2011

Juxtaposition of In-Use Vehicular Emissions Measurement Equipment

Brock A. Merritt
West Virginia University

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Recommended Citation

Merritt, Brock A., "Juxtaposition of In-Use Vehicular Emissions Measurement Equipment" (2011).
Graduate Theses, Dissertations, and Problem Reports. 3320.
<https://researchrepository.wvu.edu/etd/3320>

This Thesis is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Thesis in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Thesis has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

Juxtaposition of In-Use Vehicular Emissions Measurement Equipment

Brock A. Merritt

Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Mechanical Engineering

John Nuskowski, Ph.D., Chair
Gregory J. Thompson, Ph.D.
Benjamin C. Shade, Ph.D.

Department of Mechanical and Aerospace Engineering

Morgantown, West Virginia
2011

Keywords: Emissions, In-use Emissions, On-road Emissions, Chassis Dynamometer, Diesel
Engine Emissions

Copyright 2011 Brock A. Merritt

Juxtaposition of In-Use Vehicular Emissions Measurement Equipment

Brock A. Merritt

Abstract

A study was performed to compare measurement capabilities of two commercially available in-use portable emissions measurement systems, from different generations, in order to determine how or if changes to emissions testing standards have affected in-use equipment. The two in-use systems from different generations were the Sensors, Inc. SEMTECH-D, which would be considered first generation because it was built under the CFR 40, Part 86 standard, and the Horiba, Ltd. OBS-2200, which was considered second generation because it was built under the updated CFR 40, Part 1065 standards. Both systems underwent a series of tests in the laboratory and on-road. For the tests, five cycles were developed from on-road data collection and created into dynamometer cycles. Then those same five cycles were run on-road to generate a comparison to show differences in test methods. For the equipment comparison, both systems were tested against West Virginia University's Transportable Laboratory, which was developed according to CFR 40, Part 1065 standards for emissions testing. The comparisons were completed using both distance specific and brake specific measurements. The SEMTECH-D performed well and measured CO₂, THC, and NO_x within five percent of the laboratory. The SEMTECH-D was not as accurate with the CO measurement, which was greater than 70 percent from the laboratory readings. The OBS-2200 measured well in comparison to the laboratory for CO₂ and NO_x. These constituents were measured within four percent of the laboratory. CO and THC emissions were measured with a percent difference greater than 20 and 32 percent, respectively. Overall, neither unit outperformed the other. Each measured certain parameters and constituents better than the other but not with complete consistency. Therefore, no conclusion could be drawn on the influence of the equipment's generation on emissions testing.

Table of Contents

Abstract.....	ii
Table of Contents.....	iii
List of Figures.....	v
List of Tables.....	vii
Nomenclature.....	ix
1. Introduction and Objectives.....	1
1.1 Introduction.....	1
1.2 Objectives.....	2
2. Literature Review.....	4
2.1 Introduction.....	4
2.2 Emissions Testing.....	4
2.3 Consent Decrees.....	7
2.4 In-Use Testing and Development.....	9
2.5 Previous On-Board Emissions Systems.....	11
2.5.1 Caterpillar.....	11
2.5.2 Southwest Research Institute (SwRI).....	11
2.5.3 General Motors (GM).....	11
2.5.4 Ford Motor Company (FMC).....	12
2.5.5 United States Coast Guard.....	12
2.5.6 University of Pittsburgh.....	13
2.5.7 Flemish Institute for Technological Research (VITO).....	13
2.5.8 The Northeast States for Coordinated Air Use Management (NESCAUM).....	13
2.5.9 U.S. Environmental Protection Agency (EPA).....	14
2.5.10 Ford Motor Company (FMC) and WPI-Microprocessor Systems, Inc.	15
2.5.11 Horiba, Ltd. And NGK Insulators.....	15
2.5.12 Honda R&D Americas, Inc.....	16
2.5.13 Technical Research Center of Finland (VTT Energy).....	16
2.5.14 Clean Air Technologies International.....	16
2.5.15 Analytical Engineering, Inc. (AEI).....	17
2.5.16 Engine, Fuel, and Emissions Engineering, Inc.	17
2.5.17 University of Alberta.....	17
2.5.18 West Virginia University (WVU).....	18
2.6 CFR Compliance.....	18
2.7 Previous Aiding Studies.....	19
2.7.1 In-Use Test Studies.....	19
2.7.2 Chassis Dynamometer Comparison Studies.....	20
2.7.3 Test Route Studies.....	21
3. Experimental Setup.....	23
3.1 Test Vehicle.....	23
3.2 Test Equipment.....	24
3.2.1 West Virginia University's Transportable Laboratory.....	24
3.2.2 Sensors, Inc. SEMTECH-D.....	26
3.2.3 Horiba, Ltd. OBS 2200.....	28
3.2.4 West Virginia University's Medium-Duty Dynamometer.....	29

3.3	On-Road Routes	30
3.3.1	Morgantown-Westover Route.....	30
3.3.2	Westover to Saltwell Route	32
3.3.3	Westover to Bruceton Mills Route	33
3.4	Test Procedure.....	34
3.4.1	Laboratory Test Matrix	35
3.4.2	On-Road Test Matrix	36
3.5	Data Reduction.....	37
4.	Discussion of Results	42
4.1	Laboratory Test Results	43
4.1.1	Morgantown-Westover Cycle.....	44
4.1.2	Westover to Bruceton Mills Cycle.....	48
4.1.3	Bruceton Mills to Westover Cycle.....	51
4.1.4	Westover to Saltwell Cycle.....	54
4.1.5	Saltwell to Westover Cycle.....	57
4.2	On-Road Test Results.....	60
4.2.1	Morgantown-Westover Route.....	61
4.2.2	Westover to Bruceton Mills Route	63
4.2.3	Bruceton Mills to Westover Route	64
4.2.4	Westover to Saltwell Route	66
4.2.5	Saltwell to Westover Route	67
4.3	Fuel Consumption	69
4.3.1	Laboratory.....	69
4.3.2	On-Road.....	71
4.4	Overall Results	71
4.4.1	Equipment Comparison	72
4.4.2	Test Method Comparison.....	73
5.	Conclusions and Recommendations	75
5.1	Conclusions	75
5.2	Recommendations	77
6.	References.....	78
	Appendix A – Test Setup Photographs	84
	Appendix B – Individual Laboratory Test Results	89
	Appendix C – Individual On-Road Test Results	113
	Appendix D – Select Plots from Portions of Individual Tests.....	142

List of Figures

Figure 2-1: FTP Engine Speed [7].	5
Figure 2-2: FTP Engine Torque [7].	6
Figure 2-3: NTE Region.	10
Figure 3-1: Map of Morgantown-Westover Route [50].	31
Figure 3-2: Plot of Elevation for the Morgantown Route.	31
Figure 3-3: Map of Westover to Saltwell Route [52].	32
Figure 3-4: Plot of Elevation for the Westover to Saltwell Route.	33
Figure 3-5: Map of Westover to Bruceton Mills Route [51].	33
Figure 3-6: Plot of Elevation for the Westover to Bruceton Mills Route.	34
Figure 4-1: Plot of OBS Exhaust Flow against Laboratory LFE.	42
Figure 4-2: Plot of SEMTECH Exhaust Flow against Laboratory LFE.	43
Figure 4-3: Comparison of Power from a Laboratory Cycle and an On-Road Route (Morgantown-Westover).	74
Figure 7-1: Test Vehicle on Chassis Dynamometer.	85
Figure 7-2: In-Use Measurement Analyzers.	85
Figure 7-3: OBS (Top) and SEMTECH (Bottom) Exhaust Sample Lines.	86
Figure 7-4: Test Vehicle Outfitted for On-Road Testing (Side View).	87
Figure 7-5: Outfitted Test Vehicle (Overhead).	87
Figure 7-6: In-Use Equipment Securely Fastened in Truck Bed.	88
Figure 10-1: Exhaust Flow from Test Number MW-06.	143
Figure 10-2: CO Concentration from Test Number MW-06.	143
Figure 10-3: CO ₂ Concentration from Test Number MW-06.	143
Figure 10-4: THC Concentration from Test Number MW-06.	144
Figure 10-5: NO _x Concentration from Test Number MW-06.	144
Figure 10-6: Exhaust Flow from Test Number W2B-01.	144
Figure 10-7: CO Concentration from Test Number W2B-01.	145
Figure 10-8: CO ₂ Concentration from Test Number W2B-01.	145
Figure 10-9: THC Concentration from Test Number W2B-01.	145
Figure 10-10: NO _x Concentration from Test Number W2B-01.	146
Figure 10-11: Exhaust Flow from Test Number B2W-04.	146
Figure 10-12: CO Concentration from Test Number B2W-04.	146
Figure 10-13: CO ₂ Concentration from Test Number B2W-04.	147
Figure 10-14: THC Concentration from Test Number B2W-04.	147
Figure 10-15: NO _x Concentration from Test Number B2W-04.	147
Figure 10-16: Exhaust Flow from Test Number W2S-01.	148
Figure 10-17: CO Concentration from Test Number W2S-01.	148
Figure 10-18: CO ₂ Concentration from Test Number W2S-01.	148
Figure 10-19: THC Concentration from Test Number W2S-01.	149
Figure 10-20: NO _x Concentration from Test Number W2S-01.	149
Figure 10-21: Exhaust Flow from Test Number S2W-03.	149
Figure 10-22: CO Concentration from Test Number S2W-03.	150
Figure 10-23: CO ₂ Concentration from Test Number S2W-03.	150
Figure 10-24: THC Concentration from Test Number S2W-03.	150
Figure 10-25: NO _x Concentration from Test Number S2W-03.	151

Figure 10-26: Exhaust Flow from Test Number MW-09.....	151
Figure 10-27: CO Concentration from Test Number MW-09.....	151
Figure 10-28: CO ₂ Concentration from Test Number MW-09.....	152
Figure 10-29: THC Concentration from Test Number MW-09.....	152
Figure 10-30: NO _x Concentration from Test Number MW-09.....	152
Figure 10-31: Exhaust Flow from Test Number W2B-05.....	153
Figure 10-32: CO Concentration from Test Number W2B-05.....	153
Figure 10-33: CO ₂ Concentration from Test Number W2B-05.....	153
Figure 10-34: THC Concentration from Test Number W2B-05.....	154
Figure 10-35: NO _x Concentration from Test Number W2B-05.....	154
Figure 10-36: Exhaust Flow from Test Number B2W-05.....	154
Figure 10-37: CO Concentration from Test Number B2W-05.....	155
Figure 10-38: CO ₂ Concentration from Test Number B2W-05.....	155
Figure 10-39: THC Concentration from Test Number B2W-05.....	155
Figure 10-40: NO _x Concentration from Test Number B2W-05.....	156
Figure 10-41: Exhaust Flow from Test Number W2S-05.....	156
Figure 10-42: CO Concentration from Test Number W2S-05.....	156
Figure 10-43: CO ₂ Concentration from Test Number W2S-05.....	157
Figure 10-44: THC Concentration from Test Number W2S-05.....	157
Figure 10-45: NO _x Concentration from Test Number W2S-05.....	157
Figure 10-46: Exhaust Flow from Test Number S2W-05.....	158
Figure 10-47: CO Concentration from Test Number S2W-05.....	158
Figure 10-48: CO ₂ Concentration from Test Number S2W-05.....	158
Figure 10-49: THC Concentration from Test Number S2W-05.....	159
Figure 10-50: NO _x Concentration from Test Number S2W-05.....	159

List of Tables

Table 2-1: EPA HDDE Emissions Standards (g/bhp-hr) [10].	8
Table 2-2: California HDDE Emissions Standard (g/bhp-hr) [10].	8
Table 2-3: Changes made for 2004 and up Model Year (g/bhp-hr) [10].	8
Table 2-4: HDDE Useful Engine Life [10].	9
Table 3-1: Laboratory Test Schedule.	36
Table 3-2: On-Road Test schedule.	37
Table 3-3: Reported Parameters and Units	41
Table 4-1: Difficulties Encountered During Laboratory Testing.	44
Table 4-2: Average Results of the Laboratory Morgantown-Westover Cycle.	47
Table 4-3: Average Results of the Laboratory Westover to Bruceton Mills Cycle.	50
Table 4-4: Average Results of the Laboratory Bruceton Mills to Westover Cycle.	53
Table 4-5: Average Results of the Laboratory Westover to Saltwell Cycle.	56
Table 4-6: Average Results of the Laboratory Saltwell to Westover Cycle.	59
Table 4-7: Difficulties Encountered During On-Road Testing.	61
Table 4-8: Average Results of the On-Road Morgantown-Westover Route.	63
Table 4-9: Average Results of the On-Road Westover to Bruceton Mills Route.	64
Table 4-10: Average Results of the On-Road Bruceton Mills to Westover Route.	66
Table 4-11: Average Results of the On-Road Westover to Saltwell Route.	67
Table 4-12: Average Results of the On-Road Saltwell to Westover Route.	68
Table 4-13: Fuel Consumption Analysis of Laboratory Testing.	70
Table 4-14: Average Results of Fuel Consumption from the Laboratory Testing.	70
Table 4-15: Fuel Consumption Analysis of On-Road Testing.	71
Table 4-16: Average Results of Fuel Consumption from On-Road Testing.	71
Table 4-17: Overall Results of Laboratory Testing.	72
Table 4-18: Test Method Comparison of Laboratory and On-Road Testing.	73
Table 8-1: Test Results from B2W-01.	90
Table 8-2: Test Results from B2W-02.	91
Table 8-3: Test Results from W2B-01.	92
Table 8-4: Test Results from W2B-02.	93
Table 8-5: Test Results from W2S-01.	94
Table 8-6: Test Results from W2S-02.	95
Table 8-7: Test Results from S2W-01.	96
Table 8-8: Test Results from S2W-02.	97
Table 8-9: Test Results from MW-01.	98
Table 8-10: Test Results from MW-02.	99
Table 8-11: Test Results from MW-03.	100
Table 8-12: Test Results from MW-04.	101
Table 8-13: Test Results from MW-05.	102
Table 8-14: Test Results from S2W-03.	103
Table 8-15: Test Results from S2W-04.	104
Table 8-16: Test Results from W2S-03.	105
Table 8-17: Test Results from W2B-03.	106
Table 8-18: Test Results from W2S-04.	107
Table 8-19: Test Results from W2B-04.	108

Table 8-20: Test Results from B2W-03.....	109
Table 8-21: Test Results from B2W-04.....	110
Table 8-22: Test Results from MW-06.....	111
Table 8-23: Test Results from MW-07.....	112
Table 9-1: Test Results from MW-08.....	114
Table 9-2: Test Results from MW-09.....	115
Table 9-3: Test Results from MW-10.....	116
Table 9-4: Test Results from MW-11.....	117
Table 9-5: Test Results from MW-12.....	118
Table 9-6: Test Results from W2S-05.....	119
Table 9-7: Test Results from S2W-05.....	120
Table 9-8: Test Results from W2S-06.....	121
Table 9-9: Test Results from S2W-06.....	122
Table 9-10: Test Results from W2B-05.....	123
Table 9-11: Test Results from B2W-05.....	124
Table 9-12: Test Results from W2B-06.....	125
Table 9-13: Test Results from B2W-06.....	126
Table 9-14: Test Results from W2S-07.....	127
Table 9-15: Test Results from S2W-07.....	128
Table 9-16: Test Results from W2S-08.....	129
Table 9-17: Test Results from S2W-08.....	130
Table 9-18: Test Results from W2B-07.....	131
Table 9-19: Test Results from B2W-07.....	132
Table 9-20: Test Results from W2B-08.....	133
Table 9-21: Test Results from B2W-08.....	134
Table 9-22: Test Results from W2S-09.....	135
Table 9-23: Test Results from S2W-09.....	136
Table 9-24: Test Results from MW-13.....	137
Table 9-25: Test Results from MW-14.....	138
Table 9-26: Test Results from MW-15.....	139
Table 9-27: Test Results from MW-16.....	140
Table 9-28: Test Results from MW-17.....	141

Nomenclature

AEI	Analytical Engineering, Inc.
AMBII	Automotive Micro-Bench II
bhp-hr	Brake Horsepower-Hour
CARB	California Air Resources Board
CDL	Commercial Drivers License
CE-CERT	Department of Chemical and Environmental Engineering, Center for Environmental Research and Technology
CFR	Code of Federal Regulations
CLD	Chemiluminescent Detector
CNC	Condensation Nucleus Counter
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COV	Coefficient of Variation
CVS	Constant Volume Sampling
ECU	Engine Control Unit
EFM	Exhaust Flow Meter
EMFAC	Emission Factors
EMI	Electromagnetic Interference
EPA	Environmental Protection Agency
ESC	European Stationary Cycle
FID	Flame Ionization Detector
FMC	Ford Motor Company
FTIR	Fourier Transform Infrared
FTP	Federal Test Procedure
g/bhp-hr	Grams per Brake Horsepower-Hour
g/mi	Grams per Mile
GM	General Motors
GPS	Global Position System
HC	Hydrocarbon
HDDE	Heavy-Duty Diesel Engine
Hz	Hertz
kW	Kilowatt
LFE	Laminar Flow Element
MECA	Manufacturers of Emissions Control Association
MEL	Mobile Emissions Laboratory
MEMS	Mobile Emissions Measurement System
mm	Millimeter
MY	Model Year
NDIR	Non-Dispersive Infrared
NDUV	Non-Dispersive Ultra-Violet
NESCAUM	Northeast States for Coordinated Air Use Management
NMHC	Non-Methane Hydrocarbon
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide

NO _x	Oxides of Nitrogen
NTE	Not-To-Exceed
O ₂	Oxygen
OBD	On-Board Diagnostics
OBS	On-Board Emission Measurement System
ODEC	On-Road Diesel Emissions Characterization
PAH	Polycyclic Aromatic Hydrocarbon
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
ppm	Parts per Million
PREVIEW	Portable Real-time Emissions Vehicular Integrated Engineering Workstation
RAVEM	Ride Along Vehicle Emissions Measurement
ROVER	Real-Time On-Road Vehicle Emissions Recorder
SCF	Standard Cubic Feet
SD	Standard Deviation
SEMTECH-D	Sensors Emission Technology-Diesel
SET	Supplemental Emission Test
SHS	Sample Handling System
SO ₂	Sulfur Dioxide
SwRI	Southwest Research Institute
TEOM	Tapered Element Oscillating Microbalance
THC	Total Hydrocarbon(s)
UCR	University of California-Riverside
UDDS	Urban Dynamometer Driving Schedule
ULEV	Ultra Low Emission Vehicle
VITO	Flemish Institute for Technological Research
VOEM	VITO On-the-road Emission and Energy Measurement
VTT	Technical Research Center of Finland
WVU	West Virginia University
ZrO ₂	Zirconium Oxide

1. Introduction and Objectives

1.1 Introduction

Emissions testing is an important step in the process of engine development and certification. Manufacturers are required to meet or exceed certain standards set forth by the government regarding the amount of exhaust emissions produced. The CFR 40 part 86 and the updated part 1065 act as the “rule book” of emissions testing standards and procedures for on-road heavy duty engines in the United States. Several different forms of testing are conducted in order to complete certification.

Beginning in the late 1960's, the government researched the United States' air quality and the pollutants affecting it [1]. It was discovered that changes needed to be made in order to try and control the pollution problem. The automotive industry was affected by the changes made. Restrictions on production of constituents in the air were introduced and plans to keep reducing these numbers began. The main governed gases from exhaust emissions were carbon monoxide (CO), carbon dioxide (CO₂), oxides of nitrogen (NO_x), and total hydrocarbons (THC) [2]. The regulations can be seen in the literature review of this paper, in Tables 1 through 3. With the regulations set, engine manufacturers were required to pass emissions tests before receiving certification for production. Early test procedures only required an engine to be tested on an engine dynamometer [3]. The engine was exercised over a cycle, known as the FTP cycle, which was developed from data collected over several driving routes. It was developed to provide the best representation of what an engine would see under everyday operation. The FTP includes highway and non-highway portions from New York City, New York and Los Angeles, California. Over time it was seen that the FTP cycle was not an accurate representation of real world driving. Another form of testing, which is not outlined in the CFR for heavy-duty engines, is chassis dynamometer testing. Chassis dynamometer testing involves using the complete vehicle and applying the load to the wheels through rollers as opposed to applying the load to the flywheel of an engine. Chassis dynamometer testing better represents real world driving than engine dynamometer testing, but has limitations such as road load effects. In most cases the chassis dynamometer does not include loading due to road grade.

The cycles developed for engine and chassis testing were not the only problem causing poor representation of real world conditions. With dynamometer testing, especially engine dynamometer, several parameters can be monitored and controlled where as in the real world they cannot. For example, when doing laboratory testing, temperatures for intake air, fuel, and coolant can be controlled and idealized [4,5]. Under real world operating conditions, none of these parameters can be fully controlled. The largest reason for a change from laboratory testing came when it was discovered that manufacturers were using “defeat devices.” The defeat devices were a dual strategy programmed in the ECU to change certain parameters based how transient the engine operation was. This was a way for manufacturers to achieve increased fuel economy under certain driving conditions but pass the certification test.

The discovery of the defeat devices led to what is known as the Consent Decrees [6]. The Consent Decrees were between the United States government and six heavy-duty diesel engine manufacturers and led to the development of more stringent emissions standards. Changes included reducing emissions production standards sooner than originally planned and the development of in-use testing. In-use testing is a version of emissions testing where all data is recorded while an engine is performing its daily tasks. This required the development of on-board testing equipment, which was reduced in size, compared to its laboratory counterpart, and could withstand the abuse, which includes vibration and weather, of daily operation. Several companies had previously experimented with on-board systems but there were no requirements or regulations. As a result of the Decrees, WVU was commissioned to develop an on-board emissions measurement system. Now known as MEMS, which stands for mobile emissions measurement system, the system is considered a first generation for in-use measurement equipment. Changes in technology and changes of the CFR 40, Part 86 have led to several commercially available systems from manufacturers including Sensors, Inc. and Horiba, Ltd. There are still always questions though as to how accurate in-use equipment is compared to laboratory-grade equipment. This study was designed to examine the accuracy and consistency of modern equipment measurement as compared to laboratory-grade equipment.

1.2 Objectives

The primary objective of this project was to do a comparison of the generations of on-board test equipment. Using a SEMTECH-D and OBS 2200, a comparison was completed to see

how much, if any, improvement was made between a Part 86 designed machine (2005) and a Part 1065 designed machine (2009). The SEMTECH-D is designed per Part 86 requirements and the OBS 2200 per Part 1065 requirements. The comparison of equipment was done with both laboratory and real world testing. Laboratory testing was completed on a chassis dynamometer with WVU's Transportable Laboratory being the control for emissions measurement readings. The secondary objective of this study was to compare the laboratory results to the on-road results to achieve a sense of difference between the two test methods. Cycles were created from recorded global positioning system, or GPS, data for dynamometer use. These same routes were run on-road to compare in-use equipment. This provided the comparison between the real world effects when the equipment is operated on-road and the more controlled environment of the laboratory. Many differences were seen between the two because of the idealization of laboratory testing with the control aspects of the engine or vehicle.

2. Literature Review

2.1 Introduction

In the late 1960's, as a method to try and improve air quality, Congress passed the Air Quality Act [1]. This act separated states into different regions and gave them control over the standards and enforcement of these standards. Stemming from this act, the Environmental Protection Agency was developed. The EPA immediately began research on the automotive industry and the pollutants produced by the increasing number of automobiles. Emissions produced by internal combustion engines such as NO_x, CO, and PM can cause harm to both the environment and its inhabitants [2]. The effects of engine exhaust emissions can range from something as simple as irritation to the eyes, nose, and throat and could be as severe as a fatal injury, which has occurred due to the exposure of CO in confined areas for a long period of time. One the largest long term concerns of the exhaust pollutants is the damage done to the lungs. The tiny particles of PM are inhaled and can cause illnesses such as chronic bronchitis or lung cancer. In addition to population health, the environment is harmed by the creation of ozone which is a major component of smog. Although these facts show some form of change was necessary, the power to enforce these changes was weak [1]. Congress became involved and passed more acts which have brought automobile emission testing and control to the standard it has reached today. This review will outline the background and changes made to the test procedures mandated by the EPA for the heavy-duty diesel engine vehicles and previous ventures of development and testing of in-use emissions measurement equipment.

2.2 Emissions Testing

Emissions testing can be broken into different categories based on the type of testing that is performed. Some emissions testing is done with an engine on a dynamometer, while other testing can be done with the actual vehicle on a chassis dynamometer. The most recent form of emissions testing developed for certification requires that equipment be outfitted on the test vehicle while it executes its everyday tasks. This form of testing is referred to as “in-use” or “on-road” emissions testing. Engine dynamometer and in-use testing have guidelines which are explained by the Code of Federal Regulations [3]. For heavy-duty diesel engines, the CFR 40,

Part 86 and Part 1065 lay out the procedures for performing the tests, collecting the exhaust sample, and calculating what is required to report the collected data.

Prior to the Consent Decrees, for heavy-duty diesel engines, the EPA only mandated that engines run what is known as the FTP cycle on an engine dynamometer. The FTP cycle was developed in the 1970's after numerous vehicles were tested while driving routes in Los Angeles, California and New York City, New York [3]. Data from these tests were compiled to create a twenty minute test cycle that, in theory, would represent the typical driving conditions that a manufactured engine may endure. The cycle consists of four transient legs created from the testing previously mentioned. First, there is a section representing New York non freeway driving. This is followed by a portion of Los Angeles non freeway, then Los Angeles freeway, and finally back to the same section of New York non freeway. The problem with this cycle is that the vehicles used to create it may not accurately represent the modern vehicles that are still testing with it. Considering the two extremes, extended highway driving and “stop and go” driving, a heavy-duty diesel engine should encounter, the FTP cycle poorly represents either of them. Figure 2-1 and Figure 2-2 show the speed and torque plots of the heavy-duty FTP cycle [7].

Figure 2-1: FTP Engine Speed [7].

Figure 2-2: FTP Engine Torque [7].

Another problem found with the early test procedures was how idealized the engine testing could be made. In the laboratory setting, various parameters that affect the generation of certain constituents can be governed or controlled. For example, temperatures of air inlet, coolant, and fuel adversely affect emissions production and can be precisely controlled during engine dynamometer testing [4,5]. Other factors such as moisture in the air and driver variances are eliminated with engine dynamometer testing. When looking at chassis dynamometer testing, the previously stated factors can be controlled, but it is not as precise. Outside of temperature and air control, driver variance is shown during chassis dynamometer testing. A study in Japan has shown that with different experience levels, drivers give unrepeatable engine and emissions data [8]. An experienced driver can show better repeatability than that of an inexperienced driver but neither can accurately drive as repeatable as a computer controlled driver. Another study using vehicle data from an actual route to create a chassis dynamometer cycle showed more comparable emissions results between laboratory and real world testing [9]. In most cases, chassis dynamometer testing will be a more accurate representation of real world application.

Finally, the largest contributing factor for the improvement of engine emissions certification testing is what the EPA referred to as “defeat devices” [6]. The defeat devices were a dual strategy calibration in the engines ECU. One strategy would adjust parameters for more

reduced emissions under transient operations. Another strategy would adjust parameters for increased fuel economy under less transient or pseudo steady-state operation. Under the second strategy, in some cases, the engine may not have met some of the emissions standards. This brought on major change and what is referred to as the Consent Decrees between the United States government and six heavy-duty diesel engine manufacturers. This also became the reason for developing the latest form of emissions certification testing, which is known as in-use testing [3,6].

2.3 Consent Decrees

With the previously mentioned awareness of manufacturers utilizing control strategies to modify engine parameters, discussions began between the EPA, United States Department of Justice, CARB and the six settling heavy-duty diesel engine (S-HDDE) manufacturers in 1998 [3,6]. The S-HDDE manufacturers included Caterpillar, Cummins, Detroit Diesel, International (or Navistar), Mack, and Volvo. They reached agreements with the EPA, the Department of Justice, and CARB to modify the test procedures and emission standards previously set for engine certification. Provisions brought forth by the Decrees included penalties, engine upgrades, test procedure modifications, and timeline changes for the emissions standards. Civil penalties, as well as requirements to apportion pollution research funds, would be invoked to engine manufacturers not in compliance with the Decrees. The test procedure was slightly modified, keeping the FTP cycle certification test but adding a Supplemental Emission Test (SET) and an in-use test procedure. The SET called for steady state testing with its limit equal to that of the FTP and Not-To-Exceed (NTE) limits at 1.25 times the FTP. In-use testing procedures brought forth testing engines after they are already in the fleet and also required declaration of a useful engine life, which is a time period of how long the engine has to meet the emissions standards. This can be represented in mileage, years, or hours of operation. Finally, the last change made was shortening the time allotted, one year, to meet certain emissions standards. Tables of the emission standards (Table 2-1, Table 2-2, and Table 2-3) and useful engine life (Table 2-4) are shown below. Table 2-1 shows the emissions standards of heavy-duty diesel trucks and buses for dates ranging between the late 1980's to the late 1990's. Table 2-2 shows emissions standards for the same trucks and buses in California. Table 2-3 shows changes made for model years 2004 and 2007. Changes were not made to all constituents so some

continued to follow the guidelines of model year 1998 which are outlined in Table 2-1. Table 2-4 outlines the useful engine for pre and post 2004 model year engines [6,7].

Table 2-1: EPA HDDE Emissions Standards (g/bhp-hr) [10].

Year	HC	CO	NO _x	PM
Heavy-Duty Diesel Trucks				
1988	1.3	15.5	10.7	0.6
1990	1.3	15.5	6	0.6
1991	1.3	15.5	5	0.25
1994	1.3	15.5	5	0.1
1998	1.3	15.5	4	0.1
Urban Bus Engines				
1991	1.3	15.5	5	0.25
1993	1.3	15.5	5	0.1
1994	1.3	15.5	5	0.07
1996	1.3	15.5	5	0.05*
1998	1.3	15.5	4	0.05*
* - in-use PM standard 0.07				

Table 2-2: California HDDE Emissions Standard (g/bhp-hr) [10].

Year	NMHC	THC	CO	NO _x	PM
Heavy-Duty Diesel Truck Engines					
1987	-	1.3	15.5	6	0.6
1991	1.2	1.3	15.5	5	0.25
1994	1.2	1.3	15.5	5	0.1
Urban Bus Engines					
1991	1.2	1.3	15.5	5	0.1
1994	1.2	1.3	15.5	5	0.07
1996	1.2	1.3	15.5	4	0.05

Table 2-3: Changes made for 2004 and up Model Year (g/bhp-hr) [10].

Year	NMHC+NO _x	NMHC	PM
2004 (option 1)	2.4	NA	0.1
2004 (option 2)	2.5	0.5	0.1
Year	NO _x	NMHC	PM
2007	0.2	0.14	0.01
Unlisted constituents follow 1998 standards			

Table 2-4: HDDE Useful Engine Life [10].

