Mode for Representative Duty Cycles

This appendix provides tables that summarize the fraction of time and fraction of fuel use for each engine mode and representative duty cycle that was observed. Each table includes the amount of time spent in each engine mode and the amount of fuel used in each engine mode for each item of equipment. For duty cycles that were performed by more than one item of the same equipment type, the aggregate total for that duty cycle and equipment type is provided.

Table 9.12 Fraction of Time and Fuel Use per Mode for Backhoe “Load Truck” Duty Cycle

Mode	BH 1		BH 5		BH 6		Aggregate			
	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	7,865	2,660	3,169	901	3,668	1,158	14,702	42	4,719	11
2	471	408	2,939	3,040	2,214	2,174	5,624	16	5,622	13
3	181	202	1,529	2,041	3,565	5,045	5,275	15	7,288	16
4	82	108	534	891	2,859	4,778	3,475	10	5,777	13
5	61	91	326	711	1,037	2,082	1,424	4	2,884	6
6	28	46	405	1,071	281	4,957	714	2	6,075	14
7	20	43	552	1,627	422	1,180	994	3	2,850	6
8	22	52	307	1,004	1,002	3,327	1,331	4	4,383	10
9	37	103	270	968	752	2,863	1,059	3	3,934	9
10	13	40	75	289	206	921	294	1	1,250	3
	8,780	3,752	10,106	12,543	16,006	28,485	34,892	100	44,781	100

Table 9.13 Fraction of Time and Fuel Use per Mode for Backhoe “Move Soil” Duty Cycle

Mode	BH 3		BH 4		BH 7		BH 8		Aggregate			
	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	5,478	5,782	2,354	263	5,900	1,793	2,463	391	16,195	52	8,229	37
2	837	299	1,139	445	666	629	996	477	3,638	12	1,849	8
3	1,705	579	1,773	939	435	621	983	576	4,896	16	2,715	12
4	649	214	718	462	278	536	496	333	2,141	7	1,545	7
5	291	96	75	58	1,025	2,430	101	81	1,492	5	2,665	12
6	192	64	53	48	581	1,620	55	53	881	3	1,785	8
7	236	78	36	35	470	1,431	57	61	799	3	1,605	7
8	286	96	41	49	221	682	85	97	633	2	924	4
9	163	70	74	98	81	245	84	110	402	1	523	2
10	16	5	143	210	57	195	59	84	275	1	494	2
	9,853	7,283	6,406	2,606	9,714	10,180	5,379	2,264	31,352	100	22,333	100

Table 9.14 Fraction of Time and Fuel Use per Mode for Backhoe “Move Material” Duty Cycle

	BH 2			
Mode	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	6,716	50	2,593	21
2	2,697	20	2,993	24
3	2,429	18	3,629	29
4	907	7	1,592	13
5	258	2	548	4
6	119	1	291	2
7	103	1	286	2
8	162	1	512	4
9	9	0	25	0
10	7	0	24	0
	13,407	100	12,492	100

**Table 9.15 Fraction of Time and Fuel Use per Mode for Bulldozer “Rough Grade”
Duty Cycle**

	BD 1		BD 4		Aggregate			
Mode	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	2,564	1,053	6,539	32,482	9,103	51	33,536	73
2	304	328	1,037	596	1,341	8	925	2
3	405	635	842	692	1,247	7	1,327	3
4	446	1,009	726	483	1,172	7	1,493	3
5	472	1,316	611	472	1,083	6	1,788	4
6	374	1,247	588	521	962	5	1,768	4
7	280	1,040	477	540	757	4	1,581	3
8	108	453	434	534	542	3	987	2
9	54	257	865	1,205	919	5	1,462	3
10	12	62	578	1,105	590	3	1,167	3
	5,019	7,402	12,697	38,630	17,716	100	46,032	100

Table 9.16 Fraction of Time and Fuel Use per Mode for Bulldozer "Fine Grade" Duty Cycle

