EVALUATION OF MOBILE MONITORING TECHNOLOGIES FOR HEAVY-DUTY DIESEL-POWERED VEHICLE EMISSIONS

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FOREWORD

This report was prepared by the Department of Mechanical and Aerospace Engineering, College of Engineering and Mineral Resources, West Virginia University, WV with funding provided by the Settling Heavy-Duty Diesel Engine (S-HDDE) manufacturers (Caterpillar, Inc.; Cummins Engine Company, Inc.; Detroit Diesel Corporation; Mack Trucks, Inc.; Navistar International Transportation Corporation; Volvo Truck Corporation). This report is a summary of the work completed as part of the workplan submitted to the S-HDDE manufacturers, that is aimed at meeting the requirements of Consent Decrees entered into by the United States and the S-HDDE manufacturers.

The objective of this study was to evaluate the currently available technologies for measurement of on-board heavy-duty diesel exhaust emissions and then using the best available sub-systems to integrate a heavy-duty on-road emissions measurement system (OREMS). The unit integrated by West Virginia University is called the Mobile Emissions Measurement System (MEMS). This report describes the MEMS in detail and presents results of laboratory and in-field testing, including comparative tests with another OREMS, the Remote On-board Vehicle Emissions Recorder, which was developed by the US-EPA.

The authors express their sincere appreciation to all those who have provided assistance in the laboratory and in-field testing, data analysis, and report writing. A number of faculty, staff, and students at West Virginia University contributed to this report. Special recognition for their significant contributions goes to Robert Craven and Andy Pertl.

EXECUTIVE SUMMARY

Exhaust emissions from heavy-duty diesel engines have been a subject of intense scrutiny in the recent past. Heavy-duty diesel engines (HDDE) are one of the major contributors to the ambient levels of oxides of nitrogen and fine particulate matter. Engine manufacturers are now marketing engines that have significantly lower levels of regulated exhaust emission constituents compared to a few years ago. To ensure that the lower emissions targets are attained, it is essential that the exhaust emissions of diesel-powered vehicles be measured under real-world, on-road driving conditions.

In 1998, six heavy-duty diesel engine manufacturing companies (Settling-HDDE) entered into individual agreements with the United States government. The settling HDDE manufacturers contracted West Virginia University (WVU) to perform Phases I and II of the Consent Decrees that initiate activities to evaluate available technologies and propose a mobile measurement system to perform in-use emissions testing of heavy-duty diesel vehicles. This report is a summary of the work that was aimed at meeting the Phase I requirements of the Consent Decrees.

In order to achieve accurate in-use brake-specific mass emissions, as required by the Consent Decrees, it is imperative that a viable on-road emissions measurement system (OREMS) not only be portable, but also be capable of accurately measuring several parameters in a repeatable manner with the highest level of precision. These include engine speed, engine torque, exhaust mass flow rates, and exhaust constituent concentrations. WVU has evaluated the currently available OREMS for diesel-fueled vehicles and the individual components that could be integrated into a viable measurement system.

Based upon an extensive evaluation of the available technologies, WVU has completed the integration and testing of the Mobile Emissions Measurement System (MEMS). MEMS is capable of measuring in-use brake-specific emissions from heavy-duty diesel-powered vehicles driven over the road under real-world conditions. The MEMS employs a filtered, heated sample handling and conditioning system, a solid-state non-dispersive infrared detector for CO_2 measurement, and a zirconia sensor for NOx measurement. It relies upon engine ECU broadcasts for torque, and engine/vehicle speed data. Exhaust flow rate is measured with a

differential pressure device. All data is collected with a rugged data acquisition system, and a customized software package that allows sampling at a minimum sampling rate of 5 Hz, per Consent Decrees' requirements. Also, in accordance with these requirements allows the calculation of brake-specific mass emissions over 30 second windows within the "not-to-exceed" (NTE) zone.