Year	Useful Years	Mileage	Hours
pre 2004	8 years	290,000	NA
2004 and later	10 years	435,000	22,000

2.4 In-Use Testing and Development

With the added testing procedures for in-use testing of engines in the fleet, guidelines were developed as a testing strategy [3]. As part of the testing plans, the newly developed NTE zone would be used. The NTE region is defined as the area under an engine's torque curve where regulated emissions cannot be above a specified level. The NTE region is defined by three different criteria. Those criteria are engine speed, engine torque, and engine power. Engine speed for the NTE region is all engine speeds at or above 15% the European Stationary Cycle (ESC). The ESC is a 13 mode steady-state cycle used for engine certification in Europe. This is calculated based on an n_{lo} and n_{hi} value, where n_{lo} is the lowest engine speed that the engine can achieve 50% of maximum power and n_{hi} is the highest engine speed that the engine can achieve 70% of maximum power. The equation (Equation 1) for this calculation is:

$$15\% \text{ ESC Speed} = n_{lo} + 0.15 * (n_{hi} - n_{lo})$$

Equation 1: [3]

The boundary for engine torque of the NTE region is 30% of the maximum torque. The power boundary is determined by 30% of the maximum power. Figure 2-3 below shows the NTE region. Along with the NTE region, there are exclusion zones for in-use testing that can be affected by circumstances such as cold weather or certain engine operation periods.

Figure 2-3: NTE Region.

Concerns still arise even with the in-use testing procedures. Since these tests are transient, a technique for retrieving NTE operation was established. For an NTE event to occur, the engine must be in NTE operation for at least 30 seconds. With the shifting of gears and heavy-duty vehicles operating in populated cities, this achievement of 30 seconds of NTE operation proves to be difficult. Also, concerns arise of the emissions being produced in the excluded or non-NTE operation area.

West Virginia University (WVU) was commissioned by the S-HDDE manufacturers to develop a system for in-use testing. WVU was challenged with the task of developing a system that could travel with a vehicle, perform its daily tasks, and read emissions from the exhaust [11,12,13]. They developed what is now known as MEMS or the mobile emissions measurement system. Outside of work related to the Consent Decrees, WVU was not the only organization developing in-use test equipment. Previous ventures of on-board systems are

further outlined in the next sections excluding Sensors, Inc. SEMTECH-D and the Horiba OBS-2000 because further details on them can be found in the Experimental Setup (Section 3).

2.5 Previous On-Board Emissions Systems

Before the mandated in-use testing, early attempts were designed to be able to test engines without removal from the vehicle chassis. After the Consent Decrees, as mentioned above, instead of a desire for on-board systems, there was a need for them. Today several companies sell commercially available systems, including the above mentioned, Sensors, Inc. and Horiba Ltd..

2.5.1 Caterpillar

In 1982, Caterpillar developed an on-board bag sampling system, specifically designed to show engine compliance for NO_x [16]. It was a small system containing a probe, prefilter, sample line, pump, condensing coil, and two bags. The system was able to remove water vapor from the sample before reaching the bags. The system proved easy to operate and easy to transport, being about the size of a small suitcase. For valid data, tests showed that the engine must be operated at full load but the system produced results within 10% of laboratory equipment [14,15].

2.5.2 Southwest Research Institute (SwRI)

SwRI developed an on-board emissions sampling system capable of collecting CO, CO₂, NO_x, O₂, and PM in 1992 [17]. The system was used for inspection and maintenance of buses and was compared to EPA transient engine tests. The main goal was to accomplish collection of data without the use of a chassis dynamometer. The buses used were equipped with automatic transmissions and loaded against their transmission at various throttle positions. Measurements of CO, NO_x, and O₂ were within 5% of laboratory equipment but a preferred system for in-use testing would be continuous sampling as opposed to bag sampling [14,15].

2.5.3 General Motors (GM)

GM outfitted a 1989 3.8 liter gasoline engine, in 1993, with equipment capable of measuring HC, CO₂, CO, and NO [18]. Weighing around 400lbs and installation being in the trunk, the system used five analyzers: two made by Horiba, two made by Siemens, and one made

by Draeger. The multiple analyzers were used to measure the constituents at different concentration levels. Various on-road routes were run as well as the UDDS cycle on a chassis dynamometer to acquire the engine emissions data. Other than the systems slow sample rate, 1 Hz, causing it to perform poorly during transient events, the system was useful for in-use testing of spark-ignition engines [14,15].

2.5.4 Ford Motor Company (FMC)

Another company, in 1994, performing tests on gasoline, spark ignition engines was Ford Motor Company [19,20,21,22]. Three vehicles were tested on a chassis dynamometer to compare the in-use emissions with those collected from laboratory equipment. The three vehicles tested were a flex-fuel Taurus sedan and a Taurus wagon, both from the model year 1991, as well as a 1992 Aerostar van. The system outfitted on the Aerostar van was an FTIR and a dilution tunnel capable of measuring NO_x, HC, CO, and CO₂. Results from the on-board testing were comparable to those of the dynamometer testing with differences around 10% for NO_x, 7% for HC, 3% for CO, and 2% for CO₂. The downfall to this system stemmed from the FTIR having a slow response time making the collection of transient data inaccurate.

Ford tested the Taurus wagon, also using infrared analyzers for CO, HC, O₂, and CO₂ and utilizing an NDUV analyzer for the measurement of NO. Using the same testing technique, comparisons of the NO from the NDUV analyzer and from the laboratory chemiluminescent detector (CLD) yielded a slope of 0.8 and an R² value of 0.97 [14,15].

2.5.5 United States Coast Guard

In 1997, the Coast Guard executed tests on U.S. Coast Guard Cutters in accordance with a Clean Air Act for non-road air pollution [23,24]. Each ship tested was powered by two Caterpillar diesel engines, each producing 750-800 horsepower. The test system consisted of an Energy Efficiency Systems, Inc. Enerac 2000E capable of measuring CO, HC, NO, NO₂, SO₂, and O₂. CO₂ was inferred based on the measurements of these emissions levels. Air temperature, pressure, and relative humidity were monitored, as well as air and fuel flow by flow meters. Engine torque was also monitored by strain gages mounted on the driveshaft. Rather than pulling the exhaust sample from the exhaust stack, the sample was taken directly after the turbocharger. The research did accomplish its objective by showing that on-board emissions testing could be integrated to marine vessel use [14,15].

2.5.6 University of Pittsburgh

In 1997, the University of Pittsburgh developed a system, for inspection and maintenance, to read emissions for a fleet of natural gas vans [25]. An OTC five gas analyzer, measuring raw concentrations of HC, NO_x, CO, CO₂, and O₂, was used. Engine data was collected through the OBD port via third-party diagnostic equipment. Power was supplied through either the vehicles power outlet (cigarette lighter), or directly from the vehicle's battery. The exhaust sample was collected through a probe inserted into the tailpipe and then flowed through filtration which removed large PM particles and moisture.

The system was created specifically for gasoline powered vehicles; therefore the results for HC were biased. Also, the system had several flaws including problems with time alignment of data, mass emissions rates, auto-zeroing of the analyzer, and response time of the analyzer. Overall the system successfully measured in-use emissions of natural gas-fueled vehicles utilizing a portable, lightweight measurement system [14,15].

2.5.7 Flemish Institute for Technological Research (VITO)

VITO developed their On-the-road Emission and Energy Measurement (VOEM) to report gaseous emissions data based on distance in 1997 [26]. The system was designed for gasoline cars and diesel buses. The VOEM consisted of an NDIR analyzer for measuring CO and CO₂, a heated flame ionization detector (FID) to measure HC, and a CLD for NO_x measurement. This system gathered its diluted exhaust sample from an ejector dilutor, driven by nitrogen, probed in to the tailpipe. As a method to prevent loss of heavy hydrocarbons, a heated sample tube was used to transfer the exhaust sample from the tailpipe to the analyzer. As previously stated, emissions were reported on a distance specific basis using a calculation from fuel consumption, engine speed, and lambda values, from air to fuel ratio, along with the diluted sample measurements. In a chassis dynamometer comparison, results found errors of 10% or less for exhaust constituents excluding HC and CO. Differences for HC and CO were 20% and 25%, respectively. Also, its heavy weight of about 500 pounds made on-board emissions testing a difficult task [14,15].

2.5.8 The Northeast States for Coordinated Air Use Management (NESCAUM)

In 1998, NESCAUM worked in partnership with the U.S. Generating Company, the EPA, the Manufacturers of Emissions Control Association (MECA), and the Massachusetts

Department of Environmental Protection to perform testing on diesel engines of off-road construction equipment [27]. The equipment included in the test was a dump truck, backhoe, bulldozer, and two front-end loaders. The sampling system used a heated line to transfer the sample to a dilution tunnel. A separate line also branched off from the main sample line for continuous emissions data. At the end of the dilution tunnel was a 70 mm filter for collection of PM. Results and a comparison with an engine dynamometer proved emissions data to be unreliable with low concentrations of CO and HC, as well as a slow response time for NO_x. Comparisons showed fairly substantial errors of 38% for PM measurement, 27% for CO, 22% for HC, 12% for NO_x, and 9% for calculated fuel consumption [14,15].

2.5.9 U.S. Environmental Protection Agency (EPA)

The U.S. EPA developed their version of an on-board measurement system named the Real-time On-road Vehicle Emissions Recorder (ROVER) in 1999 [28]. Originally designed for gasoline engines, the ROVER was converted to measure emissions from diesel engines. Utilizing a Snap-On emissions analyzer, the ROVER measures HC, NO, CO, and CO₂. Emissions were reported on a distance specific basis using GPS or ECU broadcast to measure vehicle speed and distance traveled. There were several design downfalls in the sample system that created measurement accuracy problems. An unheated sample line and filter were used, creating concern with moisture in the sample and cold spots on the filter. There was no NO_x converter, which converts NO₂ to NO, used and predicting the relationship between NO and NO₂ is not easily completed, making NO_x data inaccurate. Also, the exhaust flow was altered with the addition of the sampling system because the flow tube was not adaptable to different exhaust stack sizes. This meant changing the vehicles exhaust which would in turn change the natural flow and pressure and give poor representation of in-use operation. The positive stemming from this testing was the transformation of a gasoline emissions system to a diesel engines could be done [14,15].

Again, in 2002, the EPA's Office of Research and Development studied characteristics of heavy duty diesel emissions and plume development [29]. Termed ODEC, for On-road Diesel Emissions Characterization, the unit consisted of laboratory grade equipment in a trailer with an ejector diluter system. Analyzers used for the system were a Polycyclic Aromatic Hydrocarbon (PAH) analyzer, a Tapered Element Oscillating Microbalance (TEOM), and a Condensation

Nucleus Counter (CNC). The PAH analyzer measured aromatic hydrocarbons on a photoelectric ionization principle. PM measurement was achieved with the TEOM, while the CNC was used for particle counting and sizing. The ODEC could produce data on a mass or energy basis and made progress in characterization of in-use plume development. Unrealistic PM emissions and difficulties in understanding plume sampling dilution created problems during testing. Since then, several analyzers have been replaced and the system has been redesigned for improvements of plume measuring [14].

2.5.10 Ford Motor Company (FMC) and WPI-Microprocessor Systems, Inc.

In conjunction with WPI-Microprocessor Systems, Inc., FMC developed a system in 1999 called the Portable Real-time Emissions Vehicular Integrated Engineering Workstation (PREVIEW) [30]. The system was a small design, which was small enough to fit in the passenger area of a sport utility vehicle and measures HC, NO_x, CO, and CO₂ as well as up to 40 engine parameters via the ECU. NO_x was measured using an ultraviolet analyzer while the other constituents were measured with an infrared analyzer. A comparison using FTP and Highway Fuel Economy tests on a chassis dynamometer yielded rather accurate results. Obtained errors were 12.3% for HC, 0.4% for NO_x, 3.4% for CO, and 1.5% for CO₂. The NO_x analyzer showed a fast response time, even faster than that of the laboratory grade equipment [14,15].

2.5.11 Horiba, Ltd. And NGK Insulators

In the year 2000, Horiba, Ltd and NGK Insulators developed a system to measure NO_x emitting from diesel engines [31]. This system used a solid-state zirconium oxide (ZrO₂) sensor to measure at a range from 0-1000 ppm of NO_x. Intake air flow rate was measured via a vortex volumetric flow meter. The system could also measure intake air temperature, pressure, and humidity, ambient air temperature and pressure, boost pressure, coolant temperature, engine speed, and vehicle speed. The analyzer was quite small, capable of sitting on the passenger seat, and did not require an external power source. Comparison of the analyzer to compliance testing laboratory results showed differences of 4% in NO_x, 3% in fuel recovery, and 1% in distance measurements [14,15].

2.5.12 Honda R&D Americas, Inc.

In the year 2000, Honda, in collaboration with Nicolet Instrumentation Corporation, designed an FTIR measurement system designed for advanced low emission vehicles at or below ultra low emission vehicle (ULEV) levels [32]. An ULEV emits 50% less emissions than the average vehicle for that year. The measured emissions were NMHC, NO_x, and CO. A comparison against laboratory equipment and gas bottles with known concentrations showed an accuracy within 5% [14,15].

2.5.13 Technical Research Center of Finland (VTT Energy)

The Technical Research Center of Finland, or VTT Energy, performed tests in 2001 on transit buses that were powered by a variety of fuels [33]. Their study consisted of an NDIR gaseous analyzer able to measure HC, CO, CO₂, and O₂ and an Ecophysics CLD NO_x analyzer. The 4-gas NDIR has accuracies of $\pm 0.005\%$ for CO, $\pm 0.2\%$ for CO₂, $\pm 0.4\%$ for O₂, and 2% on the range of 0-2500 ppm for NO_x. Exhaust flow was measured using a hot film flow meter with manufacturer reported accuracy of $\pm 1\%$ and a required straight exhaust section of 6.5 feet before the measurement. The vehicle speed was inaccurately and unreliably measured from the speedometer signal. Power was supplied via a gasoline generator. Fuel consumption was calculated based on CO₂ emissions for gasoline engines and by gravimetrically weighing the fuel tank for diesel engines [14].

2.5.14 Clean Air Technologies International

In 2001, Clean Air Technologies developed a system to measure NO_x, CO, CO₂, and PM for real-time in-use emissions testing [35]. For CO and CO₂ emissions measurement, an NDIR analyzer was used. NO_x measurement was collected with an electrochemical cell, which only provides an estimation of the NO emissions. An opacity meter, or smoke meter, was used for PM measurements. Exhaust flow was calculated from the vehicle's air and fuel information through the diagnostic port. If this was not available on a vehicle, temporary sensors were installed for testing to obtain the desired values. The collected exhaust sample was unheated raw exhaust, from the tailpipe. The water in the exhaust was condensed in a separation bowl.

There were testing difficulties with the measurement of engine parameters from the diagnostic port, which nullified many of the tests. There was error due to misaligned flow data and an abundant amount of noise was found in the data acquisition. Prediction of NO_x based on

NO and NO₂ was not easy because water in the exhaust and cooling of the exhaust gas may have altered NO and NO₂ concentrations. Actual differences were not compared to laboratory grade equipment but trends between the two showed similar results. PM comparisons were also not completed so the validity was inconclusive. Comparisons for flow rate were completed and showed as much as 25% error when correlated to laboratory data. Also, power was supplied from the vehicle and could have generated a parasitic load affecting the emissions produced [14].

2.5.15 Analytical Engineering, Inc. (AEI)

AEI designed its Simple Portable On-vehicle Testing (SPOT) measurement system with partial funding from the EPA in 2001 [36]. The SPOT system measured NO_x and O₂ with CO₂ being calculated from the O₂ measurement. Exhaust flow was calculated while ambient air humidity and temperature were measured. The remaining engine parameters were collected via the ECU broadcast. The unit could be monitored through a remote data link which kept less equipment in the vehicle, saving space and reducing the unit's exposure to vibration and weather [14].

2.5.16 Engine, Fuel, and Emissions Engineering, Inc.

Engine, Fuel, and Emissions Engineering, Inc. designed the Ride Along Vehicle Emissions Measurement System (RAVEM) with a constant volume sampling (CVS) system [37]. This system was designed for the application of in-use testing of gasoline, diesel, and alternative fuel vehicles. The system used an NDIR analyzer for measurements of CO and CO₂, while NO_x was measured with a heated CLD analyzer. After passing through the sample line and dilution tunnel, PM was collected on a 37 mm Teflon-coated borosilicate glass fiber filter [14].

2.5.17 University of Alberta

In 2003, the University of Alberta performed a study of the effects ambient conditions had on emissions [4]. Distance specific HC, NO_x, CO, and CO₂ was measured using NDIR based equipment. A hot wire mass air flow sensor measured airflow and fuel flow came from a fast response air to fuel ratio sensor. Also measured were coolant temperature, intake air temperature, ambient air temperature, barometric pressure, engine speed, and vehicle speed. Reported errors of 2.1% and 4.9% were found for CO and NO_x, respectively. NDIR is an

inaccurate method to measure hydrocarbons because of its response but can accurately show trends for a given fuel. The sample line used was insulated but not heated creating the potential for condensation of the exhaust sample.

2.5.18 West Virginia University (WVU)

As result of the Consent Decrees explained in Section 2.3, WVU took on the task of developing a system capable of measuring and reporting emissions on a brake specific basis [14]. This system, referred to as Mobile Emissions Measurement System or MEMS, like other systems before, was constructed with portability and durability in mind. Unlike other systems, MEMS was actually used as the forefront to the development of commercially available units. Although testing was done at several stages of MEMS development, the study of focus was conducted as a performance evaluation of MEMS, in the year 2000.

Exhaust flow of the MEMS system was measured via an Annubar system [14]. The sample system consisted of a stainless steel probe, a heated line, a heated filter, a NO_x converter, and a chiller. The exhaust probe was designed to meet CFR 40, Part 86 standards. The heated line and filter were used to reduce condensation of the sample and the filter aided in trapping heavy particulate and soot. The NO_x converter was used because most analyzers only measure NO and some NO₂ is emitted in the exhaust, so the NO_x converter converts NO₂ to NO. Finally the chiller was used to qualify emissions measurements on a dry method.

For this stage of development, the MEMS system was only designed for gaseous emissions measurement [9,10]. As part of a design goal, the gaseous analyzers chosen were all to be commercially available units. Several available units were tested and in the final design, WVU chose a Horiba BE-140 to measure HC, CO, and CO₂, and a Horiba MEXA-120 for NO_x measurement. The study focused primarily on NO_x and CO₂ and in comparison to laboratory results, MEMS measured NO_x within 5.3% and CO₂ within 6.1%. Work was measured within 0.4% of the laboratory measured work.

2.6 CFR Compliance

The EPA's Code of Federal Regulations (CFR), Part 86, is the standard for all on-road heavy-duty diesel engine emissions testing [38]. The CFR lays out testing, emissions collection, data calculation, and data reporting procedures. Recently, changes have been made to create the Part 1065 of the CFR. These changes are referred to in the Part 86 version. Part 1065

encompasses both laboratory and in-use testing and creates a similarity between the two. Therefore, most of the changes in the Part 1065 affect both testing methods equally but explained below are the changes for in-use testing.

First, it is mandated to use international units under the 1065 changes. Changes allowing alternate test procedures as long as they are equal to the ones already utilized. Also included were specifications of new test equipment technology with equivalence or improvements to the existing equipment. Along with the equipment changes, equipment calibration and checks became stricter. Procedures to improve test repeatability were implemented. Finally, changes were made to simplify calculations of emission mass and to create a more comprehensive group of symbols, definitions, and references.

2.7 Previous Aiding Studies

2.7.1 In-Use Test Studies

A study, performed in 2008, was completed to compare the SEMTECH-DS to that of a mobile emissions laboratory (MEL) [39]. The Department of Chemical and Environmental Engineering, Center for Environmental Research and Technology (CE-CERT) conducted the tests on a truck containing a 2004 Caterpillar C-15 engine. The engine was equipped with a retrofit DPF to meet the 2007 emissions standards. The control for the experiment was a MEL that had a 1065 audit performed on it for both standard laboratory and in-use testing procedures. The study consisted of running three routes chosen to best achieve an overall comparison. The routes chosen gave varying ambient air temperature of 46-88°F, varying elevation of sea level to 5000 feet, sufficient NTE operation, power line crossings, and the crossing of railroad tracks and potholes. The last two were for effects of electromagnetic interference (EMI) and vibration on the system, respectively. Trips included having the PEMS unit inside the cab and outside the cab. Conclusions drawn were that the PEMS unit was consistently higher for brake-specific NO_x and CO₂, while brake-specific CO and NMHC were around 1% of the MEL. Also drawn from this study were changed measurement allowances for 2007-2009 and the developed measurement allowances for 2010 and later model year engines.

A previous study, utilizing CE-CERT's MEL, focused on comparing in-use emissions of a fleet of trucks ranging in model year from 1996-2004 [40]. The engines found in the fleet were a 1996 Cummins M-11, a 2000 Caterpillar C-15, a 2002 Detroit Diesel Series 60, a 2003 Mack

AC 427, and a 2004 Cummins ISM. These trucks were tested over routes including highway, interstate, steady-state driving, stop and go driving, and power lugs. The power lugs were achieved by operating the vehicle at maximum engine speed and applying the brake to create a load. The results from this study provided substantial in-use emissions data of different generation trucks. These results were compared to CARB's Emission FACTors (EMFAC) model for several speeds. NO_x emissions were comparable to EMFAC predictions. Some of the trucks showed higher NO_x values for operation greater than 55 miles per hour. PM emissions were generally lower than the EMFAC values. The oldest truck had the highest PM emissions for street driving but the lowest for highway driving. The newest trucks had the highest PM during highway operation compared to the other routes. Corresponding to lower NO_x values, this shows the "NO_x/PM" tradeoff discussed in emissions generations. The THC emissions varied for the different routes as compared to the EMFAC and were the highest for the power lug route. The CO emissions produced were reasonably comparable to the EMFAC predictions in both measurements and trends. The stop and go driving route produced the highest amount of CO emissions. This study showed that emissions vary significantly based on engines and the selected routes as compared to CARB's EMFAC predicted values.

2.7.2 Chassis Dynamometer Comparison Studies

An experiment comparing chassis dynamometer to on-road emissions was conducted in Europe [41]. Using both diesel and gasoline powered vehicles; the study involved testing with European dynamometer cycles and routes around Belgium and Spain, as well as a proving ground in Spain. Although statistical differences were not published, the study showed differences in all tested areas. These areas included vehicle speed, acceleration, fuel consumption, THC, NO_x, CO, and CO₂. The predicted reason for the differences was that the dynamometer tests were too smooth to be realistic and only focus on limited engine operation regions.

Another study, done in 2007, looked at emissions of several low emissions gasoline vehicles [42]. The study involved running the vehicles on a chassis dynamometer with laboratory equipment, on a chassis dynamometer with an on-board measurement system, and on a test track utilizing the on-board measurement system. The on-board system used FTIR technology for the emissions measurement of CO, NMHC, and NO_x. The emissions produced

were similar for all three test types, but differentiations between cold and warm start tests were seen. With the test track runs, emissions were higher on initial “cold” start-up but lowered after 100 seconds. The reasoning for this was the delay of the unheated catalyst.

Comparisons between dynamometer and in-use testing have shown relatively poor relationships. Most dynamometer tests cannot accurately mimic that of real-world testing. The University of California-Riverside (UCR) now has a dynamometer, designed by Mustang Advanced Engineering, to better simulate on-road driving conditions [43]. The dynamometer consists of dual, directly connected, 300 horsepower motors attached to each roll set. It is capable of applying loads to simulate conditions such as road and wind friction. The dynamometer is designed to work with a large variety of medium and heavy-duty chassis vehicles has the ability to meet several on-road cycles as well as in-use cycles for applications such as yard tractors.

2.7.3 Test Route Studies

The EPA developed test cycles for engine and chassis dynamometer certification of manufactured engines. It has been proven that these cycles are poor representations of real-world on-road driving conditions. An automobile, on the road, will run into effects such as heavy or light traffic, uphill or downhill driving, and highway or rural roads that will produce different emissions. All of these conditions will be encountered and typically with varying trends. This narrows nothing down for a “general test route,” hence the development of in-use testing. A study was performed in Europe with an emissions compliant spark-ignited engine on the effects of emissions due to the driven route [44]. This investigation involved measuring emissions from routes with and without “stop and start” driving. It also investigated routes with grade as compared to level roads.

The study concluded that there were significant differences with all the driving scenarios versus a 30 mile per hour steady speed route [44]. Fuel consumption increased by a factor of two for a non-stop route, and up to four for a route involving stops. For downhill grade, fuel consumption was 80 percent of the steady speed route and uphill grade increased consumption by a factor of 3.5. The non-stop transient route gave emissions data higher than the steady state route by a factor of 1.8-2.2 for CO, 2.8-3.4 for NO_x, and 2.6-3.2 for THC. The route, which included stops, increased emissions by a factor of 5.1-6.2 for CO, 5.6-7.5 for NO_x, and 4.1-5.1

for THC. The downhill grade decreased the emissions, making them a factor of 0.7 for CO, 0.6 for NO_x, and 0.9 for THC as compared to the steady state route. Finally, compared to the steady state route, the uphill grade route increased the emissions production by a factor of 6.5 for CO, 6.4 for NO_x, and 6.9 for THC. This meant that the combined uphill and downhill route compared to a flat route would ultimately have higher emissions because the uphill route produced more emissions than the low downhill route emissions.

Another study that can be related to the effects a route has on emissions is the effects a driver has on emissions [14]. The more varying in nature a route is, such as grade and traffic, the more differing drivers will play a role. The study, which took place in Japan, compared an experienced driver, an inexperienced driver, and a robotic driver. The study utilized the Japan 10 mode cycle and compared runs of automatically and manually shifted transmissions. Looking at repeatability of accelerator and brake pedal operation, repeatability and stability of intake manifold pressure, and repeatability and traceability of driving speed, the study showed the robotic driver to be the most repeatable compared to the human drivers, which is expected. For just the human drivers, the study showed that the experienced driver was more repeatable for every category except intake manifold pressure stability when compared to the inexperienced driver, with a manually shifted vehicle. When using the automatically shifted vehicle, there were no significant differences between the experienced and inexperienced driver. This shows one more reason that it is hard to develop a general test procedure to cover all aspects of real-world application.

3. Experimental Setup

This chapter contains information regarding the description of the experiment, as well as the equipment used. The experiment was conducted under two settings, laboratory testing and on-road testing with various routes in and near to Morgantown, WV. The laboratory testing was performed at the Westover, WV location of West Virginia University's Center for Alternative Fuels, Engines, and Emissions. The laboratory housed the medium-duty chassis dynamometer and emissions measurement equipment used for the experiment. Also, two on-board emissions measurement systems, one designed under the CFR's Part 86 standards and the other under the updated Part 1065 standards, were installed to conduct the comparison of laboratory to on-road equipment. The second half of the study was performed with on-road testing along five different routes. The routes are further explained in this chapter. For the on-road testing, the two on-board systems were used and compared against each other to show a generational comparison. The test vehicle was a medium-duty chassis GMC 4500 truck from the WVU fleet. Photographs of the truck and equipment setup are shown in the Appendix in Figures 7-1 through 7-6.

3.1 Test Vehicle

As stated above, the test vehicle selected for this experiment was a 2004 model year GMC C4500. The vehicle was a medium-duty chassis truck with a 6.6 liter General Motors Duramax Diesel engine. The truck had a full four door cab and flat-bed chassis. It was equipped with a dual rear wheel axle and was a two-wheel drive model. Even though on-road testing is more specific to heavy-duty chassis trucks; this truck gave good representation for equipment comparison. This truck was chosen because the flat bed creates an easy environment to place the equipment on. Also, it was an automatic transmission truck so regardless of driver skill, the comparison to the dynamometer testing should have less error as shown in previous studies. The final reason that made this truck a good selection for the experiment was the fact that a medium-duty chassis does not require CDL licenses under general circumstances. For laboratory testing, a weight of 12,000 pounds was simulated. The on-road test weight of the truck was 12,500 pounds. The difference came from the fact that the dynamometer can only achieve certain weights based on a combination of the attached flywheels.

3.2 Test Equipment

3.2.1 West Virginia University's Transportable Laboratory

Dynamometer testing for the comparison was executed using West Virginia University's Transportable Laboratory [10]. Developed in 1990, the WVU Transportable Laboratory uses laboratory grade equipment housed in a box trailer for mobility. Since then, in 2007, the Transportable Laboratory was updated to meet Part 1065 standards. The set up is not designed for in-use testing but rather on site testing. To complete this task, the WVU Transportable Laboratory also consists of a transportable chassis dynamometer on a flat bed trailer. This particular dynamometer is for heavy-duty chassis trucks. In addition, WVU has a medium-duty chassis dynamometer that can be used with the mobile emissions trailer. The medium-duty chassis dynamometer was the one used for this research project.

3.2.1.1 Constant Volume Sampling (CVS) System

The WVU Transportable Laboratory uses a constant volume sampling system [47]. As opposed to the previous critical flow venturi system, the WVU system now utilizes a subsonic venturi manufactured by Flow Dyne Engineering. The measurement range is 200 to 3000 SCFM and it is capable of varying flow to keep a constant mass flow rate. Temperature and pressure is monitored in order to calculate the desired flow, which is matched by a blower that draws air through the CVS system. The exhaust sample enters a dilution tunnel where it mixes with dilution air. After traveling a sufficient amount (approximately 20 feet in a 20 inch diameter tunnel), the diluted sample is then measured for gaseous and PM emissions. Before entering the CVS system, the exhaust sample passed through an Annubar. The Annubar was the laboratory exhaust flow measurement system.

3.2.1.2 Gaseous Emissions Measurement

Although the system is designed for both gaseous and PM emissions measurement, this project focuses only on gaseous emissions data [47]. For gaseous emissions measurement, WVU uses a recently updated laboratory built according to the updated CFR 40, Part 1065. The recorded gaseous emissions include CO, CO₂, NO_x, and THC. To measure these constituents, the laboratory utilizes the Horiba, Ltd MEXA 7200D. The MEXA 7200D houses all the analyzers for measurement. The MEXA 7200D's software is capable of performing all

necessary calibrations and verifications. This setup is the same as WVU's engine dynamometer laboratory with some exceptions. One exception is the intake air conditions. Testing with the chassis dynamometer uses ambient air rather than a controlled air supply. Also, for the dynamometer testing, emissions are reported on a distance specific basis.

3.2.1.3 Horiba, Ltd. MEXA 7200D

The Horiba MEXA 7200D is a gaseous emissions analyzing unit that can measure several gases which include CO, CO₂, NO_x, and THC [47]. This is done by using different analyzers for each constituent built into one chassis. This makes the unit very ergonomic, because of its size, for the users but as effective as older, larger emissions measurement benches. The MEXA 7200D has a sample handling system (SHS) that pumps the sampled exhaust gas from the CVS system into the analyzing unit. This transfer is done through a heated filter and heated line. Also, the SHS houses an internal oil catcher and a chiller system that removes condensation from the sample. The sample is transferred to what is known as the OVN, which is the rack containing the emissions analyzers. The OVN has its own sample handling system similar to the one explained above. The OVN is also heated to prevent condensation in the sample. Also, as stated above was the MEXA 7200D's capability for calibration and checks. This is done by a solenoid valve system that can switch between zero, span, and sample gas flow. In addition, the unit consists of its own automated gas divider for linearizations and other analyzer checks.

3.2.1.3.1 *THC Measurement*

The Horiba MEXA 7200D utilizes two flame ionization detector (FID) analyzers to measure the content of THC and methane in the sample [47]. A FID analyzer works under the principle of using a hydrogen flame to measure the constituent. Once the sample is introduced to the flame, hydrocarbon species will burn and release ions. These ions are collected by electrodes on either side of the flame. When voltage is applied to the ions, current increases and this increase corresponds to the measurement of carbon atoms. One FID analyzer in the MEXA 7200D measures solely THC, while the other measures THC or methane. For the measurement of methane concentration, the analyzer uses the same FID flame concept but the sample must first travel through a non-methane cutter, which oxidizes non-methane hydrocarbon species, before being measured.