Mode	BD 2		BD 3		Aggregate			
	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	26,948	8,578	10,248	19,147	37,196	64	27,725	52
2	2,806	2,671	2,791	1,153	5,597	10	3,824	7
3	2,738	3,614	2,613	1,164	5,351	9	4,778	9
4	2,335	3,855	1,081	596	3,416	6	4,451	8
5	1,619	3,094	614	355	2,233	4	3,449	6
6	1,483	3,215	337	202	1,820	3	3,416	6
7	1,120	2,655	214	140	1,334	2	2,795	5
8	552	1,529	109	66	661	1	1,596	3
9	211	658	61	34	272	0	692	1
10	106	345	22	12	128	0	357	1
	39,918	30,213	18,090	22,871	58,008	100	53,084	100

Table 9.17 Fraction of Time and Fuel Use per Mode for Bulldozer "Stockpile" Duty Cycle

Mode	BH 5		BH 6		Aggregate			
	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	3,747	4,088	1,756	1,147	5,503	35	5,234	5
2	206	798	1,391	1,367	1,597	10	2,164	2
3	247	1,447	1,531	2,065	1,778	11	3,512	4
4	336	2,519	319	378	655	4	2,896	3
5	360	3,096	84	77	444	3	3,174	3
6	399	3,939	26	25	425	3	3,965	4
7	520	5,827	22	24	542	3	5,851	6
8	813	10,601	20	23	833	5	10,624	11
9	1,939	29,046	5	7	1,944	12	29,053	29
10	1,983	32,261	2	3	1,985	13	32,264	33
	10,550	93,623	5,156	5,115	15,706	100	98,738	100

Table 9.20 Fraction of Time and Fuel Use per Mode for Excavator "Excavate Soil" Duty Cycle

Mode	EX 3			
	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	5,970	31	1,501	5
2	144	1	109	0
3	629	3	736	2
4	1,549	8	2,335	7
5	2,053	11	4,092	13
6	3,081	16	7,248	22
7	2,618	14	7,029	22
8	1,928	10	5,839	18
9	972	5	3,295	10
10	119	1	442	1
19,063		100	32,625	100

Table 9.21 Fraction of Time and Fuel Use per Mode for Motor Grader "Resurface" Duty Cycle

Mode	MG 1		MG 4		MG 6		Aggregate			
	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	2,985	2,469	2,023	1,572	1,579	622	6,587	19	4,663	4
2	669	1,333	1,778	2,829	299	306	2,746	8	4,468	4
3	607	1,695	2,015	5,059	622	980	3,244	10	7,734	6
4	731	2,399	2,527	8,437	1,983	3,838	5,241	15	14,673	12
5	1,156	4,633	1,018	3,970	1,131	2,697	3,305	10	11,301	9
6	1,724	7,935	240	1,152	872	2,586	2,836	8	11,672	10
7	2,575	14,256	160	871	410	1,497	3,145	9	16,625	14
8	2,229	13,930	121	769	319	1,437	2,669	8	16,137	13
9	2,169	16,713	97	728	315	1,663	2,581	8	19,104	16
10	1,448	13,079	61	477	227	1,381	1,736	5	14,937	12
16,293		78,442	10,040	25,864	7,757	17,008	34,090	100	121,314	100

Table 9.22 Fraction of Time and Fuel Use per Mode for Motor Grader "Shoulder" Duty Cycle

	MG 2		MG 3		MG 5		Aggregate			
Mode	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	8,014	4,633	1,383	434	5,491	3,414	14,888	57	8,481	17
2	387	845	221	217	900	1,760	1,508	6	2,821	5
3	859	2,881	327	503	705	2,027	1,891	7	5,411	11
4	674	2,794	429	837	488	1,866	1,591	6	5,497	11
5	359	1,807	531	1,225	513	2,418	1,403	5	5,449	11
6	213	1,247	1,027	2,884	497	2,870	1,737	7	7,002	14
7	53	333	957	3,113	907	6,051	1,917	7	9,497	19
8	35	241	335	1,334	226	1,667	596	2	3,242	6
9	79	627	184	825	47	391	310	1	1,843	4
10	94	821	196	1,143	14	125	304	1	2,089	4
	10,767	16,230	5,590	12,513	9,788	22,588	26,145	100	51,330	100

Table 9.23 Fraction of Time and Fuel Use per Mode for Off-Road Tuck "Haul Soil" Duty Cycle