This report discusses the results of the laboratory and in-field evaluations, including comparative tests with the Remote On-board Vehicle Emissions Recorder (ROVER), developed by the US-EPA, that was loaned to WVU for this study. FTP cycle integrated brake-specific mass emissions of NOx reported by MEMS were within 0.5% of WVU's FTP laboratory data. Simultaneous measurements with the ROVER yielded brake-specific "NOx" mass emission differences as high as 7.9% between the ROVER and the laboratory. It should be noted that the ROVER utilizes an electrochemical cell that measures NO only with no apparent means of converting exhaust NO_2 to NO. However, in this report all ROVER data has been referred to as NOx. Other operating cycles, developed by WVU, resulted in brake-specific NOx mass emissions that were within ±4% of the laboratory values for the two systems.

However, the ROVER system was unable to calculate 30 second, brake-specific emissions within an NTE zone, which is a requirement mandated by the Consent Decrees. WVU developed an interface between the ECU and ROVER to provide an analog input to the ROVER, similar to the MEMS unit, that was proportional to the ECU-derived power. However, the ROVER cannot differentiate an NTE zone without independent engine speed and torque information. WVU employed the integrated power over 30 second windows and compared the MEMS and ROVER 30 second NOx mass emissions against the engine laboratory results. WVU was obliged to convert ROVER's nominal 1 Hz data to 5 Hz in order to permit comparison with 5 Hz laboratory data. The differences in the integrated NOx mass emissions, over the 30 second windows, ranged from -7.79% to 2.94% for the MEMS and from -11.23% to 4.27% for the ROVER.

Experimental results indicate that an OREMS integrated from currently available technologies is capable of measuring brake-specific NOx mass emissions, over 30 second windows, to within 10% of those obtained with laboratory-grade instrumentation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION AND BACKGROUND

1.1 Introduction and Objectives

Exhaust emissions from heavy-duty diesel engines (HDDE) constitute a substantial portion of urban inventories. Heavy-duty diesel engines are major contributors to the ambient levels of oxides of nitrogen and fine particulate matter. Engine manufacturers have implemented design changes that have helped minimize the levels of regulated exhaust emission constituents. To assure that this objective is achieved, it is necessary to measure the levels of these constituents in the exhaust stream of engines operating in a vehicle under real-world conditions.

The objective of this study was to evaluate the currently available on-road emission measurement systems (OREMS) for measurement of heavy-duty diesel exhaust emissions. The six settling heavy-duty diesel engine (S-HDDE) manufacturers contracted West Virginia University (WVU) to assess and propose a mobile measurement system to perform emissions testing of heavy-duty diesel vehicles. In 1998, six HDDE manufacturing companies entered into individual agreements (referred to as Consent Decrees) with the United States (US) government. The agreements state that, in addition to the standard Federal Test Procedure (FTP), engines will be tested according to the Euro III test procedure, which incorporates the steady state test and emission weighting protocols identified as the "ESC Test" in Annex III to the Proposal adopted by the Commission of the European Union on December 3, 1997. The engine manufacturers agreed that engines shall also be tested to demonstrate that they do not exceed prescribed emissions limits in a "Not To Exceed" (NTE) zone, Smoke or Alternative Opacity limits, and Transient Load Response limits. Engines must meet these limits when new and during in-use operations throughout the useful life of the engine.

WVU has previously conducted an exhaustive literature review and developed a White Paper (Attachment 1) on the availability and potentially viable in-use emissions measurement options. The White Paper was submitted to the S-HDDE in January 1999. Based upon extensive evaluations, WVU has integrated a mobile emissions measurement system (MEMS) to measure accurately in-use emissions from heavy-duty vehicles operating under on-road real-world driving conditions. All of the components of MEMS were selected for their portability, and ability to provide accurate, repeatable, and reliable brake-specific mass emission rates of gaseous pollutants from heavy-duty vehicles under a range of driving conditions. The MEMS is comprised of components that were selected on the basis of a review of currently available technologies and extensive laboratory and in-field testing of these technologies.

1.2 Existing Vehicle Emissions Testing Methods

To demonstrate that the actual levels of exhaust emissions are below the prescribed standards, engine manufacturers test a specified number of production engines before they are put into service. However, in-use engine testing poses a difficult problem, due to the expenses associated with engine removal that is necessary to perform the transient FTP test. For this reason, alternative methods that allow the engine to be tested while mounted in the vehicle are desirable.