3.2.1.3.2 *NO_x Measurement*

For the measurement of NO_x emissions, the MEXA 7200D utilizes two chemiluminescence detection (CLD) analyzers [47]. One analyzer is located in the OVN and measures a “hot” sample, while the other is located in the main analyzer rack and measures a “cold” sample. With this set up, the hot analyzer measures NO_x and the cold analyzer measures NO. CLD analyzers work under the principle of measuring energy through light. CLD analyzers measure NO with the aid of an ozone (O₃) generator. When NO and O₃ meet, NO is oxidized into NO₂. This portion of NO₂ in the sample is excited and emits energy through light. This energy is directly proportional to the measurement of NO in the exhaust sample. A NO_x converter is used to convert NO₂ to NO in the hot NO_x analyzer.

3.2.1.3.3 *CO and CO₂ Measurement*

The MEXA 7200D measures both CO and CO₂ concentration with the non-dispersive infrared (NDIR) technique [47]. NDIR analyzers work under the theory that any gas specie will absorb infrared energy at a specific wavelength and this absorption is proportional to the concentration of the gas specie. Gas will enter the NDIR chamber which consists of the gas being measured, a flexible membrane, and an infrared neutral gas. The membrane is positioned between the two gases. When the gas being measured interacts with the infrared, it expands. This expansion displaces the membrane and correlates to the concentration found in the exhaust sample. The MEXA 7200D uses two separate NDIR analyzers for the measurement of CO and CO₂. One analyzer measures low concentrations of CO while the other measures CO₂ and high concentrations of CO.

3.2.2 Sensors, Inc. SEMTECH-D

The SEMTECH-D (Sensors EMISSION TECHnology Diesel), which will also be referred to as the SEMTECH, is from the Sensors Inc. product line designed and built for on-board testing [45]. The D unit is designed to be used with specially diesel engine applications such as diesel powered trucks, agricultural equipment, construction equipment, mining equipment, and even marine diesel application. Granted the SEMTECH line is designed for on-board testing, it can also be utilized in laboratory testing as well. The SEMTECH uses stand-alone measurement systems for emissions measurement of THC, NO, NO₂, CO, CO₂, and O₂. The systems are all designed to the analytical capabilities of laboratory grade equipment but with reduction in size,

weight and power consumption. It is also designed with reduction of sensitivity to vibrations and change in ambient temperature, pressure, and humidity. In addition to the measuring capabilities, the SEMTECH is capable of data logging, digital and analog I/O, vehicle interface through the ECU, measuring ambient temperature and humidity from a weather probe, and measuring location, altitude, and speed via GPS.

3.2.2.1 Emissions Measurement

As stated above, the SEMTECH-D is capable of measuring several different gases. The measurement of THC is done with a high-precision, heated FID analyzer [45]. The measurement is done over the range of 0 to 10,000 ppm with user selectable test ranges of 100, 1,000, or 10,000 ppm. A fraction of sampled exhaust gas passes through the heated FID chamber which is constructed of stainless steel. The sampling system and FID chamber are heated to 191°C as an attempt to prevent the condensation of heavy hydrocarbons found in the exhaust sample. The user manually ignites the flame and extinguishes it if needed; but once the flame is lit, the FID is controlled by the SEMTECH software. Fuel for the FID is blended hydrogen and helium at 40/60%, respectively. The SEMTECH has the capability of accepting gas from an external port or housing a small gas bottle internally to eliminate the need for a large gas bottle.

The SEMTECH uses an NDUV analyzer to measure NO and NO₂ [45]. The NDUV analyzer is used as an improvement to previous methods where NO₂ is lost. The NDUV works under a similar concept to the NDIR analyzers. NO and NO₂ have unique absorption bands in the ultra-violet range allowing independent measurement of the two constituents. The analyzer measures at a range of 0 to 2,500 ppm for NO and from 0 to 500 ppm for NO₂. In comparison to the laboratory used CLD's, the NDUV analyzer is a favorable choice for on-board equipment.

For the measurement of CO, CO₂, and HC, the SEMTECH utilizes the Sensors, Inc. Automotive Micro-Bench II (AMBII) NDIR analyzer [45]. The sample exhaust is dried with a coalescing filter and then a thermoelectric chiller before reaching the NDIR analyzer. This is to eliminate the water vapor which would cause interference in the infrared channels. The analyzer measures CO at a range of 0-8% (0-80,000 ppm), but for a diesel engine, the range of interest is 0.1% (1000 ppm). The SEMTECH software is capable of displaying either percentage or ppm for CO.

For measuring O₂, the SEMTECH has an oxygen sensor cartridge installed onto a flow adapter which is inside the unit's chassis. The sample flows through the adapter and a signal is produced by the sensor that is proportional to the partial pressure of oxygen. This signal is then sent to the AMBII module.

3.2.2.2 Ambient Condition and Flow Measurement

Outside of emissions measurement, the SEMTECH measures data related to ambient air conditions and exhaust flow [45]. A weather probe is used to collect information regarding ambient air temperature and humidity, while the air pressure is measured by a transducer in the unit. These measurements are needed to help with correction factors applied based on ambient conditions. For exhaust flow measurement, the SEMTECH uses what Sensors, Inc. calls the electronic exhaust flow meter (EFM), which is an averaging pitot tube. The EFM reads an exhaust mass flow and post processing software calculates exhaust mass emissions for all measured exhaust gases.

3.2.3 Horiba, Ltd. OBS 2200

The Horiba, Ltd. OBS 2200 is an on-board gaseous emissions measurement system designed for real-world vehicle testing [46]. The system consists of vibration-proof analyzers, software for system control and data logging, accessory sensors, and a pitot tube style tail-pipe attachment. The system measures CO, CO₂, NO_x, and THC emissions and exhaust flow for the emission calculations. The system also records ambient air conditions, GPS data, and vehicle OBD data. The software is capable of time-trend profiles and integrated values of both mass emissions and fuel consumption.

3.2.3.1 Emissions Measurement

As previously stated, the OBS-2200, which will also be referred to as the OBS, measures the exhaust constituents; CO, CO₂, THC, and NO_x [46]. The OBS has the capability of measuring on a wet or dry basis. For this study, measurements were taken dry. To measure CO and CO₂, the system uses a heated NDIR analyzer, held at 60°C. CO can be measured in the range of 0 to 10 percent volume with an accuracy of ±2.5 percent. CO₂ can be measured in the range of 0 to 20 percent volume with an accuracy of ±2.5 percent of full scale.

A heated FID analyzer is used to measure THC emissions in the exhaust sample. The FID is managed at a temperature of 191°C after the warm-up process [46]. FID fuel is fed into the system externally to light the flame. THC emissions can be measured in the range of 0-10,000 ppm with an accuracy of ± 2.5 percent of full scale.

For measuring NO and NO_x, the OBS-2200 uses a heated CLD analyzer [46]. This analyzer is used because it is very sensitive to NO and other components have limited interference. The CLD analyzer measures both NO and NO_x in the range of 0-3000 ppm at an accuracy of ± 2.5 percent of full scale.

3.2.3.2 Ambient Condition and Exhaust Flow Measurement

The OBS-2200 measures ambient conditions to create the needed correction factors needed when performing in-use testing [46]. The atmospheric pressure measurement ranges from 0 to 115 kPa and is accurate within ± 1.5 percent of full scale. Ambient temperature is measured in the range of -40 to 85°C with an accuracy of $\pm 0.3^\circ$ at 23°C. Finally, the ambient humidity sensor measures the relative humidity between 0 and 100 percent. The accuracy is ± 1.5 percent for relative humidity at a temperature of 23°C.

The OBS utilizes a direct measurement of the vehicle exhaust flow. A transfer pipe, with a pitot tube, is installed on the exhaust system of the test vehicle [47]. The exhaust flow is calculated based on the readings of absolute pressure, differential pressure, and temperature provided by the pitot tube in the tail-pipe attachment.

3.2.4 West Virginia University's Medium-Duty Dynamometer

For completion of this project, WVU's medium-duty chassis dynamometer was used to give laboratory representation of the produced emissions [48]. The medium-duty dynamometer is capable of simulating weights in the range of 3,000 pounds to 22,000 pounds. The dynamometer consists of six main components, which include: inertia flywheels, a power absorber, a two-speed transfer case, an AC variable speed electric motor, an inline torque transducer, and the tire rollers. The transfer case listed above allows for a larger range of speeds with gear ratios of 1:1 and 2.04:1. Control of the dynamometer is accomplished through the Transportable Laboratory's software which was created by WVU. A WVU developed system consisting of the National Instruments SCXI 1001 is used for data acquisition.

3.3 On-Road Routes

WVU has previously conducted studies of this nature and has ECU data to simulate on-road routes local to the Morgantown, WV area. Five routes were utilized to conduct this study, which accounted for types of driving including urban, rural, and highway. The routes include a city trip around Morgantown that starts and ends in Westover, an interstate route from Westover to Saltwell and another interstate route from Westover to Bruceton Mills. It was proposed that the two interstate routes be repeated four times each and that the Morgantown-Westover route be repeated ten times.

3.3.1 Morgantown-Westover Route

The Morgantown-Westover route is a route that circled around and went through the city of Morgantown, WV and covered several aspects encountered in real world driving. It consisted of rural driving, urban driving, and highway driving. The route started at WVU's Westover test facility and continued to southbound I-79. The route continued and merged onto eastbound I-68. From I-68, exit 4 toward Sabraton was taken and continued along WV Route 7. The next exchange was a right hand turn onto County Road 857 toward US 119, the Mileground Road. Next the route continued southwest on US 119 until it intersected with Route 705. Route 705 was followed until it intersected Route 7 again. Route 7 was followed until the intersection of I-79 and exited onto southbound I-79. Exit 152 toward Westover was taken and Route 19 was followed back to the Industrial Park Road. This led back to the Westover test facility where the route ended. This route totaled 27.1 miles and posted varying speed limits from 25 to 70 miles per hour. A map of the route is shown in Figure 3-1 and an elevation plot in Figure 3-2.

Figure 3-1: Map of Morgantown-Westover Route [50].

Figure 3-2: Plot of Elevation for the Morgantown Route.

3.3.2 Westover to Saltwell Route

The Westover to Saltwell route was primarily interstate driving, except for entrance and exit to the interstate. The route started at the same location as the Morgantown-Westover route but instead of exiting onto I-68 from I-79, the cycle stayed on southbound I-79. The cycle continued on I-79 south until exit 125 Saltwell Rd., where the route ended. The route was also run in the reverse direction. This route is good representation of high speed driving, with elevation change less than 200 meters. The distance traveled is 30.9 miles and the posted speed limit on both interstates is 70 miles per hour. Figure 3-3 shows a map of the route and Figure 3-4 shows an elevation plot.

Figure 3-3: Map of Westover to Saltwell Route [52].

Figure 3-4: Plot of Elevation for the Westover to Saltwell Route.

3.3.3 Westover to Bruceton Mills Route

Just as the other two routes explained, this route started from the same location. The route continued toward I-79 southbound, just as the other two routes. The route exited onto I-68 eastbound. Staying on I-68, the route continued to exit 23 Bruceton Mills, where the route ended. This route was also run in the reverse direction. It is very similar to the Saltwell route in the fact that it is high speed interstate, with a posted speed limit of 70 miles per hour. The difference is that this route is a better representation for high speed travel with elevation change greater than 400 meters. The route covered 30.1 miles and can be seen in Figure 3-5. Figure 3-6 shows an elevation plot.

Figure 3-5: Map of Westover to Bruceton Mills Route [51].

Figure 3-6: Plot of Elevation for the Westover to Bruceton Mills Route.

It is to be noted that even though the routes all start from the same location, the plots show variation in the elevation of the start point. The elevation was calculated from recorded GPS data. It is known that while accurate in the horizontal direction, GPS is less accurate when reading in the vertical direction, or elevation readings. Most of the inaccuracy is found when a GPS device is slow or stopped [53].

3.4 Test Procedure

As previously stated, this project was a comparison of in-use test equipment to laboratory grade equipment. It was also an investigation of how much difference can be seen when doing dynamometer testing as compared to actual on-road, or real world, testing. To complete the laboratory testing: WVU's Transportable Laboratory, the SEMTECH-D, and the OBS 2200 were used to record emissions data. The laboratory tests were conducted on WVU's medium-duty chassis dynamometer using the above explained GMC 4500 truck. Previously collected GPS data provided the simulation of the five routes driven for the comparison. Differences between the laboratory equipment, WVU's Transportable Laboratory, and the in-use equipment, the SEMTECH-D and the OBS 2200, were examined for accuracy and consistency. Also, the project performed a generational comparison of the SEMTECH-D and the OBS 2200 to examine how, or if, the CFR 40 Part 1065 equipment standard changes effected collected emissions data. The on-road portion of the testing used only the SEMTECH-D and the OBS 2200 to collect

emissions data while actually running the routes that are simulated on the dynamometer. Data was used to show the differences between laboratory testing and in-use testing when running a created dynamometer cycle and the matching on-road route.

3.4.1 Laboratory Test Matrix

As explained above, tests were run on WVU's medium-duty chassis dynamometer over the five cycles used for this experiment. All tests were run on a warm-start basis for consistency and to eliminate the time needed to cool down for cold-start tests. Only two drivers were used to allow a break for each driver but keep consistency by using fewer drivers. The proposed plan was to complete 26 test cycles in two test days. The cycles to be completed over the two days were as follows: four Westover to Bruceton Mills cycles, four Bruceton Mills to Westover cycles, four Westover to Saltwell cycles, four Saltwell to Westover cycles, and ten Morgantown-Westover cycles. This meant running half of the above tests for each cycle each day. Problems arose during testing causing the planned test schedule to vary from the actual tests completed. The table below (Table 3-1) shows the completed test cycles of the laboratory testing.

Table 3-1: Laboratory Test Schedule.

Test ID	Cycle	Driver	Date	Start Time	End Time
B2W-01	Bruceton Mills to Westover	1	4/8/2011	15:25	15:57
B2W-02	Bruceton Mills to Westover	1	4/8/2011	16:15	16:47
W2B-01	Westover to Bruceton Mills	1	4/8/2011	17:31	18:04
W2B-02	Westover to Bruceton Mills	1	4/8/2011	18:48	19:21
W2S-01	Westover to Saltwell	2	4/8/2011	19:54	20:26
W2S-02	Westover to Saltwell	1	4/8/2011	20:49	21:21
S2W-01	Saltwell to Westover	2	4/8/2011	21:40	22:11
S2W-02	Saltwell to Westover	1	4/8/2011	22:32	23:03
MW-01	Morgantown-Westover	1	4/8/2011	23:25	0:21
MW-02	Morgantown-Westover	2	4/8/2011	0:43	1:39
MW-03	Morgantown-Westover	1	4/9/2011	9:57	10:53
MW-04	Morgantown-Westover	2	4/9/2011	11:15	12:11
MW-05	Morgantown-Westover	1	4/9/2011	12:47	1:43
S2W-03	Saltwell to Westover	1	4/9/2011	14:10	14:41
S2W-04	Saltwell to Westover	2	4/9/2011	15:01	15:32
W2S-03	Westover to Saltwell	2	4/9/2011	15:53	16:25
W2B-03	Westover to Bruceton Mills	2	4/9/2011	16:45	17:18
W2S-04	Westover to Saltwell	1	4/9/2011	17:44	18:16
W2B-04	Westover to Bruceton Mills	2	4/9/2011	18:49	19:22
B2W-03	Bruceton Mills to Westover	2	4/10/2011	11:55	12:27
B2W-04	Bruceton Mills to Westover	2	4/10/2011	12:49	1:21
MW-06	Morgantown-Westover	1	4/10/2011	19:30	20:26
MW-07	Morgantown-Westover	2	4/10/2011	21:02	21:58

3.4.2 On-Road Test Matrix

The five routes used for the dynamometer simulation were driven on-road for comparison of laboratory testing to on-road testing. Also, the accuracy and consistency of the in-use equipment, while doing real world testing, was investigated. Same as with the dynamometer testing, all tests were done on a warm-start basis. The routes were repeated the same number of times to match the dynamometer testing, with the exceptions of the Morgantown and Saltwell routes. The Morgantown route was repeated the planned ten times and the round trip of the Saltwell routes was repeated one extra time because of complications. The test schedule used for the on-road routes is shown below in Table 3-2.

Table 3-2: On-Road Test schedule.

Test ID	Route	Driver	Date	Start Time	End Time
MW-08	Morgantown-Westover	2	05/21/11	10:50	11:38
MW-09	Morgantown-Westover	1	05/23/11	16:52	17:48
MW-10	Morgantown-Westover	2	05/23/11	18:11	18:57
MW-11	Morgantown-Westover	1	05/23/11	19:19	20:05
MW-12	Morgantown-Westover	2	05/23/11	20:21	21:03
W2S-05	Westover to Saltwell	2	05/24/11	7:15	7:46
S2W-05	Saltwell to Westover	2	05/24/11	8:02	8:33
W2S-06	Westover to Saltwell	1	05/24/11	8:51	9:23
S2W-06	Saltwell to Westover	1	05/24/11	9:39	10:12
W2B-05	Westover to Bruceton Mills	2	05/24/11	10:34	11:05
B2W-05	Bruceton Mills to Westover	2	05/24/11	11:20	11:51
W2B-06	Westover to Bruceton Mills	1	05/24/11	12:10	12:42
B2W-06	Bruceton Mills to Westover	1	05/24/11	13:01	13:32
W2S-07	Westover to Saltwell	2	05/25/11	7:28	7:59
S2W-07	Saltwell to Westover	2	05/25/11	8:19	9:04
W2S-08	Westover to Saltwell	1	05/25/11	9:20	9:51
S2W-08	Saltwell to Westover	1	05/25/11	10:27	11:01
W2B-07	Westover to Bruceton Mills	2	05/25/11	12:08	12:40
B2W-07	Bruceton Mills to Westover	2	05/25/11	12:54	1:04
W2B-08	Westover to Bruceton Mills	1	05/25/11	14:53	15:23
B2W-08	Bruceton Mills to Westover	1	05/25/11	15:39	16:09
W2S-09	Westover to Saltwell	1	05/25/11	16:36	17:08
S2W-09	Saltwell to Westover	1	05/25/11	17:25	17:56
MW-13	Morgantown-Westover	1	05/25/11	18:18	19:04
MW-14	Morgantown-Westover	2	05/25/11	19:24	20:07
MW-15	Morgantown-Westover	1	05/25/11	20:24	21:09
MW-16	Morgantown-Westover	2	05/25/11	21:27	22:08
MW-17	Morgantown-Westover	1	05/25/11	22:26	23:07

3.5 Data Reduction

The data reduction goal was to utilize the data that was reduced by each unit's reduction software. This proved to be a problem because the software was not accurately calculating all parameters. For one, as mentioned above, the SEMTECH's exhaust flow and mass emissions calculations were corrected 9.7% by the equation below (Equation 2), where $SEMTECH_{act}$ is the corrected value and $SEMTECH_{meas}$ is the value measured from the testing.

$$SEMTECH_{act} = \frac{SEMTECH_{meas}}{1.0931}$$

Equation 2

Another reduction software issue with both systems was brake specific power calculations. Further investigation proved that the best method to obtain the power to calculate brake specific emissions was through the ECU data, which was SAE J1939 protocol. The laboratory did not collect ECU data and it also only had power calculations at the rear wheels. For the comparison to be most accurate, an integrated power through ECU engine speed and torque collected via from each in-use unit was used for the laboratory calculation. This does not affect any of the actual volume or mass emissions calculations and still provides an accurate comparison of analyzers. The calculation for power was completed using the method below (Equation 3), where Power is the horsepower associated with a given data point, %Torque is the percent of maximum torque of the engine, 590 is the maximum torque in foot-pounds, RPM is the associated engine speed for the torque value, and 5252 is a conversion factor to horsepower. Other methods of calculating power from torque require the use of friction torque and percent load but the method used of percent torque of the maximum torque value proved to work the best in this study.

$$Power = \frac{\left(\frac{\%Torque}{100} * 590\right) * RPM}{5252}$$

Equation 3

With power calculations accounted for and less than 1 percent difference between the SEMTECH and the OBS power calculations, brake specific mass emissions were calculated. Also, distance specific emissions were calculated based on the mass emissions and distance traveled. The equations (Equation 4 and Equation 5) for both are listed below, where, first, BSE is the brake specific emissions represented in grams per brake horsepower hour, which is the integrated mass emitted over the integrated power or work for a given test.

$$BSE = \frac{\sum \dot{E} \Delta t}{\sum P \Delta t}$$

Equation 4

The second equation is distance specific emissions, where DSE is the distance specific emissions with the unit of grams per mile, which is the integrated mass emitted over the total distance traveled of each given cycle.

$$DSE = \frac{\sum \dot{E} \Delta t}{Dist}$$

Equation 5

To aid in the confidence of the reduced data, other calculations were completed for exhaust flow, carbon balance, and fuel consumption. Since CO₂ analyzers are typically very accurate, the exhaust flow calculation should correlate directly with the measurement of CO₂ mass emissions. This means that the percent error between CO₂ measurement and exhaust flow for the measurement systems should be close to equal. The equations below (Equation 6, Equation 7, and Equation 8) represent exhaust flow, carbon balance, and fuel consumption, respectively. Exhaust volume, V, is in standard cubic feet (SCF) and is the sum of all instantaneous exhaust flow rate points in SCFM.

$$V = \sum \dot{V} \Delta t$$

Equation 6

CarbBal represents the carbon consumption in grams based on the fraction of carbon in each emission constituent, CO represents the total carbon monoxide in grams, CO₂ represents the total carbon dioxide in grams, HC represents the total hydrocarbons in grams, and hydrogen-to-carbon ratio, HtoC, of 1.85. It is to be noted that the fuel consumption equations are with an assumption of diesel fuel consisting of hydrogen and carbon only and different correlations would be needed for different fuels such as biodiesel.

$$CarbBal = \frac{12.011}{12.011 + (HtoC * 1.008) * HC} + (0.429 * CO) + (0.273 * CO)$$

Equation 7

FuelCons represents the fuel consumption in grams and utilizes the CarbBal calculation.

$$FuelCons = CarbBal * \frac{12.011 + (HtoC * 1.008)}{12.011}$$

Equation 8

The final calculations used in the reduction of data were the calculation of percent error and coefficient of variation (COV). Error was calculated between both pieces of in-use equipment and the laboratory as well as between the two pieces of in-use equipment. For the laboratory error comparison the equation below (Equation 9) was used. In the equation, InUse represents the in-use measurement, either from the SEMTECH or the OBS, used in the error comparison and Laboratory represents the laboratory measurement.

$$\% Error = \frac{InUse - Laboratory}{Laboratory} * 100$$

Equation 9

For the comparison of the two in-use units, the equation (Equation 10) varied slightly. There is no control in this comparison so the divisor is the average of the two measurements. Each test unit was represented by its respective name.

$$\% Error = \frac{SEMTECH - OBS}{0.5 * (SEMTECH + OBS)} * 100$$

Equation 10

The COV was calculated based on the standard deviation, SD, and the mean of the data points being examined. Equation 11 shows the calculation used for coefficient of variation.

$$COV = \frac{SD}{Mean} * 100$$

Equation 11

Based on the above calculations, certain key parameters unless otherwise declared were examined and reported each test cycle. The emissions constituents considered in this study were CO, CO₂, THC, and NO_x. They were reported on a concentration, mass, distance specific, and

brake specific basis. In order to calculate the distance and brake specific emissions, the mileage and work done over the cycle were used. The concentration emissions from the laboratory equipment were not compared against in-use equipment because the laboratory measures diluted concentrations as opposed to the raw concentrations from the in-use equipment. Also a carbon balance was completed to acquire fuel consumption values. This was compared to gravimetric fuel consumption. The table below (Table 3-3) shows the parameters examined along with the units they were reported in. To analyze the significance of the results, a Student T-Test with a p-value of 0.05 was performed and any data considered having significant difference will be bold in the results.

Table 3-3: Reported Parameters and Units

Parameter	Units
Distance	miles
Work	bhp-hr
Exhaust Volume	SCF
CO	%
CO₂	%
THC	ppm
NO_x	ppm
CO	grams
CO₂	grams
THC	grams
NO_x	grams
CO	g/mi
CO₂	g/mi
THC	g/mi
NO_x	g/mi
CO	g/bhp-hr
CO₂	g/bhp-hr
THC	g/bhp-hr
NO_x	g/bhp-hr
Carbon Balance	grams
Fuel Consumption	grams

4. Discussion of Results

As stated in previous chapters, the primary focus in this study was to achieve a generational comparison of two commercially available in-use testing units. The two units represented first generation CFR 40, part 86 standards and second generation CFR 40, part 1065 standards and were the SEMTECH-D, built by Sensors Inc., and the OBS-2200, built by Horiba Ltd., respectively. The systems were compared against WVU's CFR 40, part 1065 compliant laboratory, which was considered the control for this experiment. Laboratory and on-road testing was executed to also acquire information for comparison of repeatability between the types of testing.

Finding a fully functional SEMTECH-D posed a problem because it is no longer built, as it has been updated with a newer model. One was obtained for the duration of the testing but had not been used since 2008. The OBS-2200 is owned by WVU and had been recently used for in-use projects. Both systems, regardless of previous use, were examined for any flaws. Also, all calibration procedures outlined by the manufacturers were executed to verify operation of gaseous analyzers and exhaust flow measurement. The only problem found among both systems was the exhaust flow measurement calibration of the SEMTECH-D. In comparison to a flow bench, the SEMTECH's EFM was found to be 9.3% higher than the LFE flow measurement. Figure 4-1 and Figure 4-2 below show flow plots of the exhaust flow measurement systems for both the OBS and the SEMTECH, respectively. It should be noted that the OBS-2200 showed poor agreement at low flow rates.

Figure 4-1: Plot of OBS Exhaust Flow against Laboratory LFE.

Figure 4-2: Plot of SEMTECH Exhaust Flow against Laboratory LFE.

4.1 Laboratory Test Results

As with any experiment, difficulties were expected with testing and equipment. Since this was an equipment comparison, any difficulty encountered during a test with the SEMTECH-D or OBS-2200 was not considered to null the test results. The comparison was not limited to measurement capability, but also incorporated overall reliability and consistency. The most common problem encountered while testing was keeping the FID flame lit on the OBS-2200 analyzer. This was found to be a problem with the setup as opposed to the OBS unit itself. The FID fuel was being supplied to both units from one bottle using a T fitting. This proved to be an insufficient way to supply FID fuel and was changed. Tests that the FID flame was lost still provide good data for other emissions constituents. Also, for HC comparison of equipment, the data was analyzed and evaluated only for the period of time that the FID was lit. Another problem encountered was with the laboratory dynamometer acquisition system. Information of the power absorber torque from the eddy current dynamometer was lost during one test. This was fixed but did not pose a large problem because torque information was being acquired from ECU data. This had to be done for accurate representation of torque for brake specific power calculations and an explanation is provided in the next section. Another test resulted in a loss of motor torque which does pose a problem because the dynamometer was unable to simulate load and grade as it was supposed to. Finally, with repairs fixing the dynamometer motor, the largest malfunction encountered was a catastrophic failure of one of the dynamometer rollers. This caused an early ending to the laboratory testing and caused the total number of tests completed to

be 23 of the proposed 26. All test cycles that were incomplete were Morgantown cycles and caused the total of Morgantown cycles to be seven instead of the planned 10. Below, Table 4-1 shows the problems encountered per each test. Dates and times can be seen in Table 3-1 of Section 3. Individual test results are shown in Appendix B (Table 8-1 through Table 8-23). A portion of sample laboratory test plots are shown in Appendix D (Figure 10-1 through Figure 10-25).

Table 4-1: Difficulties Encountered During Laboratory Testing.

Test ID	Cycle	Problem(s) Encountered
B2W-01	Bruceton Mills to Westover	OBS FID not lit
B2W-02	Bruceton Mills to Westover	OBS FID not lit
W2B-01	Westover to Bruceton Mills	NA
W2B-02	Westover to Bruceton Mills	NA
W2S-01	Westover to Saltwell	NA
W2S-02	Westover to Saltwell	Lost OBS FID
S2W-01	Saltwell to Westover	Lost OBS FID
S2W-02	Saltwell to Westover	Lost OBS FID
MW-01	Morgantown-Westover	Lost OBS FID
MW-02	Morgantown-Westover	SEMTECH did not sample
MW-03	Morgantown-Westover	Lost OBS FID
MW-04	Morgantown-Westover	Lost OBS FID
MW-05	Morgantown-Westover	Lost OBS FID
S2W-03	Saltwell to Westover	NA
S2W-04	Saltwell to Westover	NA
W2S-03	Westover to Saltwell	NA
W2B-03	Westover to Bruceton Mills	NA
W2S-04	Westover to Saltwell	NA
W2B-04	Westover to Bruceton Mills	NA
B2W-03	Bruceton Mills to Westover	OBS sample line not connected
B2W-04	Bruceton Mills to Westover	Lost eddy current dynamometer torque
MW-06	Morgantown-Westover	NA
MW-07	Morgantown-Westover	NA

4.1.1 Morgantown-Westover Cycle

As previously stated, the Morgantown-Westover cycle was the cycle with the best representation of varying situations. It included highway, rural, and city sections. Seven test cycles were completed, as opposed to the proposed ten, because of catastrophic failure of one of the dynamometer rollers. Another problem encountered with the Morgantown-Westover cycles

was the OBS FID extinguishing before the test ended. Issues encountered with the SEMTECH data collection prevented the use of SEMTECH data for test number MW-02. Hydrocarbon data from the OBS was invalid for test numbers MW-01, MW-03, MW-04, and MW-05. Table 4-1 supplies explanations for the non-use of tests in the overall results.

Table 4-2 below shows the results from laboratory testing of the Morgantown-Westover cycle. The laboratory measured all parameters except for mass and distance based CO, THC, and NO_x with a COV less than 10 percent. The above mentioned parameters were measured with a COV of less than 15 percent.

The SEMTECH read within two percent, when compared to the laboratory, for both the distance traveled and the work done over the cycle. The exhaust volume measured between the systems was also close, with the SEMTECH reading, on average, 2.6 percent higher than the laboratory system. Mass emissions measurement of the SEMTECH, for CO₂, THC, and NO_x, were all within four percent of the laboratory. CO₂ read almost the same as the laboratory, only being under by 0.8 percent. CO on the other hand was significantly higher with an average difference of 81.6 percent. Although the SEMTECH read higher on every test for CO emissions, there were two tests in particular that read above 90 percent higher. Distance specific and brake specific emissions for each constituent fell within two percent of its respective mass emissions difference. The SEMTECH showed a coefficient of variation less than 13 percent for all parameters except for mass, brake specific and distance base CO. The COV for those parameters was approximately 30 percent.