	OT 1		OT 2		OT 3		Aggregate			
Mode	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	15,772	15,656	4,792	4,546	3,965	3,894	24,529	77	24,096	39
2	1,412	3,725	384	1,385	237	811	2,033	6	5,921	10
3	927	3,133	209	1,082	66	342	1,202	4	4,556	7
4	718	3,098	101	651	38	248	857	3	3,997	7
5	765	4,136	52	398	32	246	849	3	4,780	8
6	618	3,686	20	174	51	463	689	2	4,322	7
7	407	2,571	3	30	44	436	454	1	3,037	5
8	337	2,329	1	11	58	639	396	1	2,979	5
9	340	2,769	1	13	41	473	382	1	3,255	5
10	450	4,313	2	26	9	110	461	1	4,450	7
	21,746	45,416	5,565	8,316	4,541	7,663	31,852	100	61,395	100

Table 9.24 Fraction of Time and Fuel Use per Mode for Track Loader "Fine Grade" Duty Cycle

Mode	TL 1			
	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	2,746	50	4,827	34
2	124	2	118	1
3	59	1	96	1
4	90	2	207	1
5	593	11	1,748	12
6	1,074	19	3,702	26
7	513	9	2,057	14
8	230	4	1,046	7
9	51	1	267	2
10	35	1	205	1
	5,515	100	14,273	100

Table 9.25 Fraction of Time and Fuel Use per Mode for Track Loader "Move Material" Duty Cycle

Mode	TL 2			
	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	1,324	25	745	6
2	639	12	835	6
3	275	5	465	4
4	237	5	590	4
5	346	7	951	7
6	347	7	876	7
7	472	9	1,389	10
8	626	12	2,452	18
9	561	11	2,652	20
10	423	8	2,336	18
	5,250	100	13,290	100

Table 9.26 Fraction of Time and Fuel Use per Mode for Track Loader "Stockpile" Duty Cycle

Mode	TL 3			
	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	1,273	39	621	6
2	2	0	2	0
3	93	3	173	2
4	120	4	344	3
5	217	7	766	7
6	167	5	701	6
7	146	4	668	6
8	151	5	772	7
9	377	11	2,169	20
10	760	23	4,617	43
	3,306	100	10,833	100

Table 9.27 Fraction of Time and Fuel Use per Mode for Wheel Loader "Move Soil" Duty Cycle

Mode	WL 1		WL 5		Aggregate			
	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	8,095	6,270	9,902	4,609	17,997	67	10,879	34
2	2,640	3,909	986	986	3,626	13	4,894	15
3	1,308	2,560	218	336	1,526	6	2,896	9
4	878	2,158	210	423	1,088	4	2,581	8
5	695	1,985	105	250	800	3	2,235	7
6	498	1,631	102	275	600	2	1,906	6
7	303	1,110	60	189	363	1	1,299	4
8	302	1,266	87	336	389	1	1,602	5
9	298	1,408	75	327	373	1	1,735	5
10	208	1,164	82	443	290	1	1,606	5
	15,225	23,460	11,827	8,175	27,052	100	31,634	100

**Table 9.28 Fraction of Time and Fuel Use per Mode for Wheel Loader "Load Truck"
Duty Cycle**

Mode	WL 2		WL 3		WL 4		Aggregate			
	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	Fuel (g)	Time (s)	F _{Time} (%)	Fuel (g)	F _{Fuel} (%)
1	10,196	5,633	2,017	530	2,324	792	14,537	50	6,955	19
2	1,884	2,636	463	377	1,427	1,144	3,774	13	4,157	12
3	2,229	4,139	235	309	1,114	1,192	3,578	12	5,641	16
4	1,724	3,971	187	293	464	637	2,375	8	4,901	14
5	1,471	4,099	125	236	221	356	1,817	6	4,691	13
6	710	2,302	106	230	230	436	1,046	4	2,969	8
7	439	1,624	88	232	298	623	825	3	2,479	7
8	228	956	76	231	384	960	688	2	2,147	6
9	102	476	62	220	231	691	395	1	1,388	4
10	81	416	44	181	26	101	151	1	697	2
	19,064	26,252	3,403	2,840	6,719	6,931	29,186	100	36,024	100

9.7 Appendix G: Residual Plots for Fuel Use and Emission Rates Response Plots

This appendix provides the residual plots used to check the conditions of multiple linear regression for the response plots of the estimated versus the actual values for fuel use and emission rates of NO_x, HC, CO, and PM. The residual plots include normal probability plots, residuals versus the fitted values, histogram of the residuals, and residuals versus the observation order. The residual plots were generated by Minitab.

