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A work-based window method for calculating in-use brake-specific oxides of nitrogen emissions of heavy -duty diesel engines

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**A Work-Based Window Method for Calculating In-Use Brake-Specific
Oxides of Nitrogen Emissions of Heavy-Duty Diesel Engines**

Benjamin C. Shade

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

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in
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ABSTRACT

Heavy-duty diesel engines (HDDEs) are currently certified in an engine dynamometer test cell over defined test cycles, such as the Federal Test Procedure (FTP) or the Supplemental Emissions Test (SET). In addition to certification testing, those HDDEs are subjected to in-use testing where gaseous emissions levels are not to exceed 125% of the certification level plus an additional 0.5 g/bhp-hr for instrument and analyzer inaccuracies. These HDDEs are required to meet these limits in the Not-To-Exceed (NTE) zone, which is defined by 40 CFR §86.1370-2007. In this method, emissions are calculated when an engine is operating in the NTE zone for a continuous time period of at least 30 seconds in length.

A work window based method has been developed to calculate in-use emissions for all engine speeds and engine loads. At each data point in an in-use test, engine speed and engine torque are read from the engine's electronic control unit, and along with time, are used to determine instantaneous engine power. Instantaneous work is calculated using this power and the time differential in the data collection. Work is then summed until the desired amount of work is accumulated. The emissions levels are then calculated for that window of work. It was determined that a work window equal to the theoretical FTP cycle work best provides a means of comparison to the FTP certification standard. Also, a failure criterion has been established based on the amount of power in the work window to determine if a particular work window is legitimate.

Data from engines ranging in model year from 1996 to 2003 of 31 different test vehicles were evaluated for over 180 in-use tests. These engines had displacements from approximately 6 L to 12 L with power ratings from roughly 300 hp to 500 hp. The main focus of the study was on brake-specific oxides of nitrogen (NO_x) emissions from these engines. For 84% of all tests, the maximum work window bsNO_x results were below the maximum bsNO_x values calculated using the 30 second window NTE approach. The repeatability of in-use tests based on individual engine, test route, and engine certification family was examined by comparing averages and standard deviations of the results. Technology comparisons showed that for identical displacements and ratings, 2003 engines produced average ranges of 17% to 47% less NO_x than 2001 engines. Highway test routes caused engines built prior to 2001 to emit 26% higher bsNO_x values than urban test routes. No individual route appeared to cause 2001 and newer engines to emit higher NO_x emissions than other routes.

It was concluded that the work window method provides an accurate alternative approach to calculating brake-specific in-use NO_x emissions. Results for over 57% of the tests show that average in-use brake-specific NO_x emissions were at or below the FTP NO_x certification level of these engines. A variation of the work window was also developed based on distance to study inventory emissions for a few select in-use tests.

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NOMENCLATURE AND ABBREVIATIONS

AECD	Auxiliary Emissions Control Device
BDC	Bottom Dead Center
bhp	Brake Horsepower
BM2Sab	Bruceton Mills to Sabraton Test Route
bsfc	Brake-Specific Fuel Consumption
bsCO ₂	Brake-Specific Carbon Dioxide
bsNO _x	Brake-Specific Oxides of Nitrogen
CAD	Computer Aided Design
CARB	California Air Resources Board
CBD	Central Bus District Chassis Dynamometer Cycle
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
ECM	Engine Control Module
ECT	Engine Coolant Temperature
ECU	Engine Control Unit
EERL	Engine and Emissions Research Laboratory
EGR	Exhaust Gas Recirculation
EGS	Electrochemical Gas Sensor
EGT	Exhaust Gas Temperature
ESC	European Stationary Cycle
ETC	European Transient Cycle
EU	European Union
FIE	Fuel Injection Equipment
FTIR	Fourier Transform Infrared
FTP	Federal Test Procedure
GPS	Global Positioning System
HC	Hydrocarbons
HDDE	Heavy-Duty Diesel Engine
I/M	Inspection and Maintenance
ihp	Indicated Horsepower
IMP	Inlet Manifold Pressure
IMT	Inlet Manifold Temperature
JRC	Joint Research Centre
lpm	Liters Per Minute
MEMS	Mobile Emissions Measurement System
mep	Mean Effect Pressure
Mrgtwn	Morgantown Test Route
NESCAUM	Northeast States for Coordinated Air Use Management
NDIR	Non-Dispersive Infrared
NDUV	Non-Dispersive Ultraviolet
NH ₄	Ammonia
NJ1	1 st Leg of New Jersey Test Route

NJ2	2 nd Leg of New Jersey Test Route
NJ3	3 rd Leg of New Jersey Test Route
NJ4	4 th Leg of New Jersey Test Route
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Oxides of Nitrogen
NTE	Not-To-Exceed
O ₂	Oxygen
O ₃	Ozone
OICA	Organisation Internationale des Constructeurs d'Automobiles
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
ppm	Parts Per Million
PREVIEW	Portable Real-Time Emission Vehicular Integrated Engineering Workstation
QC/QA	Quality Control / Quality Assurance
RAVEM	Ride Along Vehicle Emissions Measurement System
ROVER	Real-time On-road Vehicle Emissions Recorder
RPM	Revolutions per Minute
Sab2BM	Sabraton to Bruceton Mills Test Route
Sab2SW	Sabraton to Saltwell Test Route
Sab2Wash	1 st Leg of Pittsburgh Test Route
scfm	Standard Cubic Feet Per Minute
SET	Supplemental Emissions Test
SPOT	Simple Portable On-vehicle Testing
SW2Sab	Saltwell to Sabraton Test Route
TDC	Top Dead Center
THC	Total Hydrocarbons
UDDS	Urban Dynamometer Driving Schedule Chassis Dynamometer Cycle
US EPA	United States Environmental Protection Agency
VGT	Variable Geometry Turbocharger
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds
WashPA1	2 nd Leg of Pittsburgh Test Route
WashPA2	3 rd Leg of Pittsburgh Test Route
WashPA3	4 th Leg of Pittsburgh Test Route – Phase III
WashPA32Sab	4 th Leg of Pittsburgh Test Route – Phase IV
WVU	West Virginia University

1 INTRODUCTION

1.1 Background

In 1998, six heavy-duty diesel engine manufacturers (Caterpillar, Inc.; Cummins Engine Company, Inc.; Detroit Diesel Corporation; Navistar International Transportation Corp.; Mack Trucks, Inc. and Renault V. I., s. a.; and Volvo Truck Corporation) entered into Consent Decrees with the United States Department of Justice, the United States Environmental Protection Agency (US EPA), and the California Air Resources Board (CARB). The US EPA found reason to believe that these engine manufacturers were using techniques in their engine development to meet the certification requirements of the Federal Test Procedure (FTP), but were developing their engines in a manner that would increase certain emissions during real world engine operation by using defeat devices, or auxiliary emissions control devices (AECDs). An AECD is engine programming that may be used as an engine protection algorithm, but affects emissions levels. Certain AECDs have been deemed acceptable by the US EPA, such as adjusting fuel injection timing and fuel quantities or reducing the flow of exhaust gas recirculation (EGR) to reduce engine coolant temperature to avoid overheating of the engine, as long as they are active only a small percentage of engine operation. These AECDs were thought to change mainly oxides of nitrogen (NO_x) and particulate matter (PM) concentrations.

The Department of Justice mandated that the settling heavy-duty diesel engine manufacturers, instead of paying penalties, should finance projects that would reduce emissions of existing engines or engineer methods to reduce emissions for future engines. Some of these projects included engine rebuild kits to reduce NO_x , exhaust aftertreatment development, fuel injection systems development, and in-use testing. A compliance auditor was also selected by each manufacturer to oversee these projects and report their status to the US EPA. The US EPA also mandated that the manufacturers provide them with tools to read engine control module data, such as engine torque and fuel injection timing [1 – 6].

A few engine certification modifications were also introduced with the onset of the Consent Decrees. The Supplemental Emissions Test (SET) was added as an additional certification cycle (see §2.2.2). Not-To-Exceed (NTE) standards were also created, where NO_x emissions cannot exceed 125% of the Federal Test Procedure certification level. Finally, heavy-duty diesel engine certification standards that were originally to become regulation in January

2004 became effective in October 2002, fifteen months ahead of schedule.

For the in-use testing project of the Consent Decrees, the settling manufacturers had the option to perform the work themselves or to contract the project. West Virginia University (WVU) received contracts from the settling heavy-duty diesel engine manufacturers to complete the in-use testing project. The program was divided into four phases. The first phase was to assess then currently available commercial in-use testing systems and analyzers to see if they could meet the requirements of an in-use testing system for heavy-duty diesel engines. If no commercially available systems were deemed to meet the requirements, then WVU was to build a system to best suit the needs of an in-use testing system. WVU found no systems that fulfilled the requirements of an in-use testing system during the research that was conducted during Phase I. Thus, the Mobile Emissions Measurement System (MEMS) was designed and developed by WVU (see §4.1). Several analyzers were tested and qualified to measure hydrocarbons (HC), carbon dioxide (CO₂), carbon monoxide (CO), and oxides of nitrogen (NO_x). During Phase I, particulate matter was not a major concern at the time due to the difficulties in developing a gravimetric system for in-use testing. Several different flow measurement methods were also examined, including a venturi, an Annubar®, a vortex shedder, a hot film anemometer, and a pitot static tube [7].

Objectives of the second phase were to develop testing protocols and over the road test routes [8]. During this phase, a truck instrumented with MEMS was driven over four test routes in and around Morgantown, WV, and the greater Pittsburgh, PA, area. Two of the routes were designed so that the truck would be operating in both urban and highway timing modes. The remaining two routes are comprised of mostly highway operation. The routes were required to be at least 45 minutes in length with at least one of the routes having a minimum of 15 minutes of truck operation at 65 mph or greater [2]. Numerous tests were conducted during Phase II comparing MEMS to laboratory grade analyzers. Results from these tests showed that MEMS could report brake-specific NO_x emissions to within 5% of laboratory results.

Phase III of the project involved using MEMS to test pre-Consent Decree engines using testing protocols and test routes that were established in Phase II of the program. During this phase over thirty vehicle configurations were tested, ranging from engine model year 1994 to 2001. For Phase III testing, engine torque was calculated using broadcast engine percent load and the lug curve of the engine. The test routes included Sab2BM, BM2Sab, Sab2SW, SW2Sab,

WashPA1, WashPA2, WashPA3, and Mrgtwn. Further explanation of these routes and the data collected therein can be found elsewhere [9 – 11].

Phase IV, the final phase of the in-use testing program, employed MEMS to test engines ranging from model years 2001 to 2003. During this phase, engine families were selected by the US EPA for testing for each model year. A minimum of four engines per family from at least two sources (where applicable) were tested within the engine's Useful Life. Two of the vehicles are then to be retested when the engine has accumulated 150% or greater of its Useful Life. The data were collected using the test procedures and test routes (with accepted modifications) that were developed in Phase II of the program. It is from this phase that the data were gathered for this dissertation.

1.2 Engine Certification

Heavy-duty diesel engines are subjected to a series of tests that must be passed before they can be sold commercially in the United States. These tests are mandated by the US EPA and may include the FTP for on-highway heavy-duty diesel engines, the SET, the Federal Smoke Test, and additional steady-state and transient tests. These tests are conducted in a transient capable engine dynamometer test cell with a full scale constant volume sampling (CVS) dilution tunnel using equipment and emissions analyzers suitable for performing such a task. Inlet air temperature and humidity are controlled. The dilution air in the CVS system can also be controlled for temperature and / or humidity.

When an engine manufacturer submits a request to the US EPA for certification, the manufacturer is given a code identifying that engine as belonging to a particular engine family. The code includes the engine model year, the engine manufacturer, the displacement of the engine, and an identifier indicating that particular engine family. An example of an engine family code for a 1998 Detroit Diesel S60 12.7 L is WDDXH12.7EGD [3]. Typically the certification limits in a particular engine family are set forth by the engine with the highest horsepower rating in the family. It is the results of certification tests from this particular engine that establish a comparison for all in-use testing data from engines of that particular family.

1.3 Problem Statement

Many heavy-duty diesel engine manufacturers and research engineers believe that the certification cycles mandated by the US EPA are no longer representative of real-world in-use

operation of heavy-duty diesel engines. Much of the in-use data collected to date by many different organizations support this claim. This study attempts to compare some of the data collected during Phases III and IV of the Consent Decree in-use testing program to engine certification cycles and the engine family emissions limits of those engines. Data that have been evaluated using the current methodology accepted by the settling heavy-duty diesel engine manufacturers and the US EPA are presented along with a new method based on a work window that incorporates all engine speed and load points during an in-use test.

1.4 Objectives

The objectives of this study are multifaceted. The primary objectives are to examine the procedures for heavy-duty diesel engine certification and to develop a secondary method for determining emissions levels, primarily those of NO_x, during in-use operation of heavy-duty diesel engines. This method is based on a predetermined window of work, rather than a window of time. The history and development of certification cycles and regulatory standards will also be presented and reviewed.

In-use testing presents a different challenge than engine certification testing in an engine dynamometer test cell. The needs and requirements of an in-use testing system, often referred to as a PEMS (Portable Emissions Measurement System), along with a summary of many in-use testing systems that have been developed and tested by different equipment manufacturers, research organizations, educational institutions, and regulatory agencies will be discussed.

A discussion of pollutant formation will be presented to develop a background for understanding diesel combustion. An overview of diesel combustion will be discussed, along with several different types of advanced diesel engine technologies that have been used to reduce exhaust emissions of diesel engines, namely NO_x and PM.

Work window power and duty cycle information from test runs will be used along with brake-specific NO_x results to develop failure criteria for the work window method. Once data have been analyzed using the work window method, results of in-use testing will be compared based on engine technologies and test routes. Repeatability of the work window test results will be examined. An error analysis will be performed to determine the accuracy of brake-specific NO_x results from the work window method. Finally, a variation of the work window method will be used to examine these data to study emissions inventories of a few select vehicles.

2 REVIEW OF LITERATURE

2.1 Introduction

On-highway heavy-duty diesel engines are used in a wide range of applications. They are used in both urban and rural transit buses to haul commuters. They are used in road tractors to haul commercial goods throughout the country. Cement mixers and pumpers use heavy-duty diesel engines in the construction industry. Dump trucks rely on heavy-duty diesel engines to haul aggregate, dirt, and debris to and from job sites. Whether it be the food that we eat, the homes in which we live, or the vehicles that we drive, it is almost certain that a portion of them was made possible through the use of a heavy-duty diesel engine.

On-highway heavy-duty diesel engines certified by the US EPA for use in the United States during recent years have ranged in displacement from under 3 liters to over 16 liters [12]. Engines are classified as either heavy heavy-duty, medium heavy-duty, or light heavy-duty based on the gross vehicle weight rating (GVWR) of the vehicle in which they are used, vehicle application and design characteristics, and engine design. Light heavy-duty diesel engines, which can range from 70 to 170 hp, typically have a non-sleeved cylinder block, and are not fully rebuildable. Vehicles with light heavy-duty diesel engines normally have a GVWR of less than 19,500 lb. These engines may be used in recreational vehicles, small delivery vans, and light-duty pickup trucks. Medium heavy-duty diesel engines, which can range from 170 to 250 hp, may or may not have sleeved cylinder blocks and might be rebuildable. Vehicles with these engines typically have a GVWR in the range of 19,500 to 33,000 lb. Some examples are school buses, straight trucks, and a variety of service vehicles. Finally, heavy heavy-duty diesel engines are built primarily for durability and are rebuildable several times. These engines normally have power ratings greater than 250 hp, with a few exceptions. Vehicles with heavy heavy-duty engines include road tractors, dump trucks, cement mixers, large transit buses, and refuse collection vehicles. These vehicles have a high GVWR, generally in excess of 33,000 lb [13].

All heavy-duty diesel engines are subjected to engine certification tests as set forth by the US EPA. Standards for certain emissions constituents may be different depending on application, but typically test cycles and procedures remain the same. Heavy-duty diesel engine certification tests are performed on an engine dynamometer capable of transient operation using the Federal Test Procedure (FTP). Recently, additional cycles have been required by the US

EPA to investigate dual engine mapping strategies. In addition to cycles, the US EPA created an area of engine operation known as the Not-To-Exceed (NTE) zone. In this area of engine operation, emissions are not allowed to exceed certification levels by more than a predetermined factor plus an additive component that may disappear in the future. To fully explore this NTE zone, in-use testing has been implemented by the US EPA and other regulatory agencies to examine and assess real-world in-use emissions of heavy-duty diesel engines.

2.2 Heavy-Duty Diesel Engine Certification Cycles

Heavy-duty diesel engines are used in applications varying from power generation to marine use to on-highway transportation. Since engine manufacturers do not necessarily dictate the application of their engines, it is necessary to certify engines using an engine dynamometer to conduct tests over pre-described cycles. For US applications, on-highway engines are subjected to the FTP and the SET.

2.2.1 Federal Test Procedure

The Federal Test Procedure is a transient engine dynamometer cycle with setpoints based on engine speed and engine torque. In order for the cycle to be representative, the setpoints are normalized based on the engine's lug curve. These setpoints are shown in Figure 2.1. The cycle has points where the engine is motored by the dynamometer. These points are set to -10% for representation in Figure 2.1. The FTP is 1200 seconds in duration, and consists of 4 parts, each 300 seconds in length. The first part is known as the New York Non-Freeway, the second as the Los Angeles Non-Freeway, the third as the Los Angeles Freeway, and the fourth as the New York Non-Freeway (repeated). Developed during the early 1970s by the US EPA from data collected during the CAPE-21 study, the FTP is based on an experimental study of urban and highway traffic in and around New York, NY, and Los Angeles, CA [14]. For engine certification, the cycle is completed twice, with the first test being a cold start and the second being a hot start. A 20 minute soak period separates the two tests. Emissions are collected continuously throughout each cycle. A weighted average, as shown in Equation 2.1, is used to determine a composite brake-specific result for the cycles using constituent mass and individual cycle work.

$$A_{wm} = \frac{(1/7)g_c + (6/7)g_h}{(1/7)bhp \cdot hr_c + (6/7)bhp \cdot hr_h} \quad \text{Equation 2.1}$$

The composite result is based on 1/7 of the results of the cold test and 6/7 of the results of the hot test.

Figure 2.1 Federal Test Procedure Normalized Engine Speed and Load Setpoints

2.2.2 Supplemental Emissions Test

The Supplemental Emissions Test (SET), also known as the European Stationary Cycle (ESC) or the Organisation Internationale des Constructeurs d'Automobiles (OICA) cycle, is a 13 mode steady-state engine dynamometer cycle that is 28 minutes in length. It was adopted by the US EPA for engine certification after the 1998 Consent Decrees were established. Setpoints for this cycle are based on the engine's lug curve. The speed n_{lo} is defined as the engine speed below rated speed at which full load power is 50% of the maximum power of the engine. The speed n_{hi} is defined as the engine speed above rated speed at which full load power is 70% of maximum power of the engine. The speeds A, B, and C are based on the following equations:

$$A = 0.25 \times (n_{hi} - n_{lo}) + n_{lo} \quad \text{Equation 2.2}$$

$$B = 0.50 \times (n_{hi} - n_{lo}) + n_{lo} \quad \text{Equation 2.3}$$

$$C = 0.75 \times (n_{hi} - n_{lo}) + n_{lo} \quad \text{Equation 2.4}$$

At each speed, the engine is run at loads of 25%, 50%, 75%, and 100% of full load torque at that speed. The SET also contains a mode at the low idle speed. Each mode has a weighting factor associated with it. Emissions are sampled at the end of each mode after a stabilization period. Table 2.1 outlines the specifics of the SET [13]. In addition to the thirteen setpoints, three mystery points are selected by the EPA upon submission of the data. These mystery points are located between the A and C speeds between 25% and 100% engine load. The emissions results of these three points must not exceed 125% of the interpolated emissions value at the mystery point.

Table 2.1 Supplemental Emissions Test Setpoints

Mode	Engine Speed	Engine Torque (%)	Weighting Factor (%)	Mode Length (min)	Sampling Time (s)
1	idle	-	15	4	60
2	A	100	8	2	30
3	B	50	10	2	30
4	B	75	10	2	30
5	A	50	5	2	30
6	A	75	5	2	30
7	A	25	5	2	30
8	B	100	9	2	30
9	B	25	10	2	30
10	C	100	8	2	30
11	C	25	5	2	30
12	C	75	5	2	30
13	C	50	5	2	30

2.2.3 European Transient Cycle

The European Transient Cycle (ETC) is a transient engine dynamometer cycle. The ETC is made up of three 600 second phases, totaling 1800 seconds in length. The first phase is meant to represent city driving. The second phase represents rural driving. The third and final phase

represents highway driving. Emissions are measured continuously throughout the cycle. The setpoints for the ETC are shown graphically in Figure 2.2 [15]. Like the FTP, the ETC has points where the engine is motored by the dynamometer. These points are also set to -10% for representation in Figure 2.2.

Figure 2.2 European Transient Cycle Normalized Engine Speed and Load Setpoints

2.3 Not-To-Exceed Region

The Not-To-Exceed (NTE) region is defined as the engine speed and torque area where engine speed is greater than the n_{15} speed and engine torque is greater than or equal to 30% of the maximum engine torque or greater than or equal to 30% of maximum engine power, whichever is greater [1]. The speed n_{15} is calculated from the following equation:

$$n_{15} = 0.15 \times (n_{hi} - n_{lo}) + n_{lo} \quad \text{Equation 2.5}$$

The NTE region for a heavy-duty diesel engine is shown in Figure 2.3. Although not applicable in this study, there exists a carve-out region for particulate matter, which can be seen in the figure, that is defined as the region below the line from the intersection of the n_{hi} speed and

70% of maximum power and the intersection of 30% of maximum torque and the B speed or 30% of maximum power, whichever is farther to the right, depending on the specific engine. A carve-out region is an area under the lug curve in the NTE region where levels of a particular emissions constituent are not applicable to in-use regulations.

Figure 2.3 Not-To-Exceed Region

Additional criteria for determining whether or not an engine is operating in the NTE region exist that have developed over the past few years but were not used in this study. These additional criteria include conditions based on altitude, ambient temperature, engine brake-specific fuel consumption (bsfc), inlet manifold temperature and pressure (IMT, IMP), and engine coolant temperature (ECT). The criteria for an engine to be operating in the NTE zone are:

1. Engine speed $> n_{15}$ speed
2. Engine torque $\geq 30\%$ of maximum torque
3. Engine power $\geq 30\%$ of maximum power
4. Vehicle altitude ≤ 5500 ft
5. Ambient temperature ≤ 100 °F at sea level to 86 °F at 5500 ft

6. $\text{bsfc} \leq 105\%$ of the minimum bsfc if an engine is not coupled to a multi-speed manual or automatic transmission
7. Engine operation must be outside of any engine manufacturer petitioned exclusion zone
8. Engine operation must be outside of any NTE region where an engine manufacturer declares that less than 5% of in-use operation occurs
9. For EGR-equipped engines, $\text{IMT} \geq 86\text{ }^{\circ}\text{F}$ to $100\text{ }^{\circ}\text{F}$, depending on IMP
10. For EGR-equipped engines, $\text{ECT} \geq 125\text{ }^{\circ}\text{F}$ to $140\text{ }^{\circ}\text{F}$, depending on IMP
11. If equipped, an engine's aftertreatment system's or systems' temperature(s) $\geq 482\text{ }^{\circ}\text{F}$

If all of these 11 conditions are satisfied simultaneously for a 30 second window, then that window is considered a 30 second NTE event [16].

For this study, if items 1 through 3 were satisfied for a period of 30 continuous seconds, then the engine was considered to be operating in an NTE event during that period. Other conditions were not considered. Current in-use testing regulations state that an NTE event is defined as a 30 second continuous window of engine operation within the NTE zone. If an engine operates in the NTE zone for a continuous period longer than 30 seconds, then there exist several 30 second windows of operation. For example, if an engine operates in the NTE zone for a period of 35 seconds, and 5 Hz data is collected, then there are a total of 26 NTE 30 second events. More recently, heavy-duty diesel engine manufacturers have lobbied to alter the definition of an NTE event. They believe that once an engine is operating in the NTE zone for a minimum of 30 seconds, the single event should continue until the engine is no longer operating in the NTE zone. In this method, termed a continuous NTE event, brake-specific emissions tend to be lower than those of 30 second windows due to a greater number of samples in the event and thus, better averaging.

While a heavy-duty diesel engine is operating within the NTE region in an NTE event, its NO_x emissions levels are supposed to be within 125% of the certification standard of that engine. Currently an additional 0.5 g/bhp-hr is added to the limit to allow for instrumentation errors and differences. For example, an engine with a $\text{NO}_x + \text{NMHC}$ certification level of 2.5 g/bhp-hr is limited to an in-use NO_x level of 3.625 g/bhp-hr ($1.25 \times 2.5\text{ g/bhp-hr} + 0.5\text{ g/bhp-hr}$). In-use limits normally restrain NO_x levels rather than $\text{NO}_x + \text{NMHC}$ levels due to the inability for accurate and repeatable in-use measurements of hydrocarbons and methane hydrocarbons combined with the fact that NMHC concentrations are typically very low.

2.4 Emissions Certification Levels

The first Clean Air Act was established by the United States Federal Government in 1963 to improve ambient air quality [17]. California became the first state to place emission regulations on vehicles when it established CARB in 1967. The US EPA created the first nationwide emissions regulations for heavy-duty diesel engines with amendments to the first Clean Air Act in 1970. The pattern of regulatory changes for NO_x and PM from 1970 to 2010 can be seen in Figure 2.4.

Figure 2.4 History of US EPA Regulation of Oxides of Nitrogen and Particulate Matter [18]

As can be seen in Figure 2.4, many changes have been made to regulatory levels of NO_x and PM. While PM levels have been unchanged for nearly 13 years, NO_x levels have been reduced significantly every few years. In 2007, heavy-duty diesel engine manufacturers are required to have 50% of their engines meet 2010 emissions requirements. This change from current standards (those implemented in October 2002) is perhaps the most difficult challenge for manufacturers to meet. In the past, engine developers were typically able to meet NO_x and PM requirements through the use of advanced technology in fuel injection equipment. In October of 2002, many engine manufacturers met NO_x + NMHC levels of 2.5 g/bhp-hr through

the use of exhaust gas recirculation (EGR). Now for the first time, heavy-duty diesel engine manufacturers must rely on both advanced engine technologies and exhaust gas aftertreatment to meet regulatory standards set forth by the US EPA.

Not all heavy-duty diesel engines are subjected to the same engine emissions certification levels. Engines that are designed and sold for use in urban bus applications have typically been required to meet more stringent NO_x and PM standards. These differences can be seen in Table 2.2 and Table 2.3. However, in 2010, all heavy-duty diesel engines will be required to meet the same standards, regardless of application.

Table 2.2 Heavy-Duty Diesel Engine Certification Levels

Model Year	HC (g/bhp-hr)	NMHC (g/bhp-hr)	CO (g/bhp-hr)	NO _x (g/bhp-hr)	NO _x +NMHC (g/bhp-hr)	PM (g/bhp-hr)
1988	1.3	-	15.5	10.7	-	0.60
1990	1.3	-	15.5	6.0	-	0.60
1991	1.3	-	15.5	5.0	-	0.25
1994	1.3	-	15.5	5.0	-	0.10
1998	1.3	-	15.5	4.0	-	0.10
2004*	1.3	0.5	15.5	-	2.5 ⁺	0.10
2010	1.3	0.14	15.5	-	0.2	0.01

* Became effective October 2002 for settling HDDE manufacturers

⁺ Implies a maximum NMHC level of 0.5 g/bhp-hr

Table 2.3 Urban Bus Engine Certification Levels

Model Year	HC (g/bhp-hr)	NMHC (g/bhp-hr)	CO (g/bhp-hr)	NO _x (g/bhp-hr)	NO _x +NMHC (g/bhp-hr)	PM (g/bhp-hr)
1991	1.3	-	15.5	5.0	-	0.25
1993	1.3	-	15.5	5.0	-	0.10
1994	1.3	-	15.5	5.0	-	0.07
1996	1.3	-	15.5	5.0	-	0.05
1998	1.3	-	15.5	4.0	-	0.05
2004*	1.3	0.5	15.5	-	2.5 ⁺	0.05
2010	1.3	0.14	15.5	-	0.2	0.01

* Became effective October 2002 for settling HDDE manufacturers

⁺ Implies a maximum NMHC level of 0.5 g/bhp-hr

2.5 Requirements of an In-Use Testing System

An in-use testing system must have certain operational characteristics in order to be practical for in-use emissions testing. The system must accurately and reliably measure the

levels of certain exhaust constituents. These measurements must be repeatable and correlate with measurements that are made utilizing laboratory-grade instruments, both for bottled gas standards and engine exhaust. The system should be capable of reliably measuring oxides of nitrogen (NO_x), total hydrocarbons (THC), carbon monoxide (CO), and carbon dioxide (CO_2) mass emissions at the highest accuracy levels. Presently, determination of THC and CO seems to be problematic, due to limitations of currently available concentration measurement technology, and has therefore been assigned a lower priority than CO_2 and NO_x measurements. PM measurements are also desirable, but are currently improbable due to lack of available technology and feasibility and the vague description of what exactly defines PM. Accurate calibration procedures should also be incorporated into the measurement system.

In order for an in-use testing system to be classified as a PEMS, it must be portable. Available space is limited in many heavy-duty vehicles for the accommodation of on-board emissions measurement instrumentation. Hence, the system must be compact in size and lightweight, so that it may be easily installed on the vehicle. The system needs to be able to attach to the exhaust pipe of the vehicle for exhaust flow rate measurement, and therefore must be capable of accommodating a very broad range of exhaust system designs. An in-use testing system must also be able to withstand a wide variety of ambient conditions [9].

2.6 Previous In-Use Emissions Measurement Systems

In-use emissions measurement systems have been developed for and employed in inspection and maintenance (I/M) programs and in various research activities, including emissions inventories and human exposure studies, over the past 25 years. A brief review of some of these emissions measurement systems is presented in this section. A more detailed explanation of these systems can be found elsewhere [7, 10 – 11, 14, 19 – 22].

Caterpillar, Inc. (1982) developed a portable bag collection system to determine fuel specific NO_x emissions from in-use diesel engines [23]. It was designed so that manufacturers could label engines that comply with emissions regulations, and the in-field measurement of NO_x emissions would verify this compliance. The system consisted of a probe, prefilter, sample line, pump, air-cooled condensing coil, and two collection bags. Testing showed that the test vehicle had to be operated at full-load conditions to obtain valid data. Results showed that the portable Caterpillar bag collection system could report NO_x emissions within 10% of laboratory

instruments on a concentration basis.

Southwest Research Institute (1992) developed a portable on-board testing system based on an integrated bag approach to measure diesel emissions from buses with automatic transmissions for I/M purposes [24]. The study compared emissions from the buses during 30-second intervals at various throttle positions to the emissions measured by the US EPA during transient engine testing. The goal of the research was to be able to perform testing and gather information without the use of a chassis dynamometer. Gaseous emissions and particulate matter were both collected.

General Motors (1993) instrumented a 1989 gasoline-fueled 3.8-liter displacement Pontiac Bonneville SSE passenger car to measure its emissions [25]. The vehicle was driven on various city and highway routes to obtain the desired emissions data. The system was capable of measuring HC, CO₂, CO, and NO using several different infrared-based analyzers. The exhaust flow measurement was made using a Kurz Instruments, Inc. flow meter while intake flow was measured using stock flow meter signals. A relationship between exhaust flow and intake flow was then developed, allowing for the inference of the exhaust flow from the intake flow. Dynamometer tests were performed using the UDDS cycle to characterize the emission rates of HC and CO. Concerns of the system included its slow data collection rate and its inability to record transient events.