The OBS proved to have measuring capabilities similar to that of the SEMTECH with slight exception. Both distance and work were measured within 0.5 percent of the laboratory equipment. For exhaust volume, the OBS measured 2.1 percent lower than the laboratory system. Mass emissions measurement between the OBS and laboratory were close between CO₂ and NO_x, but not as close for CO and THC. CO₂ and NO_x were both measured within 6 percent, while CO and THC emissions were measured within 45 percent. There was one test that had much higher THC measured by the OBS at just below 60 percent. All distance specific and brake specific emissions were within 1 percent of the respective mass emissions. The coefficient of variation also proved to be similar to the SEMTECH results with the OBS having a COV less than 12 percent for all of the parameters except mass, brake specific and distance CO as well as mass THC emissions. For these parameters, a COV was shown greater than 28 percent.

The difference seen between the SEMTECH and OBS for distance and work was 2.1 and 0.5 percent respectively. The exhaust volume differed by 4.6 percent among the two. Mass emissions of CO₂ and NO_x were within five percent of each other. Mass emissions measurements for CO and THC differed 93.7 percent and 32.9 percent, respectively. Distance and brake specific emissions between the OBS and SEMTECH differed within two percent of their respective mass emissions differences. The Student's T-Test showed that there were significant differences with CO measurements of both units and THC measurements of the OBS.

Table 4-2: Average Results of the Laboratory Morgantown-Westover Cycle.

Parameter	Units	Laboratory		SEMTECH		OBS		Difference		
		Average	COV	Average	COV	Average	COV	Laboratory vs SEMTECH	Laboratory vs OBS	SEMTECH vs OBS
Distance	miles	26.85	1.0%	26.43	1.0%	26.99	0.9%	-1.6%	0.5%	2.1%
Work	bhp-hr	69.72	5.7%	69.64	6.2%	69.97	6.3%	-0.1%	0.4%	0.5%
Exhaust Volume	SCF	10511	3.2%	10780	2.9%	10293	4.8%	2.6%	-2.1%	4.6%
CO	grams	38.99	12.3%	70.81	30.1%	25.63	34.3%	81.6%	-34.3%	93.7%
CO₂	grams	33487	6.3%	33230	7.0%	34677	8.1%	-0.8%	3.6%	4.3%
THC	grams	4.801	13.6%	4.986	9.0%	6.953	43.3%	3.9%	44.8%	32.9%
NOx	grams	178.2	10.9%	182.9	11.2%	188.3	10.8%	2.7%	5.7%	2.9%
CO	g/mi	1.453	13.1%	2.676	29.6%	0.952	35.5%	84.1%	-34.5%	95.0%
CO₂	g/mi	1248	7.2%	1258	7.8%	1286	9.0%	0.8%	3.0%	2.2%
THC	g/mi	0.179	14.1%	0.189	9.8%	0.259	10.8%	5.5%	44.7%	31.3%
NOx	g/mi	6.641	11.8%	6.928	12.2%	6.982	11.8%	4.3%	5.1%	0.8%
CO	g/bhp-hr	0.558	6.9%	1.020	30.3%	0.364	28.7%	82.9%	-34.7%	94.9%
CO₂	g/bhp-hr	480.2	0.6%	477.1	2.3%	495.3	3.0%	-0.7%	3.1%	3.8%
THC	g/bhp-hr	0.069	8.9%	0.072	3.7%	0.095	4.4%	4.1%	38.6%	28.4%
NOx	g/bhp-hr	2.550	5.1%	2.621	5.1%	2.686	4.8%	2.8%	5.3%	2.5%

4.1.2 Westover to Bruceton Mills Cycle

The Westover to Bruceton Mills cycle incorporated higher speed driving with increased grade. Four cycles were completed, which was the proposed amount of tests for comparison. No problems were encountered while operating any of the four cycles, therefore all of the test data were used to reach average results. The table below (Table 4-3) shows the averaged results from the Westover to Bruceton Mills cycle. The laboratory measured all parameters except for mass, brake specific, and distance specific THC and NO_x with a COV of less than 7 percent. THC and NO_x however, were measured with a COV above 37 percent.

Comparing the SEMTECH to the laboratory, distance and work results were accurate, with the SEMTECH reading below on average of 0.5 percent for both. Exhaust volume was also accurate, being less than the laboratory by only 1.1 percent. The average mass emissions were not as accurate as the Morgantown cycle results. This was mainly from one test, W2B-02. The THC and NO_x measurements of this test were significantly higher for the laboratory results. The other three tests' results were much more repeatable. Mass emissions for CO₂ were measured below the laboratory by 5.3 percent. THC and NO_x emissions measurement averaged 23 percent lower than the laboratory. The percent difference for the CO measurement of the SEMTECH was, on average, 73.2 percent higher than the laboratory. As with the last test cycle, the SEMTECH was consistently higher than the laboratory but it appeared that two tests showed much higher values. Distance and brake specific emissions measurements varied by no more than one percent when compared to their respective mass emissions measurements. The SEMTECH measured all parameters with a COV fewer than eight percent except for mass, brake specific, and distance specific CO. These parameters were measured with a COV of less than 20 percent.

When comparing the OBS and the laboratory, distance and work were both measured within 0.7 percent. Exhaust volume measurement was, on average, two percent lower than the laboratory. Similar to the SEMTECH, the OBS mass emissions were further off than the Morgantown-Westover cycle results. CO₂ measurement was an average of 6.7 percent higher than the laboratory. CO, THC, and NO_x emissions measurements were all less than 20 percent but greater than 10 percent within that of the laboratory measurements. Distance and brake specific results were all within one percent of their respective mass emissions results. The OBS

measured all parameters except CO with a variation of less than eight percent while mass, brake specific, and distance specific CO all had a COV at or above 39 percent.

Results from the Westover to Bruceton Mills cycle, for the SEMTECH compared to the OBS, showed that distance, work, and exhaust volume were all measured with a difference no larger than 1.1 percent. Mass emissions differences for CO₂ and NO_x were less than 12 percent different. Mass emissions difference values for CO and THC were 70.1 and 35.6 percent, respectively. The differences for distance and brake specific emissions were within two percent of the respective mass emissions differences for each constituent. The Student's T-Test showed that the CO measurement by the SEMTECH was a statistically significant difference from the laboratory while the OBS showed none. Significant differences between the two units were seen for CO, CO₂, THC, and NO_x emissions measurements.

Table 4-3: Average Results of the Laboratory Westover to Bruceton Mills Cycle.

Parameter	Units	Laboratory		SEMTECH		OBS		Difference		
		Average	COV	Average	COV	Average	COV	Laboratory vs SEMTECH	Laboratory vs OBS	SEMTECH vs OBS
Distance	miles	30.01	0.3%	29.86	0.3%	30.20	0.3%	-0.5%	0.6%	1.1%
Work	bhp-hr	78.54	2.5%	78.34	2.5%	78.74	2.5%	-0.3%	0.3%	0.5%
Exhaust Volume	SCF	10843	3.4%	10729	3.2%	10628	4.3%	-1.1%	-2.0%	0.9%
CO	grams	33.56	6.7%	58.13	19.2%	27.97	40.8%	73.2%	-16.7%	70.1%
CO₂	grams	38844	3.9%	36772	4.9%	41457	4.7%	-5.3%	6.7%	11.9%
THC	grams	4.914	47.8%	3.885	3.6%	5.571	7.5%	-21.0%	13.4%	35.7%
NO_x	grams	258.0	38.2%	199.2	6.4%	219.5	1.7%	-22.8%	-14.9%	9.7%
CO	g/mi	1.118	6.9%	1.947	19.4%	0.927	40.9%	74.1%	-17.2%	71.0%
CO₂	g/mi	1295	4.1%	1232	5.0%	1373	4.8%	-4.9%	6.0%	10.8%
THC	g/mi	0.164	48.0%	0.130	3.7%	0.184	7.6%	-20.6%	12.6%	34.6%
NO_x	g/mi	8.603	38.4%	6.669	6.4%	7.267	1.6%	-22.5%	-15.5%	8.6%
CO	g/bhp-hr	0.427	4.3%	0.741	17.8%	0.353	39.0%	73.5%	-17.3%	70.9%
CO₂	g/bhp-hr	494.5	2.0%	469.6	5.3%	526.4	3.0%	-5.0%	6.4%	11.4%
THC	g/bhp-hr	0.063	47.3%	0.050	2.4%	0.071	5.8%	-20.7%	13.1%	35.1%
NO_x	g/bhp-hr	3.282	37.7%	2.545	7.8%	2.788	2.5%	-22.5%	-15.0%	9.1%

4.1.3 Bruceton Mills to Westover Cycle

As proposed, four tests were completed for the Bruceton Mills to Westover cycle. Problems arose on three of the four test cycles. OBS hydrocarbon data was only available from one test. Therefore, the comparison for the OBS hydrocarbon will not be an accurate representation. Also, no emissions data was collected from the OBS for test number B2W-03. Table 4-4 shows the results from the Bruceton Mills to Westover cycle. The results showed that the laboratory had larger variation on most parameters when compared to the previous two cycles. All parameters had a COV between 14 and 28 percent except for distance, mass and distance specific CO emissions, brake specific CO₂ emissions, and brake specific NO_x emissions. These parameters all showed a variation below 10 percent.

The comparison between the laboratory and the SEMTECH showed that the SEMTECH read within 0.6 percent below the laboratory equipment, for distance and work. The exhaust volume measurement of the SEMTECH was 2.9 percent below the laboratory. Mass emissions measurement of CO₂ and NO_x were within six percent of the laboratory. THC mass emissions differed by 11.7 percent and CO mass emissions were different by 48.8 percent. Distance and brake specific emissions difference values were within one percent of their respective mass emissions difference values. The SEMTECH also showed higher COV results when compared to the previous two cycles. Showing a COV less than 12 percent was the distance, exhaust volume, mass and distance specific THC, brake specific CO₂ emissions, and brake specific NO_x emissions. All other parameters had a variation of greater than 17 percent with a max of 37.1 percent for brake specific CO emissions.

The comparison of the average results between the laboratory and the OBS showed that distance and work were measured within 0.6 percent of the laboratory. Exhaust volume was measured, on average, with a difference of six percent below the laboratory measurement. Mass emissions measurement of CO, CO₂, and NO_x was accomplished with difference values within 10 percent. The THC mass emissions were measured with a difference of 19.4 percent but were only a result of one test. All distance and brake specific measurements were within one percent of their respective mass emissions measurement differences for each constituent. The OBS showed COV results below 10 percent for distance, mass and distance specific CO emissions, brake specific CO₂ emissions, and brake specific NO_x emissions. The remaining parameters,

with the exception of mass, distance specific, and brake specific THC emissions, were measured with a COV less than 28 percent. The THC emissions values were not included because only one test's results were retrieved.

When comparing SEMTECH and the OBS, the two units measured distance, work, and exhaust volume within 1.3 percent. Mass emissions were measured with a difference of less than five percent for CO₂ and NO_x. CO and THC mass emissions were measured with differences of less than 58 and 29 percent, respectively. The distance and brake specific mass emissions recorded were within two percent of the respective mass emissions differences for each constituent. The Student's T-Test analysis showed no significant differences.

Table 4-4: Average Results of the Laboratory Bruceton Mills to Westover Cycle

Parameter	Units	Laboratory		SEMTECH		OBS		Difference		
		Average	COV	Average	COV	Average	COV	Laboratory vs SEMTECH	Laboratory vs OBS	SEMTECH vs OBS
Distance	miles	29.38	0.2%	29.21	0.2%	29.55	0.2%	-0.6%	0.6%	1.2%
Work	bhp-hr	68.20	17.7%	67.97	17.7%	68.42	20.5%	-0.3%	0.3%	0.7%
Exhaust Volume	SCF	9863	14.4%	9580	11.7%	9276	15.7%	-2.9%	-6.0%	3.2%
CO	grams	35.25	8.3%	52.45	35.3%	33.055	9.8%	48.8%	-6.2%	45.4%
CO ₂	grams	33364	19.6%	31642	18.6%	30689	20.0%	-5.2%	-8.0%	3.1%
THC	grams	4.469	20.4%	3.948	4.4%	5.339		-11.7%	19.4%	29.9%
NO _x	grams	176.1	19.2%	173.9	18.5%	159.9	19.3%	-1.3%	-9.2%	8.4%
CO	g/mi	1.200	8.5%	1.795	35.2%	1.118	9.9%	49.6%	-6.8%	46.5%
CO ₂	g/mi	1136	19.6%	1083	18.5%	1038	19.8%	-4.6%	-8.6%	4.3%
THC	g/mi	0.152	20.3%	0.135	4.6%	0.181		-11.1%	19.0%	29.0%
NO _x	g/mi	5.995	19.2%	5.951	18.3%	5.407	19.1%	-0.7%	-9.8%	9.6%
CO	g/bhp-hr	0.536	27.5%	0.792	37.1%	0.515	27.3%	47.8%	-3.9%	42.4%
CO ₂	g/bhp-hr	487.7	2.8%	465.6	5.1%	461.7	1.5%	-4.5%	-5.3%	0.8%
THC	g/bhp-hr	0.067	25.8%	0.060	22.8%	0.106		-10.8%	57.7%	55.6%
NO _x	g/bhp-hr	2.577	2.6%	2.557	3.8%	2.409	2.3%	-0.8%	-6.5%	6.0%

4.1.4 Westover to Saltwell Cycle

The Westover to Saltwell cycle was repeated four times, as proposed in the test plan. Problems encountered with the OBS during the second test eliminated hydrocarbon data from that particular test. All other data from the four test cycles was used for the comparison. Table 4-5 shows that the laboratory measured all parameters with a COV less than 12 percent for the Westover to Saltwell cycles.

In comparison to the laboratory, the SEMTECH measured distance, work, and exhaust volume had an average difference within two percent. Mass emissions measurements were all relatively close with the exception of CO. CO was measured with an average difference of 99.7 percent from the laboratory. Once again, the CO measured consistently high which led to an investigation of the measurement range. This investigation is explained in the conclusions. On the other hand, CO₂, THC, and NO_x mass emissions were all measured within four percent of the laboratory. Distance and brake specific emissions values for the respective constituents fell within 1.5 percent of the mass emissions difference values. Aside from mass, distance specific, and brake specific CO emissions, which were measured with a COV less than 24 percent, the other parameters were measured with a variation less than eight percent.

As mentioned above, all test data was used, in the comparison of the OBS to the laboratory, with the exception of THC data from the second test cycle. The OBS measured distance and work within one percent of the laboratory. Exhaust volume was measured at a difference of 1.2 percent lower than the laboratory. CO₂ and NO_x mass emissions were both measured within 10 percent. CO was measured at a difference of 20.2 percent below that of the laboratory measurement. THC mass emissions were measured with a difference of 44.6 percent. Distance and brake specific emissions measurements were all within one percent of their respective mass emissions measurements. The OBS measured all parameters with a COV less than or equal to five percent with the exception of CO mass, distance specific, and brake specific emissions, which showed a COV greater than 34 percent.

From the results, it is shown that the SEMTECH and OBS measured distance and work within two percent of each other. Exhaust volume is measured closely, with a difference of 0.6 percent. Mass emission measurement differences CO₂ and NO_x fell within 10 percent between the two units. CO and THC mass emissions differ greater than 34 percent. The large CO difference stemmed from the high CO measurement of the SEMTECH. Distance and brake

specific mass emissions values were within two percent of their respective mass emissions difference values. The Student's T-Test showed significant difference for the measurement of CO by the SEMTECH and measurement of CO₂ and NO_x by the OBS. As a result, a significant difference was seen for all three constituents when comparing the SEMTECH to the OBS.

Table 4-5: Average Results of the Laboratory Westover to Saltwell Cycle.

Parameter	Units	Laboratory		SEMTECH		OBS		Difference		
		Average	COV	Average	COV	Average	COV	Laboratory vs SEMTECH	Laboratory vs OBS	SEMTECH vs OBS
Distance	miles	30.50	0.1%	30.17	1.4%	30.73	0.2%	-1.1%	0.7%	1.8%
Work	bhp-hr	78.12	2.2%	77.76	2.4%	78.47	2.1%	-0.5%	0.5%	0.9%
Exhaust Volume	SCF	10423	3.0%	10235	3.6%	10296	2.8%	-1.8%	-1.2%	0.6%
CO	grams	30.24	11.2%	60.380	22.5%	24.12	36.3%	99.7%	-20.2%	85.8%
CO₂	grams	38303	2.5%	37673	2.8%	41502	2.6%	-1.6%	8.4%	9.7%
THC	grams	3.310	9.6%	3.430	7.5%	4.787	3.8%	3.6%	44.6%	36.4%
NO_x	grams	193.6	4.9%	189.6	4.8%	209.1	5.0%	-2.1%	8.0%	9.8%
CO	g/mi	0.991	11.2%	2.006	23.8%	0.785	36.1%	102.3%	-20.8%	87.5%
CO₂	g/mi	1256	2.5%	1249	2.5%	1351	2.4%	-0.5%	7.6%	7.8%
THC	g/mi	0.109	9.6%	0.114	7.0%	0.156	3.8%	4.8%	43.7%	34.4%
NO_x	g/mi	6.347	4.9%	6.286	4.6%	6.806	4.9%	-1.0%	7.2%	7.9%
CO	g/bhp-hr	0.387	9.0%	0.777	23.2%	0.306	34.6%	101.1%	-20.7%	86.9%
CO₂	g/bhp-hr	490.3	0.4%	484.4	0.5%	528.8	0.7%	-1.2%	7.9%	8.8%
THC	g/bhp-hr	0.042	7.4%	0.044	5.1%	0.062	2.7%	4.1%	45.5%	35.3%
NO_x	g/bhp-hr	2.478	4.0%	2.438	3.9%	2.664	3.4%	-1.6%	7.5%	8.9%

4.1.5 Saltwell to Westover Cycle

The Saltwell to Westover cycle was also repeated the proposed four times. Problems occurred on test numbers S2W-01 and S2W-02 which made hydrocarbon emissions data invalid for the OBS. As with the Bruceton Mills to Westover cycle data, comparisons were made for the hydrocarbon emissions of the valid tests but are not accurate for overall comparison. Otherwise, all other reported data is considered valid. The table below (Table 4-6) shows the results of the Saltwell to Westover cycles. The laboratory measured all parameters with a COV less than five percent.

In comparison to the laboratory, the SEMTECH measured distance and work within 0.6 percent of the laboratory. Exhaust volume was measured with a difference, on average, of 1.2 percent below the laboratory. Mass emission measurements were all close with the exception of CO. CO₂, THC, and NO_x mass emissions were all measured within three percent of the laboratory, while CO was measured at a difference of 50.8 percent. Again, the measurement was consistently higher. Distance and brake specific emissions differences were all within one percent of the respective mass emissions differences between the SEMTECH and laboratory. The SEMTECH measured all parameters with a variation less than five percent, with the exception of mass, distance specific, and brake specific CO emissions. The CO emissions were measured with a COV less than 12 percent.

It can be seen that the OBS measured distance and work within one percent of the laboratory. Exhaust volume was measured at a difference of 2.6 percent lower, by the OBS. CO₂ and NO_x mass emissions were both measured within eight percent of the laboratory measurements. CO and THC mass emissions were both measured at a difference above 25 and below 45 percent, respectively. Once again, THC emissions measurements were not valid for an overall comparison, because only two tests were averaged, but were shown for completeness. Distance and brake specific mass emissions were within one percent of their respective mass emissions difference values. The OBS measured with a COV less than three percent for all parameters except mass, distance specific, and brake specific CO and THC emissions. CO emissions were measured with a variation of less than 14 percent. Variation of THC emissions were not shown because there was a lack of valid tests to calculate the COV correctly.

Comparing the SEMTECH and the OBS, the two units measured distance, work, and exhaust volume were within 1.5 percent of each other. Mass emissions measurements differed

within 10 percent for both CO₂ and NO_x. Mass emissions measurements of CO and THC were greater than 70 and 30 percent, respectively. The distance and brake specific emissions differed by less than two percent of their respective mass emissions difference values. Once again, the THC values from this cycle were not valid for an overall comparison of the OBS but were shown for completeness. From the Student's T-Test results, it was found that there was a statistically significant difference for the SEMTECH CO reading. The OBS measured CO, CO₂, and THC with a significant difference from the laboratory.

Table 4-6: Average Results of the Laboratory Saltwell to Westover Cycle.

Parameter	Units	Laboratory		SEMTECH		OBS		Difference		
		Average	COV	Average	COV	Average	COV	Laboratory vs SEMTECH	Laboratory vs OBS	SEMTECH vs OBS
Distance	miles	30.46	0.2%	30.30	0.2%	30.65	0.2%	-0.5%	0.6%	1.1%
Work	bhp-hr	73.81	1.9%	73.63	1.9%	73.99	1.8%	-0.2%	0.2%	0.5%
Exhaust Volume	SCF	9772	2.2%	9659	2.1%	9516	1.5%	-1.2%	-2.6%	1.5%
CO	grams	28.77	3.4%	43.38	11.6%	20.68	13.2%	50.8%	-28.1%	70.9%
CO₂	grams	35631	1.6%	34795	1.4%	37851	0.9%	-2.3%	6.2%	8.4%
THC	grams	3.330	4.6%	3.425	4.5%	4.745		2.9%	42.5%	31.2%
NO_x	grams	185.0	4.8%	182.5	4.6%	198.3	2.8%	-1.4%	7.2%	8.3%
CO	g/mi	0.945	3.4%	1.431	11.4%	0.675	13.3%	51.5%	-28.6%	71.9%
CO₂	g/mi	1170	1.5%	1148	1.3%	1235	0.8%	-1.9%	5.6%	7.3%
THC	g/mi	0.109	4.6%	0.113	4.5%	0.155		3.4%	41.6%	30.0%
NO_x	g/mi	6.074	4.8%	6.022	4.6%	6.471	2.8%	-0.9%	6.5%	7.2%
CO	g/bhp-hr	0.390	1.9%	0.589	11.9%	0.280	13.7%	51.2%	-28.2%	71.3%
CO₂	g/bhp-hr	482.8	0.6%	472.6	1.2%	511.6	1.4%	-2.1%	6.0%	7.9%
THC	g/bhp-hr	0.045	2.8%	0.047	3.0%	0.064		3.1%	41.2%	30.8%
NO_x	g/bhp-hr	2.505	3.0%	2.478	2.9%	2.680	1.5%	-1.1%	7.0%	7.9%

4.2 On-Road Test Results

As expected and discovered by the laboratory testing, difficulties also arose while performing the on-road testing. It was also expected that the on-road testing would provide more problems than that of the laboratory testing. A problem that occurred before any testing could begin was finding a sufficient power supply. This task was completed with three gasoline generators totaling 10.5 kW of power. The generators were mounted at the very rear of the test vehicle, several feet behind the exhaust stack to eliminate any effects on the emissions measurement. Another trouble encountered, but only with the SEMTECH-D unit, was overheating of equipment. This only occurred when the vehicle was parked between test routes. The SEMTECH FID would rise out of range and extinguish the flame until the operating temperature range was met. This difficulty was prevented by supplying cooling air via fans when parked in between tests. The last problems encountered all stemmed from the same origin. The nature of on-road, or in-use, testing is rough on equipment due to the fact that the equipment is installed on the vehicle and undergoes all vibrations and weather conditions of real-world driving. The equipment is designed to handle the abuse, but still does not do this flawlessly every test. Some difficulties with the generators were experienced because they were equipped with oil level sensors that would shut the engines off when low oil level was sensed. This occurred, even with proper oil level, on occasion while traveling around a sharp turn. The emissions measurement equipment held up well, having minimal problems, with few exceptions. As experienced with the OBS-2200 by WVU on previous projects, there were few instances where it would not record data. The real time data being monitored on the laptop computer would be fine but the recorded data would be incomplete. Also, the vibrations due to rough roads affected the EFM connection of the SEMTECH unit. This connection was lost twice while performing on-road test cycles. The table below (Table 4-7) shows the difficulties encountered during on-road testing. Also, dates and times for test completion can be seen in Table 3-2. Individual on-road test results are located in Appendix C (Table 9-1 through Table 9-28). Portions of sample on-road test plots are shown in Appendix D (Figure 10-26 through Figure 10-50).

Table 4-7: Difficulties Encountered During On-Road Testing.

Test ID	Route	Problem(s) Encountered
MW-08	Morgantown-Westover	OBS data froze
MW-09	Morgantown-Westover	NA
MW-10	Morgantown-Westover	NA
MW-11	Morgantown-Westover	NA
MW-12	Morgantown-Westover	NA
W2S-05	Westover to Saltwell	NA
S2W-05	Saltwell to Westover	NA
W2S-06	Westover to Saltwell	NA
S2W-06	Saltwell to Westover	NA
W2B-05	Westover to Bruceton Mills	NA
B2W-05	Bruceton Mills to Westover	NA
W2B-06	Westover to Bruceton Mills	OBS data froze
B2W-06	Bruceton Mills to Westover	NA
W2S-07	Westover to Saltwell	No SEMTECH OBD
S2W-07	Saltwell to Westover	No SEMTECH OBD
W2S-08	Westover to Saltwell	No SEMTECH OBD
S2W-08	Saltwell to Westover	No SEMTECH data
W2B-07	Westover to Bruceton Mills	NA
B2W-07	Bruceton Mills to Westover	Test abort for truck fueling issue
W2B-08	Westover to Bruceton Mills	NA
B2W-08	Bruceton Mills to Westover	SEMTECH EFM came disconnected
W2S-09	Westover to Saltwell	No SEMTECH OBD
S2W-09	Saltwell to Westover	NA
MW-13	Morgantown-Westover	NA
MW-14	Morgantown-Westover	NA
MW-15	Morgantown-Westover	NA
MW-16	Morgantown-Westover	NA
MW-17	Morgantown-Westover	NA

4.2.1 Morgantown-Westover Route

The Morgantown-Westover route, for on-road testing, was completed the proposed ten times with only one mishap. The only difficulty encountered, while testing the Morgantown-Westover route, was with the OBS during test number MW-08. The details were explained in Table 4-7. Table 4-8 shows the averaged results from the Morgantown cycle. The recorded distance and work were both measured with a difference less than two percent. Exhaust volume for the Morgantown-Westover route was found to differ on average by 5.7 percent. The concentration emissions of CO₂ were measured with a difference of 5.5 percent. Both THC and

NOx concentration emissions were measured with a difference below 13 percent. CO was measured with less consistency between the two units, having a difference of 43.4 for concentration emissions. Mass emissions varied slightly from that of the concentration emissions values. CO₂, THC, and NOx were all measured within 10 percent between the two units. CO mass emissions were measured with a difference of 33.8 percent. All distance and brake specific emissions were measured within two percent of their respective mass emissions differences for the Morgantown-Westover route. The SEMTECH measured all parameters with a COV less than 10 percent except for CO related parameters. CO concentration, mass emissions, distance specific emissions, and brake specific emissions showed a variation less than 15 percent. The OBS showed similar results with a COV less than six percent for parameters excluding CO. For the parameters including CO emissions, the OBS measured with a COV of greater than 37 percent. The Student's T-Test analysis showed statistically significant differences between all of the measured parameters with the exception of distance, work, and mass based THC emissions.

Table 4-8: Average Results of the On-Road Morgantown-Westover Route.

Parameter	Units	SEMTECH		OBS		Difference
		Average	COV	Average	COV	SEMTECH vs OBS
Distance	miles	26.55	0.1%	27.02	0.2%	1.8%
Work	bhp-hr	51.85	5.3%	52.31	5.4%	0.9%
Exhaust Volume	SCF	8237	4.7%	7783	4.1%	5.7%
CO	%	0.020	14.9%	0.013	48.3%	43.4%
CO₂	%	4.649	1.7%	4.913	2.0%	5.5%
THC	ppm	33.72	6.2%	37.89	4.2%	11.7%
NOx	ppm	251.4	2.7%	222.3	1.9%	12.3%
CO	grams	51.01	14.6%	36.27	42.2%	33.8%
CO₂	grams	23334	5.2%	25352	5.9%	8.3%
THC	grams	4.701	9.4%	5.042	5.0%	7.0%
NOx	grams	121.0	5.4%	110.2	5.4%	9.4%
CO	g/mi	1.922	14.7%	1.342	42.3%	35.5%
CO₂	g/mi	879.0	5.3%	938.2	5.9%	6.5%
THC	g/mi	0.177	9.5%	0.187	5.1%	5.2%
NOx	g/mi	4.559	5.4%	4.077	5.4%	11.1%
CO	g/bhp-hr	0.984	13.3%	0.685	37.9%	35.8%
CO₂	g/bhp-hr	450.1	0.9%	484.6	2.0%	7.4%
THC	g/bhp-hr	0.091	6.7%	0.096	4.2%	6.3%
NOx	g/bhp-hr	2.334	2.2%	2.107	2.1%	10.3%

4.2.2 Westover to Bruceton Mills Route

The Westover to Bruceton Mills route was completed four times, as proposed, and also with one occurrence of an OBS problem. This was the same repeated problem seen during the Morgantown-Westover route and can be seen in Table 4-7. The table below (Table 4-9) shows the averaged results excluding test number W2B-06. On average, the recorded distance and work differed, respectively, by 2.2 percent and 0.6 percent. The exhaust volume was measured very closely, between the SEMTECH and OBS, with a difference of 0.1 percent. Concentration emissions were varied with a difference of 72.8 percent for CO, 5.4 percent for CO₂, 17.3 percent for THC, and 13.6 percent for NOx. Mass emissions also varied between the two units with average differences of 73.7 percent for CO, 13.6 percent for CO₂, 19.4 percent of THC, and 3.9 percent for NOx. Distance and brake specific emissions results differed within 2.5 percent of their respective mass emissions results. The SEMTECH measured all parameters, with the

exception of CO related parameters which had a COV greater than 38 percent, with a variation less than nine percent. The OBS measured all parameters with a COV less than 15 percent except for the parameters involving CO. Concentration, mass emissions, distance specific emissions, and brake specific emissions, for CO, were measured with a variation greater than 22 percent. Statistically significant differences were shown only for concentration emissions measurement of CO₂ and THC.

Table 4-9: Average Results of the On-Road Westover to Bruceton Mills Route.