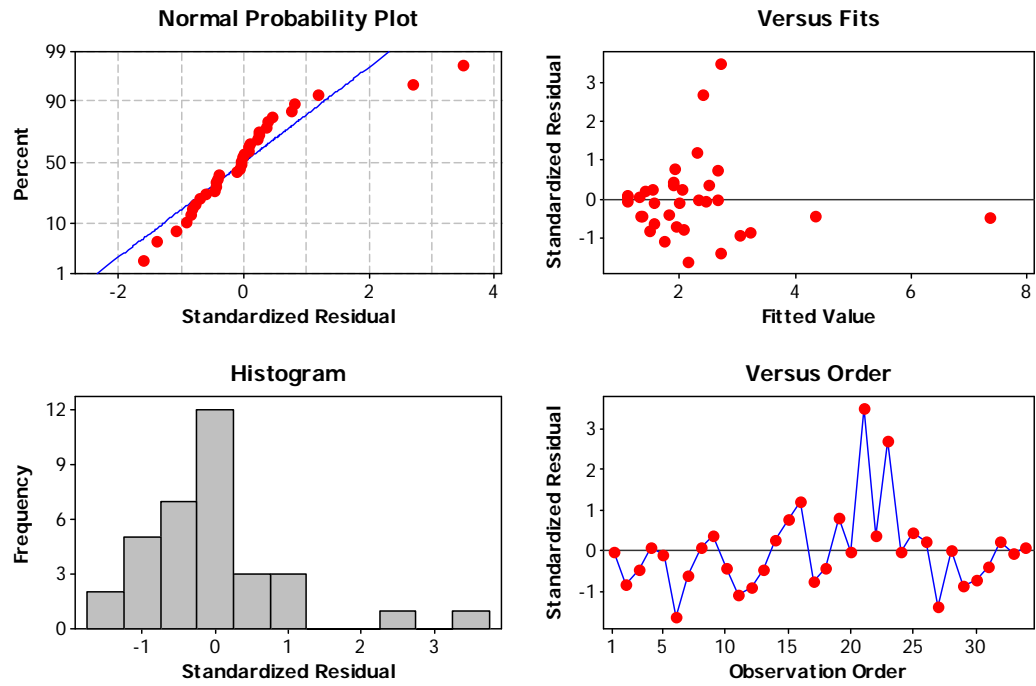


Figure 9.41 Residual Plots for Fuel Use Response Plot

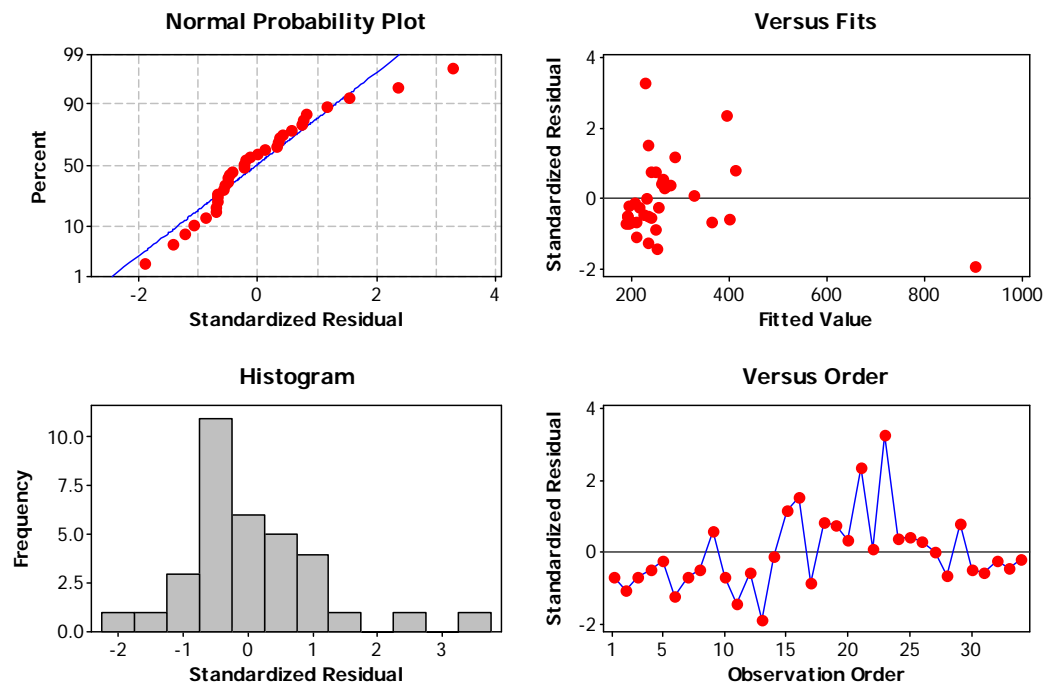