Ford Motor Company (1994) devised a testing apparatus to measure emissions from three different gasoline-fueled passenger vehicles [26 – 29]. The objective of the study was to compare on-board measurements to those obtained using remote equipment. Each test vehicle was capable of monitoring and controlling various engine parameters, while only two were capable of measuring real-time emissions of the vehicle. A van was equipped with a system comprised of an FTIR and a dilution tunnel. Gaseous emissions measured were CO₂, CO, NO_x, and HC. When compared to results obtained from chassis dynamometer tests, the FTIR exhibited very slow response times, making it unsuitable for an on-board testing apparatus. A passenger car was implemented with an infrared-based analyzer to monitor HC, CO, CO₂, and O₂ emissions. An NDUV (non-dispersive ultraviolet) analyzer was used to record measurements of NO. Comparisons were made between the on-board NDUV NO measurements and laboratory equipment (slope = 0.8, R² = 0.97) using a chassis dynamometer.

The United States Coast Guard (1997) developed a system to measure emissions from the

engines of three patrol boats as part of the 1990 Clean Air Act for non-road air pollution [30, 31]. The boats were each powered by two engines, each of approximately 800 hp. The system was capable of measuring CO, NO, NO₂, SO₂, O₂, and HC using an Energy Efficiency Systems, Inc. Enerac 2000E. CO₂ concentrations were inferred from these measurements. Testing procedures were based on ISO 8178 standards. The main objective of the experiment was to adapt a portable emissions analyzer for shipboard use. Air flow was measured digitally using the electronic Flowhood by Shortridge. Fuel flow was measured with in-line flow meters. Ambient air temperature, pressure, and relative humidity were also monitored. Engine torque was measured via driveshaft mounted strain gages and transmitted through radio frequency. Emissions were sampled directly from the engine, rather than from a stack, with the instrumentation confined to a small area.

The University of Pittsburgh (1997) developed an I/M system to measure the emissions from a fleet of natural gas-fueled passenger vans [32]. A five-gas analyzer was used to determine the raw exhaust concentrations of HC, CO, CO₂, NO_x, and O₂. Engine data were also collected via third-party diagnostic equipment. Raw exhaust was sampled through a probe inserted into the tailpipe of the vehicle. The exhaust flow rate was determined from the fuel and intake air mass flow, reported through the electronic control system. Data were collected using a laptop computer, and reduced using in-house developed software. Since the system was developed for gasoline-fueled vehicles, the hydrocarbon results were biased. The system provided a means of measuring real world, in-use emissions from natural gas-fueled vehicles using a lightweight and portable testing apparatus.

The Flemish Institute for Technological Research (1997), or VITO, conducted on-board emissions tests with the VOEM (VITO's On-the-road Emission and Energy Measurement) system on gasoline-fueled cars and diesel-fueled buses. This system contained an NDIR-based analyzer for CO and CO₂, an HFID for HC, and a chemiluminescent-based analyzer for NO_x determination. The system obtained its diluted exhaust sample from a nitrogen-driven ejector placed in the tailpipe of the vehicle. Emissions were reported in terms of g/km or g/s by combining dilute exhaust measurements with fuel consumption, engine speed, and air/fuel ratio values. The VOEM system was heavy, weighing approximately 500 lb, making on-board, in-use testing difficult.

NESCAUM (1998), the Northeast States for Coordinated Air Use Management, along

with the US Generating Co., the US EPA, the Manufacturers of Emission Control Association (MECA), and the Massachusetts Department of Environmental Protection, conducted tests to evaluate in-use emissions from diesel-fueled off-road construction vehicles [33]. Vehicles tested were a dump truck, two front-end loaders, a backhoe, and a bulldozer. A heated, self-contained, computerized sampling system was used to obtain emissions data. A heated sampling line transferred the raw exhaust sample to a mini-dilution tunnel. A slipstream of this sample was extracted through other sampling lines to obtain continuous emissions measurements. Bag samples were collected for the analysis of THC, NO_x, and CO. A 70-mm filter was placed at the exit of a mini-dilution tunnel to obtain PM measurements. CO₂ was used to infer fuel consumption.

The Office of Mobile Sources at the US EPA (1999) developed a mobile testing device known as ROVER (Real-time On-road Vehicle Emissions Recorder). Currently, ROVER is still in use by the US EPA. The system was originally designed to measure the emissions from gasoline-fueled vehicles, but was converted to measure diesel-fueled engine emissions. An Annubar® differential pressure device is used to determine the flow of exhaust. HC, CO, CO₂, and NO, are measured using a Snap-On MT3505 emissions analyzer. The ROVER originally reported measured emissions on a distance-specific basis (g/mile), but has been updated to report brake-specific emissions. Problems with the ROVER system include an unheated sampling line, unheated filter, the absence of a NO_x converter, and the exhaust flow measurement tube. The ROVER system showed that a gasoline-based emissions system could be modified for use in measuring diesel emissions. The unit is small, lightweight, and portable, making its installation in a heavy-duty diesel-fueled vehicle rather simple.

Ford Motor Company (1999), along with WPI-Microprocessor Systems, Inc., developed a portable system known as PREVIEW (Portable Real-time Emission Vehicular Integrated Engineering Workstation) [34]. PREVIEW was a fully integrated system capable of sampling water-laden exhaust. It recorded emissions measurements of HC, CO, CO₂, and NO_x, and up to 40 engine parameters. HC, CO, and CO₂ were measured with an infrared-based analyzer, while NO_x was measured with an ultraviolet-based analyzer. The system also accepted auxiliary inputs from on-board instrumentation, such as temperature sensors and air/fuel measurement devices. A laptop computer was used to instantaneously display and collect data at a frequency of 1 Hz.

Horiba, Ltd. (2000) and NGK Insulators, Ltd. developed an on-board NO_x emissions measurement system for diesel-powered vehicles [35]. The system used solid-state sensors made of zirconium oxide (ZrO₂) and other ceramic materials to measure NO_x concentrations, air/fuel ratio, and excess-air ratio. Intake air pressure and temperature, intake air relative humidity, boost pressure, ambient pressure and temperature, vehicle speed, engine speed, and coolant temperature were also recorded. Compared to laboratory results from compliance testing, the system was capable of reporting NO_x mass emissions measurements within 4%, fuel consumption measurements within 3%, and distance measurements within 1%.

Honda R&D Americas, Ltd., Honda R&D Co., Ltd, and Nicolet Instrument Corp. (2000) presented preliminary work on an FTIR-based system for measuring real-world emissions from light-duty gasoline-powered vehicles [36]. The target pollutants were NMHC, NO_x, and CO. Several issues, such as temporal resolution and vibration isolation, were not resolved in the system.

The Technical Research Center of Finland (2001), also known as VTT Energy, performed on-road emissions testing on transit busses [37]. An NDIR 4-gas analyzer was used to measure HC, CO, CO₂, and O₂. An ECO PHYSICS CLD 700 RE was used to measure NO_x concentrations. Exhaust flow rate was measured using a hot film flow meter. The vehicle speed was collected using the speedometer signal of the vehicle. A gasoline generator was used to power the system. Gravimetric analysis was performed to determine fuel consumption before and after the test. The system was not compared to laboratory grade analyzers.

Clean Air Technologies International (2001) developed an in-use testing system utilizing an NDIR analyzer to measure CO and CO₂ concentrations and an electrochemical cell to measure NO_x concentrations [38]. PM concentrations were determined using a photo detector and two laser beams. The exhaust flow rate was determined from ECU broadcast air and fuel flow data. The exhaust sample was obtained from the tailpipe of the vehicle. Problems arose in the areas of data alignment, data acquisition noise, and engine parameter measurement. This system was later used in 2003 by North Carolina State University in a study to develop procedures for in-use testing and characterization of highway emissions from vehicles with engines fueled by both ethanol blend (E85) and gasoline [10].

Analytical Engineering, Inc. (2001) developed a system known as the Simple Portable On-vehicle Testing (SPOT) system [39]. SPOT was capable of measuring NO_x and O₂. CO₂

data were inferred from the O₂ data collected. The system also measured exhaust mass flow, ambient conditions, and engine data. Data were transferred to the acquisition system via a cellular link. The system was later upgraded with a converging nozzle for exhaust flow rate measurement. A ZrO₂ sensor was placed next to the nozzle for NO_x measurement. The system was also used by AEI to conduct in-use testing on off-road diesel engines for the US EPA.

Engine, Fuel, and Emissions Engineering, Inc. (2001) designed the Ride Along Vehicle Emissions Measurement System (RAVEM) to measure the in-use emissions of diesel, gasoline, and alternative fuels vehicles [40]. The apparatus was based on a patented continuous proportioning method and was capable of measuring CO, CO₂, NO_x, and PM. The system also collected bag samples for more in depth analysis. The RAVEM system was tested in parallel with a chassis dynamometer equipped with a full-flow CVS system [41]. Good correlation was exhibited with laboratory analyzers for CO₂, NO_x, and PM, while CO results showed poor correlation with the full-flow CVS system.

The EPA Office of Research and Development (2002) designed the On-Road Diesel Emissions Characterization (ODEC) to study the characteristics of heavy-duty diesel exhaust stacks, emissions, and plume development [42, 43]. The ODEC system was housed in a trailer containing emissions analyzers and an ejector type dilution system. The laboratory grade emissions analyzers were capable of measuring PM, polycyclic aromatic hydrocarbons (PAHs), and particle sizes. The system was able to report emissions on a brake-specific basis. The ODEC system had difficulty in obtaining PM measurements and meeting the dilution requirements for plume sampling.

Sensors, Inc. (2002) developed a commercially available system for in-use diesel emissions testing, the SEMTECH-D. Similarly, Sensors, Inc. developed the SEMTECH-G, a system capable of measuring emissions from gasoline engines. In the SEMTECH-D, emissions concentrations are measured using a compact FID for total hydrocarbons (THC), an NDUV analyzer for a simultaneous measurement of NO and NO₂, an NDIR analyzer for CO and CO₂, and an electrochemical cell for O₂. The system can be controlled by a personal computer through a wired or wireless connection. The SEMTECH-D can collect ECU data, and if desired, ambient weather data through an external probe. Time-specific mass emissions are calculated by combining the emission concentrations and exhaust flow rate. Exhaust flow rate can be determined from ECU fuel rate or via the SEMTECH-EFM, a differential pressure type flow

meter. The system utilizes a heated line and filter to prevent condensation of heavy hydrocarbons. The exhaust sample is dried by a thermoelectric chiller before passing through the NDUV, NDIR, and electrochemical analyzers [44]. The system is currently being used by many heavy-duty diesel engine manufacturers for the US EPA's manufacturer run in-use testing program.

Horiba, Ltd. (2002) developed a wet-based, heated NDIR analyzer to be used on an on-board emissions measurement system [45]. The on-board measurement system consisted of the heated NDIR, an Annubar® flow meter, and an air/fuel ratio sensor. For diesel fueled test vehicles, a ZrO₂ sensor was installed directly into the exhaust pipe for NO_x measurements. Smoke opacity was measured using an opacity meter installed directly in the exhaust pipe.

The University of Alberta (2003) developed a system to measure exhaust emissions and fuel consumption while also focusing on ambient and vehicle operating parameters from gasoline powered vehicles over predetermined routes [46]. A Vetronix PXA-1100 five gas analyzer was used to measure HC, CO, CO₂, and NO_x. The intake air was measured using a hot wire mass air flow sensor, while an air/fuel ratio sensor aided in determining fuel flow rate. The insulated sample lines did not insure temperatures above the dew point. Errors may have occurred because of condensation in the non-heated sample lines. The system did not report brake-specific mass emissions.

Horiba Instruments, Inc. (2004) developed the commercially available OBS-1300 to perform on-board emissions measurements [47]. The system consisted of a MEXA-720 NO_x and air/fuel ratio sensor, a MEXA-1170 HNDIR analyzer, and a pitot tube flow meter. A laptop computer was used to log and analyze data. The pitot flow meter, a temperature sensor, and the MEXA-720 were contained in an attachment that mounted on the end of the tailpipe of the test vehicle. The exhaust sample was drawn through a heated line and heated filter to the heated NDIR analyzer. The mass of emissions could be viewed on a rate basis or as an integrated total. The OBS-1300 was eventually removed from the commercial market to make improvements to the system. An updated version is to be released in 2006.

3 FUNDAMENTALS OF COMBUSTION

3.1 Combustion Processes

Internal combustion engines are divided into two classifications: spark ignition and compression ignition. In a spark ignition engine, the amount of air going into the cylinder is controlled, and the amount of fuel is typically dependent on the amount of air. A spark, typically introduced by an electrode, supplies the source of ignition of the air and fuel mixture. Some typical fuels for a spark ignition engine are gasoline, ethanol, and natural gas. In a compression ignition engine, the amount of fuel injected into the cylinder is controlled. The absence of a throttle like that of a spark ignition engine helps to reduce pumping losses. The amount of air drawn into the cylinder is dependent on engine power and inlet manifold pressure. Ignition occurs a short period, known as the ignition delay, after the point when the pressure and temperature of the mixture in the cylinder are above the ignition point of the fuel. Diesel is the most common fuel for compression ignition engines.

The combustion process of a modern four-stroke compression ignition engine is complex. On a simple level, air is drawn into the cylinder during the intake stroke. At the desired point during the compression stroke, fuel is injected into the cylinder through small holes in the tip of a fuel injector. The fuel atomizes into droplets and vaporizes as it mixes with the high temperature and high pressure air in the cylinder. When the temperature and pressure of the mixture is above that of the ignition point of the fuel, and the ignition delay passes, combustion occurs. Combustion first starts in small pockets of the mixture and then may continue to ignite the entire mixture as the fuel injection event nears its completion [48]. The amount of torque produced during the expansion process depends on the working gas pressure in the cylinder and the quantity of fuel injected. The hot gases produced during the combustion event exit the cylinder during the exhaust stroke.

Stoichiometric combustion is defined as the complete combustion of a fuel so that the only products of combustion for complete reaction are carbon dioxide and water. Nitrogen is also in the products of the reaction, as it is a large portion of the air in the reactants. The stoichiometric reaction for a generalized fuel is given in Equation 3.1.

where a_s is the stoichiometric molar air-fuel ratio for the fuel in the reaction. Solving for the unknowns in the reaction using conservation of mass yields

$$\begin{aligned} a_s &= \alpha + \frac{\beta}{4} - \frac{\gamma}{2} \\ n_1 &= \alpha \\ n_2 &= \frac{\beta}{2} \\ n_3 &= \frac{\delta}{2} + 3.76\left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right) \end{aligned} \quad \text{Equation 3.2}$$

The stoichiometric air-fuel ratio can be written as

$$(A/F)_s = \frac{28.97(4.76a_s)}{12.01\alpha + 1.008\beta + 16.00\gamma + 14.01\delta} \quad \text{Equation 3.3}$$

The chemical formula for diesel fuel is $C_{14.4}H_{24.9}$, with a stoichiometric air-fuel ratio of 14.30 [49]. Diesel, like other hydrocarbon fuels, typically contains little or no oxygen or nitrogen, resulting in both γ and δ being negligible. In actuality, the composition of diesel fuel can vary substantially, depending on the amount of sulfur in the fuel, presence of lubricants or anti-gel compounds, or other additives.

The fuel-air equivalence ratio, ϕ , is defined as the stoichiometric air-fuel ratio divided by the actual air-fuel ratio. It is also equal to the actual fuel-air ratio, F/A , divided by the stoichiometric fuel-air ratio, $(F/A)_s$.

$$\phi = \frac{\text{Stoich Air} - \text{Fuel}}{\text{Actual Air} - \text{Fuel}} = \frac{(A/F)_s}{A/F} = \frac{F/A}{(F/A)_s} \quad \begin{array}{ll} \phi < 1 & \text{Lean} \\ \phi = 1 & \text{Stoichiometric} \\ \phi > 1 & \text{Rich} \end{array} \quad \text{Equation 3.4}$$

Diesel engines typically operate lean during normal engine operation. A typical air-fuel ratio for a heavy-duty diesel engine ranges from 18:1 at full load conditions to 100:1 at idle [48].

3.2 Formation of Emissions

To fully understand diesel emissions, it is necessary to understand how diesel emissions are formed. The major emissions of an internal combustion engine are oxides of nitrogen (NO_x), carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), and carbon dioxide (CO_2). For a diesel fueled engine, NO_x and PM are regulated most strictly by the US EPA. Pollutant formation is highly dependent on the distribution of the fuel spray during the injection event and how the distribution changes due to mixing over time. Figure 3.1 shows the formation mechanisms of NO, HC, and soot (PM) for premixed areas and controlled mixing for a diesel engine. NO forms in the burned gas region of the mixture where the temperature is high. Areas of the mixture where the air/fuel ratio and temperature are non-uniform also promote NO formation, but the highest rate of NO formation occurs in regions where the mixture is close to stoichiometric. PM forms in rich areas of the fuel spray core within the flame region. Oxidation occurs when PM comes in contact with unburned oxygen, producing the characteristic yellow flame of diesel combustion. HC is mainly produced in regions where the flame quenches on the cylinder wall or where excess air prevents the start of combustion or causes incomplete combustion. The following sections further discuss the formation of these pollutants.

Figure 3.1 Pollutant Formation Mechanisms in a Direct Injection Compression Ignition Engine [48]

A problem that engine developers face is the NO_x / PM tradeoff. Often a method used to reduce NO_x will result in an increase in PM. Likewise, a method used to reduce PM may increase NO_x emissions [50]. As a decrease in the diffusion flame temperature will decrease NO_x emissions, it will also reduce the amount of PM that can be oxidized. Figure 3.2 shows the effect of fuel injection pressure on PM and NO_x emissions. Injection pressures beyond 130 MPa are believed to have minimal effect. Currently, no feasible methods are known to reduce both in-cylinder NO_x and PM simultaneously. In future engines utilizing exhaust gas aftertreatment, the NO_x / PM tradeoff will not be as much of a significant problem as it is currently. Engine developers may focus on reducing engine NO_x emissions and rely on aftertreatment technology, most likely a diesel particulate filter, to meet regulatory levels of PM.

Figure 3.2 PM vs. NO_x Tradeoff as a Function of Injection Pressure [50]

3.2.1 Oxides of Nitrogen

Oxides of nitrogen form during the combustion process due to the presence of oxygen in the combustion chamber. Nitric oxide (NO), nitrogen dioxide (NO₂), and other oxygen compounds of nitrogen are grouped together and commonly termed NO_x. The major source of nitrogen for the combustion process is atmospheric nitrogen, though in diesel engines, a portion may come from fuel [51]. Perhaps the most important region of time for NO_x formation is the area beginning at the start of combustion and ending just after the cylinder pressure has reached its maximum. Three major reaction mechanisms that form NO are the extended Zeldovich (or thermal) mechanism, the Fenimore (or prompt) mechanism, and the N₂O intermediate mechanism [49]. The Zeldovich mechanism is the most important in internal combustion engines, and is made up of the following three reactions.

The first reaction is endothermic and is also the controlling reaction of the mechanism. The second and third reactions are exothermic. The third reaction can be found in rich mixtures. Each reaction produces an atom in an excited and unstable state. These unstable atoms seek to bond with other molecules in the combustion chamber to reach stability. In the first reaction of the Zeldovich mechanism, an oxygen atom seeks nitrogen, resulting in NO and an unstable atom of nitrogen, which seeks oxygen in the second reaction, resulting in NO and an unstable oxygen atom. The first two reactions of the Zeldovich mechanism feed themselves as long as there is enough heat from combustion to support the process. Researchers have added the third reaction to extend the mechanism. Some unstable nitrogen atoms are thought to bond with hydroxide radicals to form NO and an unstable atom of hydrogen.

The burned gas region behind the flame front is able to absorb energy from the combustion mixture due to its high pressure and temperature, resulting in the formation of nitric oxide. The flame front provides energy to dissociate nitrogen into nitrogen radicals and causes reactions to occur that lead to nitric oxide producing chains. Although nitric oxide may form in the flame front, the amount of nitric oxide produced in the post flame gases may be greater than that from the Zeldovich mechanism due to increased pressures during combustion [48].

A significant amount, as much as 10 – 30%, of the total NO_x produced during the combustion process of a diesel engine can be NO₂, particularly at light engine loads [48]. NO₂ is formed due to the kinetics of formation freezing during the expansion or power stroke as the piston moves downward. During this process, cooler excess air in the cylinder mixes with the hot gases ending the reaction mechanism. NO₂ is formed in the first reaction here. However, NO₂ can be readily converted back to NO.

During the engine certification process, oxides of nitrogen are measured using a heated chemiluminescent analyzer. This detection method is incapable of measuring NO₂ directly. NO₂ is converted to NO through the use of an internal converter, so that it may react with ozone (O₃) to undergo analysis for a total NO_x measurement in the sample. Thus, the total NO_x concentration that is reported is based on an analyzer reading of NO. Converter efficiency tests

are to be performed to ensure that NO_2 is being accounted for properly. Current in-use testing systems typically use a zirconium oxide sensor, a chemiluminescent detector, or an NDUV based analyzer to determine NO_x concentrations. A converter may or may not be used in these systems, depending on the technology being used.

3.2.2 Hydrocarbons

Hydrocarbons envelop a wide range of compounds in diesel exhaust, including simple non-reactive molecules, complex ring structures, and aldehydes [51]. In the diesel combustion process, hydrocarbons form as fuel is absorbed in deposits and oil layers in the cylinder, from fuel remaining in the tip of the fuel injector at the end of the fuel injection event that later diffuses into the combustion chamber, or from lean mixtures [49, 50]. Hydrocarbon emissions are strongly dependent on the operating conditions of the engine. Periods of engine idle and light loading produce much higher levels of hydrocarbons than periods of high loading [48].

Hydrocarbons can form in areas of lean mixtures. Figure 3.3 shows a diesel fuel spray schematic. Areas where the equivalence ratio, ϕ , is less than unity promote hydrocarbon formation. This area is primarily on the boundary of the jet, outside of where ignition occurs. In this area, the mixture is too lean to combust during the main combustion event. However, some of the components in this region, unburned fuel and partially oxidation products, may combust later in the expansion process. Some of them will leave the cylinder as hydrocarbon emissions.

Figure 3.3 Diesel Engine Fuel Spray Showing Equivalence Ratio Contours at Time of Ignition [48]

Quantities of fuel that enter the combustion chamber after the combustion process can lead to formation of hydrocarbons. The design of the injector tip can have a major effect. The nozzle sac can hold fuel that can vaporize and enter the combustion chamber through the nozzle holes. A portion of this quantity of fuel, or all of it, may leave the cylinder as unburned hydrocarbons, as it slowly mixes with the surrounding air.

Quenching of the fuel will also increase hydrocarbon emissions. When an engine is operating at low temperatures, the fuel that impinges on the cylinder walls can lead to engine misfire and production of white smoke. Both of these events will result in drastically higher hydrocarbon emissions.

A heated flame ionization detector is used to measure total hydrocarbons during diesel engine certification testing. The entire sampling system for hydrocarbons must be heated well above the dew point temperature of the sample, to approximately 190 °C, to avoid condensation of hydrocarbons and thus absorption issues. Currently regulations set by the US EPA call for a measurement of non-methane hydrocarbons (NMHC), which are included in the $\text{NO}_x + \text{NMHC}$ value. Non-methane hydrocarbon concentrations can be determined through the use of a methane cutter or a methane hydrocarbon analyzer. NMHC levels can be calculated by subtracting methane hydrocarbon results from total hydrocarbon results; although this method may lead to error as both values may be small values.

3.2.3 Carbon Monoxide

Carbon monoxide is controlled in internal combustion engines by the fuel to air equivalence ratio. CO is an intermediate product of hydrocarbon combustion. CO appears in rich mixtures due to the fact that there is not enough oxygen to bond with the carbon in the fuel to form CO₂ or to oxidize remaining CO in the combustion process. Diesel engines typically emit a low level of CO, as they operate on the lean side of stoichiometric and have a large amount of oxygen present [48]. Therefore, they do not create high levels of CO during the combustion process. However, at near stoichiometric conditions, combustion in locally rich regions in the gas mixture can cause formation of CO. During engine laboratory tests, the low levels of carbon monoxide are measured using an NDIR based analyzer.

3.2.4 Carbon Dioxide

Carbon dioxide is one of the main products of hydrocarbon combustion. In a stoichiometric reaction of carbon, oxygen, and hydrogen, only CO₂ and water would be results of combustion [51]. The amount of CO₂ detected in diesel exhaust plays an important role in the carbon balance process. That is, based upon the hydrogen-to-carbon ratio of the fuel used for combustion, a carbon balance can be performed to determine accuracy of fuel consumption and to check for leaks in the system, either engine or sample system related. This method is a crucial element of in-use testing. Like that for CO, an NDIR based analyzer is used to measure CO₂ in laboratory testing. CO₂ emissions are currently unregulated by the US EPA, but if measured during engine certification, must be reported.

3.2.5 Particulate Matter

Particulate matter is a major pollutant of diesel engines. Inhalation of these particles can cause respiratory problems and have been shown to be carcinogenic. Particulate matter in diesel engines is exhausted as visible smoke or soot in the exhaust gas, to which organic compounds can become absorbed [49]. As far as the engine certification process is concerned, particulate matter is defined as any particles other than water that can be collected on a filter that is kept at 52 °C or less in a diluted sample stream. It can come from many sources, such as the incomplete combustion of hydrocarbons in the fuel, from lubricating oil, or from sulfur in the fuel [48]. It can be caused by excessive richness, poor oil control, overfueling, engine misfire, poor combustion quality, injection nozzle leaks, and wear of engine components [15].

During the combustion process, over 90% of the particulate produced is oxidized in the cylinder. Only 5 to 10% of the particulate formed enters the exhaust stream [50]. The rate of diesel particulate formation is highest at the beginning of the diffusion burning process when the fuel spray is cut off from its air supply and surrounded by very hot products of the premixed burning. The amount of particulate matter formed during combustion is a function dependent heavily on the equivalence ratio. As the equivalence ratio doubles, the amount of particulate matter produced increases by an order of magnitude [49].

The US EPA has received criticism regarding control of particulate matter emissions from foreign regulatory agencies due to its focus on a gravimetric regulation. Due to the wide ranges of particle compositions, foreign regulatory agencies have instituted regulations based on particle sizes. Smaller particles, although they may be few in amount, can cause more damage in humans by imbedding deeper in the respiratory system than larger particles. Diesel exhaust aftertreatment (see §3.3.4) may reduce the amount of particulate matter produced from diesel engines, but may also cause additional harm due to the finer ash and smaller particles emitted.

3.3 Engine Technologies

Today's modern heavy-duty diesel engines must not only meet certification requirements set forth by the US EPA, but they must also be comprised of robust and durable systems. The major systems of an HDDE can be classified as fuel injection equipment, air handling (i.e. turbocharging), power cylinder, and exhaust aftertreatment. The following sections give a synopsis of each of these systems.

3.3.1 Fuel Injection Equipment

Diesel engines can be classified as one of two combustion chamber designs, the first being direct injection, and the second being indirect injection. In a direct injection engine, fuel is injected directly into a single open combustion chamber. In an indirect injection engine, fuel is injected into a chamber that is upstream of the main combustion chamber. Presently, nearly all of commercially available heavy-duty diesel engines utilize direct injection systems. Some of these systems are discussed herein.

In the past, the most common injection system on a heavy-duty diesel engine was a mechanical system consisting of a transfer pump, an injection pump, and a nozzle assembly. This system, sometimes known as a pump-line-nozzle system, proved to be durable, but lacked

the control required to meet increasingly more stringent heavy-duty emissions requirements. More accurate control of these systems became available with electronic sensing of rack position. However, precise control of the injection event, regarding rate and duration, was not possible. A solution to the problems met with an in-line system can be solved using a unit pump injection system. In this setup, fuel is delivered to individual pumps via a transfer pump. Electronic solenoids can then be activated to deliver high pressure fuel to the nozzle assembly. A unit pump system allows for more accurate timing of injection events, as well as control of the shape of the event. A third type of injection strategy is a common rail system. Here, a low pressure pump feeds a high pressure pump that delivers fuel to a common rail, or manifold, at a regulated pressure. The rail is connected to each individual injector through a transfer line. Each injector typically has a solenoid that is activated based on an engine control unit (ECU) signal to deliver the fuel to the combustion chamber.

More recently, many heavy-duty diesel engines have switched to a electronic unit injector system. In this arrangement, which is similar in logic to a unit pump system, an electronic solenoid controls the timing and metering of the injection event. Unlike the unit pump system, though, the solenoid is packaged at the injector. This system is advantageous in an overhead camshaft arrangement, as the camshaft / rocker assembly can be used to drive the plunger in the injector [48].

Often, in advanced engine control technology, levels of emissions can be largely influenced by the characteristics of the injection event. Some of these characteristics may include, but may not be limited to, injection timing, multiple injections, rate shaping, and injection pressure. Late injection timing will reduce NO_x formation during the combustion event, as combustion pressures and temperatures will be lower than that of early injection timing. Figure 3.4 shows this phenomenon. More recently, with advances in common rail and unit injection technology, flexible injection events have been used to reduce emissions, noise, and wear on the engine and provide more power at lower engine speeds.

Figure 3.4 Relationship Between Injection Timing and Cylinder Pressure [15]

3.3.2 Power Cylinder

The power cylinder in a diesel engine consists mainly of the components that form the boundaries of the combustion chamber. Piston geometry plays an important role in the combustion process. Bowl geometry, along with inlet port geometry, regulates mixing by controlling the amount of swirl in the cylinder. Piston ring position affects squish volume and may create a pocket that may aid in soot formation. The cylinder head forms the upper boundary of the combustion chamber. The cylinder head contains the inlet and exhaust valves through which gases flow, as well as the fuel injector.

Although it can be thought of as part of the air handling system, exhaust gas recirculation (EGR) is included here in the power cylinder due to its impact on the combustion process. Exhaust gas recirculation has been an effective method of controlling in-cylinder NO_x formation in spark ignition engines for many years. Recently, heavy-duty diesel engines have been equipped with EGR to reduce NO_x to the current regulation of 2.5 g/bhp-hr for NO_x + NMHC for on-highway heavy-duty diesel engines. In this process, a portion of the exhaust gas is captured and mixed with fresh inlet air and reintroduced into the combustion chamber, where it displaces some of the oxygen present in the inlet air. Often an EGR cooler must be present to cool the hot exhaust gas to lower the temperature of combustion to reduce NO_x formation.

There are several means of performing exhaust gas recirculation. Perhaps the most

common is a high-pressure loop, shown in Figure 3.5, where a portion of the gas in the exhaust manifold is extracted to the inlet air while the remaining exhaust gas enters the turbocharger. In a low-pressure loop system, a portion of the exhaust gas post turbocharger is routed to the inlet air. EGR can also be achieved in the combustion chamber with valve timing. The exhaust valve closing event can be delayed so that a portion of the exhaust gas may reenter the combustion chamber as fresh inlet air is drawn into the cylinder. Similarly, the exhaust valve can be closed early to trap a portion of the exhaust gas in the cylinder so that it may mix with fresh air during the inlet stroke. Early opening of the inlet valve is another method of accomplishing EGR in an engine. In this method, the inlet valve is opened while the in-cylinder pressure is greater than that in the inlet manifold, resulting in some exhaust gas mixing with the fresh inlet air.

Large quantities of exhaust gas (greater than ~25%) can be introduced into the inlet stream to greatly reduce engine-out NO_x levels. However, greater amounts of EGR can contribute to more rapid engine wear, greater soot loading in the engine oil, and higher PM emissions. EGR combined with late fuel injection timings can also promote excessive soot formation in the engine oil.

Figure 3.5 High Pressure EGR System [52]

3.3.3 Turbocharger Technology

Heavy-duty diesel engines use turbocharging to increase the density of the inlet air, resulting in an enhancement of power, torque, and mean effective pressure from any given engine displacement. The most common method of turbocharging involves a compressor and a turbine connected by a single shaft. The exhaust gases from the engine drive the turbine, which in turn, drives the compressor, and thus, results in an increase in the density of the inlet air.