Parameter	Units	SEMTECH		OBS		Difference
		Average	COV	Average	COV	SEMTECH vs OBS
Distance	miles	30.96	3.2%	30.30	0.0%	2.2%
Work	bhp-hr	61.77	1.2%	62.14	1.2%	0.6%
Exhaust Volume	SCF	8410	0.2%	8400	8.9%	0.1%
CO	%	0.022	38.9%	0.010	22.5%	72.8%
CO₂	%	5.669	1.5%	5.982	1.0%	5.4%
THC	ppm	32.12	8.2%	38.20	3.5%	17.3%
NOx	ppm	273.0	8.1%	238.1	7.5%	13.6%
CO	grams	56.66	43.3%	26.16	31.6%	73.7%
CO₂	grams	27745	1.2%	31787	8.2%	13.6%
THC	grams	4.266	6.5%	5.185	10.9%	19.4%
NOx	grams	134.1	8.1%	128.9	14.7%	3.9%
CO	g/mi	1.839	44.4%	0.863	31.6%	72.2%
CO₂	g/mi	896.6	2.1%	1049	8.2%	15.7%
THC	g/mi	0.138	4.5%	0.171	10.9%	21.6%
NOx	g/mi	4.327	5.3%	4.254	14.7%	1.7%
CO	g/bhp-hr	0.919	43.8%	0.422	32.4%	74.2%
CO₂	g/bhp-hr	449.2	0.1%	511.2	7.0%	12.9%
THC	g/bhp-hr	0.069	5.5%	0.083	9.7%	18.8%
NOx	g/bhp-hr	2.170	7.0%	2.072	13.5%	4.6%

4.2.3 Bruceton Mills to Westover Route

The Bruceton Mills to Westover route provided more problems than the previous two analyzed cycles. The routes from the first test set were problem free, but the test routes from the second set failed to produce valid data. Details of these problems were explained in Table 4-7. Data from test number B2W-07 was completely void while exhaust volume and mass emissions

data was void only for the SEMTECH during test number B2W-08. Because of this, exhaust volume measurement and mass emissions comparisons will not be accurate because less than three tests were averaged. The table below (Table 4-10) shows the results from the Bruceton Mills to Westover cycles. It is shown that on average distance traveled and work done over the cycle were both within 2.5 percent of each other between the SEMTECH and OBS. Average exhaust volume measurement, which is not valid because less than three data sets were obtained, was found to have a difference of 0.6 percent from the two valid tests. Concentration emissions were varied, but not as much as the previous test results, with all differences being below 20 percent. As with exhaust volume, mass emissions measurements were not accurately represented for an average, but all recorded results were within 27 percent between the SEMTECH and OBS with NO_x measurements under one percent different. A COV analysis was completed only for distance, work, and emissions concentration values of the SEMTECH, due to the lack of data for the other parameters. The COV was less than 10 percent for the SEMTECH. The OBS showed a COV greater than 34 percent for CO related parameters and a COV less than nine percent for the remaining parameters. The Student's T-Test showed statistically significant differences between concentration emissions of CO₂, THC, and NO_x emissions. It also shows significant difference for the mass emissions of CO₂ and THC.

Table 4-10: Average Results of the On-Road Bruceton Mills to Westover Route.

Parameter	Units	SEMTECH		OBS		Difference
		Average	COV	Average	COV	SEMTECH vs OBS
Distance	miles	30.38	3.3%	29.70	0.0%	2.3%
Work	bhp-hr	57.56	1.9%	57.61	1.2%	0.1%
Exhaust Volume	SCF	8089	NA	8136	3.7%	0.6%
CO	%	0.018	9.0%	0.015	39.3%	14.9%
CO₂	%	5.520	0.7%	5.812	1.2%	5.2%
THC	ppm	32.55	4.0%	38.40	3.0%	16.5%
NO_x	ppm	269.8	1.3%	247.4	3.6%	8.7%
CO	grams	40.67	NA	52.60	34.9%	25.6%
CO₂	grams	25710	NA	29787	2.9%	14.7%
THC	grams	4.188	NA	5.129	1.5%	20.2%
NO_x	grams	123.4	NA	123.6	7.4%	0.1%
CO	g/mi	1.362	NA	1.771	34.9%	26.1%
CO₂	g/mi	861.2	NA	1003	2.9%	15.2%
THC	g/mi	0.140	NA	0.173	1.5%	20.7%
NO_x	g/mi	4.133	NA	4.160	7.4%	0.7%
CO	g/bhp-hr	0.699	NA	0.907	34.4%	25.8%
CO₂	g/bhp-hr	442.1	NA	513.5	3.6%	14.9%
THC	g/bhp-hr	0.072	NA	0.088	2.6%	20.4%
NO_x	g/bhp-hr	2.122	NA	2.130	8.4%	0.4%

4.2.4 Westover to Saltwell Route

The Westover to Saltwell route was repeated five times because of data issues. The routes from the first set had no issues while the second set did pose issues. The SEMTECH distance, work, and distance and brake specific emissions data were invalid for test numbers W2S-05, W2S-06, and W2S-07. As with the Bruceton Mills to Westover route, comparisons were made, but were not an accurate representation for distance and brake specific emissions results. Refer to the table below (Table 4-11) for average results from the Westover to Saltwell route. Table 4-11 shows that distance, work, and exhaust volume data, between the SEMTECH and OBS, differed below 3 percent. Concentration emissions data measured differed less than 16 percent for CO, CO₂, THC, and NO_x. Mass emissions were also close for the four constituents, with difference values no larger than 13.5 percent. The distance and brake specific emissions

results with the exception of CO were all within 11 percent, while a measured CO difference of less than 18 percent occurred. Distance and brake specific numbers were not an accurate representation because only two tests were averaged for the results. Excluding distance, work, distance specific emissions, and brake specific emissions, both units measured all parameters except CO concentration and mass with a COV less than 10 percent. CO concentration and mass was measured with a COV greater than or equal to 23 percent. Results from the Student's T-Test showed that CO₂, THC, and NO_x concentration and mass emissions were measured with a statistically significant difference.

Table 4-11: Average Results of the On-Road Westover to Saltwell Route.

Parameter	Units	SEMTECH		OBS		Difference
		Average	COV	Average	COV	SEMTECH vs OBS
Distance	miles	30.71	NA	31.05	NA	1.1%
Work	bhp-hr	64.03	NA	64.47	NA	0.7%
Exhaust Volume	SCF	8477	1.6%	8250	2.9%	2.7%
CO	%	0.018	23.3%	0.018	33.5%	0.9%
CO₂	%	5.774	4.3%	6.137	3.4%	6.1%
THC	ppm	33.66	7.9%	39.22	4.3%	15.2%
NO_x	ppm	257.7	4.8%	227.6	4.3%	12.4%
CO	grams	45.03	23.0%	49.100	38.1%	8.6%
CO₂	grams	27907	2.9%	31175	3.3%	11.1%
THC	grams	4.599	9.0%	5.265	5.3%	13.5%
NO_x	grams	123.4	3.0%	115.2	4.0%	6.8%
CO	g/mi	1.616	NA	1.353	NA	17.7%
CO₂	g/mi	929.9	NA	1009	NA	8.1%
THC	g/mi	0.155	NA	0.170	NA	9.5%
NO_x	g/mi	4.033	NA	3.632	NA	10.4%
CO	g/bhp-hr	0.780	NA	0.654	NA	17.6%
CO₂	g/bhp-hr	446.1	NA	485.7	NA	8.5%
THC	g/bhp-hr	0.074	NA	0.082	NA	10.0%
NO_x	g/bhp-hr	1.934	NA	1.749	NA	10.0%

4.2.5 Saltwell to Westover Route

The Saltwell to Westover route was also repeated five times because of SEMTECH issues. The distance and brake specific data of the SEMTECH from test number S2W-07 could

not be used for comparison. There was no data recorded by the SEMTECH for test number S2W-08. The three other test routes completed did have complete data. The average results of the Saltwell to Westover routes are shown in Table 4-12. It is shown that, for on-road testing, the Saltwell to Westover route produced the most consistent measurements between the SEMTECH and OBS, with only NO_x concentration having a difference larger than 15 percent. Distance, work, and exhaust volume measurement results all differ below 1.1 percent. CO and CO₂ concentration measurements were both within 10 percent of each other and hydrocarbon measurements were with 15 percent. The mass emission measurements were very similar with all constituent measurements having a difference under 15 percent. Both units showed similar results for the measured COV. All parameters involving CO were measured with a COV greater than 22 percent while all remaining parameters were measured with a variation less than nine percent. The Student's T-Test results showed no statistically significant differences.

Table 4-12: Average Results of the On-Road Saltwell to Westover Route.

Parameter	Units	SEMTECH		OBS		Difference
		Average	COV	Average	COV	SEMTECH vs OBS
Distance	miles	30.58	0.3%	30.90	0.0%	1.0%
Work	bhp-hr	56.80	2.5%	57.17	2.6%	0.7%
Exhaust Volume	SCF	7981	0.4%	7961	3.6%	0.3%
CO	%	0.017	23.5%	0.018	24.0%	8.0%
CO ₂	%	5.530	1.7%	5.871	3.8%	6.0%
THC	ppm	35.75	8.3%	40.83	2.0%	13.3%
NO _x	ppm	259.5	5.7%	220.8	2.7%	16.1%
CO	grams	38.81	25.1%	44.54	23.6%	13.8%
CO ₂	grams	24751	2.1%	28581	6.8%	14.4%
THC	grams	4.631	8.1%	5.283	4.2%	13.2%
NO _x	grams	114.1	6.9%	105.5	6.4%	7.8%
CO	g/mi	1.269	25.3%	1.441	23.6%	12.7%
CO ₂	g/mi	809.4	2.1%	924.9	6.8%	13.3%
THC	g/mi	0.151	8.2%	0.171	4.2%	12.1%
NO _x	g/mi	3.731	7.0%	3.414	6.4%	8.9%
CO	g/bhp-hr	0.681	22.7%	0.781	24.4%	13.6%
CO ₂	g/bhp-hr	435.8	0.5%	499.6	4.4%	13.6%
THC	g/bhp-hr	0.081	5.8%	0.092	2.9%	12.6%
NO _x	g/bhp-hr	2.007	4.4%	1.844	3.9%	8.5%

4.3 Fuel Consumption

Throughout the experimentation, fuel was supplied to the truck via an external tank as opposed to the factory fuel tank. This method was utilized in order to record gravimetric fuel consumption. Another method used to retrieve fuel consumption data was by carbon balance. By recording the gravimetric consumption and comparing the values to calculated carbon balance fuel consumption, a check of analyzer accuracy was achieved. Emissions measurement accuracy can be based on the difference of gravimetric and carbon balance fuel consumption. As with the cycle and route data, a Student's T-Test with a p-value of 0.05 was performed to show statistically significant difference. The significant difference is shown in bold in the tables.

4.3.1 Laboratory

The laboratory testing analysis of fuel consumption included comparing gravimetric fuel consumption to the carbon balance fuel consumption of the laboratory equipment, the SEMTECH, and the OBS. Test numbers W2B-02, MW-02, and B2W-03 were excluded from the analysis. These tests were excluded for problems encountered, such as lost connections of equipment and invalid emissions measurement. Table 4-13 shows the fuel consumption comparison per cycle and Table 4-14 shows the differences for each unit. In Table 4-13, it is shown that all cycles had a fuel consumption variation less than nine percent except for the Bruceton to Westover cycle. That cycle showed a variation greater than 19 percent. Among the three measurement systems, there was no difference higher than 7.7 percent in any cycle. The laboratory showed an average difference of 0.1 percent. The SEMTECH and OBS showed average differences of 3.3 and 4.2 percent, respectively. Statistically significant differences were seen for the OBS during the Westover to Saltwell and Saltwell to Westover cycles.

Table 4-13: Fuel Consumption Analysis of Laboratory Testing.

Cycle	Units	Gravimetric		Laboratory		SEMTECH		OBS	
		Average	COV	Average	COV	Average	COV	Average	COV
Morgantown-Westover	grams	10620	6.1%	10632	6.7%	10520	7.0%	11012	8.1%
Westover to Bruceton	grams	12180	4.5%	12139	4.0%	11444	4.5%	13121	5.8%
Bruceton to Westover	grams	10093	23.8%	10155	23.0%	9588	21.1%	9697	19.9%
Westover to Saltwell	grams	12275	3.9%	12099	2.5%	11915	2.8%	13105	2.6%
Saltwell to Westover	grams	11180	1.4%	11255	1.6%	10999	1.4%	11952	0.9%

Table 4-14: Average Results of Fuel Consumption from the Laboratory Testing.

Cycle	Difference (Laboratory)	Difference (SEMTECH)	Difference (OBS)
Morgantown-Westover	0.1%	-0.9%	3.7%
Westover to Bruceton	-0.3%	-6.0%	7.7%
Bruceton to Westover	0.6%	-5.0%	-3.9%
Westover to Saltwell	-1.4%	-2.9%	6.8%
Saltwell to Westover	0.7%	-1.6%	6.9%
Average	-0.1%	-3.3%	4.2%

4.3.2 On-Road

The fuel consumption analysis of on-road testing included the comparison of carbon balance fuel consumption, of the SEMTECH and the OBS, to that of the gravimetric fuel consumption. As with the laboratory testing, problems such as cable connections and invalid measurement of emissions prevented the use of some tests. The excluded test numbers were W2B-06, S2W-07, S2W-08, B2W-07, and B2W-08. The tables below (Table 4-15 and Table 4-16) show the fuel consumption analysis and the average differences per cycle, respectively. Table 4-15 shows that, in all cases, fuel consumption was measured with a COV less than nine percent. Table 4-16 shows the SEMTECH measured, on average, 8.1 percent below the gravimetric average. The OBS measured 3.9 percent higher than the gravimetric average.

Table 4-15: Fuel Consumption Analysis of On-Road Testing.

Cycle	Units	Gravimetric FC		SEMTECH CB		OBS CB	
		Average	COV	Average	COV	Average	COV
Morgantown-Westover	grams	7983	5.4%	7454	5.6%	8062	5.8%
Westover to Bruceton	grams	9503	3.5%	8783	1.1%	10043	8.2%
Bruceton to Westover	grams	8936	0.4%	8133	0.7%	9426	3.7%
Westover to Saltwell	grams	9711	4.4%	8828	2.9%	9862	3.4%
Saltwell to Westover	grams	8535	3.9%	7831	2.2%	9041	6.7%

Table 4-16: Average Results of Fuel Consumption from On-Road Testing.

Cycle	Difference (SEMTECH)	Difference (OBS)
Morgantown-Westover	-6.6%	1.0%
Westover to Bruceton	-7.6%	5.7%
Bruceton to Westover	-9.0%	5.5%
Westover to Saltwell	-9.1%	1.5%
Saltwell to Westover	-8.3%	5.9%
Average	-8.1%	3.9%

4.4 Overall Results

This section, as with the previous, looks more at the overall comparison of the results as opposed to individual test cycles. The primary purpose for this study was to examine the effects of changes made to in-use equipment based on upgrading emissions standards and technology.

The second was to examine the variation between laboratory testing and in-use testing. Since different cycles were completed to perform this study, overall comparisons were done by distance and brake specific emissions values only.

4.4.1 Equipment Comparison

As previously stated, this study was to examine the measuring capabilities of two in-use emissions measuring systems of different generations. One unit, Sensor's SEMTECH-D, was built under the CFR 40, Part 86 standards for in-use testing. The other, Horiba's OBS-2200, was built under the CFR 40, Part 1065 standards. Both units were compared against WVU's Transportable Laboratory, which was built according to 1065. It was assumed that for this reason the OBS has the advantage when being compared to a 1065 compliant laboratory. The table below (Table 4-17) shows the average differences, in comparison to the laboratory, of the SEMTECH and the OBS for the five completed cycles. With the exception of CO emissions of both units and THC emissions of the OBS, all parameters showed an average difference from the laboratory less than or equal to five percent.

Table 4-17: Overall Results of Laboratory Testing.

Parameter	Units	Average Difference (SEMTECH)	Average Difference (OBS)
Exhaust Volume	SCF	-0.9%	-2.8%
CO	grams	70.8%	-21.1%
CO₂	grams	-3.0%	3.4%
THC	grams	-4.5%	32.9%
NOx	grams	-5.0%	-0.6%
CO	g/mi	72.3%	-21.6%
CO₂	g/mi	-2.2%	2.7%
THC	g/mi	-3.6%	32.3%
NOx	g/mi	-4.2%	-1.3%
CO	g/bhp-hr	71.3%	-21.0%
CO₂	g/bhp-hr	-2.7%	3.6%
THC	g/bhp-hr	-4.0%	39.2%
NOx	g/bhp-hr	-4.6%	-0.3%

4.4.2 Test Method Comparison

The second examination involved in this study was looking at the difference between the test methods executed. It is claimed that laboratory testing is too idealized compared to the real world application. Cycle data was collected to develop dynamometer test cycles which should have been accurate representation. To examine how accurate the representation was, data from the laboratory and on-road tests were compared for the SEMTECH and the OBS. These comparisons also show which piece of equipment worked more consistent when performing in-use testing as opposed to laboratory testing. Table 4-18 shows the difference between brake and distance specific laboratory and on-road results from both the SEMTECH and the OBS. It is shown that there was no consistency between the two methods, although, if the dynamometer cycles were an accurate representation of the on-road route, the measurements should have had less difference.

Table 4-18: Test Method Comparison of Laboratory and On-Road Testing.

Parameter	Units	Difference (SEMTECH)	Difference (OBS)
CO	g/mi	-20.7%	41.2%
CO₂	g/mi	-30.8%	-24.2%
THC	g/mi	11.2%	13.4%
NO_x	g/mi	-42.1%	-51.1%
CO	g/bhp-hr	3.6%	61.9%
CO₂	g/bhp-hr	-6.4%	-1.2%
THC	g/bhp-hr	35.2%	36.7%
NO_x	g/bhp-hr	-17.9%	-28.8%

Further examination of why the test methods have such variation can be seen below. The data showed that more power was required to complete the dynamometer cycles as compared to the on-road routes, even with a lower truck weight. This discovery leads to the assumption that there may be an error in the dynamometer programming. The figure below (Figure 4-3) shows the comparison of a laboratory and an on-road Morgantown-Westover test from the SEMTECH. The plot shows power versus distance traveled. Figure 4-3 shows that the laboratory measurement was higher with minimal exceptions. Some peaks vary from the variation of the on-road route to the laboratory cycle

Figure 4-3: Comparison of Power from a Laboratory Cycle and an On-Road Route (Morgantown-Westover).

5. Conclusions and Recommendations

Since the development of emissions testing and emissions testing procedures, it has been argued that the guidelines used for engine certification do not provide sufficient representation of the “real world” application of the engines. The arguments include idealization of parameters and test cycle accuracy. When testing in a laboratory, several parameters can be controlled that may not be controllable under consumer operation of that same engine tested in the laboratory. Also, the developed test cycles, an example being the FTP, do not accurately represent real world operation. The cycle is created from four short sections of various driving scenarios. Several manufacturers and companies have experimented, in the past, with measuring emissions while the vehicle was “in-use,” but most proved to measure inaccurately when compared to a control. The governing factor for mandating in-use testing was when manufacturers were caught using “defeat devices” to pass engine certification testing but be able to perform differently under normal operation. This event brought forth the Consent Decrees. Details of the Consent Decrees were outlined in the review of this study. With an in-use test policy now mandatory, development of a system capable of the task followed. WVU developed their MEMS system which paved the way for many of the first commercially available units. As technologies and the standards of the CFR 40 changed, the in-use test equipment changed to keep up. The primary focus of this study was to do a comparison of two commercially available units, one being built under the CFR 40, Part 86 standard and the other built under the CFR 40, part 1065 standard. The secondary focus was to look at the difference between laboratory and on-road test methods.

5.1 Conclusions

In order to gather the data required to perform the study, both laboratory and on-road testing was completed. Five cycles were developed to create dynamometer cycles based on the on-road routes explained in the experimental setup. The chassis dynamometer testing was done to be able to compare each unit against a control. The units being compared were Sensor’s SEMTECH-D and Horiba’s OBS-2200. The control used for this study was WVU’s Transportable Laboratory, a CFR 40, Part 1065 laboratory.

The results showed that the SEMTECH measured distance specific and brake specific mass emissions quite accurately compared to the laboratory, with the exception of CO. On a

distance specific basis, the SEMTECH measured CO within 73 percent, CO₂ within three percent, THC within four percent, and NO_x within five percent of the laboratory. Brake specific measurement, by the SEMTECH showed a difference within 72 percent for CO, within three percent for CO₂, and within five percent for THC and NO_x. The OBS results were also respectable compared to the laboratory with the exception of CO and THC. Distance specific values resulted in a difference within 22 percent for CO, within three percent for CO₂, within 33 percent for THC, and within two percent for NO_x. The OBS measured brake specific mass emissions of CO, CO₂, THC, and NO_x within 21 percent, four percent, 40 percent, and one percent of the laboratory equipment, respectively. Problems with the FID flame of the OBS during laboratory testing lead to poor THC results when compared to the laboratory.

For the secondary focus of the study, an examination was completed for measurement consistency of the SEMTECH and OBS when comparing two different test methods. The reason for this study was to investigate the variation encountered when conducting on-road testing as compared to laboratory testing. Both in-use measurement systems' data from the laboratory and the on-road test were compared for this analysis. When comparing the two test methods, laboratory and on-road, the SEMTECH measured distance specific CO, CO₂, THC, and NO_x within 21 percent, 31 percent, 12 percent, and 43 percent, respectively. Brake specific measurements made by the SEMTECH differed within 4 percent for CO, 7 percent for CO₂, 36 percent for THC, and 18 percent for NO_x. The OBS results for this study also showed large variation, with distance specific emissions of CO within 42 percent, CO₂ within 25 percent, THC within 14 percent, and NO_x within 52 percent. Brake specific emissions measured by the OBS differed between the laboratory and on-road testing within 62 percent, 2 percent, 37 percent, and 29 percent for CO, CO₂, THC and NO_x, respectively. In both the laboratory and on-road comparisons, the SEMTECH and the OBS proved to be repeatable. COV of the SEMTECH was under 10 percent when measuring CO₂, THC, and NO_x emissions for laboratory and on-road results. CO was measured with a COV of below 30 percent for both test methods. The OBS showed very similar results with a COV below 9 percent for CO₂, THC, and NO_x. The COV of CO for the OBS was slightly higher than the SEMTECH but still fell below 33 percent.

From these two studies, it can be concluded that both systems performed well when compared to the laboratory. When comparing the two units to the laboratory measurements, neither outperforms the other overall. Each measures certain constituents better than the other.

When comparing the two test methods, it was proven by both measurement systems that the laboratory and on-road results varied greatly, ranging from differences of 1.2 to 61.9 percent. Variables such as weather conditions, traffic patterns, and even emissions in the air from other vehicles greatly affect on-road results. Both sets of results were verified by the fuel consumption analysis and the statistical analysis.

The CO measurement required further investigation. With the accuracy of the other analyzers, it is unlikely that the CO measurement was accurately represented by the results shown. One scenario, creating the large percent differences, could be that the measurement of CO was being done on a range misrepresentative of what the truck's CO production truly was. In some cases, the measurement does go over the calibration gas range. Another possibility leading to poor CO measurement was the size of the NDIR analyzer. A larger analyzer can measure low CO values more accurately but by the nature of the in-use equipment, a small analyzer must be used. This could have led to the poor measurement quality of CO emissions.

5.2 Recommendations

Although the goal of the study was accomplished with confidence in the resulting data, in order to make this study even more accurate small changes could be made. After examination of the gas bottle ranges, it is recommended that the CO be measured, by the SEMTECH and OBS, on a higher range than it was for this study. For improvement of laboratory testing, an examination should be completed of the method used to apply weight and grade loading for the chassis dynamometer. Chassis dynamometer testing was completed with a lighter weight value than that of the truck when tested on-road but the data showed that more work was required to complete the laboratory cycles. The last recommendation would be to have the in-use equipment serviced by the manufacturer to insure the most accurate calibrations and maintenance. Even though both systems passed all checks, a complete service would ensure the equipment was working at the manufacturer's specifications. Last, the comparison would be more beneficial with two units from the same time frame. Instead of using the SEMTECH-D, the upgraded SEMTECH-DS would make a better comparison.

6. References

1. "Auto Emission Testing and Standards." *Dictionary of American History*. Kirk H. Beetz 2003. Web. 22 Feb. 2011. <<http://www.encyclopedia.com>>
2. U.S. Environmental Protection Agency, "Health Assessment Document for Diesel Engine Exhaust," Prepared by the National Center for Environmental Assessment, for the Office of Transportation and Air Quality; EPA/600/8-90/057F, Washington, DC, May 2002.
3. "Code of Federal Regulations," CFR 40, Part 86, Office of the Federal Register National Archives and Records Administration, Washington, DC, 1998
4. Hawirko, J. D. and Checkel, M. D., "Quantifying Vehicle Emission Factors for Various Ambient Conditions using an On-Road, Real-Time Emissions System," SAE Technical Paper No. 2003-01-0301, SAE International, Warrendale, PA, 2003.
5. Hawirko, J. D. and Checkel, M. D., "Real-Time, On-Road Measurement of Driving Behavior, Engine Parameters and Exhaust Emissions," SAE Technical Paper No. 2002-01-1714, SAE International, Warrendale, PA, 2002.
6. "Notice of Filing of Consent Decree Under the Clean Air Act," Federal Register, Vol. 63, No. 212, Office of the Federal Register, National Archives and Records Administration, Washington DC, November 3, 1998.
7. Radermacher, A. J., "Repeatability of On-Road Routes and a Comparison of On-Road Routes to the Federal Test Procedure," M.S. Thesis, Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, 2004.
8. Noguchi, S., Konishi, T., Ogawa, Y., and Ishida, K., "Evaluating the Performance of Automatic Driving System for Use on Chassis Dynamometers," SAE Technical Paper No. 920253, SAE International, Warrendale, PA, 1992.
9. Nine, R. D., Clark, N. N., Daley, J. J., and Atkinson, C. M., "Development of a Heavy-Duty Chassis Dynamometer Driving Route," Proceedings of the Institution Mechanical Engineers, Vol. 213 No.6, Part D, pp 561-574, London, England, 1999.
10. "Emissions Standards: USA; Heavy-Duty Truck and Bus Engines." *Ecopoint Inc.* Web. 22 Feb. 2011. <<http://www.dieselnet.com/standards/us/hd.html#pre04>>
11. Gautam, M., Clark, N. N., Thompson, G. J., Carder, D. K., and Lyons, D. W., "Evaluation of Mobile Monitoring Technologies for Heavy-Duty Diesel-Powered Vehicle Emissions," Phase I Report, Submitted to the Settling Heavy-Duty Diesel Engine Manufacturers by West Virginia University, Morgantown, WV, March, 2000.

12. Gautam, M., Clark, N. N., Thompson, G. J., Carder, D. K., and Lyons, D. W., "Development of In-Use Procedures for Heavy-Duty Diesel Powered Vehicle Emissions," Phase II Report, Submitted to the Settling Heavy-Duty Diesel Engine Manufacturers by West Virginia University, Morgantown, WV, March, 2000.
13. Gautam, M., Clark, N. N., Thompson, G. J., Carder, D. K., Riddle, W. C., and Lyons, D. W., "Evaluation of In-Use Heavy-Duty Vehicle Emissions Using the Mobile Emissions Measurement System (MEMS)," Phase III Report, Submitted to the Settling Heavy-Duty Diesel Engine Manufacturers by West Virginia University, Morgantown, WV, December, 2002.
14. Gible, J. C., "Comparison of Heavy-Duty Diesel Engine Emissions Between an On-Road Route and Engine Dynamometer Simulated On-Road Cycle," M.S. Thesis, Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, 2000.
15. Shade, B. C., "A Performance Evaluation of the MEMS –An On-Road Emissions Measurement System Study," M.S. Thesis, Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, 2000.
16. Englund, M. S., "Field Compatible NO_x Emission Measurement Technique," SAE Technical Paper No. 820647, SAE International, Warrendale, PA, 1982.
17. Human, D. M. and Ullman, T. L., "Development of an I/M Short Emissions Test for Buses," SAE Technical Paper No. 920727, SAE International, Warrendale, PA 1992.
18. Kelly, N. A. and Groblicki, P. J., "Real-World Emissions from a Modern Production Vehicle Driven in Los Angeles," Journal of the Air & Waste Management Association, Vol. 43, No.10, pp 1351-1357, 1993.
19. Mackay, G. I., Nadler, S. D., Karecki, D. R., Schiff, H. I., Butler, J. W., Gierczak, C. A., and Jesion, G., "Dynamometer Intercomparison of Automobile Exhaust Gas CO/CO₂ Ratios and Temperature Between On-Board Measurements and a Remote Sensing Near Infrared Diode Laser System," Phase 1b Report to the Coordinating Research Council and National Renewable Energy Laboratory, 1994.
20. Mackay, G. I., Nadler, S. D., Karecki, D. R., Schiff, H. I., Butler, J. W., Gierczak, C. A., and Jesion, G., "Test Track Intercomparison of Automobile Exhaust Gas CO/CO₂ Ratios and Temperature Between On-Board Measurements and a Remote Sensing Near Infrared Diode Laser System," Phase 1c Report to the Coordinating Research Council and National Renewable Energy Laboratory, 1994.
21. Butler, J. W., Gierczak, C. A., Jesion, G., Stedman, D. H., and Lesko, J. M., "On-Road NO_x Emissions Intercomparison of On-Board Measurements and Remote Sensing," Final Report, Coordinating Research Council, Inc., Atlanta, GA, CRC Report No. VE-11-6, 1994.

22. Gierczak, C. A., Jesion, G., Piatak, J. W., and Butler, J. W., "On-Board Vehicle Emissions Measurement Program," Final Report, Coordinating Research Council, Inc., Atlanta, GA, CRC Report No. VE-11-1, 1994.
23. Bentz, A. P. and Weaver, E., "Marine Diesel Exhaust Emissions Measured by Portable Instruments," SAE Technical Paper No. 941784, SAE International, Warrendale, PA, 1994.
24. Bentz, A. P., "Final Summary Report on Project 3310, Marine Diesel Exhaust Emissions (Alternative Fuels)," United States Department of Transportation United States Coast Guard Systems, Report No. CG-D-08-98, 1997.
25. Vojtisek-Lom, M. and Cobb, Jr., J. T., "On-Road Light-Duty Vehicle Mass Emission Measurements Using a Novel Inexpensive On-Board Portable System," Proceedings of the Eighth CRC On-Road Vehicle Workshop, San Diego, CA, April 20-22, 1998.
26. Knight, J. K., "Measurement of Total Hydrocarbon Emissions with MEMS using a Portable FID and a Novel Exhaust Flow Meter," M.S. Thesis, Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, 2002.
27. "Construction Equipment Retrofit Project," Northeast States for Coordinated Air Use Management, Boston, MA, 1998.
28. Gautam, M., Clark, N. N., Thompson, G. J., and Lyons, D. W., "Assessment of Mobile Monitoring Technologies for Heavy-Duty Vehicle Emissions," White paper Submitted to the Settling Heavy-Duty Diesel Engine Manufacturers, Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, 1999.
29. Brown, E. J., F. G. King, W. A. Mitchell, W. C. Squier, D. B. Harris, and J. S. Kinsey. "On-Road Facility to Measure and Characterize Emissions from Heavy-Duty Diesel Vehicles," Journal of the Air & Waste Management Association, Vol. 52, No.4, pp 388-395, 2002.
30. Butler, J. W., Kornisk, T. J., Reading, A. R., and Kotenko, T. L., "Dynamometer Quality Data On-board Vehicles for Real-World Emission Measurements," Proceedings of the Ninth CRC On-Road Vehicle Workshop, April 19-21, San Diego, CA, 1999.
31. Kihara, N., Tsukamoto, T., Matsumoto, K., Ishida, K., Kon, M., and Murase, T., "Real-time On-board Measurement of Mass Emission of NO_x, Fuel Consumption, Road Load, and Engine Output for Diesel Vehicles," SAE Technical Paper No. 2000-01-1141, SAE International, Warrendale, PA, 2000.