There are two practical ways to apply a load on an engine that is mounted in a vehicle. The first is to place the vehicle on a chassis dynamometer that loads the engine while operating in place. The second is to load the engine by driving the vehicle over the road. Chassis dynamometer testing permits the use of proven laboratory-grade emissions measurement systems. Measurement of emissions while a vehicle is driven over the road requires an OREMS which has been integrated and qualified as part of this study.

It is well established that chassis dynamometer systems are reliable tools for studying vehicle emissions. Chassis dynamometers provide a method for applying a dynamic, programmable load to the drive-train of a vehicle. Measurement of speed and load are then used to infer engine power via vehicle output power, which is measured at the drive wheels. Vehicle-out emissions measured with a chassis dynamometer system are generally expressed as distance-specific or fuel-specific quantities. Existing chassis dynamometer laboratories can be used to make measurements of in-use engine emissions over the lifetime of the vehicle. These systems also provide a benchmark to assess the performance and reliability of an OREMS, which are the focus of this report.

Most heavy-duty chassis dynamometers are permanently installed, requiring that test vehicles be transported to the laboratory location. West Virginia University has developed and operates two transportable heavy-duty vehicle chassis dynamometer systems and one medium-duty chassis dynamometer that can be transported to a vehicle test site.

With a chassis dynamometer, engine loading is accomplished by driving the vehicle through a prescribed speed-time schedule while load (equal to the sum of the vehicle's inertia, applicable road load, and wind drag) is applied to the drivetrain. Most chassis dynamometers are designed to apply the load to roller(s), whereby it is transmitted to the driveline of the vehicle via the tires. The WVU transportable heavy-duty chassis dynamometers apply load directly to the drive axle by coupling through the wheel lug bolts. This approach eliminates differences between applied and programmed torque due to tire slippage or peculiar tire dynamics that are not representative of road-tire interactions. While connected to the dynamometer, the vehicle may be operated by either a driver or an automated controller according to pre-selected, or random, test cycles.

Heavy-duty chassis dynamometer systems are capable of using emissions measurement instruments and methods that are prescribed by the FTP or Euro III procedures for engine certification. Therefore, the accuracy, reliability, and repeatability of test equipment employed by chassis dynamometer laboratories are comparable to the systems used in the FTP test cells.

1.3 On-Road Mobile Emissions Measurement Systems

An alternative approach for loading a heavy-duty vehicle for testing is to drive the vehicle over the road. This method utilizes an OREMS that can be transported along with the vehicle as it is driven. An OREMS-based in-use emissions testing procedure has several advantages. One of the major advantages is that emissions tests may be conducted at a lower cost. OREMS designed for monitoring the emissions of light-duty gasoline-fueled vehicles have produced measurements that are comparable to those obtained with light-duty chassis dynamometers that operate in accordance to FTP regulations. The emissions limit standards governing light-duty vehicles, however, require distance–specific mass emissions (emissions reporting on a mass of exhaust constituent per unit distance). Although these standards require accurate assessment of distance traveled, the more difficult task of measuring engine output power is avoided. Such is not the case for an OREMS-based approach for testing heavy-duty diesel fueled vehicles.

However, a reliable and accurate OREMS for heavy-duty diesel-fueled vehicles had not been demonstrated prior to this study. One of the factors which makes the design of an OREMS system for heavy-duty vehicles more difficult than for light-duty vehicles is that the emissions limit standards are based upon units of mass of exhaust constituent per energy output of the engine rather than mass per distance traveled. Accurate measurements or inference of the engine energy output is more difficult than measurements of distance traveled by the vehicle.

An OREMS must have certain operational characteristics in order to be practical for in-use vehicle testing. Foremost, 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. It is essential that the system be capable of reliably measuring oxides of nitrogen (NOx), unburned hydrocarbons (UHC), carbon monoxide (CO), and carbon dioxide (CO_2) mass emissions at the highest accuracy levels. Presently, determination of UHC and CO seems to be problematic, due to limitations of currently-available technology, and has therefore been assigned a lower priority than CO_2 and NOx measurements. It is also essential that accurate calibration procedures be incorporated into the measurement system.