Problems encountered during engine development due to turbocharging may be that in-cylinder pressures may become too high, resulting in a failure of critical engine components. Also, the thermal stresses in the turbocharger itself may become too great.

Several turbocharging strategies may be applied when developing a heavy-duty diesel engine. These strategies may include two-stage turbocharging, where very high boost pressures can be achieved to obtain a higher engine mean effective pressure, and turbocompounding, where a second turbine is used in the exhaust stream [48]. Often an intercooler is used to increase the density of the inlet air further once it exits the compressor before it enters the engine. More recently, as exhaust gas recirculation systems have become more common on heavy-duty diesel engines, variable geometry turbochargers (VGT) have been used to increase low engine speed power. These turbochargers commonly have vanes or a moving stator in the turbine housing that can be positioned to obtain the desired pressure ratio for a given engine operating condition. A VGT can also be used to create engine back-pressure to drive EGR flow across the engine. Examples of two types of variable geometry turbochargers, sliding nozzle and rotating nozzle, are shown in Figure 3.6 and Figure 3.7.

Figure 3.6 Sliding Nozzle Assembly Variable Geometry Turbocharger [53]

Figure 3.7 Rotating Nozzle Vane Variable Geometry Turbocharger [54]

Figure 3.8 shows a typical compressor map of pressure ratio vs. volumetric flow rate at different compressor efficiencies. The line at the left of the graph represents the surge line of the compressor. Operation beyond the surge line exhibits poor performance due to the presence of severe pulsations. The curved horizontal lines represent the speed of the compressor wheel. The line to the extreme right of the plot represents where choked flow occurs [55]. Figure 3.9 shows a typical turbine map. Turbine mass flow (green curves) and turbine efficiency (red curves) are plotted as a function of pressure ratio for a range of turbine wheel speeds.

Figure 3.8 Typical Compressor Map [56]

Figure 3.9 Typical Turbine Map [57]

3.3.4 Exhaust Gas Aftertreatment

Exhaust gas aftertreatment technologies can be used to reduce mainly NO_x , PM, and HC emissions in diesel engines. The most effective form of exhaust gas aftertreatment involves filtration of the exhaust stream. However, a problem arises in reducing particulate matter emissions when large quantities of particulate collect on the filter causing increased exhaust backpressure. This problem of contamination can be solved by the filter undergoing a regeneration event, either triggered by a heat source, or by spontaneous oxidation of the particulate matter in the filter. Diesel particulate filters are made from several types of materials, including ceramic and metallic materials.

NO_x aftertreatment systems are slightly more complicated in their design than PM aftertreatment devices. Examples of NO_x aftertreatment systems are selective catalytic reduction systems (SCR), lean NO_x adsorbers (LNA), and lean NO_x catalysts (LNC). SCR systems, which have long been used to reduce NO_x emissions in stationary applications, use nitrogen compounds as reductant agents, namely ammonia or urea, to react with NO to form nitrogen and water. The catalyst material may be made of platinum, vanadium, titanium, or zeolite. NO_x adsorbers store NO_x in the catalyst washcoat during lean engine operation and then release it during rich engine operation to react with the three-way catalyst to form nitrogen. A lean NO_x catalyst, which is a type of SCR, is a third type of technology which uses hydrocarbons as a

reducing agent to lower NO_x emissions by reacting with NO_x to form nitrogen, carbon dioxide, and water.

3.4 Computer Modeling

Due to the high cost of engine instrumentation and engine testing, many engine manufacturers rely on computer modeling to assist in developing technologies to improve combustion resulting in better performance and lower emissions. Computational fluid dynamics (CFD) is a method where the working fluid's temperature, pressure, velocity, and other properties can be calculated. Engineers can import CAD files into software packages for modeling purposes rather than testing several prototype parts. These CAD files can be manipulated and meshed to create a volume of fluid for analysis. Some examples may include an inlet or exhaust manifold, a turbocharger housing, an inlet or exhaust cylinder port, and even exhaust aftertreatment devices. The results of the CFD modeling can then be used by a combustion simulator to predict power output, thermal efficiency, and even emissions levels. However, the most critical statement regarding computer modeling is that it may accurately predict trends. Due to the complex nature of combustion and the number of reactions involved, relying on the absolute numbers generated by computer modeling, especially modeling of combustion, can lead to large errors in engine development. Computer models should be viewed as calibration tools that can be used to complement engine development testing. Also, the results of engine testing may be used to further develop and calibrate the engine and combustion model.

Sandia National Laboratories recently created a conceptual combustion model of a direct-injection diesel engine. The model was based on results of laser-sheet imaging of an optically accessible, single-cylinder engine. Illustrations from this model are shown in Figure 3.10. Figure 3.10(a) shows a section through the middle of a reacting jet, as it was thought to exist prior to the use of laser-sheet imaging. Figure 3.10(b) shows a section through the middle of a reacting jet during the injection event based on the results of the conceptual model derived from laser-sheet imaging. The updated results show more detail on NO formation zones and soot formation and oxidation zones, particularly along the boundary of the jet, than the first illustration. However, validation of these results has not been performed [58]. Products of rich combustion, CO, unburned HC, and soot, are thought to form in the internal region of the jet. CO_2 and H_2O form in the transition region near the boundary of the jet. NO_x is formed on the

high temperature boundary of the jet (green area), where the mixture is lean.

Figure 3.10 Sandia National Laboratories DI Diesel Combustion Models [58]

4 EXPERIMENTAL SETUP

4.1 Experimental Equipment

The equipment used for data collection during this experiment was the Mobile Emissions Measurement System (MEMS). MEMS was developed by West Virginia University beginning in 1999 as a Consent Decree project sponsored by the settling heavy-duty diesel engine manufacturers. Since 1999, several changes and upgrades have been made to MEMS to improve its performance and reliability. MEMS consists of three major subsystems: the emissions measurement system, the exhaust flow measurement system, and the data acquisition system. Each of these systems is summarized in the following sections.

4.1.1 Emissions Measurement System

The emissions measurement system of MEMS is housed in a stainless steel enclosure. The main components of the system are a heated line, a heated filter, a NO₂ to NO converter, a Horiba MEXA-120 or MEXA-720 NO_x analyzer, a pump, a pressure regulator, a chiller, and a Horiba BE-140AD multigas analyzer. The emissions measurement system is shown in its enclosure in Figure 4.1.

4.1.1.1 Horiba MEXA-120 / 720

The Horiba MEXA-120 is a sensor that was used in early versions of MEMS to measure NO_x concentrations in the exhaust. More recently, MEMS emissions measurement systems were upgraded to the Horiba MEXA-720, a newer version of the sensor that has the additional capability to report oxygen concentrations in the exhaust sample.

The MEXA-120 (or MEXA-720) is a zirconium oxide based sensor. The principle of operation is based on the diffusion of oxygen ions through dual platinum coated zirconium oxide chambers when heated to a high temperature of approximately 700 °C. The amount of current required to maintain a constant voltage across the second chamber as the oxygen ions are pumped out of that chamber is proportional to the NO concentration in the sample [22].

4.1.1.2 Horiba BE-140AD

The Horiba BE-140AD multigas analyzer uses an NDIR based method to determine CO₂ concentrations in the exhaust. The analyzer is also capable of measuring HC and CO, but its

capabilities are limited. The CO concentrations in raw diesel exhaust are too low for the resolution of this analyzer to accurately report. Since the analyzer is not heated, it can also have HC hangup issues, which can skew results. Therefore, the BE-140AD analyzer is used to report only CO₂ measurements to allow for a carbon balance calculation for quality control and quality assurance purposes.

Figure 4.1 MEMS Emissions Measurement System Installed In a Test Vehicle

4.1.2 Exhaust Flow Measurement System

To determine mass rate emissions, an accurate measurement, or inferred value, of the exhaust flow rate is necessary. MEMS uses a differential pressure device inserted into a length of exhaust piping that is mounted in the exhaust system of the candidate vehicle to measure exhaust flow. The Annubar®, by Dieterich Standard, Inc., shown in Figure 4.2, is a multi-port averaging device that works on the Bernoulli principle [59]. The diamond shape of the device creates an area of large pressure upstream and a low pressure downstream. A pressure transducer accurately measures this differential pressure. Along with the temperature and absolute pressure of the exhaust gas and the pipe diameter, and a variety of parameters associated with the Annubar®, the exhaust flow rate can be calculated.

Figure 4.2 Annubar® Flow Meter

4.1.3 Data Acquisition System

Signals from the emissions measurement system, the flow measurement system, the ambient box, the engine control unit, and the global positioning system are input into the data acquisition system of MEMS. The data acquisition system of MEMS is housed in a separate enclosure than the emissions measurement system due to sensitivity of its components. For the engines tested in the early portion of the study, a custom built computer was used to acquire analog data signals, serial data, and engine information. As the project proceeded, upgrades were made to the data acquisition systems to use notebook computers and an enclosure containing data acquisition cards and various data converters. A recent version of the data acquisition system is shown in Figure 4.3.

Figure 4.3 MEMS Data Acquisition System Installed In a Test Vehicle

4.1.3.1 ECU Communication

Parameters such as engine speed and estimated engine torque are read from the engine control unit to determine engine power and brake-specific emissions. Other engine information may also be read from the ECU such as, but not limited to, coolant temperature, oil temperature, oil pressure, inlet manifold temperature, and boost pressure. Proprietary information, such as fuel injection timing, may also be read from the engine control unit by sending a message to the ECU via a communication adapter like the one shown in Figure 4.4 and reading a returned message [60]. For most engines, engine information was read using SAE Surface Vehicle Recommended Practices J1587 and / or J1939 protocols [61, 62].

Figure 4.4 Dearborn Group DPA4

4.1.3.2 Global Positioning System

MEMS uses a global positioning system (GPS) to determine vehicle speed in addition to the vehicle speed broadcast from the ECU. The vehicle speed from the GPS sensor provides a means of quality control and quality assurance. In the case that an ECU has been reprogrammed, the vehicle speed can be inaccurate unless certain parameters, such as tire diameter and final drive ratio, have been updated. Errors in ECU vehicle speed associated with excessive tire wear are eliminated if the GPS vehicle speed is used in data analysis. The GPS sensor also provides a method of mapping the route from the longitude and latitude data that it provides. When interested in inventory emissions (see Chapter 6), the use of the GPS vehicle speed eliminates the errors associated with test vehicle variance of vehicle speed. A limitation of a global positioning system is that the altitude reported by the system can be inaccurate.

4.1.4 MEMS Software

Nearly all of the software used for MEMS was written and developed by personnel at West Virginia University [21]. The software programs are written in Microsoft Visual Basic to be used on a Windows PC. Some of the ECU information was collected using commercially available software [63].

4.1.4.1 Data Acquisition

The data acquisition code contained both calibration and data collection features. Prior to installation of the system, the program was used to calibrate pressure transducers and thermocouples and store vehicle information. Then prior to a test, the program was used to zero and span transducers and analyzers. During a test, the program recorded data from analyzers, transducers, thermocouples, a GPS, and the engine control unit.

4.1.4.2 Data Post Processing

Once the test was completed, the post processing software was used to convert the data collected during the test into engineering units. The post processor time aligned data from different sources and created files that could be used to further understand and interpret the data. Files that contained raw and calculated values for each channel were created as well as summary files for each test. The files created that contain engineering values were the files that were used for the tests used in this study.

4.2 Test Engines and Selection Criteria

Due to the sensitive nature of the data being presented in this report, no specifics have been given that would identify engine manufacturers or particular engine models. Manufacturer names have been concealed, engine displacements have been grouped according to size, and horsepower ratings have been rounded to ranges of 300 hp to 450 hp. Engine model years were presented for comparison purposes. Table 4.1 identifies the engines used for this study.

Table 4.1 Test Engines Identification

Displacement Range	Model Year	Approximate Rating (hp)
I	1998	200
I	2003	300
II	2003	350
II	1998	350
II	2003	350
II	2003	400
II	2001	300
II	2003	300
III	1996	500
III	2002	400
III	2001	400
III	2001	450
III	2003	400
III	2003	450

In order for an engine to be a candidate for testing, it had to meet several criteria. The engine had to be of the proper certification family as selected by the US EPA for the Consent Decree in-use testing program. The engine also had to have less mileage accumulated than the Useful Life of the engine family. For heavy heavy-duty diesel engines up to model year 2004, the Useful Life for oxides of nitrogen emissions was 10 years or 290,000 miles, whichever occurred first. For model year 2004 and newer, the US EPA increased the Useful Life of a heavy heavy-duty diesel engine for all emissions to 435,000 miles or 22,000 hours of engine operation, or 10 years, whichever occurred first. Throughout an engine's Useful Life, its emissions levels are supposed to remain at a constant level or within a level equal to the certification level plus a deterioration factor that is specified by the engine manufacturer. For medium heavy-duty diesel engines used in this study, the Useful Life for NO_x emissions was specified as 185,000 miles or 10 years.

4.3 Test Routes

A suitable in-use testing route needs to satisfy multiple criteria. It must be long enough in duration to log a suitable amount of data for proper analysis, but not so long that the proper calibration of instrumentation is voided and sensor drift occurs. The route ought to consist of a range of engine operation that includes both urban and highway operation. WVU has developed

several test routes that have been used throughout the test phases of the Consent Decree in-use testing program. The data that are presented in this study were collected over the test routes that are discussed in the following sections.

4.3.1 Mrgtwn

The Morgantown route (Mrgtwn), which consisted of both urban and highway operation, began and ended on Earl Core Rd at the I-68 interchange in Morgantown, WV. The route continued west to Hartman Run Rd and south onto the Mileground Rd. The route then continued north on Rt. 705 to Chestnut Ridge Rd to Van Voorhis Rd. The route continued onto Patteson Dr and then north onto Monongahela Blvd to Star City. The route then continued onto Osage Rd to I-79 South to I-68 East. At exit 4 on I-68 East, the Morgantown route made its way back to Earl Core Rd to complete the loop. The total distance for this route was 20.5 miles. The test route is shown in Figure 4.5 while its altitude profile is shown in Figure 4.6.

Figure 4.5 Mrgtwn Route [64]

Figure 4.6 Mrgtwn Route Altitude Profile

4.3.2 Pittsburgh Test Route

The Pittsburgh test route was comprised of four test runs: Sab2Wash, WashPA1, WashPA2, and WashPA3 or WashPA32Sab. The route began and ended in the greater Morgantown, WV, area and continued in between through West Virginia and Pennsylvania. The total length of the Pittsburgh test route was 154.3 miles. The entire route is mapped in Figure 4.7, while the altitude profile of the route is shown in Figure 4.8. The difference in calculated altitude at the beginning and end of the route can be associated with drift in the ambient pressure sensor.

Figure 4.7 Pittsburgh Test Route [64]

Figure 4.8 Pittsburgh Test Route Altitude Profile

4.3.2.1 Sab2Wash

The Sabraton to Washington, PA, route (Sab2Wash), which consisted of highway operation, began at the interchange of Earl Core Rd and I-68 in Morgantown, WV. It continued on I-68 West to I-79 North. The route continued on I-79 North into Pennsylvania, and ended along side the exit ramp at Exit 19B on I-79 North in Washington, PA. The total distance for this route was 52.7 miles.

Figure 4.9 Sab2Wash Test Route [64]

4.3.2.2 WashPA1

The first Washington, PA, route (WashPA1) consisted of urban traffic operation. The route began at Exit 19B on I-79 North and continued north on Rt. 19. The route ended at a pullover on the side of Rt. 19 outside of Upper St. Clair, PA. The total distance for this route was 12.1 miles.

Figure 4.10 WashPA1 Test Route [64]

4.3.2.3 WashPA2

The second Washington, PA, route (WashPA2) consisted of both urban and highway travel. It began at the pullover area outside of Upper St. Clair, PA, and followed Rt. 19 through Mt. Lebanon, PA, to I-279, just south of Pittsburgh. The route then followed I-279 South to I-79 South to the rest area at Bridgeville, PA, where the route ended. The total distance for this route was 23.1 miles. The WashPA2 route is mapped below in Figure 4.11.

Figure 4.11 WashPA2 Test Route [64]

4.3.2.4 WashPA3 / WashPA32Sab

The WashPA3 and WashPA32Sab routes began at the southbound rest area on I-79 South at Bridgeville, PA. The routes continued on I-79 South into West Virginia. The WashPA3 route stopped at the first rest area on I-79 South in West Virginia. The total distance for the WashPA3 route was 51.8 miles. The WashPA32Sab route stopped at the end of the ramp at Exit 4 on I-68 East on Earl Core Rd. The total distance for this route was 66.4 miles. The WashPA32Sab route is mapped in Figure 4.12.

Figure 4.12 WashPA32Sab Test Route [64]

The original Morgantown and Pittsburgh routes began and ended at 1462 Earl Core Rd in Morgantown, WV. However, due to construction, the start / stop point for the test routes was shifted 1.2 miles southeast to the interchange of Earl Core Rd (Rt. 7) and I-68.

4.3.3 New Jersey Test Route

The New Jersey test route consisted of four test runs: NJ1, NJ2, NJ3, and NJ4. Figure 4.13 maps the entire New Jersey test route. The route began and ended in Mt. Arlington, NJ, and continued in between through areas of both New Jersey and Pennsylvania. The total length of the New Jersey test route was 161.4 miles. Figure 4.14 shows the altitude throughout the test route.

Figure 4.13 New Jersey Test Route [64]

Figure 4.14 New Jersey Test Route Altitude Profile

4.3.3.1 NJ1

The first leg of the New Jersey test route, NJ1, began at 176 Howard Blvd in Mt. Arlington, NJ, and continued onto I-80 East. At Exit 43, the route proceeded onto I-287 South. At Exit 21B on I-287, the route continued onto I-78 West. The route continued on I-78 West into Pennsylvania in the Allentown area. At Exit 60A on I-78 West, the route ended along side the exit ramp. The NJ1 route consisted of highway operation. The total distance for this route was 82.5 miles. The NJ1 route is mapped in Figure 4.15.

Figure 4.15 NJ1 Test Route [64]

4.3.3.2 NJ2

At Exit 60A on I-78 West, the second leg of the New Jersey test route, NJ2, continued on 309 South to 378 North. The route continued through Bethlehem, PA, to Exit 2E to 8th Ave North. The route continued on 8th Ave to Schoenersville Rd North. The route then continued onto the entrance ramp to Rt. 22 East, where it ended along side the ramp. The NJ2 route was comprised of urban travel. The total distance for this route was 11.4 miles. The NJ2 route is mapped in Figure 4.16.

Figure 4.16 NJ2 Test Route [64]

4.3.3.3 NJ3

The third leg of the New Jersey test route, NJ3, began at the entrance ramp to Rt. 22 East from Schoenersville Rd. The route continued on Rt. 22 East to the Center St / Rt. 512 North exit. The route then continued on Rt. 512 North to Rt. 33 North to Rt. 209 North at Stroudsburg, PA. The route then proceeded onto I-80 East into New Jersey. The route ended at the rest area on I-80 East at mile marker 7. Both urban and highway operation made up this route. The total distance for this route was 43.9 miles. The NJ3 route is mapped in Figure 4.17.

Figure 4.17 NJ3 Test Route [64]

4.3.3.4 NJ4

The final leg of the New Jersey test route began at the rest area on I-80 East at mile marker 7 and continued on I-80 East to Exit 30, the Howard Blvd exit. It was made up of interstate travel. The route ended at 176 Howard Blvd. The total distance for this route was 23.6 miles. The NJ4 route is mapped in Figure 4.18.

Figure 4.18 NJ4 Test Route [64]

5 ANALYSIS AND EXPERIMENTAL RESULTS

5.1 Introduction

This chapter includes an analysis of engine certification cycles, as well as an analysis of a few select in-use on-road test cycles used during the Consent Decree in-use testing program (see §4.3). These analyses attempt to justify an alternative method to calculate in-use brake-specific emissions based on a window of work, rather than a window of time, which is the currently accepted method. The development of this alternative method will be presented and tested for a total of 31 different test vehicles over more than 180 individual tests.

A method for determining the validity of a given test is also presented and used throughout this data. Results are presented in both graphical and tabular form. Summarized results are included in this chapter for all tests. Individual test results in graphical form can be found in Appendix D. Where tests have been repeated, an “R” is listed next to the test vehicle identification number in the tables. The data are separated into individual phases of the program in which the vehicles were tested, and then into displacement, engine manufacturer, and model year. Test repeatability and comparisons based upon engine technology, test vehicle, and test route will be presented.

Lastly, an alternative method of calculating emissions is examined. Brake-specific emissions based on CO₂ measurements, a carbon balance, and brake-specific fuel consumption are shown for a few selected tests. Emissions calculated using this method are often referred to as fuel-specific emissions.

5.2 Analysis of Engine Certification Cycles

A common criticism of the FTP cycle is that it is no longer representative of present day real-world engine operation. However, present day engine emissions certification compliance is still determined using the FTP cycle. Figure 5.1 shows the normalized engine speed and load setpoints for the FTP cycle relative to the normalized lug curve of a heavy-duty diesel engine. The gray area is the NTE zone, as defined in §2.3. In this plot, setpoints of closed throttled motoring have been set to 0% torque. For the FTP, only 297 of 1199 (24.7%) setpoints lie in the NTE region. Figure 5.2 shows normalized engine speed and load traces for the FTP along with an indicator of whether or not the engine is operating in a 30 second NTE event. During the

1200 second FTP, there are 55 30 second NTE events over 3 separate continuous NTE events. Relative to time, the test engine is operating in an NTE event only 11.8% during the FTP.

Figure 5.1 FTP Speed and Load Setpoints In / Out of NTE Zone

Figure 5.2 FTP NTE Events

A similar argument can be made for the SET. The setpoints of the SET are shown relative to the engine lug curve and NTE region in Figure 5.3. Out of the 13 setpoints, 9 are in the NTE region. However, this test cycle is a steady-state cycle, which has a limited representation to real-world in-use engine operation. Each of the modes of the SET has its own weighting factor, as given in Table 2.1. Relative to these weighting factors, 65% of the composite data is collected from within the NTE region.

Figure 5.3 ESC Speed and Load Setpoints In / Out of NTE Zone

The ETC has minimal application in the United States, but should be considered in this analysis. If heavy-duty diesel engines are to be sold commercially in the European Union, then they must undergo and pass certification requirements as set forth by that union. The ETC can be classified as a test cycle of lower engine speed than that of the FTP. Whereas the FTP cycle explores nearly all ranges of engine operation under the lug curve, the ETC places emphasis on engine speeds around intermediate speed, or the speed at which peak torque occurs. The setpoints for the ETC are shown in Figure 5.4 relative to the engine lug curve and NTE region. Out of 1800 setpoints, 752 lie in the NTE region, or 41.7%. In terms of NTE events, Figure 5.5 shows that during the ETC, 49 30 second NTE events occur over 3 continuous NTE events. This means that the engine is operating in a 30 second NTE event during only 7.6% of the ETC.

Figure 5.4 ETC Speed and Load Setpoints In / Out of NTE Zone

Figure 5.5 ETC NTE Events

This section has discussed three major heavy-duty diesel engine certification cycles and the amount of time that an engine spends in a 30 second NTE event during each respective certification test. Figure 5.6 shows the engine speed and load setpoints of a heavy-duty diesel engine during a real-world in-use test cycle, NJ1 (see §4.3.3.1). The vehicle was a transit bus with an engine of approximately 350 hp operating on an interstate highway. It can be seen from the figure that the engine spent most of its operation around intermediate speed, at idle, or at 100% load operation. During this test, the engine was operating in the NTE region 59.2% of the time (17616 out of 29768 setpoints). Figure 5.7 shows the duty cycle for this test. For this particular test, the engine spent over 60% of its operation between 1400 and 1500 rpm.

Figure 5.6 In-Use Highway Test Speed and Load Points In / Out of NTE Zone

Figure 5.7 In-Use Highway Test Duty Cycle

Figure 5.8 shows the engine speed and torque traces for the NJ1 cycle, as well as an NTE event indicator. During this test, there were 7668 30 second NTE events over 35 continuous NTE events. The engine was operating in a 30 second NTE event 43.2% of the time. The number of 30 second NTE events is much greater than that of the FTP and ETC due to the fact that data was collected at 5 Hz during this test. Both the FTP and ETC have setpoints of engine speed and torque defined on a 1 Hz basis. There are 1527 1 Hz 30 second NTE events for this test. Either way, the on-road in-use test reveals that although the engine was certified using the FTP and SET cycles, in terms of the number of NTE events and actual engine operation, the certification cycles are not representative of this engine's performance.

Figure 5.8 On-Road Highway Cycle NTE Events

Figure 5.6 through Figure 5.8 discuss NTE operation of a highway cycle. It is expected that highway operation produces many more NTE events than urban operation due to the nature of engine operation during highway driving. Figure 5.9 shows the engine speed and torque points for a Mrgtwn test route (see §4.3.1), which consists of both urban and highway driving, of a road tractor of approximately 350 hp. The data in this figure surface an important issue concerning ECU broadcast torque. Many of the torque values exceed the maximum torque at a given engine speed based on the engine lug curve. Even the entire lug curve seems to be shifted towards the lower speed range. But these high torque values have not been eliminated in the data set. They are included and taken to be correct, although they are most likely incorrect. If these points are above the 15% ESC speed, then they are included in the NTE zone. For this Mrgtwn test, 4925 out of the 12264 data points are in the NTE zone, or 40.1%. Figure 5.10 shows the duty cycle for this Mrgtwn test. The engine spent over 17% of the time at idle and over 48% of its operation at less than 100 ft-lb of torque.

Figure 5.9 In-Use Urban / Highway Test Speed and Load Points In / Out of NTE Zone

Figure 5.10 In-Use Urban / Highway Test Duty Cycle

Figure 5.11 shows the engine speed and torque traces and NTE events for the Mrgtwn test under evaluation. For the test, there were 944 30 second NTE events over 8 continuous NTE events. The engine was operating in a 30 second NTE event 17.4% of the time. The highly transient engine operation characteristic of an urban test reduces the number of NTE events, which can be seen in the first 1500 seconds of the test. When the engine operates over the highway portion of the Mrgtwn route, the number of NTE events increases, as can be seen during most of the second half of the test.

Figure 5.11 On-Road Urban / Highway Cycle NTE Events

Several explanations can be given that might explain why current real-world in-use operation of HDDEs differs so greatly from the FTP when it was based on real-world in-use data. The FTP was developed from data collected during the early 1970s. Since then, commercial truck and bus traffic has increased significantly. Populations in many major cities have gotten larger, and the mass transit systems have had to adjust to the never-ending changes. The amount of commercial truck traffic has also risen over the past 35 years. Engine and vehicle characteristics have also changed since the FTP was developed. Engine power to vehicle weight ratios have increased. Transient engine response has changed due to engineering advances in

turbocharging. Electronic governors have replaced mechanical governors to limit engine speed. Similarly, maximum vehicle speeds can be limited electronically.

Figure 5.12 shows estimates of the increase in amount of vehicle miles traveled (VMT) and reduction of vehicle emissions since 1970 and what is predicted until the year 2030. While the tonnage of volatile organic compounds has had an overall decrease since 1970, the tonnage of NO_x is estimated to be nearly equal to that in 1970. However, the VMT has nearly doubled since 1970, so the NO_x emissions for an individual vehicle have had to decrease, as vehicle travel is having a smaller effect on emissions [65]. The increase in NO_x emissions from 1990 to 2000 may be due to the introduction of electronic engine controls and dual control map strategies.

Figure 5.12 Vehicle Miles Traveled and Vehicle Emissions [65]

When analyzing how much time an engine operates in or out of the NTE region, or how many 30 second NTE events or continuous NTE events occur during a test, the amount of time an engine spends operating outside of the NTE region may become a significant portion of the test, especially during periods of low engine power output or long idle operation. Heavy-duty diesel engine manufacturers are required to broadcast an accurate estimated engine torque output via an ECU datalink for all engine operation. The following section will present an alternative method to calculating in-use brake-specific emissions for all ranges of engine operation. The

method integrates emissions data over a predetermined window of work, rather than time, to obtain a brake-specific emissions result. The author believes that this method will help in gathering engine emissions data both inside the NTE region, and outside the NTE region, an area that has had limited focus during heavy-duty diesel engine in-use testing to date.

5.3 Explanation of Method

The parameters required to determine the amount of work performed by the engine during its in-use operation are ECU engine speed (N), ECU engine torque (T), and time (Δt). The engine speed is recorded from the ECU, as well as engine torque. In this study, data were collected at 5 Hz. Instantaneous work can be calculated for each data point in the data set. Then, beginning at each point in the data set, the instantaneous work is summed until the desired amount of work has been accumulated. This point in time is marked as i^* . This amount of accumulated work is denoted as the work window. This calculation is given in Equation 5.1.

$$WorkWindow(bhp \cdot hr) = \sum_{i=0}^{i^*} \left(\frac{N_i \left(\frac{rev}{min} \right) \times T_i (ft \cdot lb_f)}{\left(\frac{1 rev}{2\pi rad} \right) \left(\frac{60 sec}{1 min} \right) \left(\frac{550 ft \cdot lb_f}{1 sec \cdot bhp} \right)} \times \Delta t_i (sec) \times \left(\frac{1 hr}{3600 sec} \right) \right)$$

Equation 5.1

To determine raw exhaust brake-specific mass emissions, the concentration of the desired gas constituent ($[X]$), exhaust gas flow rate ($\dot{Q}$), constituent density (ρ), time (Δt), and the work window are all required measurements. Each of the signals of these variables must be time aligned with one another to account for sample delays specific to the particular variable. Equation 5.2 shows how each of these items is used.

$$bs[X] \left(\frac{g}{bhp \cdot hr} \right) = \frac{\sum_{i=0}^{i^*} \left\{ \frac{[X]_i (ppm)}{10^6} \times \rho_x \left(\frac{g}{ft^3} \right) \times \dot{Q}_i \left(\frac{ft^3}{sec} \right) \times \Delta t_i (sec) \right\}}{WorkWindow(bhp \cdot hr)}$$

Equation 5.2

The final important calculation in the work window method is the time duration of the work window. The window size is calculated by summing the time increment of the data from the beginning point in the data set to the point in the data set where the target amount of work has been accumulated.

$$WindowSize \text{ (min)} = \sum_{i=0}^{i^*} \Delta t_i \text{ (sec)} \times \left(\frac{1 \text{ min}}{60 \text{ sec}} \right) \quad \textbf{Equation 5.3}$$

Once the work window, the brake-specific mass concentration of an exhaust constituent, and window size have been calculated for a point in the data set, the process is repeated beginning at the next point in the data set. The process continues until the amount of work in the “n+1” window is less than the amount of desired work.

Figure 5.13 shows bsNO_x results based on the work window method compared to NTE bsNO_x results for a range of work windows of 1 bhp-hr to 75 bhp-hr for a Sab2Wash test of a 2003 engine of approximately 9 L displacement and 300 hp in a transit bus. The 1 bhp-hr work window produces high bsNO_x results at various points throughout the test. For small work windows, periods of high engine speed and torque may produce periods of higher NO_x. As the work window interval grows larger, the bsNO_x results approach a much more constant level, which ideally is desired to be equal to the FTP NO_x certification level of the engine.

Figure 5.13 Sab2Wash bsNO_x Results for a Range of Work Windows for a 2003 Engine of Approximately 9 L Displacement with 300 hp Rating

Figure 5.14 shows the window size and bsNO_x results and their variations for this Sab2Wash test. For increasing amounts of work in the work window, the standard deviation decreases for a respective work window as the average bsNO_x value approaches a constant result. For this test, the average bsNO_x values approach 2.9 g/bhp-hr for large work windows. The certification family emissions limit for this particular engine is 2.7 g/bhp-hr.