32. Truex, T. J., Collins, J. F., Jetter, J. J., Knight, B., Hayashi, T., Kishi, N., and Suzuki, N., "Measurement of Ambient Roadway and Vehicle Exhaust Emissions-An Assessment of Instrument Capability and Initial On-Road Test Results with an Advanced Low Emission Vehicle," SAE Technical Paper No. 2000-01-1142, SAE International, Warrendale, PA, 2000.
33. Jetter, J., Maeshiro, S., Hatcho, S., and Klebba, R., "Development of an On-Board Analyzer for Use on Advanced Low Emission Vehicles," SAE Technical Paper No. 2000-01-1140, SAE International, Warrendale, PA, 2000.
34. Ikonen, M, Westerholm, M., and Nyulnd, N, "Emission and Fuel Consumption Measurements for Transit Buses Running on Gaseous Fuels Using a Mobile Measurement System," SAE Technical Paper No. 2001-02-3638, SAE International, Warrendale, PA, 2001.
35. Vojtisek-Lom, M., and Allsop, J. E., "Development of Heavy-Duty Diesel Portable, On-Board Mass Exhaust Emissions Monitoring System With NO_x, CO₂, And Qualitative PM Capabilities," SAE Technical Paper No. 2001-01-3641, SAE International, Warrendale, PA, 2001.
36. Czachura, B., Brandon, L., and May, A., "Demonstration of the 'Simple, Portable On-Vehicle Testing' (SPOT) System on a Class 8 Vehicle," Proceedings of the 11th CRC On-Road Vehicle Emissions Workshop, 2001.
37. Weaver, C. S. and Balam-Almanza, M.V. "Development of the 'RAVEM' Ride-Along Vehicle Emissions Measurement System for Gaseous and Particulate Emissions," SAE Technical Paper No. 2001-01-3644, SAE International, SAE International, Warrendale, PA, 2001.
38. "Regulatory Announcement: Changed Test Procedures for Non-road Engines and Heavy-Duty Highway Engines." *Environmental Protection Agency*. 2005. Web. 22 Feb. 2011. < <http://www.epa.gov/oms/regs/techamendments/420f05036.htm> >
39. Johnson, K., Durbin, T., Cocker III, D. R., and Miller, J. W., "On-Road Comparison of a Portable Emission Measurement System with a Mobile Reference Laboratory for a Heavy-Duty Diesel Vehicle (On-Road Validation of a Gaseous PEMS with a Full CVS Reference Laboratory and a DPF Equipped 2004 Heavy-Duty Diesel Vehicle)." *Atmospheric Environment*, Vol. 43, No.18, pp 1-25, 2008.
40. Miller, J. W., Durbin, T., and Johnson K., "Evaluation of On-Road Results from a Test Fleet of Heavy-Duty Trucks". Technical report Submitted to California Air Resources Board by CE-CERT, Riverside, CA, 2007.
41. Pelkmans, L. and Debal, P., "Comparison of On-Road Emissions with Emissions Measured on Chassis Dynamometer Test Cycles." *Transportation Research Part D: Transport and Environment*, Vol. 11, No. 4, pp 233-241, 2006.

42. Collins, J. F., Shepherd, T., Durbin, T., Lents, J., Norbeck, J. N., and Barth, M., "Measurements of In-Use Emissions from Modern Vehicles Using an On-Board Measurement System," *Environmental Science and Technology*, Vol. 41, No. 18, pp 6654-6661, 2007.
43. Mustang Advanced Engineering, "Project Spotlights." Mustang Advanced Engineering, Twinsburg, OH, 2010.
44. Li, H., Andrews, G. E., Daham, B., Bell, M., Tate, J., and Ropkins, K., "Impact of Traffic Conditions and Road Geometry on Real-world Urban Emissions Using a SI Car," *Energy and Resources Research Institute, School of Process, Environmental, and Material Engineering and Institute for Transport Studies, The University of Leeds, UK*, 2007.
45. Shahinian, V. D., "SEMTECH-D User's Manual" Sensors, Inc., Saline, Michigan, Document: 9510-064, Revision: 3.7.1, May 2005.
46. "On-board Emission Measurement System OBS-2200 Instruction Manual," Horiba, Ltd., Ann Arbor, Michigan, March 2009.
47. Ryskamp, R. H., "Exploration of Injection Strategy and Fuel Property Effects on Advanced Combustion," M.S. Thesis, Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, 2010.
48. Zia, S. A., "The Effect of Different Road Load Implementation Strategies on Fuel Economy of USPS Step Vans," M.S. Thesis, Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, 2009.
49. "Heavy-Duty FTP Transient Cycle." *Ecopoint Inc.* Web. 14 March 2011.
< http://www.dieselnet.com/standards/cycles/ftp_trans.html>
50. "Morgantown Route." Scale Undetermined; Brock Merritt; 'Google Maps.'
<http://maps.google.com/maps?saddr=Unknown+road&daddr=39.6322841,-79.9753951+to:39.5866545,-79.9454373+to:39.6273901,-79.9286809+to:39.6331483,-79.9279344+to:39.6561256,-79.9484621+to:39.6387009,-80.0007862+to:39.6323191,-79.975663+to:Unknown+road&hl=en&sl=39.621755,-79.973345&sspn=0.048791,0.07699&geocode=FRlgXAIIdKq87-w%3BFZy9XAIIdHaw7-yljvZ96iHs1iDHyxZuLxouFVg%3BFV4LXAIIdlyE8-yntN2ICHn01iDHRlcO_XAXbcg%3BFX6qXAIIdmGI8-yk92PaCV3s1iDEumo4r3oJIHQ%3BFfzAXAIIdgmU8-ykvTMz7UHs1iDFDOg_mD86tyQ%3BFb0aXQIdUhU8-ylpK633EHs1iDEY43mZn_HwIg%3BFazWXAIId7kg7-ynT-1-35Hs1iDFCcxoeESvnMQ%3BFb-9XAIIdEas7-ykddbCJiHs1iDGejspTiJPKdg%3BFSHgXAIIdMK07-w&mra=dme&mrsp=8&sz=14&via=1,2,3,4,5,6,7&z=14>, 20 June 2011.

51. "Westover to Bruceton Mills Route." Scale Undetermined; Brock Merritt; 'Google Maps.' <http://maps.google.com/maps?saddr=Unknown+road&daddr=39.63255,-79.97722+to:W+Virginia+131+W%2FBenedum+Dr%2FRte+73&hl=en&sll=39.59008,-80.061836&sspn=0.195255,0.307961&geocode=FRlgXAIIdKq87-w%3BFaa-XAIId_KQ7-ykddbCJiHs1iDGfjSpTiJPKdg%3BFZ5OWAIId4uA3-w&mra=dpe&mrsp=1&sz=12&via=1&z=12>, 20 June 2011.
52. "Westover to Saltwell Route." Scale Undetermined; Brock Merritt; 'Google Maps.' <http://maps.google.com/maps?saddr=Unknown+road&daddr=39.63278,-79.97811+to:39.6288,-79.98763+to:Bruceton+Mills,+WV&hl=en&ll=39.616797,-79.683838&spn=0.195179,0.307961&sll=39.612301,-79.974632&sspn=0.048798,0.07699&geocode=FRlgXAIIdKq87-w%3BFYy_XAIIdgqE7-yn_uTT5iHs1iDGnsRqEfU85Fw%3BFQCwXAIIdUnw7-ylBCHvECnw1iDFHiNPpGECirQ%3BFcQkXQIducVA-yljvQ2wZ1s1iDHG2UX3yRflrw&mra=dpe&mrsp=1&sz=14&via=1,2&z=12>, 20 June 2011.
53. Stombaugh, T.S. and Clement, B.R., "Unraveling the GPS Mystery," Ohio State University Fact Sheet, Food, Agriculture, and Biological Engineering, Ohio State University, Columbus, Ohio, 1999.

Appendix A – Test Setup Photographs

Figure 0-1: Test Vehicle on Chassis Dynamometer.

Figure 0-2: In-Use Measurement Analyzers.

Figure 0-3: OBS (Top) and SEMTECH (Bottom) Exhaust Sample Lines.

Figure 0-4: Test Vehicle Outfitted for On-Road Testing (Side View).

Figure 0-5: Outfitted Test Vehicle (Overhead).

Figure 0-6: In-Use Equipment Securely Fastened in Truck Bed.

Appendix B – Individual Laboratory Test Results

Table 0-1: Test Results from B2W-01.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	29.42	29.29	-0.4	29.60	0.6	-1.0
Work	bhp-hr	75.20	74.99	-0.3	75.41	0.3	-0.6
CO	%	0.002	0.014	150.4	0.010	133.8	33.4
CO₂	%	1.488	5.574	115.7	5.662	116.8	-1.6
THC	ppm	13.46	21.57	46.3	0.186	-194.5	196.6
NOx	ppm	76.95	300.8	118.5	295.7	117.4	1.7
Exh Vol	SCF	1033	1029	-0.4	982.0	-5.1	4.7
Exh T	°C	310.8	346.0	10.7	346.1	10.8	-0.0
Exh P	kPa(g)	0.166	1.892	167.8	0.600	113.4	103.7
Amb T	°C		27.20	100.0	21.27	100.0	24.5
Amb P	kPa	97.69	111.3	13.0	97.86	0.2	12.8
Carbon Balance	grams	10094	9817	-2.8	9370	-7.4	4.7
Fuel Consumption	grams	11662	11341	-2.8	10825	-7.4	4.7
CO	grams	32.71	50.804	43.3	35.85	9.2	34.5
CO₂	grams	36907	35868	-2.9	34267	-7.4	4.6
THC	grams	5.449	3.916	-32.7	0.021	-198.5	197.9
NOx	grams	193.7	194.1	0.2	180.4	-7.1	7.3
CO	g/mi	1.112	1.734	43.8	1.211	8.6	35.5
CO₂	g/mi	1255	1224	-2.4	1158	-8.0	5.6
THC	g/mi	0.185	0.134	-32.3	0.001	-198.5	197.9
NOx	g/mi	6.584	6.627	0.7	6.096	-7.7	8.4
CO	g/bhp-hr	0.435	0.677	43.6	0.475	8.9	35.1
CO₂	g/bhp-hr	490.8	478.3	-2.6	454.4	-7.7	5.1
THC	g/bhp-hr	0.072	0.052	-32.5	0.000	-198.5	197.9
NOx	g/bhp-hr	2.576	2.589	0.5	2.393	-7.4	7.9

Table 0-2: Test Results from B2W-02.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	29.39	29.24	-0.5	29.60	0.7	-1.2
Work	bhp-hr	73.73	73.50	-0.3	73.95	0.3	-0.6
CO	%	0.002	0.023	172.4	0.009	138.4	84.4
CO₂	%	1.218	4.970	121.3	5.676	129.3	-13.3
THC	ppm	10.31	21.37	69.8	-0.171	-206.7	203.2
NOx	ppm	61.60	284.8	128.9	289.5	129.8	-1.6
Exh Vol	SCF	1007	998.4	-0.9	984.7	-2.3	1.4
Exh T	°C	315.1	342.9	8.5	342.6	8.4	0.1
Exh P	kPa(g)	0.339	0.702	69.9	0.643	62.0	8.9
Amb T	°C		27.96	100.0	20.85	100.0	29.1
Amb P	kPa	97.67	111.2	13.0	97.81	0.1	12.8
Carbon Balance	grams	9817	8699	-12.1	9348	-4.9	-7.2
Fuel Consumption	grams	11341	10049	-12.1	10800	-4.9	-7.2
CO	grams	32.71	76.61	80.3	29.481	-10.4	88.9
CO₂	grams	35898	31732	-12.3	34196	-4.9	-7.5
THC	grams	3.292	3.732	12.5	-0.019	-202.4	202.1
NOx	grams	188.4	178.6	-5.3	174.8	-7.5	2.2
CO	g/mi	1.113	2.620	80.8	0.996	-11.1	89.8
CO₂	g/mi	1221	1085	-11.8	1155	-5.6	-6.2
THC	g/mi	0.112	0.128	13.1	-0.001	-202.4	202.1
NOx	g/mi	6.410	6.109	-4.8	5.906	-8.2	3.4
CO	g/bhp-hr	0.444	1.042	80.6	0.399	-10.7	89.3
CO₂	g/bhp-hr	486.9	431.7	-12.0	462.4	-5.2	-6.9
THC	g/bhp-hr	0.045	0.051	12.8	0.000	-202.4	202.1
NOx	g/bhp-hr	2.555	2.430	-5.0	2.364	-7.8	2.8

Table 0-3: Test Results from W2B-01.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	29.97	29.84	-0.4	30.20	0.8	-1.2
Work	bhp-hr	80.36	80.16	-0.3	80.56	0.3	-0.5
CO	%	0.002	0.018	164.3	0.010	140.9	55.5
CO₂	%	1.294	4.717	113.9	6.305	131.9	-28.8
THC	ppm	9.437	21.25	77.0	34.30	113.7	-47.0
NOx	ppm	65.20	248.5	116.9	314.2	131.3	-23.3
Exh Vol	SCF	1119	1105	-1.3	1128	0.9	-2.1
Exh T	°C	303.6	339.8	11.3	336.8	10.4	0.9
Exh P	kPa(g)	0.331	0.808	83.7	0.818	84.7	-1.3
Amb T	°C		24.71	100.0	19.73	100.0	22.4
Amb P	kPa	97.70	111.3	13.0	97.82	0.1	12.9
Carbon Balance	grams	10867	9515	-13.3	12099	10.7	-23.9
Fuel Consumption	grams	12554	10993	-13.3	13977	10.7	-23.9
CO	grams	35.31	68.13	63.5	41.36	15.8	48.9
CO₂	grams	39737	34735	-13.4	44234	10.7	-24.1
THC	grams	3.711	4.009	7.7	6.146	49.4	-42.1
NOx	grams	207.4	182.3	-12.9	223.3	7.4	-20.2
CO	g/mi	1.178	2.283	63.9	1.369	15.0	50.0
CO₂	g/mi	1326	1164	-13.0	1465	9.9	-22.9
THC	g/mi	0.124	0.134	8.2	0.204	48.7	-40.9
NOx	g/mi	6.920	6.111	-12.4	7.395	6.6	-19.0
CO	g/bhp-hr	0.439	0.850	63.7	0.513	15.5	49.4
CO₂	g/bhp-hr	494.5	433.3	-13.2	549.1	10.5	-23.6
THC	g/bhp-hr	0.046	0.050	8.0	0.076	49.2	-41.6
NOx	g/bhp-hr	2.580	2.275	-12.6	2.772	7.2	-19.7

Table 0-4: Test Results from W2B-02.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	29.91	29.77	-0.5	30.10	0.6	-1.1
Work	bhp-hr	78.97	78.79	-0.2	79.15	0.2	-0.5
CO	%	0.002	0.019	167.1	0.010	140.3	64.9
CO₂	%	1.261	5.604	126.5	6.291	133.2	-11.6
THC	ppm	8.326	20.44	84.2	33.68	120.7	-48.9
NOx	ppm	63.98	287.5	127.2	324.4	134.1	-12.1
Exh Vol	SCF	1086	1076	-1.0	1051	-3.3	2.3
Exh T	°C	297.0	330.8	10.8	327.8	9.9	0.9
Exh P	kPa(g)	0.331	0.752	77.7	0.862	88.9	-13.6
Amb T	°C		24.54	100.0	19.81	100.0	21.3
Amb P	kPa	97.84	111.4	13.0	97.86	0.0	13.0
Carbon Balance	grams	10971	10550	-3.9	11265	2.7	-6.6
Fuel Consumption	grams	12674	12188	-3.9	13014	2.7	-6.6
CO	grams	33.82	67.23	66.1	33.29	-1.6	67.5
CO₂	grams	40106	38528	-4.0	41195	2.7	-6.7
THC	grams	8.436	3.777	-76.3	5.607	-40.3	-39.0
NOx	grams	405.4	198.2	-68.6	214.7	-61.5	-8.0
CO	g/mi	1.131	2.258	66.5	1.106	-2.2	68.5
CO₂	g/mi	1341	1294	-3.6	1369	2.1	-5.6
THC	g/mi	0.282	0.127	-75.9	0.186	-40.9	-37.9
NOx	g/mi	13.56	6.659	-68.2	7.134	-62.1	-6.9
CO	g/bhp-hr	0.428	0.853	66.3	0.421	-1.8	67.9
CO₂	g/bhp-hr	507.9	489.0	-3.8	520.5	2.5	-6.2
THC	g/bhp-hr	0.107	0.048	-76.1	0.071	-40.5	-38.5
NOx	g/bhp-hr	5.134	2.516	-68.4	2.713	-61.7	-7.5

Table 0-5: Test Results from W2S-01.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.54	30.41	-0.4	30.80	0.9	-1.3
Work	bhp-hr	80.52	80.35	-0.2	80.69	0.2	-0.4
CO	%	0.002	0.018	163.6	0.010	138.2	58.4
CO₂	%	1.336	5.871	125.9	6.652	133.1	-12.5
THC	ppm	8.111	20.21	85.5	-1.258	-273.4	226.6
NOx	ppm	65.43	289.9	126.3	337.4	135.0	-15.2
Exh Vol	SCF	1086	1073	-1.2	1070	-1.5	0.3
Exh T	°C	302.3	339.8	11.7	336.4	10.7	1.0
Exh P	kPa(g)	0.348	0.766	75.0	0.968	94.2	-23.3
Amb T	°C		24.17	100.0	18.88	100.0	24.6
Amb P	kPa	97.94	111.5	13.0	97.86	-0.1	13.1
Carbon Balance	grams	10842	10726	-1.1	11730	7.9	-8.9
Fuel Consumption	grams	12525	12391	-1.1	13551	7.9	-8.9
CO	grams	34.81	63.68	58.6	35.64	2.3	56.5
CO₂	grams	39647	39176	-1.2	42911	7.9	-9.1
THC	grams	3.756	3.781	0.7	-0.230	-226.1	225.9
NOx	grams	197.7	193.2	-2.3	219.5	10.5	-12.7
CO	g/mi	1.141	2.094	58.9	1.157	1.4	57.6
CO₂	g/mi	1298	1288	-0.8	1393	7.1	-7.8
THC	g/mi	0.123	0.124	1.1	-0.007	-225.8	225.6
NOx	g/mi	6.474	6.353	-1.9	7.126	9.6	-11.5
CO	g/bhp-hr	0.433	0.793	58.8	0.442	2.1	56.9
CO₂	g/bhp-hr	492.4	487.6	-1.0	531.8	7.7	-8.7
THC	g/bhp-hr	0.047	0.047	0.9	-0.003	-226.0	225.8
NOx	g/bhp-hr	2.455	2.405	-2.1	2.720	10.3	-12.3

Table 0-6: Test Results from W2S-02.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.51	30.37	-0.5	30.70	0.6	-1.1
Work	bhp-hr	76.60	76.44	-0.2	76.77	0.2	-0.4
CO	%	0.001	0.016	167.9	0.008	137.1	72.6
CO₂	%	1.259	5.862	129.3	6.651	136.3	-12.6
THC	ppm	7.145	17.48	84.0	27.68	117.9	-45.2
NOx	ppm	60.40	283.4	129.7	320.4	136.6	-12.2
Exh Vol	SCF	1014	1005	-1.0	1001	-1.4	0.4
Exh T	°C	303.1	337.3	10.7	333.9	9.7	1.0
Exh P	kPa(g)	0.371	0.661	56.3	0.886	82.0	-29.0
Amb T	°C		23.39	100.0	18.00	100.0	26.1
Amb P	kPa	97.97	111.6	13.0	97.86	-0.1	13.1
Carbon Balance	grams	10225	10086	-1.4	11029	7.6	-8.9
Fuel Consumption	grams	11812	11651	-1.4	12741	7.6	-8.9
CO	grams	27.37	54.86	66.9	24.61	-10.6	76.1
CO₂	grams	37400	36848	-1.5	40345	7.6	-9.1
THC	grams	3.029	3.193	5.3	4.579	40.8	-35.7
NOx	grams	181.3	179.3	-1.1	197.6	8.6	-9.7
CO	g/mi	0.897	1.807	67.3	0.802	-11.3	77.1
CO₂	g/mi	1226	1213	-1.0	1314	6.9	-8.0
THC	g/mi	0.099	0.105	5.7	0.149	40.2	-34.6
NOx	g/mi	5.944	5.905	-0.7	6.438	8.0	-8.6
CO	g/bhp-hr	0.357	0.718	67.1	0.321	-10.8	76.5
CO₂	g/bhp-hr	488.2	482.0	-1.3	525.5	7.4	-8.6
THC	g/bhp-hr	0.040	0.042	5.5	0.060	40.6	-35.3
NOx	g/bhp-hr	2.367	2.346	-0.9	2.575	8.4	-9.3

Table 0-7: Test Results from S2W-01.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.46	30.30	-0.5	30.60	0.5	-1.0
Work	bhp-hr	73.90	73.74	-0.2	74.06	0.2	-0.4
CO	%	0.002	0.012	155.0	0.009	140.2	32.4
CO₂	%	1.223	5.815	130.5	6.709	138.3	-14.3
THC	ppm	7.764	21.28	93.1	18.98	83.9	11.4
NOx	ppm	62.35	301.9	131.5	351.7	139.8	-15.2
Exh Vol	SCF	976.8	965.3	-1.2	947.2	-3.1	1.9
Exh T	°C	311.8	342.5	9.4	339.7	8.6	0.8
Exh P	kPa(g)	0.381	0.641	50.7	0.886	79.6	-32.1
Amb T	°C		23.10	100.0	17.67	100.0	26.6
Amb P	kPa	98.00	111.6	13.0	97.86	-0.2	13.1
Carbon Balance	grams	9705	9418	-3.0	10255	5.5	-8.5
Fuel Consumption	grams	11212	10881	-3.0	11848	5.5	-8.5
CO	grams	29.38	37.43	24.1	24.54	-17.9	41.6
CO₂	grams	35494	34429	-3.1	37516	5.5	-8.6
THC	grams	3.385	3.533	4.3	3.228	-4.8	9.0
NOx	grams	182.1	177.8	-2.4	197.6	8.2	-10.6
CO	g/mi	0.964	1.235	24.6	0.802	-18.4	42.5
CO₂	g/mi	1165	1136	-2.5	1226	5.1	-7.6
THC	g/mi	0.111	0.117	4.8	0.105	-5.2	10.0
NOx	g/mi	5.980	5.867	-1.9	6.458	7.7	-9.6
CO	g/bhp-hr	0.398	0.508	24.3	0.331	-18.2	42.0
CO₂	g/bhp-hr	480.3	466.9	-2.8	506.6	5.3	-8.2
THC	g/bhp-hr	0.046	0.048	4.5	0.044	-5.0	9.5
NOx	g/bhp-hr	2.465	2.411	-2.2	2.668	7.9	-10.1

Table 0-8: Test Results from S2W-02.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.53	30.38	-0.5	30.70	0.6	-1.0
Work	bhp-hr	72.60	72.39	-0.3	72.81	0.3	-0.6
CO	%	0.001	0.015	165.0	0.007	132.3	72.0
CO₂	%	1.218	5.889	131.4	6.705	138.5	-13.0
THC	ppm	7.310	19.15	89.5	25.73	111.5	-29.3
NOx	ppm	60.63	299.6	132.7	335.8	138.8	-11.4
Exh Vol	SCF	970.9	960.1	-1.1	950.5	-2.1	1.0
Exh T	°C	309.3	342.5	10.2	339.0	9.2	1.0
Exh P	kPa(g)	0.363	0.621	52.4	0.843	79.7	-30.3
Amb T	°C		22.71	100.0	17.42	100.0	26.4
Amb P	kPa	97.99	111.6	13.0	97.88	-0.1	13.1
Carbon Balance	grams	9667	9498	-1.8	10303	6.4	-8.1
Fuel Consumption	grams	11168	10973	-1.8	11903	6.4	-8.1
CO	grams	28.00	48.79	54.2	19.95	-33.6	83.9
CO₂	grams	35356	34705	-1.9	37696	6.4	-8.3
THC	grams	3.154	3.240	2.7	4.251	29.6	-27.0
NOx	grams	176.8	176.7	-0.1	191.5	8.0	-8.0
CO	g/mi	0.917	1.606	54.6	0.650	-34.1	84.8
CO₂	g/mi	1158	1142	-1.4	1228	5.9	-7.2
THC	g/mi	0.103	0.107	3.2	0.138	29.1	-26.0
NOx	g/mi	5.792	5.818	0.5	6.238	7.4	-7.0
CO	g/bhp-hr	0.386	0.674	54.4	0.274	-33.9	84.4
CO₂	g/bhp-hr	487.0	479.4	-1.6	517.7	6.1	-7.7
THC	g/bhp-hr	0.043	0.045	3.0	0.058	29.4	-26.4
NOx	g/bhp-hr	2.436	2.442	0.2	2.630	7.7	-7.4

Table 0-9: Test Results from MW-01.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	27.10	26.66	-1.6	27.20	0.4	-2.0
Work	bhp-hr	65.32	65.07	-0.4	65.57	0.4	-0.8
CO	%	0.001	0.019	180.3	0.006	145.8	100.5
CO₂	%	0.626	4.240	148.5	4.796	153.8	-12.3
THC	ppm	6.096	24.15	119.4	0.984	-144.4	184.3
NOx	ppm	31.88	236.2	152.4	262.7	156.7	-10.6
Exh Vol	SCF	1006	1036	3.0	996.8	-0.9	3.9
Exh T	°C	221.6	245.6	10.3	242.4	8.9	1.3
Exh P	kPa(g)	0.293	0.262	-10.9	0.189	-42.9	32.4
Amb T	°C		21.26	100.0	16.96	100.0	22.5
Amb P	kPa	98.06	111.7	13.0	98.19	0.1	12.9
Carbon Balance	grams	8529	8496	-0.4	8854	3.7	-4.1
Fuel Consumption	grams	9853	9815	-0.4	10229	3.7	-4.1
CO	grams	33.69	68.09	67.6	22.08	-41.7	102.1
CO₂	grams	31175	30998	-0.6	32397	3.9	-4.4
THC	grams	4.231	4.558	7.5	0.317	-172.1	174.0
NOx	grams	164.1	168.5	2.7	175.8	6.9	-4.2
CO	g/mi	1.243	2.555	69.0	0.812	-42.0	103.6
CO₂	g/mi	1150	1163	1.1	1191	3.5	-2.4
THC	g/mi	0.156	0.171	9.1	0.012	-172.2	174.5
NOx	g/mi	6.055	6.322	4.3	6.463	6.5	-2.2
CO	g/bhp-hr	0.516	1.047	67.9	0.337	-42.0	102.6
CO₂	g/bhp-hr	477.3	476.4	-0.2	494.0	3.5	-3.6
THC	g/bhp-hr	0.065	0.070	7.8	0.005	-172.2	174.2
NOx	g/bhp-hr	2.512	2.590	3.1	2.681	6.5	-3.4

Table 0-10: Test Results from MW-02.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	26.87			27.00	0.5	
Work	bhp-hr	68.41			68.41	0.0	
CO	%	0.001			0.007	143.4	
CO₂	%	0.653			4.860	152.7	
THC	ppm	6.276			37.05	142.1	
NOx	ppm	32.93			264.3	155.7	
Exh Vol	SCF	1040			1021	-1.8	
Exh T	°C	224.3			246.7	9.5	
Exh P	kPa(g)	0.238			0.254	6.5	
Amb T	°C				16.07	100.0	
Amb P	kPa	98.09			98.19	0.1	
Carbon Balance	grams	8923			9177	2.8	
Fuel Consumption	grams	10308			10602	2.8	
CO	grams	36.34			24.15	-40.3	
CO₂	grams	32614			33557	2.9	
THC	grams	4.292			6.184	36.1	
NOx	grams	169.2			180.9	6.7	
CO	g/mi	1.352			0.894	-40.8	
CO₂	g/mi	1214			1243	2.4	
THC	g/mi	0.160			0.229	35.7	
NOx	g/mi	6.296			6.700	6.2	
CO	g/bhp- hr	0.531			0.353	-40.3	
CO₂	g/bhp- hr	476.8			490.6	2.9	
THC	g/bhp- hr	0.063			0.090	36.1	
NOx	g/bhp- hr	2.474			2.645	6.7	

Table 0-11: Test Results from MW-03.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	26.95	26.54	-1.5	27.10	0.6	-2.1
Work	bhp-hr	68.02	67.73	-0.4	68.30	0.4	-0.8
CO	%	0.001	0.025	183.1	0.007	148.0	108.8
CO₂	%	0.658	4.110	144.8	4.857	152.2	-16.6
THC	ppm	6.696	24.84	115.1	10.50	44.2	81.1
NOx	ppm	32.39	227.9	150.2	273.7	157.7	-18.3
Exh Vol	SCF	1045	1066	2.1	973.0	-7.1	9.2
Exh T	°C	224.4	250.9	11.2	247.8	9.9	1.3
Exh P	kPa(g)	0.129	0.282	74.7	0.455	111.8	-46.8
Amb T	°C		21.42	100.0	17.10	100.0	22.4
Amb P	kPa	98.33	112.0	13.0	98.19	-0.1	13.1
Carbon Balance	grams	8963	8631	-3.8	8868	-1.1	-2.7
Fuel Consumption	grams	10355	9971	-3.8	10245	-1.1	-2.7
CO	grams	37.36	92.52	84.9	24.58	-41.3	116.0
CO₂	grams	32759	31454	-4.1	32438	-1.0	-3.1
THC	grams	4.608	4.826	4.6	2.556	-57.3	61.5
NOx	grams	166.0	167.6	0.9	179.3	7.7	-6.8
CO	g/mi	1.386	3.485	86.2	0.907	-41.8	117.4
CO₂	g/mi	1216	1185	-2.6	1197	-1.6	-1.0
THC	g/mi	0.171	0.182	6.1	0.094	-57.8	63.4
NOx	g/mi	6.160	6.313	2.4	6.619	7.2	-4.7
CO	g/bhp-hr	0.549	1.366	85.3	0.360	-41.7	116.6
CO₂	g/bhp-hr	481.6	464.4	-3.7	474.9	-1.4	-2.2
THC	g/bhp-hr	0.068	0.071	5.0	0.037	-57.7	62.3
NOx	g/bhp-hr	2.441	2.474	1.4	2.626	7.3	-6.0

Table 0-12: Test Results from MW-04.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	26.86	26.45	-1.5	27.00	0.5	-2.1
Work	bhp-hr	69.73	69.45	-0.4	70.01	0.4	-0.8
CO	%	0.001	0.017	175.7	0.006	140.1	92.6
CO₂	%	0.674	4.385	146.7	4.947	152.1	-12.0
THC	ppm	6.765	24.82	114.3	15.81	80.1	44.4
NOx	ppm	33.97	243.9	151.1	264.2	154.4	-8.0
Exh Vol	SCF	1058	1089.4	2.9	1081	2.1	0.8
Exh T	°C	230.4	254.2	9.8	251.1	8.6	1.2
Exh P	kPa(g)	0.216	0.309	35.3	0.457	71.6	-38.7
Amb T	°C		22.55	100.0	17.70	100.0	24.1
Amb P	kPa	98.30	112.0	13.0	98.19	-0.1	13.1
Carbon Balance	grams	9190	9200	0.1	9789	6.3	-6.2
Fuel Consumption	grams	10617	10628	0.1	11309	6.3	-6.2
CO	grams	38.62	66.04	52.4	23.31	-49.4	95.6
CO₂	grams	33588	33580	-0.0	35810	6.4	-6.4
THC	grams	4.636	4.815	3.8	3.505	-27.8	31.5
NOx	grams	174.8	180.7	3.3	188.9	7.8	-4.4
CO	g/mi	1.438	2.496	53.8	0.863	-49.9	97.2
CO₂	g/mi	1251	1269	1.5	1326	5.9	-4.4
THC	g/mi	0.173	0.182	5.3	0.130	-28.3	33.5
NOx	g/mi	6.507	6.830	4.9	6.995	7.2	-2.4
CO	g/bhp-hr	0.554	0.951	52.8	0.333	-49.8	96.3
CO₂	g/bhp-hr	481.7	483.5	0.4	511.5	6.0	-5.6
THC	g/bhp-hr	0.066	0.069	4.2	0.050	-28.2	32.3
NOx	g/bhp-hr	2.507	2.602	3.7	2.698	7.4	-3.6