Figure 9.42 Residual Plots for NO_x Response Plot

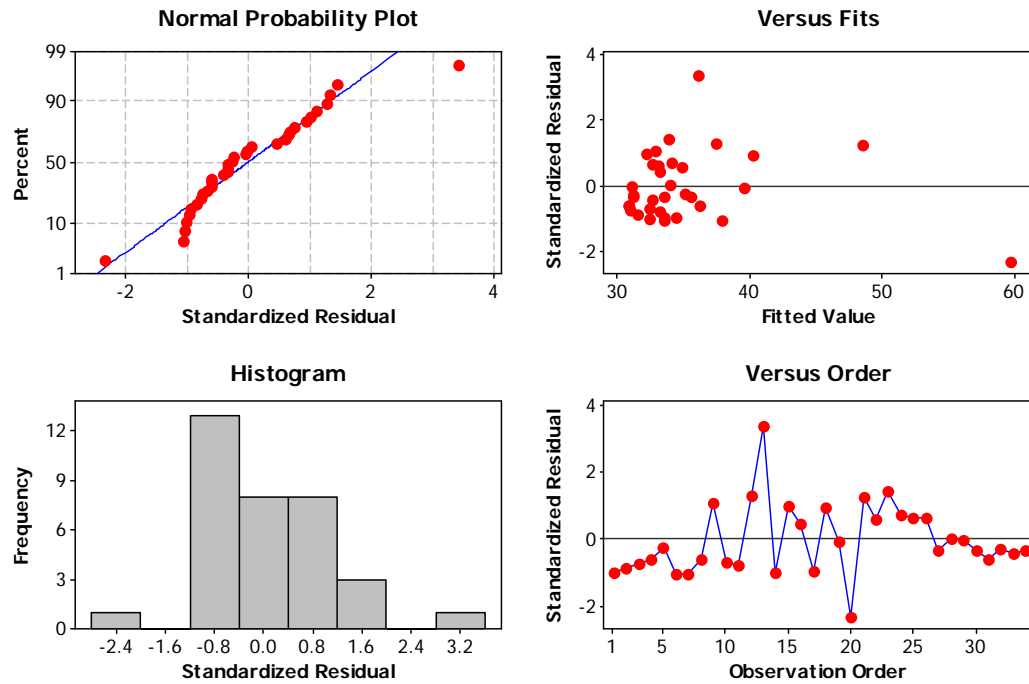


Figure 9.43 Residual Plots for HC Response Plot

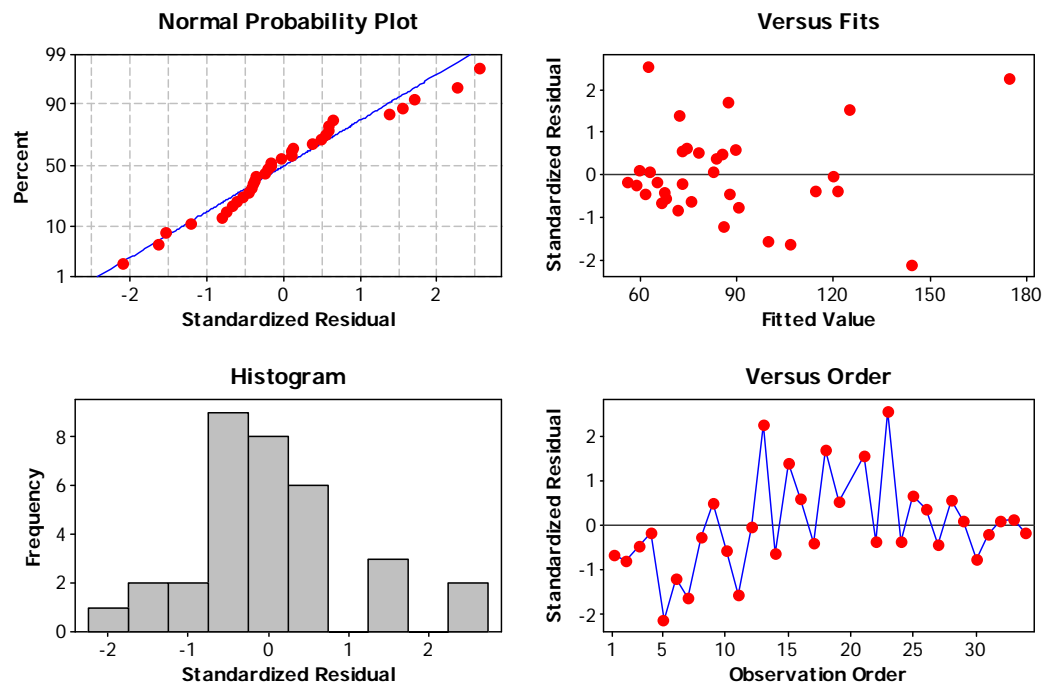