Figure 5.14 Window Size and Window bsNO_x for Varying Work Windows for a 2003 Engine of Approximately 9 L Displacement with 300 hp Rating

A second analysis was performed on a different engine, a 2001 engine of approximately 12 L displacement and 400 hp. Figure 5.15 shows work window bsNO_x results for work windows ranging from 1 bhp-hr to 75 bhp-hr compared to NTE bsNO_x results. Similar to the previous analysis, the 1 bhp-hr work window produces bsNO_x values with a large variability. As the work window interval increases, the average bsNO_x value for the individual work window becomes approximately 3.5 g/bhp-hr. The FTP bsNO_x certification level for this particular engine was 4.0 g/bhp-hr. Figure 5.16 shows the window size and variability in bsNO_x values for the work windows for this Sab2Wash test.

Figure 5.15 Sab2Wash bsNO_x Results for a Range of Work Windows for a 2001 Engine of Approximately 12 L Displacement with 400 hp Rating

Figure 5.16 Window Size and Window bsNO_x for Varying Work Windows for a 2001 Engine of Approximately 12 L Displacement with 400 hp Rating

The two tests that have been presented show that for a given test, similar results can be obtained for varying amounts of work in the work window. Figure 5.17 and Figure 5.18 show bsNO_x results for each of the analyzed Sab2Wash tests based on work windows equal to the theoretical work for the FTP and ETC for each respective engine, as well as the NTE bsNO_x results. For the 2003 engine of approximately 9 L displacement and 300 hp, the theoretical FTP work was calculated to be 18.94 bhp-hr. The theoretical ETC work was calculated to be 43.33 bhp-hr. For the 2001 engine of approximately 12 L displacement and 400 hp, the theoretical FTP work was calculated to be 30.63 bhp-hr while the ETC theoretical work was calculated to be 70.13 bhp-hr.

Figure 5.17 Sab2Wash bsNO_x Results for FTP and ETC Work Windows for a 2003 Engine of Approximately 9 L Displacement with 300 hp Rating

Figure 5.18 Sab2Wash bsNO_x Results for FTP and ETC Work Windows for a 2001 Engine of Approximately 12 L Displacement with 400 hp Rating

To provide a means of comparison to the engine certification standard for bsNO_x emissions of the engines used in this study, it is believed that a work window equal to the theoretical FTP work for the particular engine under analysis will best accomplish this task. Although in-use emissions are not expected to be equal to the FTP certification standards due to issues associated with ambient conditions, fuel properties, engine characteristics, and analyzer technologies, in-use emissions based on an FTP equivalent work window are expected to more closely resemble FTP emissions results than 30 second NTE windows. Figure 5.19 and Figure 5.20 show engine speed and torque traces, window sizes, and theoretical FTP work window bsNO_x results compared to NTE bsNO_x data for the two tests that have been evaluated in this section. Although both figures show results from the same test route, it can be seen that the results can be quite different for different vehicles. Figure 5.19 shows work window bsNO_x results that vary from 2.403 to 3.677 g/bhp-hr for a work window of 18.94 bhp-hr. Figure 5.20 shows work window bsNO_x results varying from 3.050 to 3.915 g/bhp-hr for a work window of 30.63 bhp-hr. Similar plots for all test runs evaluated in this study can be found in Appendix D.

Figure 5.19 Sab2Wash Results for an FTP Work Window for a 2003 Engine of Approximately 9 L Displacement with 300 hp Rating

Figure 5.20 Sab2Wash Results for an FTP Work Window for a 2001 Engine of Approximately 12 L Displacement with 400 hp Rating

Figure 5.21 shows a comparison of average engine speed and torque points for all work window events and all 30 second NTE events for a highway test of a 2001 engine operating in a transit bus. By encompassing all engine operation, the average engine torque points for the work window method were mainly below those of the 30 second NTE events. However, due to the automatic transmission of the transit bus, the range of engine speeds for both methods was roughly the same. Note that all of the average work window engine speed and torque points were within the NTE region.

Figure 5.21 Average Engine Speed and Torque Values for All Work Window and 30 Second NTE Events for a Highway Test of a 2001 Engine of Approximately 9 L Displacement with 350 hp Rating in a Transit Bus

A similar comparison to that given above is shown in Figure 5.22. Here, the average engine speed and torque points for all work window and 30 second NTE events are shown for a highway test of a 2001 engine operating in a road tractor. In this test, many of the NTE events were focused around the rated speed of the engine at full load. However, many of the average work window engine speed and torque points were outside of the NTE region, which showed that the engine was spending more time near the low idle condition.

Figure 5.22 Average Engine Speed and Torque Values for All Work Window and 30 Second NTE Events for a Highway Test of a 2001 Engine of Approximately 12 L Displacement with 400 hp Rating in a Road Tractor

For this same highway test, Figure 5.23 shows all of the engine speed and torque points that contain two separate work window events. One work window event contained engine operation with speeds from low idle to maximum speed with a wide range of torque values, while the other contained operating points above intermediate speed with torque varying from the engine's minimum to maximum output. For both work window events, much engine operation was seen at full load conditions, which was in the NTE zone, as well as many points outside of the NTE region.

Figure 5.23 Engine Speed and Torque Values Comprising Two Separate Work Window Events for a Highway Test of a 2001 Engine of Approximately 12 L Displacement with 400 hp Rating in a Road Tractor

Figure 5.24 shows the engine speed and torque points that comprise three separate 30 second NTE events for the same highway test of a 2001 engine in a road tractor. The three events showed very different engine operating patterns. One event had nearly all operation near the rated engine speed and torque of the engine, while a second event contained operating points traversing the boundary of the NTE region. The third event showed engine operation at nearly constant speed, which was near the intermediate speed of the engine, with torque values ranging from the lower limit of the NTE region to maximum torque of the engine at that speed. These three separate 30 second NTE events showed that a wide range of engine operating conditions can produce a 30 second NTE event.

Figure 5.24 Engine Speed and Torque Values Comprising Three Separate 30 Second NTE Events for a Highway Test of a 2001 Engine of Approximately 12 L Displacement with 400 hp Rating in a Road Tractor

5.4 FTP Theoretical Cycle Work

Cycle statistics are an important part of data analysis for the engine certification process. A heavy-duty diesel engine must meet target engine speeds and loads to the requirements outlined in 40 CFR §86.1341 [13]. To minimize biasing effects, feedback engine speed and torque may be shifted to better meet the target engine speed and torque at a point in time. Both signals must be shifted equally. Although 14.8% of the FTP cycle engine torque setpoints are associated with closed rack / 0% throttle motoring, none of these points contribute to the overall cycle work. All negative torque values are set to zero.

For this study, the theoretical FTP cycle work was used to determine the amount of work in the work window. By applying the setpoints in Appendix A to the engine lug curve, the theoretical FTP cycle work was calculated. For each engine configuration, the theoretical FTP cycle work is shown in Table 5.1. For some engine manufacturers, the ECU torque may be reported as negative during engine motored events. Any negative torque values that have been recorded from the ECU have been set to zero to comply with procedures outlined in the cycle validation criteria for the FTP.

Table 5.1 Test Engine Theoretical FTP Cycle Work

Displacement Range	Model Year	Approximate Rating (hp)	Theoretical FTP Work (bhp-hr)
I	1998	200	12.41
I	2003	300	17.84
II	2003	350	24.43
II	1998	350	26.83
II	2003	350	24.41
II	2003	400	27.22
II	2001	300	19.08
II	2003	300	18.94
III	1996	500	32.69
III	2002	400	25.74
III	2001	400	30.63
III	2001	450	34.28
III	2003	400	30.22
III	2003	450	33.09

5.5 Friction Model

Brake-specific engine emissions are reported on a basis of brake horsepower hour. Brake power is defined as the amount of power that is transferred through the output shaft of the engine. Brake power is less than the actual amount of power delivered to the piston crown during combustion, which is referred to as indicated power. According to the first law of thermodynamics, all energy must be conserved. The difference between indicated power and brake power output can be lumped into a friction term. The friction term includes forces required to overcome internal engine friction, pumping losses, and accessory loading.

Often engine certification is performed without the engine accessories that are found on engines used in heavy-duty trucks. It is not necessary to run an alternator, power steering pump, air conditioner compressor, air compressor, or even an engine fan in most engine dynamometer test cells. Deleting these items from the engine allows the manufacturer to supply the most possible power to the flywheel of the engine. This results in a greater amount of cycle work, or a larger denominator in brake-specific calculations, which lowers the brake-specific emissions levels, as the mass of the emissions constituent remains unchanged. Deleting these items from an engine during in-use testing is not an option due to functionality and safety reasons.

To estimate how much power may be lost to friction and other parasitic components, calculations were performed. First, an understanding of the geometry and physics of basic

engine cylinder operation is needed. The crankshaft, connecting rod, wrist pin, and piston of a heavy-duty diesel engine make a slider-crank mechanism. The position of the piston from top dead center (TDC), y , is given as

$$y = a(1 - \cos \omega t) + l \left(1 - \sqrt{1 - \left(\frac{a}{l} \right)^2 \sin^2 \omega t} \right) \approx a(1 - \cos \omega t) + \frac{a^2}{2l} \sin^2 \omega t$$

Equation 5.4

where a is the crank radius, l is the connecting rod length, ω is the angular velocity of the crankshaft, and t is time. Note that the product of ω and t is crank angle position, or θ . For most modern diesel engines, the ratio of the crank radius to the connecting rod length (a/l) is approximated as 1/3 [49]. The velocity, v , of the piston can be determined from the derivative of the piston position.

$$v = \frac{dy}{dt} = a\omega \left(\sin \omega t + \frac{a}{2l} \sin 2\omega t \right)$$

Equation 5.5

The piston acceleration can be determined from the second derivative of the piston position, or the derivative of the piston velocity.

$$\frac{d^2 y}{dt^2} = \frac{dv}{dt} = a\omega^2 \left(\cos \omega t + \frac{a}{l} \cos 2\omega t \right)$$

Equation 5.6

The piston position, velocity, and acceleration for one crankshaft rotation of a modern heavy-duty diesel engine are shown in Figure 5.25. Note the symmetry about bottom dead center (BDC) of all three profiles.

Figure 5.25 Piston Position from TDC, Velocity, and Acceleration Profiles as a Percentage of Maximum Value

To determine frictional losses, an average piston speed was calculated for each engine at 700, 1400, and 2100 rpm. Using curve A from Figure 5.26 shown below, the motored friction mean effective pressure was determined at these speeds. Using these values and the displacement of the engine, the motored torque values were calculated for each displacement range at each speed. These results are shown in Table 5.2. The results based on mean piston speed agree well with the frictional mean effective pressure value for total motoring loss as a function of engine speed shown in Figure 5.27.

Figure 5.26 Motored Friction Mean Effective Pressure of a Diesel Engine as a Function of Piston Speed [49]

Table 5.2 Average Motoring Mean Effective Pressure and Torque Values for Displacement Ranges I, II, and III

Displacement Range	RPM	mep (bar)	Torque (ft-lb _r)
I (6 L)	700	1.3	45.0
	1400	1.5	51.9
	2100	2.0	69.3
II (9 L)	700	1.3	73.1
	1400	1.7	93.0
	2100	2.3	124.5
III (12 L)	700	1.4	101.1
	1400	1.9	133.4
	2100	2.3	168.5

Figure 5.27 Motored Friction Mean Effective Pressure of a Diesel Engine as a Function of Engine Speed [48]

The frictional mean effective pressure data for all engine configurations are shown in Figure 5.28. It is from this data that the displacement ranges were determined. From the data, three ranges were selected. Range I includes engines of approximately 6 L displacement, Range II includes engines of approximately 9 L displacement, and Range III includes engines of approximately 12 L displacement.

Figure 5.28 Motoring Mean Effective Pressure for Displacement Ranges I, II, and III

These motoring mep calculations do not account for losses due to engine accessories, such as the engine fan, alternator, and air compressor. They are based on essential engine components. Figure 5.29 shows a power comparison for a given engine. The indicated power is based on the engine manufacturer's lug curve plus internal friction. The calculated flywheel power is based on the indicated power minus friction and engine accessory loading. The accessory loading was measured during a parking lot idle test. During an in-use test, it is believed that the ECU broadcast torque value can be an overestimate of the flywheel torque. ECU broadcast torque is most likely based on the engine lug curve, which typically does not account for the accessory loading. However, how an individual engine manufacturer may adjust the broadcast torque value is unknown for this study. Since neither engine dynamometer nor chassis dynamometer tests were conducted for any of the test engines, the broadcast torque value must be accepted and used as brake torque. It is expected that the broadcast torque value is representative of the energy delivered to the piston crown, and thus can be referred to as brake torque.

Figure 5.29 Power Comparison of a Heavy-Duty Diesel Engine of Approximately 12 L Displacement with 450 hp Rating

5.6 Duty Cycle Analysis

The duty cycle analysis of an engine involved determining the amount of time that the engine spent at a given engine speed and load. For each test in this study, the duty cycle was analyzed using the Microsoft Excel macro shown in Appendix C. Engine speed and torque were divided into 100 rpm and 100 ft-lb intervals, respectively. The amount of time spent in each interval was calculated as a percentage of the total test time. Duty cycle plots for each test run conducted in this study are shown in Appendix D. This data provides additional insight on how engines perform during their in-use operation. Also, the duty cycle of an engine during an in-use test may aid in determining if a test is legitimate or not in order to determine failure criteria.

5.7 Test Failure Criteria

The work window method may produce inaccurate or high results if a large amount of engine operation occurs at low engine speeds and low engine torques. As the engine approaches zero brake torque, instantaneous brake-specific emissions values approach infinity asymptotically. For small amounts of work that are potentially infinitesimal values, small errors could accumulate and become significant for the work window interval, and thus yield inaccurate results.

At first glance, it may seem possible to base a failure criterion on the duty cycle of the test. However, duty cycle results by themselves can be misleading. Highway test cycles typically produce a duty cycle with very little time at idle. Urban tests may spend a large portion of test time at idle depending on traffic patterns. There were many tests in this study that support these statements. There are also tests that have atypical duty cycles. For example, Figure 5.30 shows the duty cycle of a highway test with over 9% idle operation. A traffic accident caused interstate traffic to slow or stop near the end of the test. During this time, emissions were still collected. But failure cannot be based solely on duty cycle results. That same vehicle spent over 10% of the test at idle conditions during the WashPA2 route, as can be seen in Figure 5.31. Similar trends were seen for other test vehicles.

Figure 5.30 Duty Cycle for a Highway Test of a 2003 Engine of Approximately 6 L Displacement with 300 hp Rating

Figure 5.31 Duty Cycle for a Urban / Highway Test of a 2003 Engine of Approximately 6 L Displacement with 300 hp Rating

A test failure criterion has been developed by examining the brake power produced by the engine during the work window interval. Although an engine operating at or near idle conditions may meet the work window requirements, it will not produce a high amount of brake power for that given time period. It is thought that a requirement of the work window method should be that the engine produces an amount of power equal to or greater than the amount of power it generates during the FTP certification cycle. Equation 5.7 shows how the amount of power in the window can be calculated from the work window and the window size. The FTP power can be calculated using Equation 5.8. Recall that the FTP is a 20 minute test.

$$WindowPower (bhp) = \frac{WorkWindow (bhp - hr)}{WindowSize (min) \times \left(\frac{1 hr}{60 min} \right)} \quad \text{Equation 5.7}$$

$$FTP Power (bhp) = \frac{FTP Work (bhp - hr)}{20 min \times \left(\frac{1 hr}{60 min} \right)} \quad \text{Equation 5.8}$$

If the window power must be greater or equal to the FTP power, then Equation 5.9 must be true.

$$\frac{WorkWindow(bhp-hr)}{WindowSize(min) \times \left(\frac{1 hr}{60 min}\right)} \geq \frac{FTPWork(bhp-hr)}{20 min \times \left(\frac{1 hr}{60 min}\right)} \quad \text{Equation 5.9}$$

Since the amount of work in the window is theoretically equal to the work performed during the FTP, Equation 5.9 can be rearranged to show that the size of the work window must be less than or equal to 20 minutes in order for the results of the given window to be legitimate. Figure 5.32 shows an in-use highway test where the target work for the test engine was not reached within a 20 minute period for a portion of the test. This failure of the work window method appears to be caused by the engine spending an extended amount of time at idle operation.

Figure 5.32 Example of Work Window Method Failure during an In-Use Highway Test Due to Extended Idle Operation

In the data presented in the following sections, this criterion was used for all tests. For several of the WashPA2 tests, many of the work windows were considered to be invalid, as their duration was greater than 20 minutes. In the plots shown in Appendix D, invalid work windows can be seen where there are breaks in the work window bsNO_x data.

5.8 Phase III Data

The engines used in Phase III of the in-use testing program were built prior to the implementation of the Consent Decrees. These engines do not broadcast a torque value from the ECU. Instead, torque is calculated using the broadcast percent load at a given engine speed and the engine lug curve using the Equation 5.10 [66].

$$InferredTorque_{ft-lb}^{RPM} = \left(\frac{ECULoad_{\%}^{RPM} - IdleECULoad_{\%}^{RPM}}{ECULoad_{\%Max}^{RPM} - IdleECULoad_{\%}^{RPM}} \right) \times MaxTorque_{ft-lb}^{RPM}$$

Equation 5.10

One engine from each displacement range was selected. These engines are shown in Table 5.3. The test routes used for Phase III are designated as WashPA1, WashPA2, and WashPA3.

Table 5.3 Phase III Test Route Index

Test Vehicle ID	Displacement Range	Model Year	Vehicle Application	GVWR (lb)	Approximate Rating (hp)	FTP Theoretical Work (bhp-hr)	Route		
							WashPA1	WashPA2	WashPA3
1	I	1998	Box Truck	25950	200	12.41	XX	XX	XX
2	II	1998	Road Tractor	55000	350	26.83	XX	XX	XX
3	III	1996	Road Tractor	80000	500	32.69	XX	XX	XX

X = Test Weight ≥ 95% of GVWR (West Virginia Legal Limit)

5.8.1 Displacement Range I

A 1998 engine of approximately 200 hp and 6 L displacement was tested twice over three different test routes. The test vehicle was a single axle box truck with a GVWR of 25,950 lb. The FTP NO_x certification level for this engine was 4.0 g/bhp-hr, and the theoretical FTP cycle

work was 12.41 bhp-hr. The average results and standard deviation for each test are shown in Figure 5.33. The spectrum of average work window bsNO_x results was small, ranging from a minimum of 5.830 g/bhp-hr on a WashPA2 test to maximum of 6.547 g/bhp-hr on a WashPA3 test. The overall average of the bsNO_x results was 6.300 ± 0.379 g/bhp-hr. Individual test route averages were 6.123 ± 0.136 g/bhp-hr for the WashPA1 route, 6.053 ± 0.375 g/bhp-hr for the WashPA2 route, and 6.529 ± 0.263 g/bhp-hr for the WashPA3 route. Plots of individual test results can be found in §D.1.

Figure 5.33 Test Route Summary for Test Vehicle 1 – 1998 Engine of Approximately 6 L Displacement with 200 hp Rating

Table 5.4 shows the results of the work window method compared to the accepted 30 second NTE event method for the tests carried out with test vehicle 1. For a given test, the maximum, average, and minimum values are shown for both methods. The maximum values for the work window method were less than those for the NTE method for a given test. The work window average values were roughly equal to or slightly less than the NTE average test results. The minimum test results for the NTE method were significantly lower than the work window method. For test vehicle 1, the work window method had an average range of 0.947 g/bhp-hr while the NTE method had an average range of 3.807 g/bhp-hr. The coefficient of variance of

the work window bsNO_x results for all tests was 6.02%

Table 5.4 Test Vehicle 1 Work Window bsNO_x Results Compared to NTE bsNO_x Results

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
WashPA1	1	6.247	7.493	6.043	6.036	5.755	4.329
	1-R	6.401	7.377	6.207	6.281	5.997	4.194
WashPA2	1	6.701	7.594	5.810	6.073	5.237	3.618
	1-R	6.765	7.983	6.250	6.644	5.763	4.196
WashPA3	1	7.149	7.732	6.547	6.508	5.961	3.321
	1-R	6.918	7.891	6.511	6.507	5.789	3.573

5.8.2 Displacement Range II

A 1998 engine of approximately 9 L displacement and 350 hp was tested over the WashPA1, WashPA2, and WashPA3 routes. Each test was conducted twice. The vehicle was a single axle road tractor with a combined GVWR of 55,000 lb. Test results for the work window method are shown in Figure 5.34. The FTP NO_x certification level for this engine was 4.0 g/bhp-hr and the theoretical cycle work was 26.83 bhp-hr. The engine exhibited higher NO_x values for the WashPA3 route, which is a highway test. The higher values are not surprising, as the engine is most likely operating on the highway control map, which may advance fuel injection timing to improve fuel economy. Advanced injection timing is known to increase NO_x emissions. The test results from this engine reinforce the basis for the Consent Decrees discussed in §1.1. The WashPA2 routes also exhibited large variances in bsNO_x results, due to the fact that the route combines both urban and highway travel. The WashPA1 route, which is short in distance, produced small standard deviations relative to the average results. For all tests, the minimum average bsNO_x value based on work window results was 5.151 g/bhp-hr while the maximum average value was 8.101 g/bhp-hr. The overall average of the results for test vehicle 2 was 6.874 ± 1.594 g/bhp-hr, with a coefficient of variation of 23.19%. For individual test routes, the average work window bsNO_x values were 5.451 ± 0.234 g/bhp-hr, 5.372 ± 1.538 g/bhp-hr, and 7.962 ± 0.586 g/bhp-hr for the WashPA1, WashPA2, and WashPA3 routes, respectively.

Figure 5.34 Test Route Summary for Test Vehicle 2 – 1998 Engine of Approximately 9 L Displacement with 350 hp Rating

Table 5.5 shows the maximum, average, and minimum work window results compared to those of the NTE method for test vehicle 2. Similar to the results for test vehicle 1, the maximum bsNO_x values for the work window method were less than the maximum values for the NTE method. However, the average values, like the minimum values, were greater than those of the NTE method for most tests. The average range of values for the work window method was 2.740 g/bhp-hr. The average range of values for the NTE method was 6.164 g/bhp-hr. The WashPA3 route caused the engine to generate a significantly higher amount of NO_x (over 47%) than the WashPA1 and WashPA2 routes. Individual test results for test vehicle 2 can be found in §D.2.

Table 5.5 Test Vehicle 2 Work Window bsNO_x Results Compared to NTE bsNO_x Results

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
WashPA1	2	5.522	4.477	5.271	4.087	4.830	2.502
	2-R	5.911	10.584	5.645	4.922	5.439	2.912
WashPA2	2	8.377	9.350	5.151	5.132	3.848	2.868
	2-R	8.673	10.028	5.594	5.707	3.555	2.947
WashPA3	2	8.481	8.984	7.833	7.347	5.738	2.938
	2-R	9.013	10.632	8.101	7.715	6.127	2.906

5.8.3 Displacement Range III

The results of a 1996 engine of approximately 12 L displacement and 500 hp are shown in Figure 5.35 and Table 5.6. The vehicle was a road tractor with a combined GVWR of 80,000 lb. This engine was also certified to a level of 4.0 g/bhp-hr for NO_x over the FTP cycle. The target FTP work for this engine was 32.69 bhp-hr. The average bsNO_x values for both the WashPA1 and WashPA2 routes were roughly equal to the certification level of the engine. However, during the highway test, WashPA3, the engine generated 24% higher bsNO_x compared to the other routes. The overall average work window bsNO_x level was 4.435 ± 0.587 g/bhp-hr, resulting in a coefficient of variance of 13.23%. The WashPA1, WashPA2, and WashPA3 routes had test result averages of 3.678 ± 0.339 g/bhp-hr, 4.050 ± 0.493 g/bhp-hr, and 4.775 ± 0.372 g/bhp-hr, respectively. Individual test results for test vehicle 3 can be seen in §D.3.

Figure 5.35 Test Route Summary for Test Vehicle 3 – 1996 Engine of Approximately 12 L Displacement with 500 hp Rating

Table 5.6 shows the work window results compared to the NTE results for test vehicle 3. The work window results compared to the NTE results in a similar fashion to that of test vehicles 1 and 2. The average range of work window bsNO_x values was 1.141 g/bhp-hr. The average range of NTE bsNO_x values was 2.125 g/bhp-hr.

Table 5.6 Test Vehicle 3 Work Window bsNO_x Results Compared to NTE bsNO_x Results

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
WashPA1	3	3.509	3.280	3.327	2.905	3.166	2.756
	3-R	4.174	3.281	3.977	3.083	3.753	2.952
WashPA2	3	4.958	5.305	3.856	3.957	3.524	2.472
	3-R	5.641	5.495	4.223	4.219	3.803	2.596
WashPA3	3	5.564	5.484	4.747	4.485	3.968	2.581
	3-R	5.319	5.928	4.804	4.858	4.104	2.668

5.8.4 Phase III Conclusions

The data used in this study from Phase III vehicles showed that although the work window method is based on ECU broadcast torque, the approach can be used on older vehicles that broadcast a percent load value. The accuracy of both inferred torque and broadcast torque values should not differ significantly from one another, as both values are strongly based on ECU fueling data. The plots in Appendix D show that a definite difference exists for these pre-Consent Decree engines between the bsNO_x results for urban travel and highway travel. Highway bsNO_x emissions, on average, were 26% higher than urban bsNO_x emissions. This fact is not a new discovery, as mentioned previously, as it was the basis for the Consent Decrees. For most tests, the range of bsNO_x emissions based on a work window was less than the range of bsNO_x emissions based on a 30 second NTE window.

A trend exhibited by many of the Phase III vehicles was that repeat tests of a given route produced higher NO_x levels, while the standard deviations for these repeat tests remained nearly the same. The difference in results could be a function of ambient conditions, test fuel, and test driver, to name a few possibilities. However, the evaluation of these parameters was not a paramount objective of this study.

5.9 Phase IV Data

Twenty-eight of the engine / vehicle combinations tested during Phase IV of the Consent Decree in-use testing program conducted by West Virginia University for the settling heavy-duty diesel engine manufacturers were selected for this study. These engines were selected to represent a mix of engine manufacturers and a mix of applications. Engines were also selected so that comparisons may be made according to displacement, model year, engine technology, application, and test route. The engines selected for this study, their vehicle configuration, and their test route identification are given in Table 5.7.

The test vehicles were grouped according to the engine's certification family as given by the US EPA. The engine certification family identification numbers are not included here in order to retain engine manufacturer anonymousness, due to the sensitive nature of the data. All of the plots of the results of the individual tests for Phase IV vehicles can be found in §D.4, §D.5, and §D.6.

Table 5.7 Phase IV Test Route Index

Test Vehicle ID	Displacement Range	Model Year	Vehicle Application	GVWR (lb)	Approximate Rating (hp)	FTP Theoretical Work (bhp-hr)	Route								
							Mrgtwn	Sab2Wash	WashPA1	WashPA2	WashPA32Sab	NJ1	NJ2	NJ3	NJ4
4	I	2003	Transit Bus	32300	300	17.84		X	X	X	X				
5	I	2003	Transit Bus	32300	300	17.84		X	X	X	X				
6	I	2003	Transit Bus	32300	300	17.84		X	X	X	X				
7	I	2003	Transit Bus	32300	300	17.84		X	X	X	X				
8	II	2003	Transit Bus	55000	350	24.43	X		X	X	X	X	X	X	X
9	II	2003	Transit Bus	55000	350	24.43						X	X	X	X
10	II	2003	Transit Bus	55000	350	24.43						X	X	X	X
11	II	2003	Transit Bus	55000	350	24.43						X	X	X	X
12	II	2001	Transit Bus	34600	300	19.08		X	X	X	X				
13	II	2001	Transit Bus	34600	300	19.08		X	X	X	X				
14	II	2001	Transit Bus	34600	300	19.08	X	X	XX	XX	XX				
15	II	2001	Transit Bus	34600	300	19.08	X		X	X	X				
16	II	2003	Transit Bus	34600	300	18.94		X	X	X	X				
17	II	2003	Transit Bus	34600	300	18.94		X	XX	XX	XX				
18	II	2003	Transit Bus	34600	300	18.94	X	X	X	X	X				
19	II	2003	Transit Bus	34600	300	18.94		X	X	X	X				
20	II	2003	Road Tractor	80000	400	27.22	L	X	X L	X L	X L				
21	II	2003	Road Tractor	80000	350	24.41	X	L	X L	X L	X L				
22	II	2003	Road Tractor	65000	350	24.41	X		X	X	X				
23	II	2003	Road Tractor	80000	400	27.22	X	L	XX L	X L	X L				
24	III	2002	Transit Bus	54400	400	25.74		XX	XX*	X	X				
25	III	2002	Transit Bus	54400	400	25.74	X		X	X	X				
26	III	2002	Transit Bus	54400	400	25.74		X	X	X	X				
27	III	2002	Transit Bus	54400	400	25.74	X	X	X	X	X				
28	III	2001	Dump Truck	63000	450	34.28	X		X	X	X				
29	III	2001	Road Tractor	80000	400	30.63		X L	X LL	X LL	X LL				
30	III	2003	Road Tractor	80000	450	33.09	L	X	X L	X L	X L				
31	III	2003	Road Tractor	80000	400	30.22	XX	XX LL	XX LL	XX LL	XX LL				

X = Test Weight ≥ 95% of GVWR (West Virginia Legal Limit)

L = Test Weight ~ 60,000 lb

*Combined WashPA1 and WashPA2

5.9.1 Displacement Range I

Four 2003 model year engines of approximately 6 L displacement and 300 hp rating were tested over the Pittsburgh test route. The engines were in four identical transit buses, each with a GVWR of 32,300 lb. The engines were certified to a $\text{NO}_x + \text{NMHC}$ level of 2.5 g/bhp-hr. The average bsNO_x results from a work window of 17.84 bhp-hr are shown in Figure 5.36. The error bars on the chart represent one standard deviation of the data from the respective test. The average bsNO_x value for the Sab2Wash test was 2.531 g/bhp-hr with a standard deviation of 0.251 g/bhp-hr. The average plus or minus the standard deviation for the WashPA1, WashPA2, and WashPA32Sab routes were 2.343 ± 0.197 g/bhp-hr, 2.658 ± 0.359 g/bhp-hr, and 2.603 ± 0.345 g/bhp-hr, respectively. The smaller the standard deviation, and thus the smaller the coefficient of variance, the more repeatable the results were. The test results of test vehicles 4, 5, 6, and 7 showed that for most tests, the engines emitted NO_x levels close to their FTP certification level. The two exceptions were the WashPA2 and WashPA32Sab routes for test vehicle 5. The overall average bsNO_x value for these engines was 2.576 ± 0.323 g/bhp-hr, with a coefficient of variance of 12.52%. The individual averages for test vehicles 4, 5, 6, and 7, were 2.499 ± 0.166 g/bhp-hr, 2.848 ± 0.367 g/bhp-hr, 2.558 ± 0.338 g/bhp-hr, and 2.387 ± 0.137 g/bhp-hr, respectively.

Figure 5.36 Test Route Summary for Test Vehicles 4, 5, 6, and 7 – 2003 Engines of Approximately 6 L Displacement with 300 hp Rating

The results of these test vehicles are compared to the NTE results in Table 5.8. The plots from the individual tests can be seen in §D.4. The average range of bsNO_x values based on a work window of 17.84 bhp-hr for these engines was 0.823 g/bhp-hr, while the average range for the NTE bsNO_x values was 1.574 g/bhp-hr.