The OREMS must be portable. There is very limited space in many heavy-duty vehicles for accommodation of on-board emissions measurement instrumentation. Hence, the unit must be compact in size and lightweight, so that it may be easily installed on the vehicle. The OREMS will need to attach to the exhaust pipe of the vehicle, and therefore must be capable of accommodating a very broad range of exhaust system designs. Heavy-duty vehicle exhausts may exit from the rear, the top, or the side of the vehicle. Moreover, vehicles may have exhaust systems of single or dual designs, with different exhaust pipe diameters.

Diesel engines for heavy-duty vehicles are produced in a broad range of displacements in intake boost ratios. Therefore, the range of mass flow rates from the exhaust varies greatly from vehicle to vehicle. The OREMS must be capable of accommodating and reliably measuring exhaust flow rates over this broad range. In addition, it is essential that the installation of the OREMS have minimal influence on the exhaust back pressure during vehicle operation, as this affects engine performance. The possibility of inferring exhaust flow rates from intake flow rates may exist, but this approach was deemed to be less accurate than direct exhaust flow rate measurements.

The time lags and response functions in each system component must be accounted for in the analysis of the test results. Some parameters, such as speed and torque, may be inferred from engine control unit (ECU) broadcasts. However, other parameters, such as exhaust flow rate or constituent concentration may suffer from either amplitude or phase distortion resulting from the time response characteristics of the measurement system. In addition, an OREMS, with its associated sensors and sampling lines, must be expected to function accurately over a wide range of ambient conditions and varying altitudes.

On some heavy-duty vehicles, a considerable length of exhaust sampling lines may be necessary. The OREMS must be capable of accommodating variable sampling lag times related to different exhaust sampling lines.

Most heavy-duty vehicles have electrical systems that are dual-voltage, direct current (DC) in nature. At idle, these systems are generally capable of providing less than 50 amperes of current at 12 volts DC. In light of these constraints on available power, an OREMS will require an additional power source, such as a portable generator set.

In order to estimate the level of emissions constituents for heavy-duty vehicles, it is necessary to measure several parameters, including engine speed, engine torque, exhaust mass flow rates, and exhaust constituent concentration. The on-road emissions measurement system that has been integrated and tested in this study takes into account all of these factors. The following sections describe the MEMS in detail and present results of laboratory and in-field testing, including comparative tests with another OREMS unit, the Remote On-board Vehicle Emissions Recorder (ROVER), which was developed by the US-EPA.

2 PRIOR PORTABLE IN-FIELD EMISSIONS MEASUREMENT SYSTEMS

2.1 Introduction to Prior Systems

In-field 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. A review of the work performed for portable and mobile emissions measurement systems over the last 20 years follows.

2.1.1 In-Field Measurements

2.1.1.1 <u>Southwest Research Institute, 1983</u>

Work was performed by Southwest Research Institute from 1978 to 1983 to develop a system to test diesel engines in a mine for an I/M program [1]. The transportable system consisted of a portable engine dynamometer, laboratory-grade emissions instruments, volumetric fuel flow meter, and a laminar air meter. The emissions measurement system consisted of a heated flame ionization detector (HFID) for HC, non-dispersive infrared (NDIR) analyzers for CO and CO_2, a heated chemiluminescent analyzer (CLA) for NOx, and a polaragraphic analyzer for oxygen (O_2). Calibration gases for these analyzers were carried along with the unit. The particulate matter (PM) measurement system included a mini-dilution tunnel. Although this system was transportable, the level of portability was minimal and therefore, could not be used for on-board vehicle emissions measurements.

2.1.1.2 <u>Michigan Technological University, 1992</u>

Michigan Technological University (MTU) researchers developed an Emissions Measurement Apparatus (EMA) system and reported results from underground mining equipment tests [2]. The EMA was designed to measure both PM and gaseous emissions. It consisted of a dilute bag sampling system, a mini-dilution tunnel for gravimetric analysis of PM, battery powered portable emissions analyzers (for off-line bag analysis), and heated sample lines (to avoid thermophoresis and condensation related problems). A comparison of the portable emissions analyzers with the laboratory-grade analyzers on steady-state engine dynamometer tests showed that the results for CO_2 were within 5%, CO within 10%, and nitric oxide (NO) within 5%. The PM emission results were within 7% of the laboratory equipment. However, the

EMA system was too bulky and labor intensive to use as an OREMS for on-board vehicle measurements.