Figure 9.44 Residual Plots for CO Response Plot

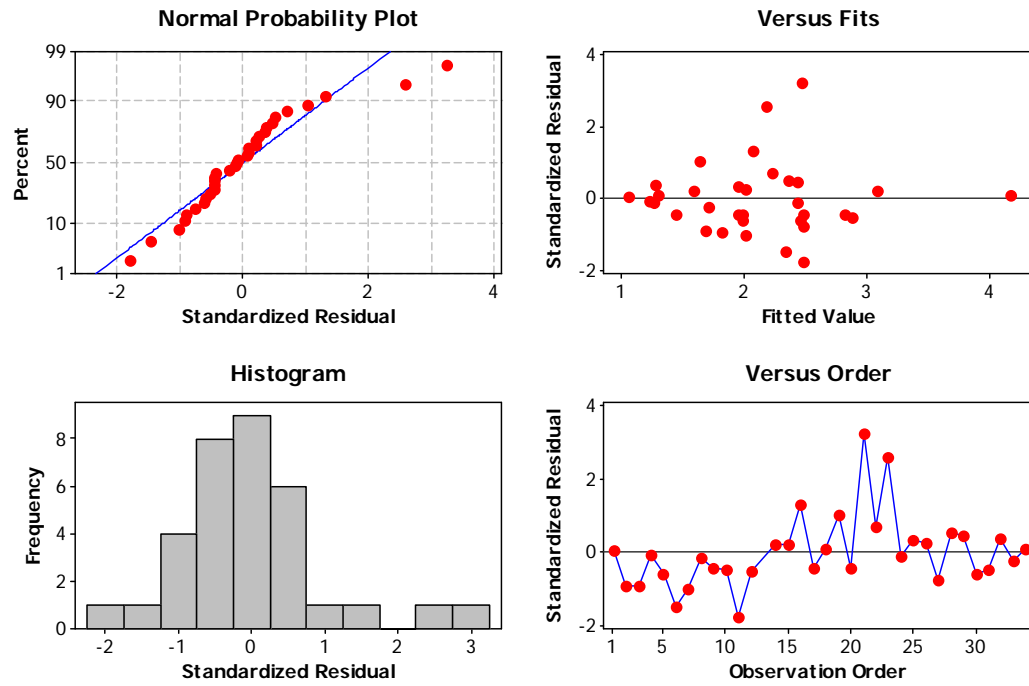


Figure 9.45 Residual Plots for PM Response Plot