Table 5.8 Test Vehicles 4, 5, 6, and 7 Work Window bsNO_x Results Compared to NTE bsNO_x Results

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
Sab2Wash	4	2.764	2.895	2.493	2.481	2.157	1.357
	5	2.963	2.795	2.646	2.419	2.299	1.092
	6	3.532	3.271	2.600	2.321	1.881	1.287
	7	2.648	2.878	2.367	2.340	2.084	1.298
WashPA1	4	2.566	2.160	2.292	1.849	2.149	1.484
	5	3.035	2.284	2.595	2.002	2.342	1.726
	6	2.352	2.080	2.251	1.830	2.196	1.664
	7	2.347	1.968	2.185	1.824	2.042	1.596
WashPA2	4	3.082	2.973	2.674	2.175	2.286	1.508
	5	3.729	2.560	2.977	2.143	2.314	1.449
	6	3.127	2.493	2.512	1.897	2.084	1.292
	7	2.713	2.906	2.460	2.195	2.157	1.226
WashPA32Sab	4	2.849	3.114	2.453	2.286	2.208	0.667
	5	4.129	4.202	2.958	2.351	2.507	0.805
	6	3.106	3.653	2.577	2.369	1.847	0.781
	7	2.770	3.218	2.392	2.255	1.985	1.030

5.9.2 Displacement Range II

Figure 5.37 shows the test results of test vehicles 8, 9, 10, and 11. These vehicles were articulating transit buses with a GVWR of 55,000 lb. The engines were of approximately 9 L in displacement and had a rating in the order of 350 hp, and the FTP target work was 24.43 bhp-hr. All of these vehicles were tested over the New Jersey test route. Test vehicle 8 was tested over both the Pittsburgh and New Jersey test routes. The NO_x + NMHC certification requirement for these engines was 2.5 g/bhp-hr. Although not significant in this study, the engines were equipped with a PM aftertreatment system. Ultra low-sulfur diesel fuel had to be used when testing these engines so that the aftertreatment system would not be contaminated.

Figure 5.37 Test Route Summary for Test Vehicles 8, 9, 10, and 11 – 2003 Engines of Approximately 9 L Displacement with 350 hp Rating

The average bsNO_x value for test vehicle 8 over the Pittsburgh test route (with the Mrgtwn route replacing the Sab2Wash route) was 1.764 ± 0.151 g/bhp-hr, compared to an average bsNO_x value of 1.871 ± 0.167 g/bhp-hr for the New Jersey test route. For all vehicles, the average bsNO_x value for the New Jersey test route was 2.086 ± 0.226 g/bhp-hr. Concerning individual test legs, the NJ1 test yielded an average of 2.134 ± 0.224 g/bhp-hr, the NJ2 test an average of 2.105 ± 0.202 g/bhp-hr, the NJ3 test an average of 2.001 ± 0.230 g/bhp-hr, and the NJ4 test an average of 2.096 ± 0.156 g/bhp-hr. All of these values were well below the FTP NO_x certification requirement for these engines. Test vehicles 8, 9, 10, and 11, respectively, produced average work window bsNO_x values of 1.819 ± 0.169 g/bhp-hr, 2.186 ± 0.126 g/bhp-hr, 2.329 ± 0.144 g/bhp-hr, and 1.954 ± 0.099 g/bhp-hr. The overall average for all tests for all vehicles was 2.027 ± 0.248 g/bhp-hr, with a coefficient of variance of 12.22%.

Table 5.9 compares the work window bsNO_x results to the NTE bsNO_x results for these test vehicles. The work window method produced a narrow range of results for these engines, with an average value of 0.40 g/bhp-hr. The average range for the NTE method was 1.2 g/bhp-hr. For the work window method, only one engine on one test produced bsNO_x levels above 2.5 g/bhp-hr. Test vehicle 10 had a maximum bsNO_x value of 2.622 g/bhp-hr on the NJ2 test route.

The conventional 30 second window NTE method produced several maximum values above 2.5 g/bhp-hr for several engines.

Table 5.9 Test Vehicles 8, 9, 10, and 11 Work Window bsNO_x Results Compared to NTE bsNO_x Results

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
Mrgtwn	8	2.162	2.419	1.891	1.916	1.717	0.627
WashPA1	8	1.722	2.207	1.622	1.776	1.531	1.299
WashPA2	8	1.881	2.390	1.703	2.034	1.476	1.494
WashPA32Sab	8	2.266	3.215	1.774	1.129	1.388	4.640E-07
NJ1	8	2.197	2.459	1.951	2.080	1.725	1.435
	9	2.554	2.887	2.201	2.307	1.969	1.642
	10	2.691	3.156	2.413	2.444	2.150	1.611
	11	2.211	2.601	1.968	1.991	1.737	1.161
NJ2	8	2.158	2.005	1.985	1.848	1.777	1.374
	9	2.252	2.168	2.073	2.003	1.913	1.676
	10	2.622	2.346	2.393	2.108	2.185	1.704
	11	2.102	2.256	1.961	1.916	1.878	1.647
NJ3	8	1.910	2.321	1.674	2.005	1.463	1.562
	9	2.306	2.719	2.164	2.276	2.038	1.642
	10	2.407	2.791	2.233	2.300	2.063	1.539
	11	2.067	2.447	1.925	1.970	1.776	1.211
NJ4	8	2.080	2.435	1.985	2.051	1.903	1.618
	9	2.480	2.761	2.252	2.281	2.105	1.433
	10	2.431	3.518	2.192	2.299	2.013	1.417
	11	2.071	2.395	1.967	1.971	1.867	1.456

A particular concern with these engines was that fact that this particular engine manufacturer did not accurately broadcast engine torque outside of the NTE region. As can be seen in some of the figures in §D.4 for these test vehicles, the engine torque was initially broadcast for all operating ranges. Figure D.73 and Figure D.81 show this pattern. After an initial period of seemingly correct operation, the minimum torque value for all engine speeds became approximately 284 ft-lb, just below 30% of the maximum torque value of the engine, or the lower limit of the NTE region. This method of broadcasting torque did not affect the NTE method of calculating emissions, but introduced error in the work window method. The work window method produced a greater amount of work than the engine was actually producing, as the reported torque values were higher than the actual torque values.

For these engines, when operating outside of the NTE region, erroneous values of torque were broadcast by the ECU. In order to use a continuous torque signal, in the post processing

software, MEMS linearly interpolated the value from the last known valid torque value to the next valid torque value. Doing this interpolation may have caused MEMS to miss some variance in the torque signal at low engine loads. Again, this process will adversely affect the work window method. It is for these reasons that this particular engine manufacturer's engines were evaluated only once during the course of this study.

Four 2001 engines of approximately 9 L displacement and 300 hp were tested over the Mrgtwn and Pittsburgh test routes. The results are shown in Figure 5.38. These vehicles were transit buses with a GVWR of 34,600 lb. The theoretical FTP work was calculated to be 19.08 bhp-hr. The FTP NO_x certification requirement for these engines was 4.0 g/bhp-hr. The results were fairly consistent, with one exception. Test vehicle 12 produced a much higher amount of NO_x during the Sab2Wash test than it did during any other test. Figure D.109 shows that during the initial period of the Sab2Wash route, the bsNO_x values were like that of other tests, at or around 4.0 g/bhp-hr. A shift then occurred, and bsNO_x values increased to values between approximately 6 and 8 g/bhp-hr. This increase was most likely due to a failure of the exhaust gas recirculation system (see §3.3.2). However, the problem must have been intermittent, as the bsNO_x values were lower for the remaining tests of the vehicle. The average bsNO_x value for all tests was 3.533 ± 0.807 g/bhp-hr, with a coefficient of variance equal to 22.85%. The average value for the Mrgtwn test was 3.514 ± 0.184 g/bhp-hr; the Sab2Wash test, 3.997 ± 1.542 g/bhp-hr; the WashPA1 test, 3.442 ± 0.311 g/bhp-hr; the WashPA2 test, 3.505 ± 0.315 g/bhp-hr; the WashPA32Sab test, 3.319 ± 0.283 g/bhp-hr. Concerning individual test vehicles, the average work window bsNO_x result for test vehicle 12 was 4.250 ± 1.394 g/bhp-hr; for test vehicle 13, 3.005 ± 0.203 g/bhp-hr; for test vehicle 14, 3.342 ± 0.236 g/bhp-hr; for test vehicle 15, 3.687 ± 0.193 g/bhp-hr.

Figure 5.38 Test Route Summary for Test Vehicles 12, 13, 14, and 15 – 2001 Engines of Approximately 9 L Displacement with 300 hp Rating

Table 5.10 shows the work window bsNO_x results for test vehicles 12 – 15 compared to those from the NTE approach. Including the high Sab2Wash test of test vehicle 12, the range of values averaged 0.930 g/bhp-hr for the work window method and 2.567 g/bhp-hr for the NTE approach. The maximum value from the work window method for most of the tests was less than the FTP certification NO_x standard for these engines.

Table 5.10 Test Vehicles 12, 13, 14, and 15 Work Window bsNO_x Results Compared to NTE bsNO_x Results

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
Mrgtwn	14	3.913	5.098	3.425	3.612	3.159	2.769
	15	3.947	4.075	3.626	3.670	3.418	3.192
Sab2Wash	12	8.011	8.957	5.754	7.065	3.439	3.480
	13	3.193	4.059	2.880	2.788	2.573	0.052
	14	4.327	10.422	3.316	3.661	2.989	3.198
WashPA1	12	3.809	5.015	3.582	3.712	3.450	2.007
	13	3.159	2.829	2.741	1.682	2.658	0.546
	14	3.380	3.452	3.274	2.939	3.203	2.411
	14-R	3.810	4.262	3.502	3.203	3.272	2.214
	15	3.907	4.935	3.707	3.484	3.587	2.232
WashPA2	12	4.093	4.185	3.719	3.553	3.356	2.496
	13	3.767	4.418	3.136	2.458	2.694	1.306
	14	3.929	4.476	3.462	2.969	3.196	2.328
	14-R	4.187	3.371	3.719	2.964	2.857	2.588
	15	4.133	4.135	3.749	3.762	3.441	2.421
WashPA32Sab	12	3.802	4.063	3.329	3.396	2.997	1.839
	13	3.608	4.521	3.074	2.694	2.750	1.271
	14	3.590	4.341	3.136	3.214	2.835	2.539
	14-R	3.936	4.612	3.379	3.609	3.024	2.584
	15	4.339	4.300	3.668	3.626	3.342	2.723

Figure 5.39 shows test results from four model year 2003 engines of approximately 9 L displacement and 300 hp. These engines were a newer version of the ones found in test vehicles 12 – 15, as they were certified to a lower NO_x level than their predecessors. The theoretical FTP work was 18.94 bhp-hr, slightly lower than that of their predecessors. The FTP NO_x + NMHC certification level for these engines was 2.7 g/bhp-hr, which was above the standard of 2.5 g/bhp-hr. The test vehicles were transit buses with a GVWR of 34,600 lb, identical to test vehicles 12 – 15, and were tested over the Morgantown and Pittsburgh test routes. At first glance, the data in the figure would lead one to think that these engines behave more like a 2001 model year engine from their NO_x emissions levels. Test vehicle 18 had higher NO_x emissions than the others, and generally had a larger variation in its results. The exhaust gas recirculation systems on these particular engines were believed to be problematic, and AECDS may have become active during the course of the tests. However, since engine faults were not apparent, the tests were believed to be valid based on the established MEMS and Consent Decree testing protocols.

The overall bsNO_x average for this family of engines was 2.949 ± 0.651 g/bhp-hr based on an FTP work window. For individual tests, the averages (where applicable) were 2.565 ±

0.681 g/bhp-hr, 3.268 ± 0.396 g/bhp-hr, 3.319 ± 0.564 g/bhp-hr, and 2.814 ± 0.542 g/bhp-hr for the Sab2Wash, WashPA1, WashPA2, and WashPA32Sab test routes, respectively. As seen in the figure, the lone Mrgtwn route had a work window bsNO_x result of 3.610 ± 0.268 g/bhp-hr. The average work window bsNO_x results for test vehicles 16, 17, 18, and 19, respectively, were 2.516 ± 0.311 g/bhp-hr, 2.721 ± 0.597 g/bhp-hr, 3.669 ± 0.549 g/bhp-hr, and 2.965 ± 0.321 g/bhp-hr.

Figure 5.39 Test Route Summary for Test Vehicles 16, 17, 18, and 19 – 2003 Engines of Approximately 9 L Displacement with 300 hp Rating

Table 5.11 compares the work window results to the NTE results for test vehicles 16 – 19. The average range of work window bsNO_x values was 1.171 g/bhp-hr while the average range for the NTE results was 2.179 g/bhp-hr. Both of these values are significant compared to the NO_x certification level of the engine. This fact, along with the large standard deviations in average test results and a coefficient of variation of 22.09% for the work window bsNO_x results, reinforces the idea that these engines did not produce repeatable bsNO_x results for either approach.

Table 5.11 Test Vehicles 16, 17, 18, and 19 Work Window bsNO_x Results Compared to NTE bsNO_x Results

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
Mrgtwn	18	4.303	4.502	3.610	3.026	3.043	2.342
Sab2Wash	16	2.963	3.380	2.465	2.160	2.062	1.696
	17	2.344	2.569	1.828	1.623	1.528	1.228
	18	5.565	5.918	3.335	2.977	2.335	1.782
	19	3.677	3.981	2.804	2.481	2.403	2.011
WashPA1	16	3.001	3.117	2.771	2.090	2.510	1.598
	17	3.210	4.077	3.092	3.033	2.994	2.023
	17-R	3.492	4.250	3.365	3.444	3.245	2.301
	18	4.194	4.496	3.804	2.999	3.364	2.295
	19	3.813	5.220	3.310	3.837	2.900	2.584
WashPA2	16	3.377	3.320	2.837	2.359	2.103	1.608
	17	3.923	3.531	3.160	2.334	2.329	1.536
	17-R	3.913	4.443	3.377	2.750	2.394	1.859
	18	4.700	3.829	3.993	3.002	2.886	2.331
	19	3.425	3.543	3.075	2.481	2.489	1.916
WashPA32Sab	16	2.696	2.940	2.289	2.009	1.891	1.441
	17	3.044	3.718	2.537	2.329	2.167	1.580
	17-R	3.265	3.546	2.739	2.354	2.296	1.569
	18	4.907	5.939	3.661	3.450	2.673	1.951
	19	3.615	4.770	2.948	2.570	2.396	1.864

Two road tractors with 2003 engines of approximately 9 L displacement and 400 hp were tested in this study over the Morgantown and Pittsburgh test routes. Both vehicles were tandem axle road tractors and had a combined legal GVWR of 80,000 lb. The target FTP work for these engines was 27.22 bhp, and the FTP NO_x + NMHC certification level was 2.5 g/bhp-hr. The vehicles were tested at two different test weights, 80,000 lb and 60,000 lb in accordance with the requirements of the Consent Decrees. The results from these tests are shown in Figure 5.40.

Test vehicle 23 produced lower NO_x values than test vehicle 20 for all test routes and test weights. The overall average work window bsNO_x value for test vehicle 20 was 2.561 ± 0.199 g/bhp-hr, with the average for the 80,000 lb test weight being 2.637 ± 0.2045 g/bhp-hr, and an average value of 2.474 ± 0.151 g/bhp-hr for the 60,000 lb test weight. The overall average work window bsNO_x value for test vehicle 23 was 2.043 ± 0.164 g/bhp-hr, with a an average value of 2.014 ± 0.177 g/bhp-hr for the 80,000 lb test weight and also 2.071 ± 0.145 g/bhp-hr for the 60,000 lb test weight. Test weight did not seem to have a significant amount of influence on the results of either vehicle.

The overall average for all of the tests of test vehicles 20 and 23 was 2.300 ± 0.317 g/bhp-hr, with a coefficient of variance of 13.77%. For individual test routes, combining both test weights for each vehicle, the average work window bsNO_x value for the Mrgtwn route was 2.179 ± 0.176 g/bhp-hr. The average for the Sab2Wash route was 2.342 ± 0.214 g/bhp-hr. The WashPA1 route produced an average bsNO_x value of 2.172 ± 0.229 g/bhp-hr, while the WashPA2 route produced an average bsNO_x result of 2.362 ± 0.335 g/bhp-hr. Finally, the WashPA32Sab route yielded an average work window bsNO_x value of 2.309 ± 0.363 g/bhp-hr.

Figure 5.40 Test Route Summary for Test Vehicles 20 and 23 – 2003 Engines of Approximately 9 L Displacement with 400 hp Rating

Table 5.12 shows the work window results for test vehicles 20 and 23 for the work window method compared to the results for the NTE method. The work window method produced results ranging from 1.543 g/bhp-hr for test vehicle 23 to 3.171 g/bhp-hr for test vehicle 20. The average range of values for a given test was 0.539 g/bhp-hr. The average range of bsNO_x values based on a 30 second window of engine operation within the NTE zone was 1.714 g/bhp-hr.

**Table 5.12 Test Vehicles 20 and 23 Work Window bsNO_x Results Compared to NTE
bsNO_x Results**

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
Mrgtwn 80k	23	2.417	2.919	2.047	2.091	1.837	1.318
Mrgtwn 60k	20	2.733	2.882	2.314	1.973	2.141	0.417
Sab2Wash 80k	20	2.724	3.116	2.532	2.442	2.329	1.880
Sab2Wash 60k	23	2.571	3.101	2.164	2.102	1.877	0.727
WashPA1 80k	20	2.473	2.669	2.250	2.118	2.069	1.577
	23	2.189	2.352	2.023	1.816	1.858	1.489
	23-R	2.207	2.677	2.119	1.907	2.049	1.607
WashPA1 60k	20	2.714	2.442	2.494	2.012	2.339	1.578
	23	2.171	2.163	1.892	1.711	1.790	1.321
WashPA2 80k	20	3.171	3.166	2.725	2.554	2.459	1.822
	23	2.468	3.082	2.055	1.934	1.748	1.056
WashPA2 60k	20	2.733	3.435	2.533	2.363	2.387	0.981
	23	2.371	2.432	2.080	1.647	1.806	0.953
WashPA32Sab 80k	20	3.004	3.442	2.738	2.695	2.540	1.862
	23	2.427	2.858	1.956	1.905	1.543	0.495
WashPA32Sab 60k	20	3.005	3.276	2.507	1.917	2.024	2.887E-04
	23	2.305	3.086	2.024	1.981	1.721	0.874

Two engines similar in all specifications to those of test vehicles 20 and 23 except rating were tested over the Morgantown and Pittsburgh routes. Test vehicles 21 and 22 had 2003 engines of approximately 9 L displacement and 350 hp rating. The theoretical FTP work for these two engines was 24.41 bhp-hr, and the FTP NO_x + NMHC certification level was 2.5 g/bhp-hr. Test vehicle 21 was a tandem axle road tractor with a combined GVWR of 80,000 lb, while test vehicle 22 was a single axle road tractor with a combined GVWR of 65,000 lb. Test vehicle 21 was tested at two weights, 80,000 lb and 60,000 lb. Figure 5.41 shows the test results from the engines of these vehicles. The overall average test result for test vehicle 21 was 2.335 ± 0.281 g/bhp-hr, with the 80,000 lb test average being 2.306 ± 0.255 g/bhp-hr and the 60,000 lb test average being 2.359 ± 0.299 g/bhp-hr. The overall average for test vehicle 22 was 2.094 ± 0.276 g/bhp-hr. The average for all tests of test vehicles 21 and 22 was 2.261 ± 0.301 g/bhp-hr, producing a coefficient of variance of 13.29%. As with test vehicles 20 and 23, the test weight did not seem to be a crucial factor in determining bsNO_x emissions levels for test vehicles 21 and 22.

Figure 5.41 Test Route Summary for Test Vehicles 21 and 22 – 2003 Engines of Approximately 9 L Displacement with 350 hp Rating

The results for test vehicles 21 and 22 for all tests comparing work window bsNO_x values to NTE bsNO_x values are shown in Table 5.13. The maximum work window value for any given test was less than the NTE bsNO_x value, a trend seen in most of the data to this point in this study. The average range of bsNO_x values for the work window method was 0.896 g/bhp-hr while the NTE method yielded an average range of 2.544 g/bhp-hr, which was slightly greater than the NO_x certification level for these engines.

The average work window bsNO_x result for the Mrgtwn route for these vehicles was 2.072 ± 0.374 g/bhp-hr. The average results for the Sab2Wash, WashPA1, WashPA2, and WashPA32Sab routes, respectively, were 2.568 ± 0.262 g/bhp-hr, 2.165 ± 0.316 g/bhp-hr, 2.105 ± 0.190 g/bhp-hr, and 2.341 ± 0.235 g/bhp-hr. Although the Sab2Wash route produced the highest average bsNO_x value, test route did not seem to greatly influence these engines.

**Table 5.13 Test Vehicles 21 and 22 Work Window bsNO_x Results Compared to NTE
bsNO_x Results**

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
Mrgtwn 80k	21	2.980	3.288	2.318	2.558	1.921	1.495
Mrgtwn 60k	22	2.627	2.843	1.821	1.822	1.522	0.557
Sab2Wash 60k	21	2.978	3.701	2.568	2.383	1.744	3.561E-03
WashPA1 80k	21	2.829	3.742	2.630	2.669	2.268	1.557
WashPA1 60k	21	2.413	2.958	2.130	1.677	1.982	1.231
	22	2.058	2.326	1.872	1.791	1.596	0.994
WashPA2 80k	21	2.778	3.242	2.184	2.236	1.815	9.050E-02
WashPA2 60k	21	2.755	2.952	2.158	1.783	1.822	6.188E-02
	22	2.389	2.896	1.982	2.016	1.794	0.885
WashPA32Sab 80k	21	2.655	3.480	2.316	2.219	1.502	3.277E-03
WashPA32Sab 60k	21	3.210	3.601	2.371	1.943	1.853	0.000E+00
	22	2.717	3.310	2.338	2.348	1.820	0.934

5.9.3 Displacement Range III

Figure 5.42 shows test results from four identical 2002 engines of approximately 12 L displacement and 400 hp rating. These engines were in articulating transit buses with a GVWR of 54,400 lb, similar to the articulating transit buses of test vehicles 8 – 11. Tests were performed over the Morgantown and Pittsburgh test routes. The theoretical FTP work for these engines was 25.74 bhp-hr, and the FTP NO_x certification level was 4.0 g/bhp-hr, as they were built prior to October 2002.

The overall work window bsNO_x average for test vehicles 24 through 27 was 6.233 ± 0.600 g/bhp-hr for all tests, with a coefficient of variance of 9.63%. The average result for the Mrgtwn route was 6.199 ± 0.774 g/bhp-hr; the Sab2Wash route, 6.185 ± 0.298 g/bhp-hr; the WashPA1 route, 6.147 ± 0.595 g/bhp-hr; the WashPA2 route 6.112 ± 0.702 g/bhp-hr; the WashPA32Sab route, 6.378 ± 0.649 g/bhp-hr. It is worth noting that the combined WashPA1 and WashPA2 route, shown as the second WashPA1 route for test vehicle 24, produced lower NO_x results than when the two routes were tested separately with test vehicle 24.

Figure 5.42 Test Route Summary for Test Vehicles 24, 25, 26, and 27 – 2002 Engines of Approximately 12 L Displacement with 400 hp Rating

Table 5.14 shows the work window results of test vehicles 24 – 27 compared the NTE results obtained using MEMS. Test vehicle 24 yielded an average bsNO_x value of 6.798 ± 0.595 g/bhp-hr for the work window method. Test vehicles 25, 26, and 27 yielded average work window bsNO_x values of 5.535 ± 0.085 g/bhp-hr, 5.966 ± 0.252 g/bhp-hr, and 6.174 ± 0.486 g/bhp-hr, respectively. The average range of bsNO_x values from the work window method was 0.831 g/bhp-hr compared to a range of 2.027 g/bhp-hr for the NTE method.

Table 5.14 Test Vehicles 24, 25, 26, and 27 Work Window bsNO_x Results Compared to NTE bsNO_x Results

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
Mrgtwn	25	5.719	6.255	5.444	5.601	5.196	4.630
	27	7.591	7.188	6.879	6.492	6.369	5.308
Sab2Wash	24	6.934	7.486	6.546	6.559	6.248	5.363
	24-R	6.515	7.063	6.202	6.188	5.953	5.113
	26	6.527	7.094	6.157	6.234	5.954	5.083
	27	6.228	6.703	5.817	5.767	5.507	4.805
WashPA1	24	7.890	7.738	7.521	6.845	7.242	5.944
	24-R	6.739	7.118	6.102	6.263	5.664	5.328
	25	5.838	6.365	5.484	5.770	5.222	4.476
	26	6.203	6.698	5.857	6.220	5.610	4.930
	27	6.030	6.390	5.707	5.591	5.424	3.412
WashPA2	24	7.855	7.788	7.145	6.977	6.110	5.817
	25	5.926	6.285	5.622	5.734	5.241	4.581
	26	6.252	6.731	5.663	5.983	5.401	3.093
	27	6.604	6.276	6.014	5.545	5.355	4.650
WashPA32Sab	24	8.041	8.232	7.274	7.057	6.624	6.007
	25	5.913	6.318	5.591	5.637	5.299	4.534
	26	6.539	7.017	6.189	6.270	5.919	5.135
	27	6.906	7.285	6.451	6.492	6.120	5.304

Figure 5.43 shows the test results of two 2001 engines of approximately 12 L displacement. Test vehicle 28, a quad-axle dump truck with a GVWR of 63,000 lb, had an engine of approximately 450 hp. Test vehicle 29, a tandem-axle road tractor, had a combined GVWR of 80,000 lb, with an engine of approximately 400 hp. This vehicle was tested at two weights. The FTP NO_x certification level for these engines was 4.0 g/bhp-hr. The theoretical FTP work for the engine in test vehicle 28 was 34.26 bhp-hr, while the theoretical FTP work for the engine in test vehicle 29 was 30.63 bhp-hr.

The results from test vehicle 28 showed lower results during urban operation than during highway operation. These results indicated that the engine's highway timing map was most like advanced to improve fuel economy, but in turn, increased NO_x emissions. The larger variations on the Mrgtwn and WashPA2 routes were due to lower NO_x emissions during the urban segments of the routes and higher NO_x emissions during the highway portions of the routes. The overall average work window bsNO_x results for test vehicle 28 was 4.532 ± 0.420 g/bhp-hr.

Test vehicle 29 produced NO_x emissions at or below its engine's certification level for all tests except the retest over the WashPA32Sab route. Even during this particular run, the average value was under 4.0 g/bhp-hr. The variation caused the bsNO_x value to exceed the 4.0 g/bhp-hr

standard. The overall average test result for test vehicle 29 was 3.459 ± 0.453 g/bhp-hr. The average bsNO_x value for the 80,000 lb test was 3.288 ± 0.468 g/bhp-hr, and the average for the 60,000 lb test was 3.577 ± 0.402 g/bhp-hr.

The overall work window test average for this particular engine family was 3.717 ± 0.639 g/bhp-hr, with a coefficient of variance of 17.19%. The Mrgtwn route produced a bsNO_x average of 4.160 ± 0.313 g/bhp-hr for the work window method. For the Pittsburgh test route, the Sab2Wash route resulted in an average of 3.601 ± 0.251 g/bhp-hr, the WashPA1 resulted in an average of 3.018 ± 0.585 g/bhp-hr, the WashPA2 route yielded an average of 3.425 ± 0.744 g/bhp-hr, and the WashPA32Sab route yielded an average of 4.004 ± 0.550 g/bhp-hr.

Figure 5.43 Test Route Summary for Test Vehicles 28 and 29 – 2001 Engines of Approximately 12 L Displacement with 450 and 400 hp Ratings

Table 5.15 shows the work window test results compared to those of the NTE method. The average range of work window bsNO_x results was 0.859 g/bhp-hr. The average range of NTE bsNO_x values based on a 30 second window of engine operation was 2.549 g/bhp-hr. Approximately two-thirds of the tests performed on these engines resulted in in-use bsNO_x emissions levels below the FTP certification standard.

**Table 5.15 Test Vehicles 28 and 29 Work Window bsNO_x Results Compared to NTE
bsNO_x Results**

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
Mrgtwn 60k	28	4.749	5.043	4.160	4.424	3.636	2.940
Sab2Wash 80k	29	3.915	4.824	3.497	3.646	3.050	2.454
Sab2Wash 60k	29	4.374	5.398	3.651	3.903	3.245	1.695
WashPA1 80k	29	2.528	3.197	2.384	2.185	2.173	1.573
WashPA1 60k	28	4.072	4.654	3.949	3.624	3.827	3.133
	29	3.026	3.202	2.845	2.724	2.598	2.106
	29-R	2.937	4.268	2.770	2.772	2.483	1.869
WashPA2 80k	29	3.203	3.953	2.750	3.059	2.410	1.759
WashPA2 60k	28	5.043	5.600	4.437	4.418	3.598	2.846
	29	4.116	5.370	3.149	3.609	2.878	2.098
	29-R	3.988	4.267	3.454	3.129	2.844	1.722
WashPA32Sab 80k	29	4.089	4.761	3.599	3.499	3.001	1.640
WashPA32Sab 60k	28	5.237	6.227	4.859	4.819	4.314	3.439
	29	3.950	4.956	3.653	3.674	3.379	2.488
	29-R	4.551	7.008	3.902	3.807	3.466	2.736

Two model year 2003 engines were tested in tandem-axle road tractors with each having a combined legal GVWR of 80,000 lb. The engine in test vehicle 30 was of approximately 12 L in displacement with a rating in the order of 450 hp. The theoretical FTP work for this engine was 33.09 bhp-hr. The engine in test vehicle 31 had a displacement of roughly 12 L and a power rating of approximately 400 hp. The theoretical FTP work for this engine was 30.22 bhp-hr. Both of these engines had an FTP NO_x + NMHC certification value of 2.5 g/bhp-hr. Test results for these engines are given in Figure 5.44.

The overall work window test average for these vehicles was 2.389 ± 0.262 g/bhp-hr, with a coefficient of variance of 10.97%. For test vehicle 30, the overall average was 2.282 ± 0.133 g/bhp-hr. For the 80,000 lb test, the average work window bsNO_x value was 2.321 ± 0.153 g/bhp-hr, while the 60,000 lb test yielded an average value of 2.262 ± 0.104 g/bhp-hr for all tests. The overall average for test vehicle 31 was 2.472 ± 0.304 g/bhp-hr. The average value for the 80,000 lb test was 2.543 ± 0.324 g/bhp-hr, and the average result for the 60,000 lb test was 2.378 ± 0.247 g/bhp-hr. Test weight did not seem to have a significant impact on the bsNO_x emissions of these vehicles.

Test route averages, for both vehicles and all test weights, were: for the Mrgtwn route, 2.251 ± 0.156 g/bhp-hr; for the Sab2Wash route, 2.374 ± 0.203 g/bhp-hr; for the WashPA1 route, 2.424 ± 0.193 g/bhp-hr, for the WashPA2 route, 2.647 ± 0.366 g/bhp-hr; for the

WashPA32Sab route, 2.303 ± 0.170 g/bhp-hr.

Figure 5.44 Test Route Summary for Test Vehicles 30 and 31 – 2003 Engines of Approximately 12 L Displacement with 450 and 400 hp Ratings

The results of the tests for vehicles 30 and 31 based on an FTP work window are shown in Table 5.16 compared to the results based on a 30 second window of operation in the NTE region. The average range of values for the work window method was 0.631 g/bhp-hr. The average range of values for the NTE method was 1.903 g/bhp-hr. Although many of the work window maximum values exceeded the FTP certification standard for NO_x emissions, nearly all of them were under 125% of the certification value. All of the test results fell under the in-use testing limit of 3.625 g/bhp-hr for these engines, although this value is based on the NTE method.