2.1.1.3 University of Minnesota, 1997

The emissions-assisted maintenance procedure (EAMP) for diesel-powered mining equipment was developed by the University of Minnesota [3]. The EAMP system was designed to be far more portable than the prior systems developed by Southwest Research Institute and MTU, but still very capable of detecting engine faults. Assessments of portability were made for various instruments including NDIR, Fourier transform infrared (FTIR) spectrophotometer, and electrochemical gas sensors (EGS). EGS sensor technology was determined to be rugged and portable. In addition, accuracy to within 5% of the measured value was obtained by using a single EGS-based instrument that measured NO, nitrogen dioxide (NO_2), CO, CO_2, and O_2. The Ecom-AC and Ecom-E analyzers by ECOM America Ltd. were found to be portable, rugged, and inexpensive. A comparison of the portable system and laboratory-grade instruments, for a diesel engine on a dynamometer, showed that the Ecom-AC analyzer emissions readings were within 5% of the laboratory-grade instruments. The Ecom-E error was slightly higher when compared against the laboratory equipment. A curve fit to known gases was employed to minimize measurement errors. The EAMP was designed to measure on-site emissions concentrations from vehicles that were loaded by stalling either their torque converters or hydrostatic transmissions.

2.1.2 On-Board Measurements

2.1.2.1 Caterpillar, 1982

A portable bag collection system was developed by Caterpillar to quantify fuel specific NOx emission levels from in-use diesel engines [4]. A two bag collection system was designed with the capability of removing water vapor before the bags. The system was powered by an on-board supply and could be operated remotely by the driver. Moreover, the collection system could fit in a "small suitcase." Engine testing showed that the portable system collected bag samples which gave results that were accurate to within 10% of laboratory-grade equipment on a parts per million (ppm) concentration basis.

2.1.2.2 Southwest Research Institute, 1992

A portable system was developed by Southwest Research Institute to measure exhaust emissions from diesel buses and to compare the data against Environmental Protection Agency's (US-EPA's) database of transient engine emissions [5]. The system was designed to collect information regarding emissions without the use of a chassis dynamometer. Several test cycles were developed to exercise the engine while the vehicle was parked. The cycles ranged from idle, no-load testing to loading the engine against the transmission through prescribed accelerator pedal positions. The prescribed test procedure could only be performed on vehicles with automatic transmissions. An Enerac 2000E was used to measure undiluted concentrations of CO, NOx, O_2, and CO_2 from a bag sample, and a mini-dilution tunnel was used for the PM measurement. Exhaust emissions concentrations measured using the portable ("suitcase" size) Enerac 2000E were within 5% of laboratory-grade instruments. However, this system, being based upon an integrated bag approach, was not used to measure continuous on-board exhaust emissions from any vehicles.

2.1.2.3 General Motors, 1993

A 1989 gasoline fueled passenger vehicle was instrumented and driven through city and highway routes to obtain real-world emissions data [6]. The 180 kg (400 lbs) data acquisition system (housed in the trunk of the vehicle) consisted of five 12 volt batteries, inverters, computers, and five different emissions analyzers. The analyzers included a Horiba MEXA 311GE for CO_2 and hydrocarbon (HC), a Horiba MEXA 324GE for HC and CO, a Siemens Ultramat 22P for HC and CO, a Siemens analyzer for NO, and a Draeger analyzer for ambient CO. Redundant measurements of CO and HC were made in order to accommodate different emissions levels. Ambient CO measurement were made to monitor the passenger compartment concentration levels.

The exhaust flow rate was inferred from the intake flow rate. Exhaust flow rate measurements, made with a Kurz flow meter, were correlated with the intake flow rates, derived from stock mass flow meter signals. The resultant relationship enabled inference of exhaust flow rates from intake flow rates. Some measurements were discounted due to time alignment problems associated with synchronizing the laptop and the diagnostic port. Concerns were also reported regarding the data collection rate (one sample per second) and its subsequent inability to capture transient events. However, the system did provide some in-use emissions data for spark ignited passenger vehicles.