Table 0-13: Test Results from MW-05.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	26.90	26.47	-1.6	27.00	0.4	-2.0
Work	bhp-hr	66.90	66.65	-0.4	67.16	0.4	-0.8
CO	%	0.001	0.012	168.6	0.008	153.5	43.0
CO₂	%	0.642	4.227	147.3	4.898	153.7	-14.7
THC	ppm	6.921	24.53	112.0	4.476	-42.9	138.3
NOx	ppm	31.43	232.3	152.3	256.8	156.1	-10.0
Exh Vol	SCF	1021	1052	3.0	1013	-0.8	3.8
Exh T	°C	222.8	248.1	10.8	245.3	9.6	1.2
Exh P	kPa(g)	0.233	0.276	16.8	0.313	29.2	-12.6
Amb T	°C		23.97	100.0	19.21	100.0	22.0
Amb P	kPa	98.21	111.9	13.0	98.19	-0.0	13.0
Carbon Balance	grams	8741	8587	-1.8	9152	4.6	-6.4
Fuel Consumption	grams	10098	9920	-1.8	10573	4.6	-6.4
CO	grams	35.69	45.64	24.5	26.34	-30.2	53.6
CO₂	grams	31949	31367	-1.8	33480	4.7	-6.5
THC	grams	4.391	4.620	5.1	1.248	-111.5	114.9
NOx	grams	163.7	167.3	2.1	173.1	5.6	-3.4
CO	g/mi	1.327	1.724	26.1	0.976	-30.5	55.5
CO₂	g/mi	1188	1185	-0.2	1240	4.3	-4.5
THC	g/mi	0.163	0.175	6.7	0.046	-111.7	116.2
NOx	g/mi	6.087	6.320	3.8	6.411	5.2	-1.4
CO	g/bhp-hr	0.533	0.685	24.8	0.392	-30.5	54.3
CO₂	g/bhp-hr	477.5	470.6	-1.5	498.5	4.3	-5.8
THC	g/bhp-hr	0.066	0.069	5.5	0.019	-111.7	115.4
NOx	g/bhp-hr	2.447	2.510	2.5	2.578	5.2	-2.7

Table 0-14: Test Results from S2W-03.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.36	30.21	-0.5	30.60	0.8	-1.2
Work	bhp-hr	73.00	72.80	-0.3	73.20	0.3	-0.6
CO	%	0.001	0.013	160.6	0.007	133.6	58.2
CO₂	%	1.217	6.009	132.7	6.879	139.9	-13.5
THC	ppm	8.207	20.19	84.4	31.04	116.4	-42.4
NOx	ppm	61.62	312.0	134.0	355.4	140.9	-13.0
Exh Vol	SCF	955.0	944.3	-1.1	937.5	-1.9	0.7
Exh T	°C	306.1	343.9	11.6	340.0	10.5	1.2
Exh P	kPa(g)	0.295	0.600	68.2	0.605	69.0	-0.9
Amb T	°C		26.13	100.0	21.29	100.0	20.4
Amb P	kPa	98.16	111.8	13.0	98.19	0.0	13.0
Carbon Balance	grams	9625	9453	-1.8	10362	7.4	-9.2
Fuel Consumption	grams	11120	10920	-1.8	11971	7.4	-9.2
CO	grams	27.86	41.31	38.9	20.07	-32.5	69.2
CO₂	grams	35203	34550	-1.9	37910	7.4	-9.3
THC	grams	3.271	3.358	2.6	4.683	35.5	-33.0
NOx	grams	183.3	180.5	-1.5	199.2	8.3	-9.9
CO	g/mi	0.918	1.367	39.4	0.656	-33.3	70.3
CO₂	g/mi	11560	1144	-1.4	1239	6.6	-8.0
THC	g/mi	0.108	0.111	3.1	0.153	34.7	-31.7
NOx	g/mi	6.039	5.976	-1.1	6.511	7.5	-8.6
CO	g/bhp-hr	0.382	0.567	39.2	0.274	-32.8	69.7
CO₂	g/bhp-hr	482.2	474.6	-1.6	517.9	7.1	-8.7
THC	g/bhp-hr	0.045	0.046	2.9	0.064	35.3	-32.4
NOx	g/bhp-hr	2.511	2.480	-1.3	2.722	8.0	-9.3

Table 0-15: Test Results from S2W-04.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.48	30.32	-0.5	30.70	0.7	-1.3
Work	bhp-hr	75.74	75.60	-0.2	75.89	0.2	-0.4
CO	%	0.002	0.014	158.1	0.006	112.3	82.3
CO₂	%	1.260	5.808	128.7	6.677	136.5	-13.9
THC	ppm	9.064	20.75	78.4	31.30	110.2	-40.5
NOx	ppm	66.07	317.9	131.2	351.1	136.6	-9.9
Exh Vol	SCF	1006	993.8	-1.2	971.4	-3.5	2.3
Exh T	°C	314.3	348.4	10.3	345.1	9.3	1.0
Exh P	kPa(g)	0.373	0.673	57.4	0.591	45.3	13.0
Amb T	°C		28.32	100.0	23.06	100.0	20.5
Amb P	kPa	98.08	111.7	13.0	98.19	0.1	12.9
Carbon Balance	grams	9972	9713	-2.6	10462	4.8	-7.4
Fuel Consumption	grams	11521	11221	-2.6	12087	4.8	-7.4
CO	grams	29.83	46.00	42.6	18.14	-48.7	86.9
CO₂	grams	36471	35495	-2.7	38280	4.8	-7.6
THC	grams	3.510	3.568	1.7	4.808	31.2	-29.6
NOx	grams	197.7	194.9	-1.4	205.0	3.6	-5.0
CO	g/mi	0.979	1.517	43.2	0.591	-49.4	87.9
CO₂	g/mi	1197	1171	-2.2	1247	4.1	-6.3
THC	g/mi	0.115	0.118	2.2	0.157	30.5	-28.4
NOx	g/mi	6.485	6.429	-0.9	6.677	2.9	-3.8
CO	g/bhp-hr	0.394	0.609	42.8	0.239	-48.9	87.2
CO₂	g/bhp-hr	481.5	469.5	-2.5	504.4	4.7	-7.2
THC	g/bhp-hr	0.046	0.047	1.8	0.063	31.0	-29.2
NOx	g/bhp-hr	2.610	2.579	-1.2	2.701	3.4	-4.7

Table 0-16: Test Results from W2S-03.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.48	30.33	-0.5	30.70	0.7	-1.2
Work	bhp-hr	78.09	77.91	-0.2	78.27	0.2	-0.5
CO	%	0.002	0.013	157.5	0.007	125.8	62.7
CO₂	%	1.292	5.861	127.7	6.718	135.5	-13.6
THC	ppm	9.016	18.99	71.2	29.91	107.4	-44.7
NOx	ppm	66.04	310.1	129.8	346.7	136.0	-11.1
Exh Vol	SCF	1041	1028	-1.3	1019	-2.2	0.9
Exh T	°C	305.9	343.2	11.5	339.5	10.4	1.1
Exh P	kPa(g)	0.413	0.696	51.1	0.514	21.9	30.0
Amb T	°C		29.23	100.0	24.28	100.0	18.5
Amb P	kPa	97.99	111.6	13.0	98.19	0.2	12.8
Carbon Balance	grams	10478	10290	-1.8	11246	7.1	-8.9
Fuel Consumption	grams	12105	11888	-1.8	12992	7.1	-8.9
CO	grams	30.75	45.52	38.8	21.66	-34.7	71.0
CO₂	grams	38322	37611	-1.9	41145	7.1	-9.0
THC	grams	3.310	3.453	4.2	4.917	39.1	-35.0
NOx	grams	203.5	200.3	-1.6	216.3	6.1	-7.7
CO	g/mi	1.009	1.501	39.2	0.705	-35.4	72.1
CO₂	g/mi	1257	1240	-1.4	1340	6.4	-7.8
THC	g/mi	0.109	0.114	4.7	0.160	38.4	-33.8
NOx	g/mi	6.676	6.604	-1.1	7.045	5.4	-6.5
CO	g/bhp-hr	0.394	0.584	39.0	0.277	-34.9	71.5
CO₂	g/bhp-hr	490.8	482.8	-1.6	525.7	6.9	-8.5
THC	g/bhp-hr	0.042	0.044	4.5	0.063	38.8	-34.5
NOx	g/bhp-hr	2.606	2.571	-1.3	2.763	5.9	-7.2

Table 0-17: Test Results from W2B-03.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.04	29.87	-0.5	30.20	0.6	-1.1
Work	bhp-hr	79.07	78.83	-0.3	79.31	0.3	-0.6
CO	%	0.002	0.013	152.3	0.005	104.8	79.0
CO₂	%	1.266	5.416	124.2	6.206	132.2	-13.6
THC	ppm	9.378	21.47	78.4	32.27	109.9	-40.2
NOx	ppm	67.32	307.0	128.1	336.0	133.2	-9.0
Exh Vol	SCF	1099	1087	-1.1	1052	-4.4	3.3
Exh T	°C	310.2	339.0	8.9	336.2	8.1	0.8
Exh P	kPa(g)	0.458	0.781	52.3	0.717	44.2	8.6
Amb T	°C		29.08	100.0	24.45	100.0	17.3
Amb P	kPa	97.97	111.6	13.0	98.06	0.1	12.9
Carbon Balance	grams	10604	10396	-2.0	11129	4.8	-6.8
Fuel Consumption	grams	12250	12010	-2.0	12857	4.8	-6.8
CO	grams	34.77	46.59	29.0	20.60	-51.2	77.4
CO₂	grams	38775	37994	-2.0	40717	4.9	-6.9
THC	grams	3.756	4.003	6.4	5.294	34.0	-27.8
NOx	grams	216.2	213.2	-1.4	220.9	2.2	-3.6
CO	g/mi	1.158	1.560	29.6	0.682	-51.7	78.3
CO₂	g/mi	1291	1272	-1.5	1348	4.3	-5.8
THC	g/mi	0.125	0.134	6.9	0.175	33.5	-26.7
NOx	g/mi	7.199	7.137	-0.9	7.316	1.6	-2.5
CO	g/bhp-hr	0.440	0.591	29.3	0.260	-51.5	77.9
CO₂	g/bhp-hr	490.4	482.0	-1.7	513.4	4.6	-6.3
THC	g/bhp-hr	0.047	0.051	6.7	0.067	33.7	-27.2
NOx	g/bhp-hr	2.735	2.705	-1.1	2.786	1.9	-3.0

Table 0-18: Test Results from W2S-04.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.48	29.55	-3.1	30.70	0.7	-3.8
Work	bhp-hr	77.26	76.36	-1.2	78.16	1.2	-2.3
CO	%	0.001	0.023	176.7	0.003	80.0	149.6
CO₂	%	1.278	6.091	130.6	6.693	135.9	-9.4
THC	ppm	7.631	18.87	84.8	28.94	116.5	-42.1
NOx	ppm	62.05	300.9	131.6	318.6	134.8	-5.7
Exh Vol	SCF	1027	989.0	-3.8	1029	0.2	-4.0
Exh T	°C	303.0	339.6	11.4	337.0	10.6	0.8
Exh P	kPa(g)	0.427	0.701	48.5	0.534	22.3	27.0
Amb T	°C		29.28	100.0	24.64	100.0	17.2
Amb P	kPa	98.04	111.6	13.0	98.19	0.2	12.8
Carbon Balance	grams	10346	10153	-1.9	11369	9.4	-11.3
Fuel Consumption	grams	11952	11730	-1.9	13134	9.4	-11.3
CO	grams	28.01	77.46	93.8	14.59	-63.0	136.6
CO₂	grams	37842	37059	-2.1	41607	9.5	-11.6
THC	grams	3.146	3.294	4.6	4.864	42.9	-38.5
NOx	grams	191.9	185.7	-3.3	203.1	5.7	-9.0
CO	g/mi	0.919	2.621	96.2	0.475	-63.7	138.6
CO₂	g/mi	1241	1254	1.0	1355	8.8	-7.8
THC	g/mi	0.103	0.111	7.7	0.158	42.2	-34.8
NOx	g/mi	6.296	6.284	-0.2	6.616	5.0	-5.1
CO	g/bhp-hr	0.363	1.014	94.7	0.187	-64.1	137.8
CO₂	g/bhp-hr	489.8	485.3	-0.9	532.3	8.3	-9.2
THC	g/bhp-hr	0.041	0.043	5.8	0.062	41.8	-36.3
NOx	g/bhp-hr	2.484	2.432	-2.1	2.599	4.5	-6.6

Table 0-19: Test Results from W2B-04.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	30.12	29.95	-0.5	30.30	0.6	-1.1
Work	bhp-hr	75.75	75.57	-0.2	75.93	0.2	-0.5
CO	%	0.001	0.014	162.5	0.004	96.1	108.9
CO₂	%	1.197	5.440	127.9	6.284	136.0	-14.4
THC	ppm	7.821	21.14	92.0	32.46	122.3	-42.2
NOx	ppm	63.26	307.9	131.8	341.2	137.4	-10.3
Exh Vol	SCF	1033	1024	-0.8	1020	-1.2	0.4
Exh T	°C	294.6	329.6	11.2	326.6	10.3	0.9
Exh P	kPa(g)	0.390	0.655	50.7	0.493	23.1	28.4
Amb T	°C		29.17	100.0	24.74	100.0	16.4
Amb P	kPa	98.03	111.6	13.0	98.19	0.2	12.8
Carbon Balance	grams	10052	9807	-2.5	10845	7.6	-10.1
Fuel Consumption	grams	11612	11329	-2.4	12529	7.6	-10.1
CO	grams	30.33	50.58	50.1	16.62	-58.4	101.1
CO₂	grams	36759	35831	-2.6	39682	7.7	-10.2
THC	grams	3.756	3.750	-0.2	5.236	32.9	-33.1
NOx	grams	202.9	202.8	-0.1	218.9	7.6	-7.6
CO	g/mi	1.007	1.688	50.5	0.549	-59.0	101.9
CO₂	g/mi	1221	1196	-2.0	1310	7.0	-9.1
THC	g/mi	0.125	0.125	0.4	0.173	32.3	-32.0
NOx	g/mi	6.738	6.770	0.5	7.225	7.0	-6.5
CO	g/bhp-hr	0.400	0.669	50.3	0.219	-58.6	101.4
CO₂	g/bhp-hr	485.3	474.2	-2.3	522.6	7.4	-9.7
THC	g/bhp-hr	0.050	0.050	0.1	0.069	32.7	-32.6
NOx	g/bhp-hr	2.679	2.684	0.2	2.883	7.4	-7.2

Table 0-20: Test Results from B2W-03.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	29.31	29.16	-0.5	29.500	0.6	-1.2
Work	bhp-hr	73.69	73.45	-0.3	73.931	0.3	-0.7
CO	%	0.002	0.009	132.4	-0.002	12086	306.4
CO₂	%	1.259	5.571	126.3	0.035	-189.3	197.5
THC	ppm	8.835	23.21	89.7	5.886	-40.1	119.1
NOx	ppm	63.69	310.9	132.0	0.690	-195.7	199.1
Exh Vol	SCF	1119	1014	-9.8	1013	-9.9	0.1
Exh T	°C	306.0	341.4	10.9	337.9	9.9	1.0
Exh P	kPa(g)	0.215	0.700	106.0	0.636	99	9.6
Amb T	°C		32.86	100.0	27.57	100.0	17.5
Amb P	kPa	98.11	111.7	13.0	98.19	0.1	12.9
Carbon Balance	grams	10137	9757	-3.8	49.16	-198.1	198.0
Fuel Consumption	grams	11711	11272	-3.8	56.79	-198.1	198.0
CO	grams	37.96	31.51	-18.6	-11.46	-373.0	428.7
CO₂	grams	37056	35678	-3.8	195.1	-197.9	197.8
THC	grams	4.811	4.152	-14.7	0.953	-133.8	125.3
NOx	grams	196.7	195.6	-0.6	0.561	-198.9	198.9
CO	g/mi	1.295	1.080	-18.1	-0.389	-371.5	424.6
CO₂	g/mi	1264	1223	-3.3	6.612	-197.9	197.9
THC	g/mi	0.164	0.142	-14.2	0.032	-134.2	126.0
NOx	g/mi	6.710	6.706	-0.1	0.019	-198.9	198.9
CO	g/bhp-hr	0.515	0.429	-18.2	-0.155	-372.2	426.4
CO₂	g/bhp-hr	502.8	485.7	-3.5	2.638	-197.9	197.8
THC	g/bhp-hr	0.065	0.057	-14.4	0.013	-134.0	125.7
NOx	g/bhp-hr	2.669	2.663	-0.2	0.008	-198.9	198.9

Table 0-21: Test Results from B2W-04.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	29.39	29.14	-0.9	29.50	0.4	-1.2
Work	bhp-hr	50.16	49.92	-0.5	50.40	0.5	-1.0
CO	%	0.002	0.019	163.8	0.017	159.1	13.5
CO₂	%	0.811	4.513	139.1	5.143	145.5	-13.0
THC	ppm	8.564	29.65	110.4	47.37	138.8	-46.0
NOx	ppm	41.03	241.7	141.9	260.3	145.5	-7.4
Exh Vol	SCF	786.1	790.7	0.6	730.5	-7.3	7.9
Exh T	°C	247.7	261.9	5.6	260.5	5.0	0.6
Exh P	kPa(g)	0.300	0.432	36.0	0.175	-52.5	84.5
Amb T	°C		36.01	100.0	31.47	100.0	13.5
Amb P	kPa	98.06	111.7	13.0	98.19	0.1	12.8
Carbon Balance	grams	6461	6384	-1.2	6463	0.0	-1.2
Fuel Consumption	grams	7464	7374	-1.2	7467	0.0	-1.2
CO	grams	37.62	50.87	29.9	33.84	-10.6	40.2
CO₂	grams	2359	23290	-1.3	23604	0.1	-1.3
THC	grams	4.326	3.993	-8.0	5.339	21.0	-28.8
NOx	grams	125.7	127.1	1.1	124.4	-1.0	2.2
CO	g/mi	1.280	1.746	30.8	1.147	-11.0	41.4
CO₂	g/mi	802.9	799.4	-0.4	800.1	-0.3	-0.1
THC	g/mi	0.147	0.137	-7.2	0.181	20.6	-27.6
NOx	g/mi	4.278	4.364	2.0	4.218	-1.4	3.4
CO	g/bhp-hr	0.750	1.019	30.4	0.671	-11.1	41.1
CO₂	g/bhp-hr	470.3	466.6	-0.8	468.4	-0.4	-0.4
THC	g/bhp-hr	0.086	0.080	-7.5	0.106	20.5	-27.9
NOx	g/bhp-hr	2.506	2.547	1.6	2.469	-1.5	3.1

Table 0-22: Test Results from MW-06.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	26.28	25.89	-1.5	26.50	0.8	-2.3
Work	bhp-hr	77.30	76.97	-0.4	77.64	0.4	-0.9
CO	%	0.001	0.013	162.3	0.013	163.0	-2.1
CO₂	%	0.743	4.666	145.0	5.518	152.5	-16.7
THC	ppm	7.182	28.96	120.5	43.61	143.4	-40.4
NOx	ppm	39.47	286.1	151.5	309.9	154.8	-8.0
Exh Vol	SCF	1103	1116	1.2	1098	-0.4	1.6
Exh T	°C	243.5	276.7	12.8	274.4	12.0	0.8
Exh P	kPa(g)	0.281	0.323	13.9	-0.226	-1847.9	1134.4
Amb T	°C		38.42	100.0	34.64	100.0	10.3
Amb P	kPa	97.55	111.0	12.9	97.86	0.3	12.6
Carbon Balance	grams	10232	9959	-2.7	10887	6.2	-8.9
Fuel Consumption	grams	11821	11505	-2.7	12578	6.2	-8.9
CO	grams	46.50	53.09	13.2	42.46	-9.1	22.2
CO₂	grams	37390	36378	-2.7	39789	6.2	-9.0
THC	grams	5.620	5.623	0.1	7.537	29.1	-29.1
NOx	grams	214.3	218.4	1.9	228.2	6.3	-4.4
CO	g/mi	1.769	2.051	14.7	1.602	-9.9	24.6
CO₂	g/mi	1423	1405	-1.2	1501	5.4	-6.6
THC	g/mi	0.214	0.217	1.6	0.284	28.3	-26.8
NOx	g/mi	8.154	8.436	3.4	8.612	5.5	-2.1
CO	g/bhp-hr	0.601	0.690	13.7	0.547	-9.5	23.1
CO₂	g/bhp-hr	483.7	472.6	-2.3	512.5	5.8	-8.1
THC	g/bhp-hr	0.073	0.073	0.5	0.097	28.7	-28.2
NOx	g/bhp-hr	2.772	2.837	2.3	2.940	5.9	-3.5

Table 0-23: Test Results from MW-07.

Parameter	Units	Laboratory	SEMTECH	SEMTECH vs Laboratory (%)	OBS	OBS vs Laboratory (%)	SEMTECH vs OBS (%)
Distance	miles	27.00	26.57	-1.6	27.10	0.4	-2.0
Work	bhp-hr	72.33	71.95	-0.5	72.72	0.5	-1.1
CO	%	0.001	0.025	180	0.006	123.9	126.7
CO₂	%	0.700	4.513	146.3	5.035	151.2	-10.9
THC	ppm	8.020	27.86	110.6	43.37	137.6	-43.6
NOx	ppm	36.03	249.7	149.6	267.9	152.6	-7.1
Exh Vol	SCF	1085	1108	2.1	1022	-6.0	8.1
Exh T	°C	235.9	264.1	11.3	262.5	10.7	0.6
Exh P	kPa(g)	0.340	0.324	-4.9	-0.089	-341.0	350.6
Amb T	°C		37.50	100.0	33.18	100.0	12.2
Amb P	kPa	97.51	111.0	12.9	97.68	0.2	12.8
Carbon Balance	grams	9561	9766	2.1	9642	0.8	1.3
Fuel Consumption	grams	11046	11282	2.1	11139	0.8	1.3
CO	grams	44.79	99.51	75.8	16.51	-92.3	143.1
CO₂	grams	34934	35601	1.9	35270	1.0	0.9
THC	grams	5.830	5.474	-6.3	7.137	20.2	-26.4
NOx	grams	195.2	195.2	-0.0	191.7	-1.8	1.8
CO	g/mi	1.659	3.745	77.2	0.609	-92.6	144.0
CO₂	g/mi	1294	1340	3.5	1301	0.6	2.9
THC	g/mi	0.216	0.206	-4.7	0.263	19.8	-24.5
NOx	g/mi	7.230	7.345	1.6	7.073	-2.2	3.8
CO	g/bhp-hr	0.619	1.383	76.3	0.227	-92.7	143.6
CO₂	g/bhp-hr	483.0	494.8	2.4	485.0	0.4	2.0
THC	g/bhp-hr	0.081	0.076	-5.8	0.098	19.6	-25.3
NOx	g/bhp-hr	2.699	2.713	0.5	2.636	-2.4	2.9

Appendix C – Individual On-Road Test Results

Table 0-1: Test Results from MW-08.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.50	22.50	16.3
Work	bhp-hr	54.89	38.31	35.6
CO	%	0.035	0.020	53.8
CO₂	%	4.713	4.759	-1.0
THC	ppm	37.82	41.04	-8.2
NOx	ppm	258.0	221.1	15.4
Exh Vol	SCF	884.8	858.9	3.0
Exh T	°C	210.8	209.5	0.6
Exh P	kPa(g)	0.049	-0.163	-373.9
Amb T	°C	24.24	24.76	-2.1
Amb P	kPa	97.95	97.80	0.1
Carbon Balance	grams	6957	7310	-4.9
Fuel Consumption	grams	8037	8444	-4.9
CO	grams	95.02	65.25	37.2
CO₂	grams	25316	26653	-5.1
THC	grams	5.857	6.193	-5.6
NOx	grams	131.1	117.6	10.9
CO	g/mi	3.585	2.900	21.1
CO₂	g/mi	955.2	1185	-21.4
THC	g/mi	0.221	0.275	-21.9
NOx	g/mi	4.946	5.226	-5.5
CO	g/bhp-hr	1.731	1.703	1.7
CO₂	g/bhp-hr	461.2	695.6	-40.5
THC	g/bhp-hr	0.107	0.162	-40.9
NOx	g/bhp-hr	2.388	3.069	-24.9

Table 0-2: Test Results from MW-09.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.49	27.00	-1.9
Work	bhp-hr	55.58	56.12	-1.0
CO	%	0.025	0.026	-0.4
CO₂	%	4.469	4.807	-7.3
THC	ppm	38.39	40.89	-6.3
NOx	ppm	243.4	214.3	12.7
Exh Vol	SCF	904.4	815.2	10.4
Exh T	°C	197.0	196.8	0.1
Exh P	kPa(g)	0.055	-0.287	-293.7
Amb T	°C	29.83	29.98	-0.5
Amb P	kPa	97.67	97.56	0.1
Carbon Balance	grams	6897	7349	-6.3
Fuel Consumption	grams	7968	8490	-6.3
CO	grams	66.47	65.36	1.7
CO₂	grams	25141	26798	-6.4
THC	grams	5.789	5.615	3.1
NOx	grams	134.2	118.4	12.5
CO	g/mi	2.509	2.421	3.6
CO₂	g/mi	949.1	992.5	-4.5
THC	g/mi	0.219	0.208	5.0
NOx	g/mi	5.066	4.386	14.4
CO	g/bhp-hr	1.196	1.165	2.6
CO₂	g/bhp-hr	452.3	477.6	-5.4
THC	g/bhp-hr	0.104	0.100	4.0
NOx	g/bhp-hr	2.415	2.110	13.5

Table 0-3: Test Results from MW-10.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.54	27.00	-1.7
Work	bhp-hr	52.35	52.77	-0.8
CO	%	0.018	0.016	14.3
CO₂	%	4.684	4.875	-4.0
THC	ppm	33.03	38.14	-14.4
NOx	ppm	254.0	225.5	11.7
Exh Vol	SCF	831.0	785.1	5.7
Exh T	°C	213.3	212.7	0.3
Exh P	kPa(g)	0.060	-0.205	-365.3
Amb T	°C	28.56	29.05	-1.7
Amb P	kPa	97.54	97.40	0.1
Carbon Balance	grams	6441	6874	-6.5
Fuel Consumption	grams	7441	7942	-6.5
CO	grams	47.34	39.17	18.9
CO₂	grams	23505	25103	-6.6
THC	grams	4.598	5.078	-9.9
NOx	grams	122.0	111.6	9.0
CO	g/mi	1.783	1.451	20.6
CO₂	g/mi	885.6	929.7	-4.9
THC	g/mi	0.173	0.188	-8.2
NOx	g/mi	4.598	4.132	10.7
CO	g/bhp-hr	0.904	0.742	19.7
CO₂	g/bhp-hr	449.0	475.7	-5.8
THC	g/bhp-hr	0.088	0.096	-9.1
NOx	g/bhp-hr	2.331	2.114	9.8

Table 0-4: Test Results from MW-11.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.55	27.10	-2.0
Work	bhp-hr	51.07	51.44	-0.7
CO	%	0.020	0.009	76.7
CO₂	%	4.675	4.984	-6.4
THC	ppm	33.91	38.82	-13.5
NOx	ppm	243.7	222.6	9.1
Exh Vol	SCF	813.4	756.4	7.3
Exh T	°C	210.2	209.3	0.4
Exh P	kPa(g)	0.052	-0.167	-379.0
Amb T	°C	27.01	27.70	-2.5
Amb P	kPa	97.46	97.31	0.2
Carbon Balance	grams	6253	6763	-7.8
Fuel Consumption	grams	7224	7813	-7.8
CO	grams	49.60	26.16	61.9
CO₂	grams	22812	24716	-8.0
THC	grams	4.663	5.020	-7.4
NOx	grams	116.4	107.9	7.6
CO	g/mi	1.868	0.965	63.7
CO₂	g/mi	859.2	912.0	-6.0
THC	g/mi	0.176	0.185	-5.3
NOx	g/mi	4.385	3.982	9.6
CO	g/bhp-hr	0.971	0.509	62.5
CO₂	g/bhp-hr	446.7	480.5	-7.3
THC	g/bhp-hr	0.091	0.098	-6.7
NOx	g/bhp-hr	2.280	2.098	8.3

Table 0-5: Test Results from MW-12.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.55	27.00	-1.7
Work	bhp-hr	49.43	49.93	-1.0
CO	%	0.020	0.012	44.5
CO₂	%	4.592	4.793	-4.3
THC	ppm	30.57	36.31	-17.2
NOx	ppm	249.4	225.4	10.1
Exh Vol	SCF	794.1	732.0	8.1
Exh T	°C	217.9	216.4	0.7
Exh P	kPa(g)	0.060	-0.089	-1014.9
Amb T	°C	24.69	25.63	-3.8
Amb P	kPa	97.49	97.31	0.2
Carbon Balance	grams	6154	6525	-5.9
Fuel Consumption	grams	7110	7539	-5.9
CO	grams	48.97	41.98	15.4
CO₂	grams	22453	23822	-5.9
THC	grams	4.219	4.669	-10.1
NOx	grams	114.7	104.4	9.3
CO	g/mi	1.845	1.555	17.1
CO₂	g/mi	845.8	882.3	-4.2
THC	g/mi	0.159	0.173	-8.4
NOx	g/mi	4.320	3.868	11.0
CO	g/bhp-hr	0.991	0.841	16.4
CO₂	g/bhp-hr	454.3	477.1	-4.9
THC	g/bhp-hr	0.085	0.094	-9.1
NOx	g/bhp-hr	2.320	2.092	10.4

Table 0-6: Test Results from W2S-05.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	30.72	31.10	-1.2
Work	bhp-hr	62.62	63.06	-0.7
CO	%	0.025	0.017	35.0
CO₂	%	6.049	6.150	-1.7
THC	ppm	36.38	41.12	-12.2
NOx	ppm	261.0	220.9	16.6
Exh Vol	SCF	841.6	818.1	2.8
Exh T	°C	257.0	255.2	0.7
Exh P	kPa(g)	0.102	0.168	-49.3
Amb T	°C	19.15	19.84	-3.6
Amb P	kPa	97.55	97.26	0.3
Carbon Balance	grams	7740	8360	-7.7
Fuel Consumption	grams	8942	9657	-7.7
CO	grams	62.78	47.57	27.6
CO₂	grams	28239	30529	-7.8
THC	grams	4.863	5.387	-10.2
NOx	grams	120.7	108.7	10.5
CO	g/mi	2.044	1.530	28.8
CO₂	g/mi	919.3	981.7	-6.6
THC	g/mi	0.158	0.173	-9.0
NOx	g/mi	3.928	3.495	11.7
CO	g/bhp-hr	1.003	0.754	28.3
CO₂	g/bhp-hr	451.0	484.1	-7.1
THC	g/bhp-hr	0.078	0.085	-9.5
NOx	g/bhp-hr	1.927	1.724	11.1