**Table 5.16 Test Vehicles 30 and 31 Work Window bsNO_x Results Compared to NTE
bsNO_x Results**

Route	Test Vehicle ID	Maximum		Average		Minimum	
		Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)	Work Window (g/bhp-hr)	NTE (g/bhp-hr)
Mrgtwn 80k	31	2.481	3.484	2.235	2.095	1.817	1.239
Mrgtwn 60k	30	2.534	3.174	2.269	2.582	1.994	2.052
Sab2Wash 80k	30	2.702	3.375	2.286	2.328	1.958	1.376
	31	3.071	4.321	2.482	2.625	2.052	1.370
Sab2Wash 60k	31	2.796	3.958	2.352	2.419	1.933	1.383
WashPA1 80k	30	2.521	3.247	2.398	2.528	2.216	1.727
	31	2.878	3.450	2.612	2.362	2.317	1.362
WashPA1 60k	30	2.285	2.907	2.187	2.496	2.085	1.537
	31	2.728	3.125	2.435	2.149	2.224	1.650
WashPA2 80k	30	2.675	3.149	2.444	2.488	2.218	1.958
	31	3.401	3.752	2.979	2.752	2.219	1.514
WashPA2 60k	30	2.487	3.202	2.279	2.535	2.125	2.165
	31	3.212	3.991	2.662	2.335	2.211	1.677
WashPA32Sab 80k	30	2.498	3.089	2.252	2.358	2.056	1.702
	31	2.857	4.343	2.450	2.665	2.068	1.432
WashPA32Sab 60k	30	2.516	3.215	2.264	2.445	1.996	1.601
	31	2.526	3.669	2.244	2.325	1.952	1.352

Figure 5.45 shows a comparison of the work window test results of test vehicles 28 and 30. The data collected from these two vehicles provide a comparison of engine technologies for engines of equal displacement and equal power rating. Test vehicle 28 used fuel injection strategies and combustion chamber geometry to control NO_x emissions. Test vehicle 30 used these same techniques, but also used variable geometry turbocharging and exhaust gas recirculation to control NO_x emissions. When compared to average results from both vehicles, it appears that the addition of a VGT and an EGR system can potentially reduce bsNO_x values by over 49%.

Figure 5.45 Test Route Summary for Test Vehicles 28 and 30 – 2001 and 2003 Engines of Approximately 12 L Displacement with 450 hp Rating

Figure 5.46 shows a comparison of results from test vehicles 29 and 31. Both of these vehicles were tested multiple times. Of particular interest are the results of test vehicle 31. When the vehicle was first tested, it had high results, with an average value of 4.296 ± 0.138 g/bhp-hr. The results from this series of tests were not used anywhere else in this study. It was determined by the engine manufacturer that the variable geometry turbocharger and EGR cooler were operating incorrectly. Necessary repairs were made to these components, and the vehicle was retested. The second test yielded lower results, with the average bsNO_x value being 2.495 ± 0.233 g/bhp-hr, or a decrease of just under 42%. Compared to the average result of the retests, the original average test result was over 72% higher. Interestingly, when test vehicle 31 was operating correctly, its emissions were only 29% lower than those of test vehicle 29, a 2001 engine with mainly fuel injection equipment to control NO_x emissions. The use of a complex emissions control strategy proves that although it may reduce emissions, its failure has the potential to raise emissions to a level that is higher than if those control strategies were nonexistent.

Figure 5.46 Test Route Summary for Test Vehicles 29 and 31 – 2001 and 2003 Engines of Approximately 12 L Displacement with 400 hp Rating

5.9.4 Phase IV Conclusions

A total of 28 heavy-duty diesel engines from Phase IV of the Consent Decree in-use testing program ranging in model year from 2001 to 2003 tested in 28 different vehicles were used for this study. The engines were from different engine manufacturers, had power ratings from approximately 300 hp to 450 hp, and had displacements from around 6 L to around 12 L.

Generally, within a given engine family, the results were repeatable. Test results that produce small standard deviations compared to the average values, and thus a small coefficient of variance, support this fact. Repeatability is believed to be a function of the test engine and test route. Procedures were followed carefully before and after all tests to assure high quality data, thus minimizing measurement errors. Comparisons were made based on engines within a given certification family and on test routes. Many engines produced in-use bsNO_x values similar to the FTP certification level for those engines. As expected, few of the Phase IV vehicles selected for this study exhibited high bsNO_x data over highway tests. Model year 2003 engines were required to meet the NO_x certification level of 2.5 g/bhp-hr for both the FTP and SET tests. During the FTP, an engine is most likely using urban control strategies, as it is highly transient. However, since the SET is a steady-state test, an engine is most likely using highway control

strategies. In post-October 2002 engines, these control strategies may be quite similar. Model year 2001 and 2002 engines in this study may have been developed to either a 4.0 g/bhp-hr or 6.0 g/bhp-hr standard for the SET, while meeting the NO_x requirement of 4.0 g/bhp-hr for the FTP. The few engines exhibiting higher NO_x values during highway operation were most likely developed to a 6.0 g/bhp-hr bsNO_x standard for the SET.

Two test engines produced much higher bsNO_x values than expected. The engine of test vehicle 12 produced 65% higher NO_x values on its Sab2Wash test than it did during other test routes. This increase was most likely due to a problem associated with the EGR or fueling systems of the engine. Investigation into the manifold air pressure, manifold air temperature, and coolant temperature during this test yield no further information to explain the increase. Test vehicle 31's engine produced 72% higher NO_x when its engine's EGR system was malfunctioning. The engine did not broadcast any fault information at the time of testing. Also, neither of these vehicles entered into a safe operation or "limp home" mode during these tests. From the data produced from these two engines, it can be concluded that although an engine may appear to be operating correctly, it may in fact be operating in a manner that can significantly increase its NO_x emissions. This phenomenon is crucial for agencies and authorities to consider when purchasing or retrofitting engines for their fleets if their goal is to reduce emissions output.

5.10 Compliance Factor Determination

It was not the paramount goal of this study to create a compliance factor for the work window method to determine if a given test passes or fails based upon its bsNO_x emissions results. The current compliance factor for the accepted method of calculating in-use emissions over a 30 second NTE window is 1.25. An additional 0.5 g/bhp-hr is added to allow for errors in instrumentation. In the future, as technology and instrumentation continues to improve, it is thought that this additional 0.5 g/bhp-hr will disappear. The in-use testing limit of 125% of the FTP certification level was created by the US EPA in agreement with individual engine manufacturers and the Engine Manufacturers Association (EMA). The results of this study could be used, perhaps, to develop a compliance factor based on a variety of conditions of engine operation rather than having a constant limit compliance factor.

Since the work window method considers all ranges of engine operation instead of engine operation only within the NTE region, it seems that another compliance method must be

developed if the work window method became an accepted technique of calculating in-use emissions. Many of the NTE requirements listed in §2.3 should still be abided by, as altitude and ambient conditions can create havoc on an engine's components and control strategies.

5.11 CO₂-Specific and Fuel-Specific Emissions

An alternative to calculating brake-specific emissions is to calculate emissions based on a measurement of CO₂ or fuel. Fuel-specific emissions can be obtained by measuring the quantity of burned fuel during the test directly, using the fuel quantity broadcast by the ECU, or inferring a fuel quantity from a carbon balance.

To perform a carbon balance, the hydrogen to carbon ratio, α , of the fuel must be known. For most #2 diesel fuels, the H:C ratio is assumed to be 1.8, as the chemical formula for diesel fuel is given as C_nH_{1.8n} [13]. However, fuel can be analyzed to obtain its actual properties. The mass of carbon in the fuel per mass of fuel, R_2 , can be found using Equation 5.11.

$$R_2 = \frac{12.011}{12.011 + 1.008\alpha} \quad \text{Equation 5.11}$$

If the masses of the products containing carbon are known, then the total mass of carbon in the products, G_s , is given as

$$G_s = R_2 \times m_{HC} + 0.429 \times m_{CO} + 0.273 \times m_{CO_2} \quad \text{Equation 5.12}$$

For tests conducted using MEMS, hydrocarbons and carbon monoxide are not reported. These values are also small, and do not contribute significantly to the result of the calculation. Therefore, the values of m_{HC} and m_{CO} in Equation 5.12 are set to zero. The mass of fuel for the test can be calculated using Equation 5.13.

$$m_{fuel} = \frac{G_s}{R_2} \quad \text{Equation 5.13}$$

Once the masses of the products of combustion and the mass of fuel are known, then emissions ratios can be calculated. Figure 5.47 shows brake-specific CO₂ results for the work window method compared to brake-specific CO₂ results from 30 second NTE events for a Sab2Wash test run. The CO₂ results from the work window method appear to correlate well with NTE calculated CO₂ emissions, just as NO_x emissions based on a work window do.

Figure 5.47 Sab2Wash bsCO₂ Results for Test Vehicle 4 Based on an FTP Work Window of 17.84 bhp-hr

The ratio of NO_x emissions to CO₂ emissions, or bsNO_x emissions to bsCO₂ emissions, can be found using Equation 5.14. This method eliminates the exhaust flow rate measurement as well as the need for broadcast engine speed and torque, provided that the data collection rates for NO_x and CO₂ concentrations are similar. In this equation, concentrations are in parts per million, densities are in grams per cubic feet, flow rates are in standard cubic feet per minute, time is in seconds, torque is in foot-pounds, and engine speed is in revolutions per minute.

$$\frac{NO_X}{CO_2} = \frac{bsNO_X}{bsCO_2} = \frac{\sum_{i=1}^n \left(\frac{\frac{[NO_X]_i}{10^6} \times \rho_{NO_X} \times \dot{Q}_i \times \Delta t_i}{\left(\frac{T_i \times N_i}{5252} \right) \times \Delta t_i} \right)}{\sum_{i=1}^n \left(\frac{\frac{[CO_2]_i}{10^6} \times \rho_{CO_2} \times \dot{Q}_i \times \Delta t_i}{\left(\frac{T_i \times N_i}{5252} \right) \times \Delta t_i} \right)} = \frac{\sum_{i=1}^n [NO_X] \times \rho_{NO_X}}{\sum_{i=1}^n [CO_2] \times \rho_{CO_2}} = \frac{m_{NO_X}}{m_{CO_2}}$$

Equation 5.14

The mass of fuel for the test, or in this case, the work window, can be calculated using Equation 5.13. Figure 5.48 shows both CO₂-specific and fuel-specific emissions for a Sab2Wash test run. It should be noted that the traces are identical, as fuel consumption is calculated solely on CO₂ measurements, as MEMS is only able to accurately report NO_x and CO₂.

Figure 5.48 Sab2Wash CO₂-Specific and Fuel-Specific Results for Test Vehicle 4 Based on an FTP Work Window of 17.84 bhp-hr

Both CO₂-specific and fuel-specific emissions have been discussed and presented here. The two are essentially the same, only different in magnitude. However, US EPA regulatory emissions are based on work, and appear that they will be based on work for several years to come. It has been proposed that brake-specific emissions can be calculated based on only NO_x and CO₂ measurements through the use of the equations mentioned previously in this chapter and an average brake-specific fuel consumption (bsfc) for the test engine. This method has not been evaluated extensively, but is included here to provide a basis for comparison. The accuracy of ECU broadcast torque has received criticism for several years from regulatory agencies. Engine manufacturers have made changes to broadcast torque calculations based on ambient conditions, inlet manifold pressure, coolant temperature, oil temperature, and other engine parameters. However, unpredictable factors, such as engine wear and oil soot level, can decrease output torque. A similar argument can be made regarding the accuracy of an average bsfc for a given engine. Figure 5.49 shows bsNO_x emissions based on inferred work from CO₂ emissions and an average bsfc for the engine of Test Vehicle 4 for all work window events compared to the work window bsNO_x values determined using ECU broadcast torque. The average bsfc for the engine was calculated to be 0.383 lb/bhp-hr. This bsfc was averaged over all work windows for each leg of the Pittsburgh test route.

Figure 5.49 bsNO_x Emissions Inferred From CO₂ Emissions and an Average bsfc for Test Vehicle 4 for a Pittsburgh Test Route Compared to Work Window bsNO_x Emissions

It appears from the figure that bsNO_x values based on CO₂ have a linear relationship with those based on ECU broadcast engine speed and torque for the Sab2Wash, WashPA1, and WashPA2 tests. The WashPA32Sab yields higher bsNO_x values using the bsfc method than the other three test legs. This might be due to highway operation, but the phenomenon does not appear in the Sab2Wash results. The results may be more accurate if the actual bsfc for the individual work window would have been used instead of an average bsfc for all work windows. This difference provides information that using an average bsfc for a test engine to determine brake-specific emissions does not eliminate errors, nor does it appear to produce more accurate brake-specific emissions than those determined by ECU broadcast torque.

6 UNCERTAINTY ANALYSIS

6.1 Introduction

All measurements made during an experiment have errors associated with them. The errors may be caused by experimental mistakes, calibration variances, system limitations, external influences, as well as many other factors. Three major classifications of error are bias or systematic error, precision or random error, and illegitimate error [67]. Bias or systematic errors are those that cause a reading to vary by an approximately equal amount or factor throughout the experiment. The cause of bias or systematic errors may be due to calibration error, system limitations, or even consistent human error. An example of a systematic error is the effect that the presence of the Annubar® flow meter has on the exhaust flow rate. Precision errors are those related to the capabilities of instrumentation and signal processing. Random errors are those that cannot be predicted, such as spikes in sensor signals, fluctuations in electronics, vibration, etc. Illegitimate errors are those that can typically be avoided with a thorough quality control / quality assurance plan.

The most significant errors in the data collected during this study are associated with ECU broadcast torque and exhaust gas flow rate. The ECU broadcast torque should be an accurate representation of the brake torque in order to determine brake-specific emissions. However, depending on how the particular engine manufacturer reports and develops the torque value may have a significant impact on the result. As mentioned previously in §5.5, the torque measured on an engine dynamometer, where engine development most likely occurs, is not necessarily equal to the brake torque during an in-use test. Engine accessories may absorb a significant amount of power from the engine. For example, the engine fan of an HDDE, when fully engaged, and engine accessories may absorb as much as 10% of the indicated power at high engine speeds. It is known that the differential pressure sensor associated with the Annubar® flow meter may not be sensitive to small differential pressures at low exhaust gas flow rates when it is calibrated for a large differential pressure, resulting in an error in calculating the exhaust gas flow rate.

Bias or systematic errors will be of focus in this chapter. It is not possible to examine all random errors, as they may not all be known. The data used for this study was obtained from test runs that are believed to be legitimate and accurate.

6.2 Uncertainty Calculations

The likelihood of the measurement of a given parameter being the true measurement is highly improbable. Every measurement has a certain error, or uncertainty, associated with it. In order to determine how those individual uncertainties may affect a calculated value, a thorough uncertainty analysis must be performed. Let the function R be dependent on the variables $x_1, x_2, \dots, x_n$, as given in Equation 6.1.

$$R = R(x_1, x_2, \dots, x_n) \quad \text{Equation 6.1}$$

Each variable, $x_1, x_2, \dots, x_n$, has a respective uncertainty, $w_1, w_2, \dots, w_n$. Then the uncertainty in R , or w_R , can be calculated by using the root-sum-square equation given in Equation 6.2.

$$w_R = \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \quad \text{Equation 6.2 [68]}$$

To fully understand the results of this study, the errors in brake-specific NO_x measurements as a function of engine speed (N), engine torque (T), NO_x concentration ($[\text{NO}_x]$), and exhaust flow rate ($\dot{Q}$) were examined. First, recall that the brake-specific NO_x value is determined by the following equation.

$$bs\text{NO}_x \left(\frac{g}{bhp \cdot hr} \right) = \sum_{i=1}^n \frac{\frac{[\text{NO}_x (ppm)]_i}{10^6} \times \rho_{\text{NO}_x} \left(\frac{g}{ft^3} \right) \times \dot{Q}_i \left(\frac{ft^3}{sec} \right) \times \Delta t_i (sec)}{\left(\frac{N_i \left(\frac{rev}{min} \right) \times T_i (ft \cdot lb_f) \times \Delta t_i (sec)}{\left(\frac{1 rev}{2\pi rad} \right) \left(\frac{60 sec}{1 min} \right) \left(\frac{550 ft \cdot lb_f}{1 sec \cdot bhp} \right)} \right)}$$

$$\text{Equation 6.3}$$

The uncertainty in the brake-specific NO_x value can be calculated using Equation 6.4.

$$w_{bsNO_x} = \sqrt{\left(\frac{\partial bsNO_x}{\partial [NO_x]} \times w_{[NO_x]}\right)^2 + \left(\frac{\partial bsNO_x}{\partial \rho_{NO_x}} \times w_{\rho_{NO_x}}\right)^2 + \left(\frac{\partial bsNO_x}{\partial \dot{Q}} \times w_{\dot{Q}}\right)^2 + \left(\frac{\partial bsNO_x}{\partial \Delta t} \times w_{\Delta t}\right)^2 + \left(\frac{\partial bsNO_x}{\partial T} \times w_T\right)^2 + \left(\frac{\partial bsNO_x}{\partial N} \times w_N\right)^2}$$

Equation 6.4

In these equations, both the density of NO_x (ρ_{NO_x}), and the time increment (Δt) are assumed to be exact, so there is no uncertainty associated with either parameter. The uncertainty for engine speed, engine torque, NO_x concentration are shown in Table 6.1.

Table 6.1 Uncertainty for Engine Speed, Engine Torque, and NO_x Concentration [19, 61]

Parameter	Uncertainty
Engine Speed	± 0.25 rpm
Engine Torque	± 20 ft-lb
NO _x Concentration	± 3% of reading

Determining the error in exhaust flow rate is more difficult than engine speed, engine torque, or NO_x concentration. The exhaust flow rate is a function of differential pressure, absolute pressure, temperature, pipe diameter, and factors associated with the Annubar® flow meter. Krishnamurthy determined that the error in the exhaust flow rate measurement in a 5 inch exhaust pipe varies from approximately 3 to 14% for the range of exhaust flow rate common to a modern heavy-duty diesel engine [10]. This error can be seen in Figure 6.1.

Figure 6.1 Error in Exhaust Flow Rate [10]

A piecewise curve-fit was applied to these data to calculate the uncertainty in the exhaust flow rate. This curve-fit is shown here.

$$w_{\dot{Q}} = \left(\frac{21.329 \exp(-0.0056 \times \dot{Q})}{100} \right) \times \dot{Q} \quad \text{for } \dot{Q} < 300$$

$$w_{\dot{Q}} = \left(\frac{-0.4179 \ln(\dot{Q}) + 6.4555}{100} \right) \times \dot{Q} \quad \text{for } \dot{Q} \geq 300$$

Equation 6.5

The exhaust flow rate uncertainty is shown in Figure 6.2. The calculated exhaust flow rate uncertainty during an in-use test is shown in Figure 6.3.

Figure 6.2 Uncertainty in Exhaust Flow Rate

Figure 6.3 Uncertainty in Exhaust Flow Rate for a Segment of a Sab2Wash Test

With all of the variables in Equation 6.4 now known, the uncertainty in the bsNO_x calculation can now be determined. However, for the work window method used in this study, the uncertainty cannot be calculated directly for all data points. Points where the engine torque is reported as zero results in an infinite uncertainty value. It should be noted, however, that Equations 6.3 and 6.4 can be used for the traditional NTE bsNO_x calculation. To resolve this problem, the uncertainty for each parameter was calculated individually for each data point. Calculated work and uncertainty in calculated work are given here.

$$work (bhp \cdot hr) = \frac{N_i \left(\frac{rev}{min} \right) \times T_i (ft \cdot lb_f) \times \Delta t_i (sec)}{\left(\frac{1 rev}{2\pi rad} \right) \left(\frac{60 sec}{1 min} \right) \left(\frac{550 ft \cdot lb_f}{1 sec \cdot bhp} \right)} \quad \text{Equation 6.6}$$

$$w_{work} = \sqrt{\left(\frac{\partial work}{\partial T} \times w_T \right)^2 + \left(\frac{\partial work}{\partial N} \times w_N \right)^2} \quad \text{Equation 6.7}$$

The uncertainty for instantaneous work calculation is shown in Figure 6.4. Again, Δt is assumed to be constant and precise. The instantaneous work for a test run along with the uncertainty at each point is shown in Figure 6.5.

Figure 6.4 Uncertainty in Instantaneous Work

Figure 6.5 Uncertainty in Work for a Segment of a Sab2Wash Test

The mass flow rate of NO_x is calculated using Equation 6.8. The uncertainty in NO_x mass flow rate is given by Equation 6.9. Again, NO_x density is assumed to be constant.

$$\dot{NO}_x \left(\frac{g}{sec} \right) = \frac{[NO_x (ppm)]_i}{10^6} \times \rho_{NO_x} \left(\frac{g}{ft^3} \right) \times \dot{Q}_i \left(\frac{ft^3}{sec} \right) \quad \text{Equation 6.8}$$

$$w_{\dot{NO}_x} = \sqrt{\left(\frac{\partial \dot{NO}_x}{\partial [NO_x]} \times w_{[NO_x]} \right)^2 + \left(\frac{\partial \dot{NO}_x}{\partial \dot{Q}} \times w_{\dot{Q}} \right)^2} \quad \text{Equation 6.9}$$

The uncertainty for the mass flow rate of NO_x is shown in Figure 6.6. The mass flow rate of NO_x for a Sab2Wash test run is shown in Figure 6.7 along with the associated uncertainty.

Figure 6.6 Uncertainty in the Mass Flow Rate of NO_x

Figure 6.7 Uncertainty in NO_x Flow Rate for a Segment of a Sab2Wash Test

Recall that the NO_x mass flow rate and instantaneous work are summed over a work window to calculate a brake-specific NO_x value, as shown in Equation 6.10.

$$Window_bsNO_{xj} \left(\frac{g}{bhp \cdot hr} \right) = \frac{\sum_{i=0}^{i^*} \left(\dot{NO}_x \left(\frac{g}{sec} \right) \times \Delta t(sec) \right)_i}{WorkWindow_j(bhp \cdot hr)} \quad \text{Equation 6.10}$$

In order to calculate the uncertainty in the bsNO_x value, the uncertainty in both the work window and the NO_x mass flow rate were summed over the window interval.

$$w_{WorkWindow} = \sum_{i=0}^{i^*} w_{work_i} \quad \text{Equation 6.11}$$

$$w_{\dot{NO}_x} = \sum_{i=0}^{i^*} w_{\dot{NO}_{x_i}} \quad \text{Equation 6.12}$$

The uncertainty in the window bsNO_x value was calculated using Equation 6.13.

$$w_{Window_bsNO_x} = \sqrt{\left(\frac{\partial Window_bsNO_x}{\partial WorkWindow} \times w_{WorkWindow} \right)^2 + \left(\frac{\partial Window_bsNO_x}{\partial \dot{NO}_x} \times w_{\dot{NO}_x} \right)^2}$$

Equation 6.13

Figure 6.8 shows the uncertainty in brake-specific NO_x for the work window method for a range of bsNO_x values representative of the engines tested during this study obtained from three separate tests of three different engine configurations for two different engine manufacturers. The data in the figure show an atypical sporadic pattern, unlike the other uncertainty plots in this analysis. This difference may be due to the fact that the same bsNO_x value can be obtained over varying ranges of engine speeds, engine torques, and NO_x mass flow rates. From this figure it might be concluded that the uncertainty in the in-use bsNO_x values for an engine is proportional to the NO_x certification level for that engine. Figure 6.9 shows the uncertainty of bsNO_x values throughout a given on-road test. The average error is 5.2% of the work window bsNO_x value, which is similar to the 5 – 7% error that was found in bsNO_x values during 30 second NTE events [10].

Figure 6.8 Uncertainty in Work Window bsNO_x

Figure 6.9 Uncertainty and Standard Deviation in bsNO_x Based on a Work Window for a Sab2Wash Test

Figure 6.9 includes the standard deviation of the brake-specific NO_x for the given Sab2Wash test. The standard deviation, σ , or sample variance, is given by

$$\sigma = \sqrt{\frac{n \sum x^2 - (\sum x)^2}{n(n-1)}} \quad \text{Equation 6.14}$$

where n is the number of samples and x represents a value in the dataset. From the figure, it is seen that the magnitude of the uncertainty based on errors associated with engine speed, engine torque, NO_x concentration, and exhaust flow rate in the work window bsNO_x values is similar to the standard deviation of the work window bsNO_x values. Therefore, it is believed that the standard deviation is an accurate representation of the uncertainty in the dataset. This standard deviation value is what was used for uncertainty for all data presented in Chapter 5. Although it should be noted that an acceptable large variance in work window bsNO_x values will have a higher standard deviation, but the uncertainty may remain small.

7 INVENTORY EMISSIONS

7.1 Introduction

Current emissions regulations for heavy-duty diesel engines are based on recorded cycle work. When a test is performed on an engine dynamometer, the engine speed and torque are recorded using speed sensors and load cells. The cycle work is determined by summing the instantaneous work at each point in the cycle. Testing can also be performed on a chassis dynamometer, where the engine and components of the vehicle can both be evaluated. West Virginia University's Heavy-Duty Transportable Laboratory is capable of this type of testing for heavy-duty diesel engines [69]. When performing tests using a chassis dynamometer, one can easily report emissions on a work-specific or distance-specific basis. Some test cycles performed on a chassis dynamometer include the Urban Dynamometer Driving Schedule (UDDS), the FTP75 (light-duty), the Central Bus District (CBD) cycle, the W. H. Martin Refuse Collection cycle, and the WVU 5-Peak cycle [15]. Some of these cycles are shown in the following figures.

Figure 7.1 UDDS Cycle

Figure 7.2 CBD Cycle

Figure 7.3 WVU 5-Peak Cycle

While the US EPA mandates that engine manufacturers meet regulatory emissions levels, they are also concerned with emissions inventory levels. Emissions inventory can be defined as the mass amount of an emissions constituent, often relative to time or distance. To determine emissions inventories, emissions can be collected over a period of time at a given location. They can also be collected from a fleet of vehicles. Data from Phase IV of the Consent Decree in-use testing program were not specifically collected for inventory purposes. However, data exist that allow mass quantities of emissions to be determined for a given vehicle, or a family of vehicles. Brake-specific mass emissions can be combined with the work accumulated over the test route to produce a mass quantity of NO_x, for example. Time based emissions can be combined with test time to produce a mass quantity. And finally, distance based emissions can be combined with distance traveled to give a mass quantity of an emissions constituent.

Perhaps distance based emissions give the most accurate measurements for emissions inventory purposes. If the test vehicle has not had significant repairs, and the deterioration factors of the engine for all emissions are known, then accumulated mileage of the test vehicle, if believed to be correct, can be used with an average emissions mass rate to determine the amount of NO_x, for example, produced by the test vehicle over its life. A major issue with calculating inventory emissions in this manner is that many assumptions are made. It is assumed that the test route is representative of typical operation of the vehicle. A highway test of a transit bus used largely in urban areas may not produce mass quantities of its emissions typical of its normal operation. Similarly, an urban test route may not produce representative mass quantities of emissions of an engine in a vehicle that is primarily used for long-haul applications. Assumptions regarding fuel properties and fuel economy are made to perform the following calculation for total mass of NO_x produced by an engine of a given vehicle.

$$NO_x(g) = \frac{bsNO_x \left(\frac{g}{bhp \cdot hr} \right) \times \rho_{fuel} \left(\frac{lb}{gal} \right) \times SpecificEnergy_{fuel} \left(\frac{bhp \cdot hr}{lb} \right) \times VMT(mi)}{FuelEconomy \left(\frac{mi}{gal} \right)}$$

Equation 7.1

Governmental regulatory agencies, such as the US EPA and CARB, use modeling software to predict emissions levels from heavy-duty trucks, as well as passenger cars, light-duty trucks, and motorcycles under different driving conditions. These models include MOBILE6, PART5, the National Mobile Inventory Model (NMIM), and the Motor Vehicle Emission Simulator (MOVES) by the US EPA, and the Emissions FACTor (EMFAC) model by CARB [11]. These models enable regulatory agencies to predict the impact of emissions levels on the health of citizens and animals and the environment [70, 71].

As with all computer software models, significant improvements can be made by calibrating the model with experimental test results. In the past, models have been compared to engine and chassis dynamometer tests. However, often these tests are performed at temperatures and pressures that are kept relatively constant throughout the test, when in reality ambient conditions can change dramatically during real-world in-use operation and testing of a vehicle. The data collected during Phase IV testing were submitted to the respective engine manufacturers whose engines were being tested. The engine manufacturer, in turn, submitted the necessary data to the US EPA for further analysis and investigation. The US EPA could use this data from over 130 Phase IV vehicles to validate their models and make improvements where necessary to further correlate model results to in-use testing data.

7.2 Data Analysis

West Virginia University has conducted testing with their Heavy-Duty Transportable Vehicle Emissions Testing Laboratory to build a database of emissions data from heavy-duty vehicles tested in the field using controlled, simulated driving conditions [72]. The data collected from these studies provide not only data for comparison and performance studies, but also provide data for the assessment of inventory emissions. Similarly, the data collected during Phase IV of the in-use testing program provide not only information regarding NTE zone operation and emissions, but also emissions data that can be used for inventory purposes.

A variation of the work window method described and tested in Chapter 5 was used to determine distance-specific emissions. These results were compared to NTE distance-specific emissions reported by MEMS. Instead of basing a moving window based on work, a moving window based on distance was used to analyze the data. Distance-specific NO_x emissions were obtained using Equation 7.2.

$$bs[X] \left(\frac{g}{mi} \right) = \sum_{i=0}^{i^*} \frac{\frac{[X]_i (ppm)}{10^6} \times \rho_x \left(\frac{g}{ft^3} \right) \times \dot{Q}_i \left(\frac{ft^3}{sec} \right) \times \Delta t_i (sec)}{ECUVehSpeed_i (mph) \times \Delta t_i (sec) \times \left(\frac{1hr}{3600 sec} \right)}$$

Equation 7.2

Figure 7.4 shows distance-specific NO_x emissions over a highway test route for a 2003 heavy-duty diesel engine of approximately 12 L displacement and 400 hp. The data in the figure show that a distance window of 1 mile resembles the NTE distance-specific NO_x data. As the distance window interval increases, the NO_x results become constant, around 10 g/mi.

Figure 7.4 WashPA32Sab Distance-Specific NO_x Results for Varying Distance Windows for Test Vehicle 31

Figure 7.5 shows the variance of window size and NO_x results for the distance windows shown above for the WashPA32Sab test. It should be noted that as the distance window increased, the average NO_x result did not change significantly. The average NO_x rate for distance windows of 5 to 40 miles ranged from 9.73 g/mi to 9.83 g/mi. The standard deviations,

however, represented by the bars in the figure, decreased significantly as the distance window increased. The explanation for this decrease is twofold. As the distance window grows in size, the number of windows decreases for the test. Also, for larger distance windows, spikes and anomalies in the data become insignificant, unlike in small distance windows.

Figure 7.5 WashPA32Sab Distance-Specific NO_x Variances for a Range of Distance Windows for Test Vehicle 31

The previous figures show data collected during highway operation of a heavy-duty diesel engine. The distance window, given in miles, is approximately equal to the window size, given in minutes. This corresponds to an average vehicle speed of approximately 60 mph for the test. The average vehicle speed for the particular test of interest was 56.3 mph, based on the ECU broadcast vehicle speed. GPS data was not recorded for this particular test to provide a comparison. The duty cycle for this particular test can be seen in Figure D.366.

Figure 7.6 shows distance-specific NO_x data collected from a 2003 engine of approximately 9 L displacement and 300 hp in a transit bus during a WashPA1 test. For this test run, NO_x results based on a distance window of 1 mile did not closely resemble the NTE distance-specific emissions for the test. The total distance for the WashPA1 route, an urban route, was approximately 12.1 miles (see §4.3.2.2). Unlike the WashPA32Sab route, the

WashPA1 route did not allow for a wide range of distance windows due to its small total distance. Results based on distance windows of 1, 2.5, 5, 7.5, and 10 miles are shown in Figure 7.6 and Figure 7.7.

Figure 7.6 WashPA1 Distance-Specific NO_x Results for Varying Distance Windows for Test Vehicle 18

Figure 7.7 WashPA1 Distance-Specific NO_x Variances for a Range of Distance Windows for Test Vehicle 18

The average vehicle speed for the WashPA1 test under consideration here was 27.2 mph based on ECU broadcast vehicle speed. The duty cycle for this test can be seen in Figure D.176. The engine spent approximately 19% of the test at idle. When the vehicle was stopped in urban traffic, the mass of NO_x continued to accumulate, while the distance did not change. This occurrence may explain the large difference in the distance-specific NO_x results for a given distance window. In the previous analysis of the WashPA32Sab test of test vehicle 31, the engine spent just over 1% at idle and therefore accumulated both NO_x mass and distance throughout the test. Figure 7.7 shows that the average NO_x value for distance windows of 1 mile to 10 miles ranged from 14.1 g/mi to 16.0 g/mi. Again, the standard deviation of the NO_x results decreased significantly as the distance window interval increased.

8 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Conclusions

The work window method is believed to produce bsNO_x values that are representative of what the engine is actually emitting over a window of operation. Short duration spikes become less significant in the work window method than they do in the 30 second NTE method. It can be seen in the many figures in Appendix D that the NTE method tends to produce bsNO_x levels that increase rapidly, peak, and decrease rapidly over continuous NTE events. High NO_x concentrations over a short period of time and transient engine operation are thought to cause this trend. The work window method includes these high concentrations, but averages them over a longer period of operation, so they become less significant. High NO_x concentrations over a long period of time will cause both the NTE method and work window method to yield high results, and show a true in-use emissions exceedance or failure, as defined by the US EPA.

Throughout the course of this study, United States regulatory standards for modern heavy-duty diesel engines were discussed. The Consent Decrees entered into by the settling heavy-duty diesel engine manufacturers, the US EPA, CARB, and the United States Department of Justice were discussed, in particular, the in-use testing program. The requirements of a PEMS were presented. Several in-use testing systems and PEMS that have been developed in the past were discussed. West Virginia University's MEMS was discussed and thought to meet nearly all of the requirements of a PEMS, qualifying it as a valid in-use testing system. Several design iterations of the MEMS were used to gather all of the data used in this study.

A review of the combustion processes of a diesel engine was presented to convey understanding of how a diesel engine functions and how its emissions are formed. In particular, how carbon monoxide, carbon dioxide, hydrocarbons, oxides of nitrogen, and particulate matter emissions are formed was included. Due to the limitations of current technologies suitable for in-use testing, only carbon dioxide and oxides of nitrogen were measured during the course of this study. Engine technologies, including fuel injection equipment, variable geometry turbocharging, exhaust gas recirculation, and exhaust gas aftertreatment were discussed to provide an understanding for data comparisons.

Heavy-duty diesel engine certification cycles, namely the FTP and SET, were presented and evaluated. It was determined that during an FTP test, based on the engine speed and torque

set points, the engine only operates in the NTE region 25% of the time. During the SET, the engine is operating in the NTE region 69% of the test. Similarly, the ETC was evaluated. It was determined that an engine only spends 42% of its operation within the NTE region during an ETC test. The definition of an accepted NTE event was discussed. Eleven different criteria, developed recently by the US EPA and engine manufacturers, must be satisfied for a continuous period of 30 seconds in order for an NTE event to occur. However, during this study, an NTE event was defined as a continuous 30 second period of engine operation within the boundaries of the NTE region relative to the test engine lug curve. During the FTP, it was calculated that the engine was operating in an NTE event only 12% of the time. During the ETC, an engine operates in an NTE event only 8% of the time. The analyses of two in-use test cycles showed that an engine was operating in the NTE region 59% of the time and in an NTE event 43% of the time for a highway test, and in the NTE region 40% of the time and in an NTE event 17% of the time for a combined urban and highway route. It is because of the large difference in these numbers that it is believed that in-use emissions should not be based solely on NTE operation and compared to FTP certification standards.

An alternative method of calculating in-use brake-specific emissions was developed. This alternative method was based on a predetermined amount of work. In this study, the theoretical FTP work for the particular test engine was chosen as the work window. The work window was moved through the data, beginning at each point in time, and ending when the desired amount of work had been accumulated. The emissions were then integrated over that period along with the exhaust gas flow rate to yield the mass of a given emissions constituent for that given work window. The mass of the constituent divided by the work window yielded brake-specific emissions.

Data from three engines from the Phase III portion of the in-use testing program were chosen to be evaluated using the work window method. These engines did not broadcast an absolute torque value from the ECU, so broadcast percent load was used with the engine's lug curve to infer a torque value. On average, the Phase III vehicles had a 26% increase in bsNO_x emissions for highway test routes over urban test routes.

The data from twenty-eight engines ranging from model year 2001 to 2003 were chosen from Phase IV of the in-use testing program to be used in this study. The engines were in transit buses, road tractors, and a dump truck. The displacement of these engines ranged from

approximately 6 L to 12 L, and ranged in horsepower from 300 to 450. The ECU broadcast torque values from these engines were taken as brake torque values and used along with time and broadcast engine speed to determine the work window. Brake-specific oxides of nitrogen emissions were evaluated based on a particular engine certification family, an individual engine, and test route.

It was found that for over 57% of the tests performed, the work window bsNO_x results were at or below the FTP NO_x certification level for a particular engine. Over 72% of the tests yielded bsNO_x results at or below 125% of the engine's FTP NO_x certification level. For many tests, as can be seen in the data tables in Chapter 5, a result based on the NTE method that exceeded the maximum allowable value did not appear as an exceedance with the work window method. For 83.6% of the in-use tests, the maximum work window bsNO_x value was below the maximum NTE bsNO_x value. The work window method is believed to be an effective means of measuring in-use emissions over a longer period of time than 30 seconds. Valid work window sizes ranged from 4 minutes to 20 minutes. The work window method was also not developed to disguise or reduce exceedances.

A “go – no go” criterion was developed for the work window method based on the amount of power output by the engine during an individual work window. This method also correlates directly with the duration of the work window. For many of the vehicles, the WashPA2 test had several points where the work window power was less than the power for the FTP certification test. These points were not included in the work window evaluation. Extremely long idle periods or long periods of intermittent idle typically caused the power in the work window to be low. The duty cycle of each test was examined to help develop this failure criterion. However, it was concluded that a test failure cannot be based on duty cycle alone. Many urban tests may have a greater percentage of time spent at or near idle and still have all legitimate work windows for the test than a highway test that may have a long period of continuous idle operation. A compliance factor was not determined for the work window method, although for most tests, the maximum values were at or below 125% of the engine's NO_x certification level.

An error analysis was performed to determine the accuracy of the work window results. Since the work window method integrates many values, including instantaneous work and NO_x mass flow rate, it was thought that small errors may become significant over the work window

interval. Errors based on exhaust gas flow rate, NO_x concentration, engine speed, and engine torque were considered. A large assumption was made in assuming the ± 20 ft-lb error for the broadcast torque value. Since engines used in this study were not tested on an engine dynamometer, the true relationship between broadcast torque and brake torque could not be determined. It was also seen for some tests that broadcast torque values can well exceed the theoretical lug curve for the engine. A curve-fit was applied to pre-existing exhaust gas flow rate error data to determine the error in the mass flow rate of NO_x. With these assumptions, it was determined that for a given set of data, the standard deviation was an accurate representation of the error in the work window method. This conclusion also assumes that the range of the data set for a given test is on the order of the calculated error.

Lastly, a variation of the work window method was applied to determine inventory emissions. Instead of basing a window on a predetermined amount of work, a window was based on a predetermined distance. This distance was then moved throughout the data, just as the work window, and emissions were calculated over that distance window. It was found that distance-specific NO_x emissions, based upon average, reach a near constant value for a large range of distance windows.

8.2 Recommendations

In-use testing results of heavy-duty diesel engines for bsNO_x emissions using the work window method is an alternative to the 30 second NTE window method. Some regulatory agencies, such as those of the European Union and the Joint Research Centre (JRC), are not fond of the NTE region, due to the high amount of engine operation outside of it. The work window method might allow agencies such as these to evaluate emissions from engines for their entire range of operation.

One option for the work window method could be to apply it to diesel engines certified to European standards and use the theoretical ETC work as the work window interval. Although the ETC work was used in the preliminary developmental stages of this study, it was not used any further as the engines used were certified only to US EPA requirements.

If the work window method were applied to the data collected from all of the vehicles and engines tested during the in-use testing program, it may yield additional information as to how the method behaves for tests with exceedances and tests with a large amount of time spent

at idle. Theoretically, an engine could have 30 second window NTE results, but never achieve enough power over any work window to pass the failure criterion. If the work window method is to be used further, the macro used to calculate the work window values needs to be improved to calculate the error for each work window, based on a true error in broadcast torque and exhaust gas flow rate. Additional statistical analysis could also be performed to determine the influence of test weight on bsNO_x emissions, as well as the sensitivity in bsNO_x emissions to test route. Future work could also include comparing work window fuel-specific emissions to work window brake-specific emissions for a number of tests for a number of vehicles, as the fuel-specific method eliminates the need for an accurate ECU broadcast torque value as well as exhaust gas flow rate.

As a quality control / quality assurance (QC/QA) procedure, the work window method results could be used to determine if an in-use test is valid. A criterion could be placed on the results based on the coefficient of variance to signify the possibility of errors associated with either the test engine or the test instruments. Since the work window method incorporates all engine speed and operation, this QC/QA procedure might provide additional insight to the data reviewer that is not apparent in the NTE data alone.

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A. APPENDIX – FTP Normalized Engine Speed and Load Used for Theoretical Cycle

Work [13]

Time	Speed	Torque									
(s)	(%)	(%)									
1	0	0	56	75.81	40	113	0	0	170	0	0
2	0	0	57	84.22	42.2	114	0	0	171	0	0
3	0	0	58	83.86	41.28	115	0	0	172	0	0
4	0	0	59	80.55	(m)	116	0	0	173	0	0
5	0	0	60	80.51	(m)	117	0	0	174	0	0
6	0	0	61	78	(m)	118	0	0	175	0	0
7	0	0	62	79.79	(m)	119	0	0	176	0	0
8	0	0	63	80.33	30.54	120	0	0	177	0	0
9	0	0	64	85.58	42.12	121	0	0	178	0	0
10	0	0	65	81.78	50	122	0	0	179	0	0
11	0	0	66	78	50	123	0	0	180	0	0
12	0	0	67	80.74	43.16	124	0	0	181	0	0
13	0	0	68	92.1	73.65	125	0	0	182	0	0
14	0	0	69	88.01	(m)	126	0	0	183	0	0
15	0	0	70	84	(m)	127	0	0	184	0	20
16	0	0	71	84	(m)	128	0	0	185	0	20
17	0	0	72	81.17	(m)	129	1.77	(m)	186	0	11.73
18	0	0	73	70.46	(m)	130	1.6	(m)	187	0	0
19	0	0	74	66	13.57	131	0	0	188	0	0
20	0	0	75	62.23	29.43	132	0	0	189	0	0
21	0	0	76	64	20	133	2.14	9.28	190	0	0
22	0	0	77	63.48	17.42	134	3.08	0	191	0	0
23	0	0	78	60.34	10	135	0	0	192	0	0
24	0	0	79	56.85	10	136	0	0	193	0	0
25	0	3.67	80	56	(m)	137	0	0	194	0	0
26	0	47.69	81	52.45	(m)	138	0	0	195	0	0
27	3.11	59.41	82	39.91	10	139	0	0	196	0	0
28	9.09	84.54	83	36.38	10	140	0	0	197	0	0
29	15.62	80	84	30	10	141	0	0	198	0	0
30	33.49	80	85	27.93	10	142	0	0	199	0	0
31	37.93	79.29	86	26	16.74	143	0	0	200	0	0
32	31.2	38.25	87	27.66	3.36	144	0	0	201	0	0
33	21.99	26.67	88	28	(m)	145	0	0	202	0	0
34	30	15.1	89	27.41	(m)	146	0	0	203	0	0
35	22.23	16.47	90	20.96	(m)	147	0	5.51	204	0	0
36	19.61	28.05	91	12.15	(m)	148	0	11.34	205	0	0
37	20	20.38	92	3.81	(m)	149	0	0	206	0	0
38	18.33	(m)	93	0	0	150	0	0	207	0	0
39	6.55	(m)	94	0	0	151	0	0	208	0	0
40	15.82	(m)	95	0	0.91	152	0	0	209	0	0
41	23.63	(m)	96	0	7.52	153	0	0	210	0	0
42	17.51	(m)	97	0	0	154	0	0	211	0	0
43	14.19	62.52	98	0	0	155	0	0	212	0	0
44	16.64	69.36	99	0	0	156	0	0	213	0	0
45	27.77	60	100	0	0	157	0	0	214	0	73.41
46	37.03	63.79	101	0	0	158	0	0.21	215	0	90
47	47.36	75.36	102	0	0	159	0	30	216	31.3	81.3
48	54.77	80	103	0	0	160	0	26.78	217	41.15	90
49	57.7	80	104	0	0	161	0	20	218	44	90
50	54.03	79.92	105	0	0	162	0	20	219	46.41	90
51	58	65.03	106	0	0	163	0	4.12	220	51.04	82.41
52	58.65	43.23	107	0	0	164	0	0	221	66.66	80
53	62.88	50	108	0	0	165	0	0	222	75.03	90
54	69.83	50	109	0	0	166	0	0	223	89.85	90
55	72	42.05	110	0	0	167	0	0	224	96.78	93.88
			111	0	0	168	0	0	225	96.91	50.94
			112	0	0	169	0	0	226	94.6	17.02

227	99.16	28.6	289	0	0	351	0	0	413	70.58	(m)
228	100	39.83	290	0	0	352	0	0	414	78	(m)
229	100	30	291	0	0	353	0	0	415	80.29	1.45
230	100	26.69	292	0	0	354	0	0	416	80.54	17.3
231	100.98	20	293	0	0	355	0	0	417	78.23	11.13
232	100.71	20	294	0	0	356	0	0	418	78.45	19.55
233	100	36.06	295	0	0	357	0	0	419	84.36	24.16
234	96.16	40	296	0	0	358	0	0	420	72.16	80
235	95.77	30	297	0	0	359	0	0	421	79.1	74.83
236	94.55	32.75	298	0	0	360	0	0	422	90.09	16.04
237	96.86	35.68	299	0	0	361	0	0	423	74.04	(m)
238	99.18	30	300	0	0	362	0	0	424	68.02	(m)
239	100	44.93	301	0	0	363	0	0	425	68.53	(m)
240	101.81	50	302	0	0	364	0	0	426	59.39	(m)
241	86.54	(m)	303	0	0	365	0	0	427	63.54	(m)
242	63.56	(m)	304	0	0	366	0	0	428	70	2.38
243	56	(m)	305	0	0	367	0	0	429	73.1	17.76
244	46	(m)	306	0	0	368	0	0	430	72.13	(m)
245	41.86	45.18	307	0	0	369	0	0	431	67.27	(m)
246	38.31	78.47	308	0	0	370	0	0	432	36.03	(m)
247	35.98	80	309	0	0	371	0	0	433	20.75	(m)
248	31.03	80	310	0	0	372	0	0	434	11.49	(m)
249	25.36	80	311	0	0	373	0	0	435	-2.09	0
250	23.05	60.97	312	0	0	374	0	0	436	-0.73	0
251	18.2	27.34	313	0	0	375	0	0	437	8.57	60
252	12.84	43.71	314	0	0	376	0	0	438	30.55	61.93
253	10.1	68.95	315	0	0	377	0	29.59	439	67.1	63
254	3.79	68.95	316	0	0	378	-1.5	87.46	440	86.03	39.85
255	1.48	44.28	317	0	0	379	8.88	100	441	89.33	30
256	0	0	318	0	0	380	46.04	100	442	91.64	30
257	0	0	319	0	0	381	76.89	100	443	97.88	10.4
258	0	0	320	0	0	382	80	100	444	97.73	1.37
259	0	0	321	0	15.55	383	82.14	94.64	445	96	10
260	0	0	322	0	20	384	85.39	83.07	446	96	0.96
261	0	0	323	24.18	19.08	385	87.7	88.51	447	96	(m)
262	0	0	324	23	10	386	92	79.83	448	85.27	28.34
263	0	24.97	325	11.56	1.86	387	92	61.66	449	87.54	30.76
264	0	17.16	326	6.87	(m)	388	94.58	66.77	450	86.16	29.18
265	0	6.2	327	6	(m)	389	102.88	60	451	88	20
266	0	10	328	0.72	(m)	390	106	72.76	452	87.21	20
267	0	10	329	0	0	391	109.18	8.43	453	86	20
268	0	0	330	0	0	392	111.91	(m)	454	87.42	20
269	0	0	331	0	0	393	82	(m)	455	88	11.32
270	0	0	332	0	0	394	79.33	(m)	456	77.84	(m)
271	0	0	333	0	0	395	71.15	(m)	457	72	(m)
272	0	0	334	0	0	396	68.84	(m)	458	71.32	(m)
273	0	0	335	0	0	397	78.35	49.17	459	70	0.04
274	0	0	336	0	0	398	82	70	460	70	(m)
275	0	0	337	0	0	399	80.65	69.46	461	74.88	(m)
276	0	0	338	0	0	400	92.85	60	462	74.06	(m)
277	0	0	339	0	0	401	97.48	60	463	67.74	(m)
278	0	0	340	0	0	402	98.95	60	464	66	(m)
279	0	0	341	0	0	403	100.74	60	465	64.23	(m)
280	0	0	342	0	0	404	103.68	43.17	466	62	(m)
281	0	0	343	0	0	405	104	10.04	467	55.94	(m)
282	0	0	344	0	0	406	80.62	20	468	54	(m)
283	0	0	345	0	0	407	83.37	20	469	66.43	(m)
284	0	0	346	0	0	408	81.06	15.29	470	75.21	70
285	0	0	347	0	0	409	80	10	471	86	54.53
286	0	0	348	0	0	410	76.86	(m)	472	86	24.56
287	0	0	349	0	0	411	74.11	(m)	473	88.81	(m)
288	0	0	350	0	0	412	71.6	(m)	474	90	(m)

475	105.48	(m)	537	0	0	599	0	0	661	89.43	92.86
476	74	(m)	538	0	0	600	0	0	662	87.11	100
477	73.34	(m)	539	0	0	601	0	0	663	86	100
478	71.02	10	540	0	0	602	0	0	664	86	100
479	76.46	29.38	541	0	0	603	0	0	665	89.66	100
480	81.61	40	542	0	0	604	0	0	666	90	99.27
481	78.16	30.39	543	0	0	605	0	0	667	90.46	90
482	74.13	26.46	544	0	(m)	606	2.52	6.3	668	92.78	90
483	90	0	545	0	0	607	10.3	17.87	669	95.09	90
484	90.87	0	546	-0.75	0	608	13.89	20	670	100.22	82.97
485	92	(m)	547	-0.56	0	609	20.2	20	671	102	80
486	93.5	(m)	548	4	(m)	610	24.07	22.59	672	102	70.18
487	94	(m)	549	0.68	(m)	611	33.33	17.5	673	102	80
488	94.13	(m)	550	0	0	612	40.3	(m)	674	97.34	50.07
489	88.96	(m)	551	0	0	613	47.85	(m)	675	87.02	(m)
490	63.25	(m)	552	0	2.6	614	66	7.78	676	86	(m)
491	62	(m)	553	0	20	615	68	10.93	677	73.12	22.19
492	49.54	45.37	554	0	20	616	67.59	32.04	678	75.77	39.62
493	52.49	86.99	555	0	7.96	617	66	40	679	75.76	48.8
494	64	90	556	0	0	618	67.04	40	680	75.11	37.23
495	64.99	90	557	0	0	619	68	40	681	78	34.34
496	71.93	93.22	558	0	78.53	620	68	48.33	682	80.37	40
497	78.87	95.21	559	1.85	60	621	75.93	99.53	683	77.51	47.49
498	82	83.64	560	11.1	63.88	622	78	100	684	81.44	50
499	86.76	80	561	16	70	623	78	100	685	82.13	39.36
500	93.71	80	562	30.05	70	624	77.07	100	686	84	27.79
501	94.87	80	563	42.88	70	625	76	100	687	84	16.21
502	103.6	80	564	56.1	70	626	76	100	688	84	15.36
503	101.23	41.89	565	63.39	66.52	627	76	100	689	85.39	26.93
504	95.48	24.85	566	70.66	59.94	628	75.63	100	690	86	30
505	98	50	567	72.98	80	629	73	97.5	691	86	30.08
506	99.79	50	568	77.87	86.46	630	76.81	90	692	85.67	40
507	106.21	46.82	569	88.03	90	631	80.26	90	693	84.65	40
508	110.84	(m)	570	90	90	632	83.44	90	694	86	35.2
509	98.55	(m)	571	92.23	100	633	84	98.79	695	87.28	30
510	70.95	(m)	572	94	100	634	84	100	696	88	22.05
511	67.27	(m)	573	94.86	100	635	83.61	100	697	86.09	(m)
512	60.96	(m)	574	96	100	636	82	100	698	83.78	(m)
513	48.03	(m)	575	97.49	100	637	83.02	94.91	699	81.47	(m)
514	52.31	(m)	576	108.84	100	638	86.67	90	700	81.7	(m)
515	54	(m)	577	110	83.92	639	89.65	90	701	85.16	(m)
516	65.27	(m)	578	104.77	(m)	640	90	99.81	702	84.52	(m)
517	78	(m)	579	87.5	(m)	641	89.45	100	703	82.21	(m)
518	57.61	(m)	580	90	0	642	86	100	704	79.89	(m)
519	42.58	(m)	581	91.38	(m)	643	86	95.47	705	77.58	(m)
520	38.81	(m)	582	81.84	(m)	644	87.22	90	706	76	6.31
521	22.37	(m)	583	65.99	(m)	645	88	90	707	79.16	0
522	3.52	(m)	584	63.68	(m)	646	88	80.74	708	75.16	27.36
523	0	0	585	60.73	(m)	647	88	79.17	709	72	40
524	-1.46	36.39	586	57.05	(m)	648	88	77.21	710	72	40
525	-0.23	5.75	587	53.47	(m)	649	88	100	711	74	38.44
526	0	0	588	50.42	(m)	650	88	94.45	712	74	30
527	0	0	589	44.31	(m)	651	88	90	713	74	30
528	0	0	590	37.58	37.91	652	88	90	714	74	36.28
529	0	0	591	33.48	20	653	90	90	715	72.43	47.86
530	0	0	592	31.16	20	654	89.63	90	716	68.23	59.43
531	0	0	593	28.85	20	655	88.68	90	717	73.8	50
532	0	0	594	22.13	20	656	90	90	718	72.52	50
533	0	0	595	9.31	(m)	657	90	90	719	74	45.85
534	0	0	596	0	0	658	91.63	81.86	720	72.85	57.18
535	0	0	597	0	0	659	92	80	721	76.38	62.7
536	0	0	598	0	0	660	90	81.29	722	81.55	60

723	80.18	60	785	96	(m)	847	104.88	40	909	0	0
724	83.6	60	786	94.08	(m)	848	104	32.85	910	0	0
725	83.44	56.4	787	78	(m)	849	104	30	911	0	0
726	86	50	788	77.45	(m)	850	104	0.3	912	0	0
727	87.35	50	789	71.67	28.96	851	103.63	11.87	913	0	0
728	86.34	50	790	67.18	80	852	100.62	13.12	914	0	0
729	86	40.11	791	66.5	87.48	853	98	5.01	915	0	0
730	88.29	61.47	792	71.43	90	854	96.68	10	916	0	0
731	88.78	63.92	793	74.13	90	855	96	(m)	917	0	0
732	86.92	50	794	75.56	92.2	856	96	(m)	918	0	0
733	86.76	50	795	74.75	100	857	96	(m)	919	0	0
734	87.55	42.24	796	77.07	94.65	858	95.43	(m)	920	0	0
735	88	49.34	797	79.38	83.08	859	94	(m)	921	0	0
736	86	50.91	798	80	71.51	860	94	(m)	922	0	0
737	86	67.45	799	80.01	69.93	861	95.52	5.18	923	0	0
738	86	81.88	800	82.33	58.36	862	97.83	(m)	924	0	0
739	87.13	70	801	84	50	863	98	(m)	925	0	0
740	89.44	77.21	802	84	59.58	864	98	(m)	926	0	0
741	91.76	88.78	803	84	76.36	865	97.22	(m)	927	0	3.67
742	90.07	89.65	804	84	80	866	96	6.35	928	0	47.69
743	92	80	805	84	70.49	867	96	12.98	929	3.11	59.41
744	92.7	80	806	82	80	868	96	10	930	9.09	84.54
745	94	80	807	81.47	82.66	869	95.93	10	931	15.62	80
746	94	80	808	80	90	870	92	10	932	33.49	80
747	94	80	809	77.68	90	871	92	10	933	37.93	79.29
748	94	80	810	74.52	75.24	872	92.98	14.89	934	31.2	38.25
749	94	81.37	811	77.58	78.96	873	94	13.54	935	21.99	26.67
750	94.59	87.05	812	81.89	80	874	90.79	42.12	936	30	15.1
751	96	57.4	813	80.42	80	875	88.08	40.4	937	22.23	16.47
752	96	42.19	814	82	83.68	876	86.23	30	938	19.61	28.05
753	96	42.33	815	83.05	79.5	877	88	32.75	939	20	20.38
754	96	40	816	84	70	878	87.14	44.32	940	18.33	(m)
755	96	38.37	817	84	61.6	879	84.82	50	941	6.55	(m)
756	96	12.83	818	84	50.03	880	82.51	50	942	15.82	(m)
757	96	(m)	819	86	60	881	82	50	943	23.63	(m)
758	96	(m)	820	86	60	882	82.12	40	944	17.51	(m)
759	96	(m)	821	86	69.39	883	83.13	35.64	945	14.19	62.52
760	97.74	7.37	822	88.51	73.73	884	80	20	946	16.64	69.36
761	100.05	19.74	823	88.43	70	885	84.26	51.95	947	27.77	60
762	102	11.83	824	88	70	886	86.62	66.21	948	37.03	63.79
763	102	26.81	825	94	70.99	887	84.31	60	949	47.36	75.36
764	103	49.96	826	94.51	80	888	81.99	9.96	950	54.77	80
765	104	60	827	95.17	80	889	79.35	1.61	951	57.7	80
766	102.37	60	828	95.14	80	890	75.36	19.56	952	54.03	79.92
767	103.94	60	829	94.54	80	891	73.05	40	953	58	65.03
768	104	40	830	94	80	892	70.73	8.35	954	58.65	43.23
769	104	25.75	831	94	77.89	893	68.42	(m)	955	62.88	50
770	103.12	(m)	832	94	31.99	894	47.15	8.95	956	69.83	50
771	100.8	(m)	833	94	43.57	895	35.79	10	957	72	42.05
772	100	(m)	834	94	60.28	896	32.95	7.38	958	75.81	40
773	101.83	44.88	835	94	63.29	897	29.16	(m)	959	84.22	42.2
774	102	36.4	836	94	76.57	898	16.47	(m)	960	83.86	41.28
775	102	(m)	837	94	89.86	899	2.13	(m)	961	80.55	(m)
776	102	(m)	838	94.29	90	900	0	0	962	80.51	(m)
777	100.91	(m)	839	97.8	87	901	0	0	963	78	(m)
778	101.4	(m)	840	102.91	80	902	0	0	964	79.79	(m)
779	100.28	(m)	841	104	73.85	903	0	0	965	80.33	30.54
780	97.97	(m)	842	104	62.28	904	0	0	966	85.58	42.12
781	96	(m)	843	104	69.29	905	0	0	967	81.78	50
782	96	10	844	106	70	906	0	0	968	78	50
783	96	0.23	845	106	62.7	907	0	0	969	80.74	43.16
784	96	(m)	846	106	40	908	0	0	970	92.1	73.65

971	88.01	(m)	1029	0	0	1087	0	20	1145	56	(m)
972	84	(m)	1030	0	0	1088	0	11.73	1146	46	(m)
973	84	(m)	1031	1.77	(m)	1089	0	0	1147	41.86	45.18
974	81.17	(m)	1032	1.6	(m)	1090	0	0	1148	38.31	78.47
975	70.46	(m)	1033	0	0	1091	0	0	1149	35.98	80
976	66	13.57	1034	0	0	1092	0	0	1150	31.03	80
977	62.23	29.43	1035	2.14	9.28	1093	0	0	1151	25.36	80
978	64	20	1036	3.08	0	1094	0	0	1152	23.05	60.97
979	63.48	17.42	1037	0	0	1095	0	0	1153	18.2	27.34
980	60.34	10	1038	0	0	1096	0	0	1154	12.84	43.71
981	56.85	10	1039	0	0	1097	0	0	1155	10.1	68.95
982	56	(m)	1040	0	0	1098	0	0	1156	3.79	68.95
983	52.45	(m)	1041	0	0	1099	0	0	1157	1.48	44.28
984	39.91	10	1042	0	0	1100	0	0	1158	0	0
985	36.38	10	1043	0	0	1101	0	0	1159	0	0
986	30	10	1044	0	0	1102	0	0	1160	0	0
987	27.93	10	1045	0	0	1103	0	0	1161	0	0
988	26	16.74	1046	0	0	1104	0	0	1162	0	0
989	27.66	3.36	1047	0	0	1105	0	0	1163	0	0
990	28	(m)	1048	0	0	1106	0	0	1164	0	0
991	27.41	(m)	1049	0	5.51	1107	0	0	1165	0	24.97
992	20.96	(m)	1050	0	11.34	1108	0	0	1166	0	17.16
993	12.15	(m)	1051	0	0	1109	0	0	1167	0	6.2
994	3.81	(m)	1052	0	0	1110	0	0	1168	0	10
995	0	0	1053	0	0	1111	0	0	1169	0	10
996	0	0	1054	0	0	1112	0	0	1170	0	0
997	0	0.91	1055	0	0	1113	0	0	1171	0	0
998	0	7.52	1056	0	0	1114	0	0	1172	0	0
999	0	0	1057	0	0	1115	0	0	1173	0	0
1000	0	0	1058	0	0	1116	0	73.41	1174	0	0
1001	0	0	1059	0	0	1117	0	90	1175	0	0
1002	0	0	1060	0	0.21	1118	31.3	81.3	1176	0	0
1003	0	0	1061	0	30	1119	41.15	90	1177	0	0
1004	0	0	1062	0	26.78	1120	44	90	1178	0	0
1005	0	0	1063	0	20	1121	46.41	90	1179	0	0
1006	0	0	1064	0	20	1122	51.04	82.41	1180	0	0
1007	0	0	1065	0	4.12	1123	66.66	80	1181	0	0
1008	0	0	1066	0	0	1124	75.03	90	1182	0	0
1009	0	0	1067	0	0	1125	89.85	90	1183	0	0
1010	0	0	1068	0	0	1126	96.78	93.88	1184	0	0
1011	0	0	1069	0	0	1127	96.91	50.94	1185	0	0
1012	0	0	1070	0	0	1128	94.6	17.02	1186	0	0
1013	0	0	1071	0	0	1129	99.16	28.6	1187	0	0
1014	0	0	1072	0	0	1130	100	39.83	1188	0	0
1015	0	0	1073	0	0	1131	100	30	1189	0	0
1016	0	0	1074	0	0	1132	100	26.69	1190	0	0
1017	0	0	1075	0	0	1133	100.98	20	1191	0	0
1018	0	0	1076	0	0	1134	100.71	20	1192	0	0
1019	0	0	1077	0	0	1135	100	36.06	1193	0	0
1020	0	0	1078	0	0	1136	96.16	40	1194	0	0
1021	0	0	1079	0	0	1137	95.77	30	1195	0	0
1022	0	0	1080	0	0	1138	94.55	32.75	1196	0	0
1023	0	0	1081	0	0	1139	96.86	35.68	1197	0	0
1024	0	0	1082	0	0	1140	99.18	30	1198	0	0
1025	0	0	1083	0	0	1141	100	44.93	1199	0	0
1026	0	0	1084	0	0	1142	101.81	50			
1027	0	0	1085	0	0	1143	86.54	(m)			
1028	0	0	1086	0	20	1144	63.56	(m)			