Table 0-7: Test Results from S2W-05.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	30.53	30.90	-1.2
Work	bhp-hr	55.39	55.72	-0.6
CO	%	0.014	0.016	-16.8
CO₂	%	5.447	5.637	-3.4
THC	ppm	33.83	39.97	-16.6
NOx	ppm	248.8	214.2	15.0
Exh Vol	SCF	796.4	798.8	-0.3
Exh T	°C	251.4	249.8	0.7
Exh P	kPa(g)	0.089	0.199	-76.2
Amb T	°C	20.61	21.06	-2.1
Amb P	kPa	97.55	97.25	0.3
Carbon Balance	grams	6625	7449	-11.7
Fuel Consumption	grams	7654	8605	-11.7
CO	grams	32.633	42.76	-26.9
CO₂	grams	24202	27202	-11.7
THC	grams	4.388	5.212	-17.2
NOx	grams	107.3	100.0	7.0
CO	g/mi	1.069	1.384	-25.7
CO₂	g/mi	792.9	880.3	-10.5
THC	g/mi	0.144	0.169	-16.0
NOx	g/mi	3.514	3.237	8.2
CO	g/bhp-hr	0.589	0.767	-26.3
CO₂	g/bhp-hr	437.0	488.2	-11.1
THC	g/bhp-hr	0.079	0.094	-16.6
NOx	g/bhp-hr	1.937	1.795	7.6

Table 0-8: Test Results from W2S-06.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	30.70	31.00	-1.0
Work	bhp-hr	65.44	65.87	-0.7
CO	%	0.014	0.014	0.6
CO₂	%	6.032	6.447	-6.7
THC	ppm	33.76	39.54	-15.8
NOx	ppm	266.0	234.1	12.8
Exh Vol	SCF	855.5	810.0	5.5
Exh T	°C	263.3	261.9	0.6
Exh P	kPa(g)	0.104	0.141	-30.0
Amb T	°C	22.26	22.85	-2.6
Amb P	kPa	97.55	97.29	0.3
Carbon Balance	grams	7903	8782	-10.5
Fuel Consumption	grams	9130	10146	-10.5
CO	grams	36.46	36.44	0.0
CO₂	grams	28876	32096	-10.6
THC	grams	4.646	5.192	-11.1
NOx	grams	127.0	116.9	8.3
CO	g/mi	1.187	1.175	1.0
CO₂	g/mi	940.5	1035	-9.6
THC	g/mi	0.151	0.167	-10.1
NOx	g/mi	4.137	3.770	9.3
CO	g/bhp-hr	0.557	0.553	0.7
CO₂	g/bhp-hr	441.2	487.2	-9.9
THC	g/bhp-hr	0.071	0.079	-10.5
NOx	g/bhp-hr	1.941	1.774	9.0

Table 0-9: Test Results from S2W-06.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	30.70	30.90	-0.7
Work	bhp-hr	56.74	57.11	-0.7
CO	%	0.015	0.023	-42.8
CO₂	%	5.508	5.896	-6.8
THC	ppm	34.26	40.89	-17.7
NOx	ppm	253.6	222.6	13.0
Exh Vol	SCF	796.2	766.3	3.8
Exh T	°C	249.9	249.2	0.3
Exh P	kPa(g)	0.098	0.128	-26.5
Amb T	°C	22.61	23.09	-2.1
Amb P	kPa	97.57	97.30	0.3
Carbon Balance	grams	6792	7604	-11.3
Fuel Consumption	grams	7846	8784	-11.3
CO	grams	33.74	55.82	-49.3
CO₂	grams	24811	27748	-11.2
THC	grams	4.444	5.104	-13.8
NOx	grams	112.3	103.3	8.3
CO	g/mi	1.099	1.806	-48.7
CO₂	g/mi	808.2	898.0	-10.5
THC	g/mi	0.145	0.165	-13.2
NOx	g/mi	3.658	3.344	9.0
CO	g/bhp-hr	0.595	0.977	-48.7
CO₂	g/bhp-hr	437.3	485.8	-10.5
THC	g/bhp-hr	0.078	0.089	-13.2
NOx	g/bhp-hr	1.979	1.809	9.0

Table 0-10: Test Results from W2B-05.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	30.13	30.30	-0.6
Work	bhp-hr	61.19	61.57	-0.6
CO	%	0.019	0.013	38.0
CO₂	%	5.606	5.941	-5.8
THC	ppm	31.63	37.10	-15.9
NOx	ppm	249.5	219.0	13.0
Exh Vol	SCF	843.0	795.1	5.9
Exh T	°C	263.1	262.8	0.1
Exh P	kPa(g)	0.132	0.141	-6.3
Amb T	°C	22.34	23.03	-3.0
Amb P	kPa	96.77	96.55	0.2
Carbon Balance	grams	7536	8235	-8.9
Fuel Consumption	grams	8706	9514	-8.9
CO	grams	48.50	35.66	30.5
CO₂	grams	27515	30095	-9.0
THC	grams	4.231	4.762	-11.8
NOx	grams	122.5	111.8	9.1
CO	g/mi	1.610	1.177	31.1
CO₂	g/mi	913.0	993.2	-8.4
THC	g/mi	0.140	0.157	-11.3
NOx	g/mi	4.066	3.691	9.7
CO	g/bhp-hr	0.793	0.579	31.1
CO₂	g/bhp-hr	449.7	488.8	-8.3
THC	g/bhp-hr	0.069	0.077	-11.2
NOx	g/bhp-hr	2.002	1.817	9.7

Table 0-11: Test Results from B2W-05.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	29.42	29.70	-0.9
Work	bhp-hr	57.70	58.05	-0.6
CO	%	0.017	0.019	-6.2
CO ₂	%	5.560	5.819	-4.6
THC	ppm	32.56	39.70	-19.8
NOx	Ppm	265.9	237.2	11.4
Exh Vol	SCF	805.0	800.2	0.6
Exh T	°C	254.2	252.8	0.6
Exh P	kPa(g)	0.112	0.119	-6.4
Amb T	°C	23.83	24.25	-1.8
Amb P	kPa	96.81	96.56	0.3
Carbon Balance	grams	7003	7947	-12.6
Fuel Consumption	grams	8090	9181	-12.6
CO	grams	38.63	50.63	-26.9
CO ₂	grams	25577	29014	-12.6
THC	grams	4.191	5.088	-19.3
NOx	grams	120.7	117.1	3.0
CO	g/mi	1.313	1.705	-26.0
CO ₂	g/mi	869.3	976.9	-11.7
THC	g/mi	0.142	0.171	-18.4
NOx	g/mi	4.103	3.944	4.0
CO	g/bhp-hr	0.669	0.872	-26.3
CO ₂	g/bhp-hr	443.2	499.8	-12.0
THC	g/bhp-hr	0.073	0.088	-18.7
NOx	g/bhp-hr	2.092	2.018	3.6

Table 0-12: Test Results from W2B-06.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	Miles	29.96	20.20	38.9
Work	bhp-hr	59.43	36.89	46.8
CO	%	0.017	0.010	54.7
CO ₂	%	5.467	5.724	-4.6
THC	Ppm	36.57	39.40	-7.4
NOx	Ppm	260.1	206.6	22.9
Exh Vol	SCF	819.4	-39.80	220.4
Exh T	°C	252.9	246.8	2.4
Exh P	kPa(g)	0.119	0.860	-151.2
Amb T	°C	25.00	25.76	-3.0
Amb P	kPa	96.87	96.66	0.2
Carbon Balance	grams	7166	198.2	189.2
Fuel Consumption	grams	8279	229.0	189.2
CO	grams	41.26	-1.884	219.1
CO ₂	grams	26169	730.3	189.1
THC	grams	4.739	-0.390	235.9
NOx	grams	124.8	0.283	199.1
CO	g/mi	1.377	-0.093	229.1
CO ₂	g/mi	873.6	36.16	184.1
THC	g/mi	0.158	-0.019	255.6
NOx	g/mi	4.168	0.014	198.7
CO	g/bhp-hr	0.694	-0.051	231.8
CO ₂	g/bhp-hr	440.3	19.80	182.8
THC	g/bhp-hr	0.080	-0.011	261.1
NOx	g/bhp-hr	2.101	0.008	198.5

Table 0-13: Test Results from B2W-06.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	Miles	30.29	29.70	2.0
Work	bhp-hr	58.60	57.98	1.1
CO	%	0.019	0.019	3.0
CO₂	%	5.510	5.877	-6.4
THC	Ppm	31.24	38.05	-19.7
NOx	Ppm	270.5	250.6	7.6
Exh Vol	SCF	812.7	827.0	-1.8
Exh T	°C	253.6	246.0	3.0
Exh P	kPa(g)	0.098	0.080	20.9
Amb T	°C	25.34	25.71	-1.4
Amb P	kPa	96.78	96.55	0.2
Carbon Balance	grams	7077	8371	-16.8
Fuel Consumption	grams	8176	9671	-16.8
CO	grams	42.72	54.56	-24.3
CO₂	grams	25843	30561	-16.7
THC	grams	4.186	5.171	-21.1
NOx	grams	126.1	130.0	-3.0
CO	g/mi	1.410	1.837	-26.3
CO₂	g/mi	853.1	1029	-18.7
THC	g/mi	0.138	0.174	-23.0
NOx	g/mi	4.163	4.376	-5.0
CO	g/bhp-hr	0.729	0.941	-25.4
CO₂	g/bhp-hr	441.0	527.1	-17.8
THC	g/bhp-hr	0.071	0.089	-22.1
NOx	g/bhp-hr	2.152	2.242	-4.1

Table 0-14: Test Results from W2S-07.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles		31.10	
Work	bhp-hr		62.82	
CO	%	0.016	0.018	-12.4
CO ₂	%	5.504	5.966	-8.1
THC	ppm	36.09	40.48	-11.5
NOx	ppm	236.1	215.2	9.3
Exh Vol	SCF	859.1	865.7	-0.8
Exh T	°C	251.1	255.9	-1.9
Exh P	kPa(g)	0.084	0.296	-111.9
Amb T	°C	19.17	19.62	-2.3
Amb P	kPa	97.84	97.48	0.4
Carbon Balance	grams	7706	8713	-12.3
Fuel Consumption	grams	8902	10066	-12.3
CO	grams	41.64	51.70	-21.6
CO ₂	grams	28145	31817	-12.3
THC	grams	5.072	5.684	-11.4
NOx	grams	118.2	114.1	3.6
CO	g/mi		1.662	
CO ₂	g/mi		1023	
THC	g/mi		0.183	
NOx	g/mi		3.667	
CO	g/bhp-hr		0.823	
CO ₂	g/bhp-hr		506.5	
THC	g/bhp-hr		0.090	
NOx	g/bhp-hr		1.816	

Table 0-15: Test Results from S2W-07.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	30.84	10.50	98.4
Work	bhp-hr		76.65	
CO	%	0.012	-0.014	-2967.7
CO ₂	%	5.521	0.366	175.2
THC	ppm	33.48	10.71	103.1
NOx	ppm	242.0	25.18	162.3
Exh Vol	SCF	825.6	580.6	34.8
Exh T	°C	254.4	124.5	68.6
Exh P	kPa(g)	0.071	0.057	22.9
Amb T	°C	21.34	26.16	-20.3
Amb P	kPa	97.90	97.70	0.2
Carbon Balance	grams	7041	368.5	180.1
Fuel Consumption	grams	8134	425.7	180.1
CO	grams	29.28	-12.25	487.5
CO ₂	grams	25731	1364	179.9
THC	grams	4.523	1.410	104.9
NOx	grams	110.5	10.49	165.3
CO	g/mi	0.949	-1.166	-1951.9
CO ₂	g/mi	834.3	129.9	146.1
THC	g/mi	0.147	0.134	8.8
NOx	g/mi	3.581	0.999	112.8
CO	g/bhp-hr		-0.160	
CO ₂	g/bhp-hr		17.80	
THC	g/bhp-hr		0.018	
NOx	g/bhp-hr		0.137	

Table 0-16: Test Results from W2S-08.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles		31.00	
Work	bhp-hr		64.84	
CO	%	0.016	0.027	-54.5
CO ₂	%	5.664	6.205	-9.1
THC	ppm	31.81	37.36	-16.0
NOx	ppm	260.5	227.9	13.3
Exh Vol	SCF	856.0	823.2	3.9
Exh T	°C	262.0	257.8	1.6
Exh P	kPa(g)	0.134	0.148	-9.6
Amb T	°C	22.72	23.54	-3.6
Amb P	kPa	97.86	97.58	0.3
Carbon Balance	grams	7551	8709	-14.3
Fuel Consumption	grams	8723	10061	-14.3
CO	grams	39.85	79.02	-65.9
CO ₂	grams	27582	31762	-14.1
THC	grams	4.406	5.056	-13.7
NOx	grams	125.0	115.2	8.2
CO	g/mi		2.549	
CO ₂	g/mi		1025	
THC	g/mi		0.163	
NOx	g/mi		3.716	
CO	g/bhp-hr		1.219	
CO ₂	g/bhp-hr		489.8	
THC	g/bhp-hr		0.078	
NOx	g/bhp-hr		1.777	

Table 0-17: Test Results from S2W-08.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles		30.90	
Work	bhp-hr		60.75	
CO	%		0.015	
CO ₂	%		6.080	
THC	ppm		41.63	
NOx	ppm		225.6	
Exh Vol	SCF		823.4	
Exh T	°C		245.9	
Exh P	kPa(g)		0.071	
Amb T	°C		25.91	
Amb P	kPa		97.57	
Carbon Balance	grams		8426	
Fuel Consumption	grams		9734	
CO	grams		35.04	
CO ₂	grams		30793	
THC	grams		5.534	
NOx	grams		113.1	
CO	g/mi		1.134	
CO ₂	g/mi		996.5	
THC	g/mi		0.179	
NOx	g/mi		3.660	
CO	g/bhp-hr		0.577	
CO ₂	g/bhp-hr		506.9	
THC	g/bhp-hr		0.091	
NOx	g/bhp-hr		1.861	

Table 0-18: Test Results from W2B-07.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	30.67	30.30	1.2
Work	bhp-hr	61.48	61.89	-0.7
CO	%	0.032	0.009	110.6
CO ₂	%	5.640	5.953	-5.4
THC	ppm	29.76	37.83	-23.9
NOx	ppm	275.8	240.9	13.5
Exh Vol	SCF	839.9	799.1	5.0
Exh T	°C	257.0	255.6	0.6
Exh P	kPa(g)	0.110	-0.051	546.9
Amb T	°C	27.31	28.13	-3.0
Amb P	kPa	96.92	96.74	0.2
Carbon Balance	grams	7575	8329	-9.5
Fuel Consumption	grams	8751	9622	-9.5
CO	grams	84.23	20.76	120.9
CO ₂	grams	27603	30461	-9.8
THC	grams	4.008	4.964	-21.3
NOx	grams	135.8	125.5	7.8
CO	g/mi	2.746	0.685	120.1
CO ₂	g/mi	899.9	1005	-11.1
THC	g/mi	0.131	0.164	-22.5
NOx	g/mi	4.426	4.143	6.6
CO	g/bhp-hr	1.370	0.335	121.3
CO ₂	g/bhp-hr	449.0	492.2	-9.0
THC	g/bhp-hr	0.065	0.080	-20.7
NOx	g/bhp-hr	2.208	2.029	8.5

Table 0-19: Test Results from B2W-07.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles		7.900	
Work	bhp-hr		21.80	
CO	%		0.009	
CO ₂	%		6.396	
THC	ppm		37.76	
NOx	ppm		268.1	
Exh Vol	SCF		276.5	
Exh T	°C		260.6	
Exh P	kPa(g)		-0.038	
Amb T	°C		29.45	
Amb P	kPa		95.22	
Carbon Balance	grams		3065	
Fuel Consumption	grams		3540	
CO	grams		8.731	
CO ₂	grams		11208	
THC	grams		1.707	
NOx	grams		47.27	
CO	g/mi		1.105	
CO ₂	g/mi		1419	
THC	g/mi		0.216	
NOx	g/mi		5.984	
CO	g/bhp-hr		0.401	
CO ₂	g/bhp-hr		514.2	
THC	g/bhp-hr		0.078	
NOx	g/bhp-hr		2.169	

Table 0-20: Test Results from W2B-08.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	32.07	30.30	5.7
Work	bhp-hr	62.64	62.98	-0.5
CO	%	0.015	0.009	54.9
CO ₂	%	5.76	6.053	-4.9
THC	ppm	34.95	39.67	-12.6
NOx	ppm	293.6	254.53	14.2
Exh Vol	SCF	840.1	925.9	-9.7
Exh T	°C	267.1	265.9	0.5
Exh P	kPa(g)	0.121	-0.008	226.8
Amb T	°C	30.07	30.74	-2.2
Amb P	kPa	96.74	96.58	0.2
Carbon Balance	grams	7696	9516	-21.2
Fuel Consumption	grams	8891	10994	-21.2
CO	grams	37.23	22.04	51.2
CO ₂	grams	28117	34805	-21.3
THC	grams	4.559	5.828	-24.4
NOx	grams	144.0	149.3	-3.6
CO	g/mi	1.161	0.728	45.9
CO ₂	g/mi	876.8	1149	-26.9
THC	g/mi	0.142	0.192	-30.0
NOx	g/mi	4.489	4.927	-9.3
CO	g/bhp-hr	0.594	0.350	51.7
CO ₂	g/bhp-hr	448.9	552.7	-20.7
THC	g/bhp-hr	0.073	0.093	-23.9
NOx	g/bhp-hr	2.298	2.371	-3.1

Table 0-21: Test Results from B2W-08.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	31.43	29.70	5.7
Work	bhp-hr	56.37	56.81	-0.8
CO	%	0.016	0.008	64.4
CO ₂	%	5.490	5.740	-4.5
THC	ppm	33.84	37.44	-10.1
NOx	ppm	273.0	254.4	7.1
Exh Vol	SCF	126.9	860.3	-148.6
Exh T	°C	252.0	258.1	-2.4
Exh P	kPa(g)	0.139	0.002	195.2
Amb T	°C	30.26	30.67	-1.3
Amb P	kPa	96.68	96.48	0.2
Carbon Balance	grams	1306	8320	-145.7
Fuel Consumption	grams	1509	9612	-145.7
CO	grams	5.597	21.00	-115.8
CO ₂	grams	4773	30426	-145.8
THC	grams	0.710	5.240	-152.3
NOx	grams	23.17	134.8	-141.3
CO	g/mi	0.178	0.707	-119.5
CO ₂	g/mi	151.9	1024	-148.4
THC	g/mi	0.023	0.176	-154.6
NOx	g/mi	0.737	4.539	-144.1
CO	g/bhp-hr	0.099	0.370	-115.3
CO ₂	g/bhp-hr	84.67	535.6	-145.4
THC	g/bhp-hr	0.013	0.092	-151.9
NOx	g/bhp-hr	0.411	2.373	-141.0

Table 0-22: Test Results from W2S-09.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles		31.00	
Work	bhp-hr		60.50	
CO	%	0.017	0.012	38.8
CO ₂	%	5.620	5.918	-5.2
THC	ppm	30.27	37.59	-21.6
NOx	ppm	265.0	239.8	10.0
Exh Flow	SCF	826.1	807.9	2.2
Exh T	°C	256.3	255.3	0.4
Exh P	kPa(g)	0.092	-0.132	-1123.3
Amb T	°C	31.57	32.05	-1.5
Amb P	kPa	97.40	97.27	0.1
Carbon Balance	grams	7310	8117	-10.5
Fuel Consumption	grams	8445	9378	-10.5
CO	grams	44.44	30.76	36.4
CO ₂	grams	26694	29670	-10.6
THC	grams	4.010	5.004	-22.1
NOx	grams	125.5	121.3	3.5
CO	g/mi		0.992	
CO ₂	g/mi		957.1	
THC	g/mi		0.161	
NOx	g/mi		3.911	
CO	g/bhp-hr		0.509	
CO ₂	g/bhp-hr		490.5	
THC	g/bhp-hr		0.083	
NOx	g/bhp-hr		2.004	

Table 0-23: Test Results from S2W-09.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	30.52	30.90	-1.3
Work	bhp-hr	58.26	58.68	-0.7
CO	%	0.021	0.015	36.2
CO ₂	%	5.634	6.080	-7.6
THC	ppm	39.16	41.63	-6.1
NOx	ppm	276.3	225.6	20.2
Exh Vol	SCF	801.8	823.4	-2.7
Exh T	°C	260.6	245.9	5.8
Exh P	kPa(g)	0.097	0.071	31.3
Amb T	°C	31.64	25.91	19.9
Amb P	kPa	97.34	97.56	-0.2
Carbon Balance	grams	6917	8426	-19.7
Fuel Consumption	grams	7991	9734	-19.7
CO	grams	50.05	35.04	35.3
CO ₂	grams	25241	30793	-19.8
THC	grams	5.061	5.534	-8.9
NOx	grams	122.7	113.1	8.2
CO	g/mi	1.640	1.134	36.5
CO ₂	g/mi	827.2	996.5	-18.6
THC	g/mi	0.166	0.179	-7.7
NOx	g/mi	4.022	3.660	9.4
CO	g/bhp-hr	0.859	0.597	36.0
CO ₂	g/bhp-hr	433.2	524.8	-19.1
THC	g/bhp-hr	0.087	0.094	-8.2
NOx	g/bhp-hr	2.106	1.927	8.9

Table 0-24: Test Results from MW-13.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.55	27.00	-1.7
Work	bhp-hr	57.27	57.85	-1.0
CO	%	0.018	0.017	1.3
CO₂	%	4.676	5.092	-8.5
THC	ppm	33.40	36.26	-8.2
NOx	ppm	244.1	217.2	11.7
Exh Vol	SCF	870.3	838.1	3.8
Exh T	°C	228.0	226.9	0.5
Exh P	kPa(g)	0.063	-0.182	-414.3
Amb T	°C	30.39	30.96	-1.9
Amb P	kPa	97.53	97.39	0.2
Carbon Balance	grams	7008	7824	-11.0
Fuel Consumption	grams	8096	9039	-11.0
CO	grams	47.87	50.69	-5.7
CO₂	grams	25580	28564	-11.0
THC	grams	4.804	5.092	-5.8
NOx	grams	128.9	120.0	7.2
CO	g/mi	1.803	1.877	-4.0
CO₂	g/mi	963.4	1058	-9.4
THC	g/mi	0.181	0.189	-4.2
NOx	g/mi	4.854	4.443	8.8
CO	g/bhp-hr	0.836	0.876	-4.7
CO₂	g/bhp-hr	446.7	493.7	-10.0
THC	g/bhp-hr	0.084	0.088	-4.8
NOx	g/bhp-hr	2.251	2.074	8.2

Table 0-25: Test Results from MW-14.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.57	27.00	-1.6
Work	bhp-hr	50.51	50.91	-0.8
CO	%	0.023	0.006	118.8
CO₂	%	4.713	4.993	-5.8
THC	ppm	32.75	37.28	-13.0
NOx	ppm	257.2	226.9	12.5
Exh Vol	SCF	801.8	782.6	2.4
Exh T	°C	218.1	216.9	0.6
Exh P	kPa(g)	0.057	-0.124	-536.3
Amb T	°C	27.90	28.70	-2.9
Amb P	kPa	97.48	97.30	0.2
Carbon Balance	grams	6291	7050	-11.4
Fuel Consumption	grams	7268	8145	-11.4
CO	grams	55.28	17.42	104.1
CO₂	grams	22944	25781	-11.6
THC	grams	4.410	4.935	-11.2
NOx	grams	120.7	113.0	6.5
CO	g/mi	2.080	0.645	105.3
CO₂	g/mi	863.5	954.9	-10.0
THC	g/mi	0.166	0.183	-9.6
NOx	g/mi	4.542	4.186	8.2
CO	g/bhp-hr	1.094	0.342	104.7
CO₂	g/bhp-hr	454.3	506.4	-10.9
THC	g/bhp-hr	0.087	0.097	-10.4
NOx	g/bhp-hr	2.389	2.220	7.3

Table 0-26: Test Results from MW-15.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.53	27.00	-1.8
Work	bhp-hr	49.55	50.01	-0.9
CO	%	0.020	0.006	111.0
CO ₂	%	4.630	4.888	-5.4
THC	ppm	34.51	39.14	-12.6
NOx	ppm	252.9	219.8	14.0
Exh Vol	SCF	805.1	761.9	5.5
Exh T	°C	211.1	209.9	0.6
Exh P	kPa(g)	0.054	-0.072	-1405.4
Amb T	°C	25.21	26.06	-3.3
Amb P	kPa	97.45	97.23	0.2
Carbon Balance	grams	6127	6666	-8.4
Fuel Consumption	grams	7078	7700	-8.4
CO	grams	49.99	20.62	83.2
CO ₂	grams	22348	24367	-8.7
THC	grams	4.699	5.088	-8.0
NOx	grams	117.0	104.4	11.4
CO	g/mi	1.885	0.764	84.7
CO ₂	g/mi	842.5	902.5	-6.9
THC	g/mi	0.177	0.188	-6.2
NOx	g/mi	4.413	3.868	13.2
CO	g/bhp-hr	1.009	0.412	84.0
CO ₂	g/bhp-hr	451.1	487.3	-7.7
THC	g/bhp-hr	0.095	0.102	-7.0
NOx	g/bhp-hr	2.362	2.088	12.3

Table 0-27: Test Results from MW-16.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.58	27.10	-1.9
Work	bhp-hr	50.67	51.17	-1.0
CO	%	0.021	0.014	39.9
CO₂	%	4.705	4.850	-3.0
THC	ppm	32.60	36.20	-10.5
NOx	ppm	256.1	223.4	13.7
Exh Vol	SCF	804.2	774.3	3.8
Exh T	°C	218.2	216.6	0.7
Exh P	kPa(g)	0.068	0.046	37.5
Amb T	°C	23.16	24.04	-3.7
Amb P	kPa	97.46	97.21	0.3
Carbon Balance	grams	6308	6747	-6.7
Fuel Consumption	grams	7287	7795	-6.7
CO	grams	54.56	37.513	37.0
CO₂	grams	23007	24640	-6.9
THC	grams	4.496	4.877	-8.1
NOx	grams	117.7	106.5	10.0
CO	g/mi	2.053	1.384	38.9
CO₂	g/mi	865.6	909.2	-4.9
THC	g/mi	0.169	0.180	-6.2
NOx	g/mi	4.428	3.932	11.9
CO	g/bhp-hr	1.077	0.733	38.0
CO₂	g/bhp-hr	454.1	481.6	-5.9
THC	g/bhp-hr	0.089	0.095	-7.2
NOx	g/bhp-hr	2.323	2.082	10.9

Table 0-28: Test Results from MW-17.

Parameter	Units	SEMTECH	OBS	Percent Difference
Distance	miles	26.56	27.00	-1.6
Work	bhp-hr	50.23	50.60	-0.7
CO	%	0.015	0.010	38.5
CO₂	%	4.695	4.933	-4.9
THC	ppm	34.31	37.99	-10.2
NOx	ppm	262.3	225.3	15.2
Exh Vol	SCF	789.1	759.0	3.9
Exh T	°C	214.3	213.2	0.5
Exh P	kPa(g)	0.070	0.090	-24.2
Amb T	°C	21.77	22.58	-3.6
Amb P	kPa	97.50	97.22	0.3
Carbon Balance	grams	6086	6672	-9.2
Fuel Consumption	grams	7031	7708	-9.2
CO	grams	39.05	27.53	34.6
CO₂	grams	22218	24380	-9.3
THC	grams	4.633	5.006	-7.8
NOx	grams	117.5	105.3	11.0
CO	g/mi	1.470	1.020	36.2
CO₂	g/mi	836.4	903.0	-7.7
THC	g/mi	0.174	0.185	-6.1
NOx	g/mi	4.423	3.899	12.6
CO	g/bhp-hr	0.777	0.544	35.3
CO₂	g/bhp-hr	442.3	481.9	-8.6
THC	g/bhp-hr	0.092	0.099	-7.0
NOx	g/bhp-hr	2.339	2.080	11.7

Appendix D – Select Plots from Portions of Individual Tests

Figure 0-1: Exhaust Flow from Test Number MW-06.

Figure 0-2: CO Concentration from Test Number MW-06.

Figure 0-3: CO₂ Concentration from Test Number MW-06.

Figure 0-4: THC Concentration from Test Number MW-06.

Figure 0-5: NOx Concentration from Test Number MW-06.

Figure 0-6: Exhaust Flow from Test Number W2B-01.

Figure 0-7: CO Concentration from Test Number W2B-01.

Figure 0-8: CO₂ Concentration from Test Number W2B-01.

Figure 0-9: THC Concentration from Test Number W2B-01.

Figure 0-10: NOx Concentration from Test Number W2B-01.

Figure 0-11: Exhaust Flow from Test Number B2W-04.

Figure 0-12: CO Concentration from Test Number B2W-04.

Figure 0-13: CO₂ Concentration from Test Number B2W-04.

Figure 0-14: THC Concentration from Test Number B2W-04.

Figure 0-15: NO_x Concentration from Test Number B2W-04.

Figure 0-16: Exhaust Flow from Test Number W2S-01.

Figure 0-17: CO Concentration from Test Number W2S-01.

Figure 0-18: CO₂ Concentration from Test Number W2S-01.

Figure 0-19: THC Concentration from Test Number W2S-01.

Figure 0-20: NOx Concentration from Test Number W2S-01.

Figure 0-21: Exhaust Flow from Test Number S2W-03.

Figure 0-22: CO Concentration from Test Number S2W-03.

Figure 0-23: CO₂ Concentration from Test Number S2W-03.

Figure 0-24: THC Concentration from Test Number S2W-03.

Figure 0-25: NOx Concentration from Test Number S2W-03.

Figure 0-26: Exhaust Flow from Test Number MW-09.

Figure 0-27: CO Concentration from Test Number MW-09.

Figure 0-28: CO₂ Concentration from Test Number MW-09.

Figure 0-29: THC Concentration from Test Number MW-09.

Figure 0-30: NO_x Concentration from Test Number MW-09.

Figure 0-31: Exhaust Flow from Test Number W2B-05.

Figure 0-32: CO Concentration from Test Number W2B-05.

Figure 0-33: CO₂ Concentration from Test Number W2B-05.

Figure 0-34: THC Concentration from Test Number W2B-05.

Figure 0-35: NOx Concentration from Test Number W2B-05.

Figure 0-36: Exhaust Flow from Test Number B2W-05.

Figure 0-37: CO Concentration from Test Number B2W-05.

Figure 0-38: CO₂ Concentration from Test Number B2W-05.

Figure 0-39: THC Concentration from Test Number B2W-05.

Figure 0-40: NOx Concentration from Test Number B2W-05.

Figure 0-41: Exhaust Flow from Test Number W2S-05.

Figure 0-42: CO Concentration from Test Number W2S-05.

Figure 0-43: CO₂ Concentration from Test Number W2S-05.

Figure 0-44: THC Concentration from Test Number W2S-05.

Figure 0-45: NO_x Concentration from Test Number W2S-05.

Figure 0-46: Exhaust Flow from Test Number S2W-05.

Figure 0-47: CO Concentration from Test Number S2W-05.

Figure 0-48: CO₂ Concentration from Test Number S2W-05.

Figure 0-49: THC Concentration from Test Number S2W-05.

Figure 0-50: NOx Concentration from Test Number S2W-05.