(m) indicates motoring torque

B. APPENDIX – Macro to Calculate bsNO_x Values Based on an Input Work Window

```
Sub workwindow()  
Dim worktarget As Single  
  
'Work Window Macro  
'Ben Shade 10/03/05  
'Macro sums instantaneous work until total work equals theoretical FTP work  
'Then calculates bsNOx emissions based on an interval over that work window to compare to 30 sec NTE  
window  
  
worktarget = InputBox("FTP Work Target", "Enter Theoretical FTP Work") 'asks the user for theoretical  
FTP work  
  
Count = 0 'initialize variables  
worksum = 0  
NOxSum = 0  
  
For i = 64 To 65535 'finds the maximum row number with valid data  
    If Worksheets("sheet1").Cells(i, 1) = "" Then  
        rowmax = i - 1  
        i = 65535  
    End If  
Next  
  
For Row = 64 To rowmax 'loop from first row of data to last row of data  
  
    If Row = 64 Then  
        Worksheets("sheet1").Cells(64, 5) = 0 'instantaneous work at first point is zero  
    End If  
  
    If Row > 64 Then  
        Worksheets("sheet1").Cells(Row, 5) = Worksheets("sheet1").Cells(Row, 4) * 0.2 / 3600 'calculates and  
displays instantaneous work  
    End If  
  
Next  
  
For RowOut = 64 To rowmax 'outer loop from first row to last  
  
    For RowIn = RowOut To rowmax 'inner loop from outer loop to last  
  
        worksum = worksum + Worksheets("Sheet1").Cells(RowIn, 5) 'calculate the work window (bhp-hr)  
        NOxSum = NOxSum + Worksheets("Sheet1").Cells(RowIn, 8) 'calculate the NOx window (g/s)  
  
        Count = Count + 0.2 'acts as a time increment recorder  
  
        If RowIn = rowmax And worksum < worktarget Then  
            End  
        End If  
  
        If worksum >= worktarget Then 'when theoretical work has been reached, calculated values are  
output  
  
            Worksheets("Sheet1").Cells(RowOut, 6) = worksum 'outputs the work window
```

```
Worksheets("Sheet1").Cells(RowOut, 7) = Count / 60 'outputs the time for work window in minutes
Worksheets("Sheet1").Cells(RowOut, 9) = NOxSum 'outputs the NOx window
Worksheets("Sheet1").Cells(RowOut, 10) = NOxSum * 0.2 / worksum 'outputs the bsNOx for the
work window
```

```
worksum = 0 'reinitializes the variables to zero
```

```
Count = 0
```

```
NOxSum = 0
```

```
RowIn = rowmax 'assigns RowIn to max row value to kick out of inner loop
```

```
End If
```

```
Next
```

```
Next
```

```
End Sub
```


C. APPENDIX – Macro to Calculate Duty Cycle

```
Sub dutycycle()  
,  
'Duty Cycle Macro  
'Ben Shade 01/17/06  
'macro calculates the duty cycle of a MEMS test  
  
For i = 64 To 65535 'finds the maximum row number with valid data  
    If Worksheets("sheet1").Cells(i, 1) = "" Then  
        rowmax = i - 1  
        i = 65535  
    End If  
Next  
  
increment = 100 / (rowmax - 63) 'calculate value to output table values as percent of time  
  
For Row = 3 To 22 'loop to initialize array as 0  
    For Col = 3 To 27  
        Worksheets("sheet3").Cells(Row, Col) = 0  
    Next  
Next  
  
Torque = 0 'loop for torque axis  
For Row = 3 To 22  
    Worksheets("sheet3").Cells(Row, 2) = Torque + 100  
    Torque = Torque + 100  
Next  
  
RPM = 500 'loop for rpm axis  
For Col = 3 To 27  
    Worksheets("sheet3").Cells(2, Col) = RPM + 100  
    RPM = RPM + 100  
Next  
  
For Row = 64 To rowmax 'loop from first row of data to last row of data  
    For RPM = 600 To 3000 Step 100 'loop for RPM range  
        EcuSpeed = Worksheets("sheet1").Cells(Row, 2) 'lookup engine speed  
        If EcuSpeed >= (RPM - 100) And EcuSpeed < RPM Then  
            For Torque = 100 To 2000 Step 100 'loop for Torque range  
                EcuTorque = Worksheets("sheet1").Cells(Row, 3) 'lookup broadcast torque value  
                If EcuTorque >= (Torque - 100) And EcuTorque < Torque Then  
                    Worksheets("sheet3").Cells((Torque / 100) + 2, (RPM / 100) - 3) =  
(Worksheets("sheet3").Cells((Torque / 100) + 2, (RPM / 100) - 3) + increment) 'increment the table  
                End If  
            Next  
        End If  
    Next  
Next  
End Sub
```

D. APPENDIX – Additional Figures

D.1 Phase III Displacement Range I

Figure D.1 Test Vehicle 1 WashPA1

Figure D.4 Test Vehicle 1 WashPA1 Repeat Duty Cycle

Figure D.2 Test Vehicle 1 WashPA1 Duty Cycle

Figure D.5 Test Vehicle 1 WashPA2

Figure D.3 Test Vehicle 1 WashPA1 Repeat

Figure D.6 Test Vehicle 1 WashPA2 Duty Cycle

Figure D.7 Test Vehicle 1 WashPA2 Repeat

Figure D.10 Test Vehicle 1 WashPA3 Duty Cycle

Figure D.8 Test Vehicle 1 WashPA2 Repeat Duty Cycle

Figure D.11 Test Vehicle 1 WashPA3 Repeat

Figure D.9 Test Vehicle 1 WashPA3

Figure D.12 Test Vehicle 1 WashPA3 Repeat Duty Cycle

D.2 Phase III Displacement Range II

Figure D.13 Test Vehicle 2 WashPA1

Figure D.16 Test Vehicle 2 WashPA1 Repeat Duty Cycle

Figure D.14 Test Vehicle 2 WashPA1 Duty Cycle

Figure D.17 Test Vehicle 2 WashPA2

Figure D.15 Test Vehicle 2 WashPA1 Repeat

Figure D.18 Test Vehicle 2 WashPA2 Duty Cycle

Figure D.19 Test Vehicle 2 WashPA2 Repeat

Figure D.22 Test Vehicle 2 WashPA3 Duty Cycle

Figure D.20 Test Vehicle 2 WashPA2 Repeat Duty Cycle

Figure D.23 Test Vehicle 2 WashPA3 Repeat

Figure D.21 Test Vehicle 2 WashPA3

Figure D.24 Test Vehicle 2 WashPA3 Repeat Duty Cycle

D.3 Phase III Displacement Range III

Figure D.25 Test Vehicle 3 WashPA1

Figure D.28 Test Vehicle 3 WashPA1 Repeat Duty Cycle

Figure D.26 Test Vehicle 3 WashPA1 Duty Cycle

Figure D.29 Test Vehicle 3 WashPA2

Figure D.27 Test Vehicle 3 WashPA1 Repeat

Figure D.30 Test Vehicle 3 WashPA2 Duty Cycle

Figure D.31 Test Vehicle 3 WashPA2 Repeat

Figure D.34 Test Vehicle 3 WashPA3 Duty Cycle

Figure D.32 Test Vehicle 3 WashPA2 Repeat Duty Cycle

Figure D.35 Test Vehicle 3 WashPA3 Repeat

Figure D.33 Test Vehicle 3 WashPA3

Figure D.36 Test Vehicle 3 WashPA3 Repeat Duty Cycle

D.4 Phase IV Displacement Range I

Figure D.37 Test Vehicle 4 Sab2Wash

Figure D.40 Test Vehicle 4 WashPA1 Duty Cycle

Figure D.38 Test Vehicle 4 Sab2Wash Duty Cycle

Figure D.41 Test Vehicle 4 WashPA2

Figure D.39 Test Vehicle 4 WashPA1

Figure D.42 Test Vehicle 4 WashPA2 Duty Cycle

Figure D.43 Test Vehicle 4 WashPA32Sab

Figure D.46 Test Vehicle 5 Sab2Wash Duty Cycle

Figure D.44 Test Vehicle 4 WashPA32Sab Duty Cycle

Figure D.47 Test Vehicle 5 WashPA1

Figure D.45 Test Vehicle 5 Sab2Wash

Figure D.48 Test Vehicle 5 WashPA1 Duty Cycle

Figure D.49 Test Vehicle 5 WashPA2

Figure D.52 Test Vehicle 5 WashPA32Sab Duty Cycle

Figure D.50 Test Vehicle 5 WashPA2 Duty Cycle

Figure D.53 Test Vehicle 6 Sab2Wash

Figure D.51 Test Vehicle 5 WashPA32Sab

Figure D.54 Test Vehicle 6 Sab2Wash Duty Cycle

Figure D.55 Test Vehicle 6 WashPA1

**Figure D.58 Test Vehicle 6 WashPA2
Duty Cycle**

**Figure D.56 Test Vehicle 6 WashPA1
Duty Cycle**

Figure D.59 Test Vehicle 6 WashPA32Sab

Figure D.57 Test Vehicle 6 WashPA2

**Figure D.60 Test Vehicle 6 WashPA32Sab
Duty Cycle**

Figure D.61 Test Vehicle 7 Sab2Wash

Figure D.64 Test Vehicle 7 WashPA1 Duty Cycle

Figure D.62 Test Vehicle 7 Sab2Wash Duty Cycle

Figure D.65 Test Vehicle 7 WashPA2

Figure D.63 Test Vehicle 7 WashPA1

Figure D.66 Test Vehicle 7 WashPA2 Duty Cycle

Figure D.67 Test Vehicle 7 WashPA32Sab

**Figure D.68 Test Vehicle 7 WashPA32Sab
Duty Cycle**

D.5 Phase IV Displacement Range II

Figure D.69 Test Vehicle 8 Mrgtwn

Figure D.72 Test Vehicle 8 WashPA1 Duty Cycle

Figure D.70 Test Vehicle 8 Mrgtwn Duty Cycle

Figure D.73 Test Vehicle 8 WashPA2

Figure D.71 Test Vehicle 8 WashPA1

Figure D.74 Test Vehicle 8 WashPA2 Duty Cycle

Figure D.75 Test Vehicle 8 WashPA32Sab

Figure D.78 Test Vehicle 8 NJ1 Duty Cycle

Figure D.76 Test Vehicle 8 WashPA32Sab Duty Cycle

Figure D.79 Test Vehicle 8 NJ2

Figure D.77 Test Vehicle 8 NJ1

Figure D.80 Test Vehicle 8 NJ2 Duty Cycle

Figure D.81 Test Vehicle 8 NJ3

Figure D.84 Test Vehicle 8 NJ4 Duty Cycle

Figure D.82 Test Vehicle 8 NJ3 Duty Cycle

Figure D.85 Test Vehicle 9 NJ1

Figure D.83 Test Vehicle 8 NJ4

Figure D.86 Test Vehicle 9 NJ1 Duty Cycle

Figure D.87 Test Vehicle 9 NJ2

Figure D.90 Test Vehicle 9 NJ3 Duty Cycle

Figure D.88 Test Vehicle 9 NJ2 Duty Cycle

Figure D.91 Test Vehicle 9 NJ4

Figure D.89 Test Vehicle 9 NJ3

Figure D.92 Test Vehicle 9 NJ4 Duty Cycle

Figure D.93 Test Vehicle 10 NJ1

Figure D.96 Test Vehicle 10 NJ2 Duty Cycle

Figure D.94 Test Vehicle 10 NJ1 Duty Cycle

Figure D.97 Test Vehicle 10 NJ3

Figure D.95 Test Vehicle 10 NJ2

Figure D.98 Test Vehicle 10 NJ3 Duty Cycle

Figure D.99 Test Vehicle 10 NJ4

Figure D.102 Test Vehicle 11 NJ1 Duty Cycle

Figure D.100 Test Vehicle 10 NJ4 Duty Cycle

Figure D.103 Test Vehicle 11 NJ2

Figure D.101 Test Vehicle 11 NJ1

Figure D.104 Test Vehicle 11 NJ2 Duty Cycle

Figure D.105 Test Vehicle 11 NJ3

Figure D.108 Test Vehicle 11 NJ4 Duty Cycle

Figure D.106 Test Vehicle 11 NJ3 Duty Cycle

Figure D.109 Test Vehicle 12 Sab2Wash

Figure D.107 Test Vehicle 11 NJ4

Figure D.110 Test Vehicle 12 Sab2Wash Duty Cycle

Figure D.111 Test Vehicle 12 WashPA1

**Figure D.114 Test Vehicle 12 WashPA2
Duty Cycle**

**Figure D.112 Test Vehicle 12 WashPA1
Duty Cycle**

**Figure D.115 Test Vehicle 12
WashPA32Sab**

Figure D.113 Test Vehicle 12 WashPA2

**Figure D.116 Test Vehicle 12
WashPA32Sab Duty Cycle**

Figure D.117 Test Vehicle 13 Sab2Wash

**Figure D.120 Test Vehicle 13 WashPA1
Duty Cycle**

**Figure D.118 Test Vehicle 13 Sab2Wash
Duty Cycle**

Figure D.121 Test Vehicle 13 WashPA2

Figure D.119 Test Vehicle 13 WashPA1

**Figure D.122 Test Vehicle 13 WashPA2
Duty Cycle**

**Figure D.123 Test Vehicle 13
WashPA32Sab**

**Figure D.126 Test Vehicle 14 Mrgtwn
Duty Cycle**

**Figure D.124 Test Vehicle 13
WashPA32Sab Duty Cycle**

Figure D.127 Test Vehicle 14 Sab2Wash

Figure D.125 Test Vehicle 14 Mrgtwn

**Figure D.128 Test Vehicle 14 Sab2Wash
Duty Cycle**

Figure D.129 Test Vehicle 14 WashPA1

Figure D.132 Test Vehicle 14 WashPA1 Repeat Duty Cycle

Figure D.130 Test Vehicle 14 WashPA1 Duty Cycle

Figure D.133 Test Vehicle 14 WashPA2

Figure D.131 Test Vehicle 14 WashPA1 Repeat

Figure D.134 Test Vehicle 14 WashPA2 Duty Cycle

Figure D.135 Test Vehicle 14 WashPA2 Repeat

Figure D.138 Test Vehicle 14 WashPA32Sab Duty Cycle

Figure D.136 Test Vehicle 14 WashPA2 Repeat Duty Cycle

Figure D.139 Test Vehicle 14 WashPA32Sab Repeat

Figure D.137 Test Vehicle 14 WashPA32Sab

Figure D.140 Test Vehicle 14 WashPA32Sab Repeat Duty Cycle

Figure D.141 Test Vehicle 15 Mrgtwn

**Figure D.144 Test Vehicle 15 WashPA1
Duty Cycle**

**Figure D.142 Test Vehicle 15 Mrgtwn
Duty Cycle**

Figure D.145 Test Vehicle 15 WashPA2

Figure D.143 Test Vehicle 15 WashPA1

**Figure D.146 Test Vehicle 15 WashPA2
Duty Cycle**

**Figure D.147 Test Vehicle 15
WashPA32Sab**

**Figure D.148 Test Vehicle 15
WashPA32Sab Duty Cycle**

Figure D.149 Test Vehicle 16 Sab2Wash

**Figure D.150 Test Vehicle 16 Sab2Wash
Duty Cycle**

Figure D.151 Test Vehicle 16 WashPA1

**Figure D.152 Test Vehicle 16 WashPA1
Duty Cycle**

Figure D.153 Test Vehicle 16 WashPA2

Figure D.156 Test Vehicle 16 WashPA32Sab Duty Cycle

Figure D.154 Test Vehicle 16 WashPA2 Duty Cycle

Figure D.157 Test Vehicle 17 Sab2Wash

Figure D.155 Test Vehicle 16 WashPA32Sab

Figure D.158 Test Vehicle 17 Sab2Wash Duty Cycle

Figure D.159 Test Vehicle 17 WashPA1

Figure D.162 Test Vehicle 17 WashPA1 Repeat Duty Cycle

Figure D.160 Test Vehicle 17 WashPA1 Duty Cycle

Figure D.163 Test Vehicle 17 WashPA2

Figure D.161 Test Vehicle 17 WashPA1 Repeat

Figure D.164 Test Vehicle 17 WashPA2 Duty Cycle

Figure D.165 Test Vehicle 17 WashPA2 Repeat

Figure D.168 Test Vehicle 17 WashPA32Sab Duty Cycle

Figure D.166 Test Vehicle 17 WashPA2 Repeat Duty Cycle

Figure D.169 Test Vehicle 17 WashPA32Sab Repeat

Figure D.167 Test Vehicle 17 WashPA32Sab

Figure D.170 Test Vehicle 17 WashPA32Sab Repeat Duty Cycle

Figure D.171 Test Vehicle 18 Mrgtwn

Figure D.174 Test Vehicle 18 Sab2Wash
Duty Cycle

Figure D.172 Test Vehicle 18 Mrgtwn
Duty Cycle

Figure D.175 Test Vehicle 18 WashPA1

Figure D.173 Test Vehicle 18 Sab2Wash

Figure D.176 Test Vehicle 18 WashPA1
Duty Cycle

Figure D.177 Test Vehicle 18 WashPA2

Figure D.180 Test Vehicle 18 WashPA32Sab Duty Cycle

Figure D.178 Test Vehicle 18 WashPA2 Duty Cycle

Figure D.181 Test Vehicle 19 Sab2Wash

Figure D.179 Test Vehicle 18 WashPA32Sab

Figure D.182 Test Vehicle 18 Sab2Wash Duty Cycle

Figure D.183 Test Vehicle 19 WashPA1

**Figure D.186 Test Vehicle 19 WashPA2
Duty Cycle**

**Figure D.184 Test Vehicle 19 WashPA1
Duty Cycle**

**Figure D.187 Test Vehicle 19
WashPA32Sab**

Figure D.185 Test Vehicle 19 WashPA2

**Figure D.188 Test Vehicle 19
WashPA32Sab Duty Cycle**

Figure D.189 Test Vehicle 20 Sab2Wash 80k

Figure D.192 Test Vehicle 20 WashPA1 80k Duty Cycle

Figure D.190 Test Vehicle 20 Sab2Wash 80k Duty Cycle

Figure D.193 Test Vehicle 20 WashPA2 80k

Figure D.191 Test Vehicle 20 WashPA1 80k

Figure D.194 Test Vehicle 20 WashPA2 80k Duty Cycle

**Figure D.195 Test Vehicle 20
WashPA32Sab 80k**

**Figure D.198 Test Vehicle 20 Mrgtwn 60k
Duty Cycle**

**Figure D.196 Test Vehicle 20
WashPA32Sab 80k Duty Cycle**

**Figure D.199 Test Vehicle 20 WashPA1
60k**

Figure D.197 Test Vehicle 20 Mrgtwn 60k

**Figure D.200 Test Vehicle 20 WashPA1
60k Duty Cycle**

Figure D.201 Test Vehicle 20 WashPA2 60k

Figure D.204 Test Vehicle 20 WashPA32Sab 60k Duty Cycle

Figure D.202 Test Vehicle 20 WashPA2 60k Duty Cycle

Figure D.205 Test Vehicle 21 Mrgtwn 80k

Figure D.203 Test Vehicle 20 WashPA32Sab 60k

Figure D.206 Test Vehicle 21 Mrgtwn 80k Duty Cycle

Figure D.207 Test Vehicle 21 WashPA1 80k

Figure D.210 Test Vehicle 21 WashPA2 80k Duty Cycle

Figure D.208 Test Vehicle 21 WashPA1 80k Duty Cycle

Figure D.211 Test Vehicle 21 WashPA32Sab 80k

Figure D.209 Test Vehicle 21 WashPA2 80k

Figure D.212 Test Vehicle 21 WashPA32Sab 80k Duty Cycle

Figure D.213 Test Vehicle 21 Sab2Wash 60k

Figure D.216 Test Vehicle 21 WashPA1 60k Duty Cycle

Figure D.214 Test Vehicle 21 Sab2Wash 60k Duty Cycle

Figure D.217 Test Vehicle 21 WashPA2 60k

Figure D.215 Test Vehicle 21 WashPA1 60k

Figure D.218 Test Vehicle 21 WashPA2 60k Duty Cycle

**Figure D.219 Test Vehicle 21
WashPA32Sab 60k**

**Figure D.222 Test Vehicle 22 Mrgtwn
Duty Cycle**

**Figure D.220 Test Vehicle 21
WashPA32Sab 60k Duty Cycle**

Figure D.223 Test Vehicle 22 WashPA1

Figure D.221 Test Vehicle 22 Mrgtwn

**Figure D.224 Test Vehicle 22 WashPA1
Duty Cycle**

Figure D.225 Test Vehicle 22 WashPA2

Figure D.228 Test Vehicle 22 WashPA32Sab Duty Cycle

Figure D.226 Test Vehicle 22 WashPA2 Duty Cycle

Figure D.229 Test Vehicle 23 Mrgtwn 80k

Figure D.227 Test Vehicle 22 WashPA32Sab

Figure D.230 Test Vehicle 23 Mrgtwn 80k Duty Cycle

Figure D.231 Test Vehicle 23 WashPA1 80k

Figure D.234 Test Vehicle 23 WashPA1 80k Repeat Duty Cycle

Figure D.232 Test Vehicle 23 WashPA1 80k Duty Cycle

Figure D.235 Test Vehicle 23 WashPA2 80k

Figure D.233 Test Vehicle 23 WashPA1 80k Repeat

Figure D.236 Test Vehicle 23 WashPA2 80k Duty Cycle

**Figure D.237 Test Vehicle 23
WashPA32Sab 80k**

**Figure D.240 Test Vehicle 23 Sab2Wash
60k Duty Cycle**

**Figure D.238 Test Vehicle 23
WashPA32Sab 80k Duty Cycle**

**Figure D.241 Test Vehicle 23 WashPA1
60k**

**Figure D.239 Test Vehicle 23 Sab2Wash
60k**

**Figure D.242 Test Vehicle 23 WashPA1
60k Duty Cycle**

Figure D.243 Test Vehicle 23 WashPA2 60k

Figure D.246 Test Vehicle 23 WashPA32Sab 60k Duty Cycle

Figure D.244 Test Vehicle 23 WashPA2 60k Duty Cycle

Figure D.245 Test Vehicle 23 WashPA32Sab 60k

D.6 Phase IV Displacement Range III

Figure D.247 Test Vehicle 24 Sab2Wash

Figure D.250 Test Vehicle 24 Sab2Wash Repeat Duty Cycle

Figure D.248 Test Vehicle 24 Sab2Wash Duty Cycle

Figure D.251 Test Vehicle 24 WashPA1

Figure D.249 Test Vehicle 24 Sab2Wash Repeat

Figure D.252 Test Vehicle 24 WashPA1 Duty Cycle

Figure D.253 Test Vehicle 24 WashPA2

Figure D.256 Test Vehicle 24 WashPA1 & WashPA2 Combined Duty Cycle

Figure D.254 Test Vehicle 24 WashPA2 Duty Cycle

Figure D.257 Test Vehicle 24 WashPA32Sab

Figure D.255 Test Vehicle 24 WashPA1 & WashPA2 Combined

Figure D.258 Test Vehicle 24 WashPA32Sab Duty Cycle

Figure D.259 Test Vehicle 25 Mrgtwn

Figure D.262 Test Vehicle 25 WashPA1 Duty Cycle

Figure D.260 Test Vehicle 25 Mrgtwn Duty Cycle

Figure D.263 Test Vehicle 25 WashPA2

Figure D.261 Test Vehicle 25 WashPA1

Figure D.264 Test Vehicle 25 WashPA2 Duty Cycle

**Figure D.265 Test Vehicle 25
WashPA32Sab**

**Figure D.266 Test Vehicle 26 Sab2Wash
Duty Cycle**

**Figure D.267 Test Vehicle 26 Sab2Wash
Duty Cycle**

**Figure D.268 Test Vehicle 26 WashPA1
Duty Cycle**

**Figure D.269 Test Vehicle 26 WashPA1
Duty Cycle**

**Figure D.270 Test Vehicle 26 WashPA1
Duty Cycle**

Figure D.271 Test Vehicle 26 WashPA2

Figure D.274 Test Vehicle 26 WashPA32Sab Duty Cycle

Figure D.272 Test Vehicle 26 WashPA2 Duty Cycle

Figure D.275 Test Vehicle 27 Mrgtwn

Figure D.273 Test Vehicle 26 WashPA32Sab

Figure D.276 Test Vehicle 27 Mrgtwn Duty Cycle

Figure D.277 Test Vehicle 27 Sab2Wash

**Figure D.280 Test Vehicle 27 WashPA1
Duty Cycle**

**Figure D.278 Test Vehicle 27 Sab2Wash
Duty Cycle**

Figure D.281 Test Vehicle 27 WashPA2

Figure D.279 Test Vehicle 27 WashPA1

**Figure D.282 Test Vehicle 27 WashPA2
Duty Cycle**

**Figure D.283 Test Vehicle 27
WashPA32Sab**

**Figure D.284 Test Vehicle 27
WashPA32Sab Duty Cycle**

Figure D.285 Test Vehicle 28 Mrgtwn

**Figure D.286 Test Vehicle 28 Mrgtwn
Duty Cycle**

Figure D.287 Test Vehicle 28 WashPA1

**Figure D.288 Test Vehicle 28 WashPA1
Duty Cycle**

Figure D.289 Test Vehicle 28 WashPA2

Figure D.292 Test Vehicle 28 WashPA32Sab Duty Cycle

Figure D.290 Test Vehicle 28 WashPA2 Duty Cycle

Figure D.293 Test Vehicle 29 Sab2Wash 80k

Figure D.291 Test Vehicle 28 WashPA32Sab

Figure D.294 Test Vehicle 29 Sab2Wash 80k Duty Cycle

Figure D.295 Test Vehicle 29 WashPA1 80k

Figure D.298 Test Vehicle 19 WashPA2 80k Duty Cycle

Figure D.296 Test Vehicle 29 WashPA1 80k Duty Cycle

Figure D.299 Test Vehicle 29 WashPA32Sab 80k

Figure D.297 Test Vehicle 29 WashPA2 80k

Figure D.300 Test Vehicle 29 WashPA32Sab 80k Duty Cycle

Figure D.301 Test Vehicle 29 Sab2Wash 60k

Figure D.304 Test Vehicle 29 WashPA1 60k Duty Cycle

Figure D.302 Test Vehicle 29 Sab2Wash 60k Duty Cycle

Figure D.305 Test Vehicle 29 WashPA1 60k Repeat

Figure D.303 Test Vehicle 29 WashPA1 60k

Figure D.306 Test Vehicle 29 WashPA1 60k Repeat Duty Cycle

Figure D.307 Test Vehicle 29 WashPA2 60k

Figure D.310 Test Vehicle 29 WashPA2 60k Repeat Duty Cycle

Figure D.308 Test Vehicle 29 WashPA2 60k Duty Cycle

Figure D.311 Test Vehicle 29 WashPA32Sab 60k

Figure D.309 Test Vehicle 29 WashPA2 60k Repeat

Figure D.312 Test Vehicle 29 WashPA32Sab 60k Duty Cycle

**Figure D.313 Test Vehicle 29
WashPA32Sab 60k Repeat**

**Figure D.316 Test Vehicle 30 Sab2Wash
80k Duty Cycle**

**Figure D.314 Test Vehicle 29
WashPA32Sab 60k Repeat Duty Cycle**

**Figure D.317 Test Vehicle 30 WashPA1
80k**

**Figure D.315 Test Vehicle 30 Sab2Wash
80k**

**Figure D.318 Test Vehicle 30 WashPA1
80k Duty Cycle**

Figure D.319 Test Vehicle 30 WashPA2 80k

Figure D.322 Test Vehicle 30 WashPA32Sab 80k Duty Cycle

Figure D.320 Test Vehicle 30 WashPA2 80k Duty Cycle

Figure D.323 Test Vehicle 30 Mrgtwn 60k

Figure D.321 Test Vehicle 30 WashPA32Sab 80k

Figure D.324 Test Vehicle 30 Mrgtwn 60k Duty Cycle

Figure D.325 Test Vehicle 30 WashPA1 60k

Figure D.328 Test Vehicle 30 WashPA2 60k Duty Cycle

Figure D.326 Test Vehicle 30 WashPA1 60k Duty Cycle

Figure D.329 Test Vehicle 30 WashPA32Sab 60k

Figure D.327 Test Vehicle 30 WashPA2 60k

Figure D.330 Test Vehicle 30 WashPA32Sab 60k Duty Cycle

Figure D.331 Test Vehicle 31 Mrgtwn 80k

Figure D.334 Test Vehicle 31 Mrgtwn 80k Repeat Duty Cycle

Figure D.332 Test Vehicle 31 Mrgtwn 80k Duty Cycle

Figure D.335 Test Vehicle 31 Sab2Wash 80k

Figure D.333 Test Vehicle 31 Mrgtwn 80k Repeat

Figure D.336 Test Vehicle 31 Sab2Wash 80k Duty Cycle

**Figure D.337 Test Vehicle 31 Sab2Wash
80k Repeat**

**Figure D.340 Test Vehicle 31 WashPA1
80k Duty Cycle**

**Figure D.338 Test Vehicle 31 Sab2Wash
80k Repeat Duty Cycle**

**Figure D.341 Test Vehicle 31 WashPA1
80k Repeat**

**Figure D.339 Test Vehicle 31 WashPA1
80k**

**Figure D.342 Test Vehicle 31 WashPA1
80k Repeat Duty Cycle**

Figure D.343 Test Vehicle 31 WashPA2 80k

Figure D.346 Test Vehicle 31 WashPA2 80k Repeat Duty Cycle

Figure D.344 Test Vehicle 31 WashPA2 80k Duty Cycle

Figure D.347 Test Vehicle 31 WashPA32Sab 80k

Figure D.345 Test Vehicle 31 WashPA2 80k Repeat

Figure D.348 Test Vehicle 31 WashPA32Sab 80k Duty Cycle

**Figure D.349 Test Vehicle 31
WashPA32Sab 80k Repeat**

**Figure D.352 Test Vehicle 31 Sab2Wash
60k Duty Cycle**

**Figure D.350 Test Vehicle 31
WashPA32Sab 80k Repeat Duty Cycle**

**Figure D.353 Test Vehicle 31 Sab2Wash
60k Repeat**

**Figure D.351 Test Vehicle 31 Sab2Wash
60k**

**Figure D.354 Test Vehicle 31 Sab2Wash
60k Repeat Duty Cycle**

**Figure D.355 Test Vehicle 31 WashPA1
60k**

**Figure D.358 Test Vehicle 31 WashPA1
60k Repeat Duty Cycle**

**Figure D.356 Test Vehicle 31 WashPA1
60k Duty Cycle**

**Figure D.359 Test Vehicle 31 WashPA2
60k**

**Figure D.357 Test Vehicle 31 WashPA1
60k Repeat**

**Figure D.360 Test Vehicle 32 WashPA2
60k Duty Cycle**

Figure D.361 Test Vehicle 31 WashPA2 60k Repeat

Figure D.364 Test Vehicle 31 WashPA32Sab 60k Duty Cycle

Figure D.362 Test Vehicle 31 WashPA2 60k Repeat Duty Cycle

Figure D.365 Test Vehicle 31 WashPA32Sab 60k Repeat

Figure D.363 Test Vehicle 31 WashPA32Sab 60k

Figure D.366 Test Vehicle 31 WashPA32Sab 60k Repeat Duty Cycle