2.1.2.4 Ford Motor Company, 1994

The emissions results from three different instrumented gasoline-fueled passenger vehicles are detailed in several reports [7-10]. The impetus of the study was to compare on-board measurements to remote measurement techniques. An On-Board Emissions (OBE) system, housed in an Aerostar van, consisted of an FTIR, and a dilution tunnel. The OBE was compared against Horiba laboratory-grade equipment for the vehicle on a chassis dynamometer. The comparison showed that the OBE system was within (on average) 2% for CO_2, 3% for CO, 10% for NOx, and 7% for HC. The on-road test showed that the OBE system was within (on average) 10% for CO, 1% for CO_2, 6.6% for NOx, and 1% for HC when compared against laboratory-grade equipment. However, the FTIR-based system has very slow transient response and may not be suitable for on-board emissions measurements of transient vehicle operations.

A Ford Taurus was instrumented with infrared-based analyzers (manufactured by MPSI) for measuring CO, HC, O_2, and CO_2, and an unspecified fast response (1.1 seconds) non-dispersive ultraviolet (NDUV) system for measuring NO. Comparisons were made between the on-board NDIR analyzers and laboratory-grade equipment for measuring NO. However, a correlation of 0.97, with a slope of 0.8, was found between the fast response NDUV analyzer and a conventional chemiluminescent instrument. All of the above systems were designed for gasoline-fueled vehicles.

2.1.2.5 U.S. Coast Guard, 1997

A 1992 SAE paper and a 1997 report describe the on-board testing of U.S. Coast Guard Cutters to assess the emissions as part of the 1990 Clean Air Act for non-road air pollution [11,12]. Although the system was recognized as being too bulky and lacking portability, it demonstrated that emissions tests could be performed on-board a ship. The emissions of CO, NO, NO_2, sulfur dioxide (SO_2), O_2, and HC were monitored with an Energy Efficiency Systems, Inc., Enerac 2000E. CO_2 was inferred from the measured emissions. The monitoring system incorporated air and fuel flow measurements and provided for inference of engine-out torque via driveshaft mounted strain gauges. Radio frequency (RF) transmitters were used to record the shaft torque and speed via Wireless Data Corporation power metering equipment.

2.1.2.6 University of Pittsburgh, 1997

An on-board emissions measurement system for I/M was developed for natural gas-powered passenger vans at the University of Pittsburgh [13]. A RG240 five-gas analyzer from OTC SPX was used to measure the undiluted gas concentrations of HC, CO, CO_2, NOx (actually NO), and O_2. Engine data were collected via the on-board diagnostic (OBD-II) plug with third-party diagnostic equipment. The emissions measurement equipment was designed for gasoline-fueled vehicles, thus, the HC results were biased. It was reported that the system did fulfill some of the goals of providing an inexpensive, portable system capable of measuring real-world, in-use emissions from natural gas-fueled vehicles. However, some issues remain unresolved, for example, determination of mass emission rates, time alignment of signals, and analyzer (and the system) response times.

2.1.2.7 Flemish Institute for Technological Research, 1997

VITO, The Flemish Institute for Technological Research, performed on-board emission measurements with a system called VOEM (Vito's On-the-road Emission and Energy Measurement system). The system used NDIR analyzers to measure CO_2 and CO, a flame ionization detector (FID) to determine HC concentrations, and a chemiluminescent analyzer to measure NOx. A nitrogen-driven ejector was used to draw a portion of the tailpipe exhaust and dilute it in order to prevent water condensation. A high temperature sampling line (190°C) prevented the loss of heavy hydrocarbons that are associated with diesel exhaust. Partial dilute exhaust measurements were combined with fuel consumption, engine speed, and lambda value determination (to derive total exhaust flow quantities) in order to present gaseous emissions on a g/km and g/s basis. Tests were performed on both gasoline cars and diesel buses. Data generated by the VOEM was compared against a fixed chassis dynamometer. All errors were reported to be below 10%, with the exception of 20% for CO and 25% for HC for the diesel engine vehicles. The weight of the unit was 230 kg (500 lbs). The unit was powered by a 12-volt battery which provided one hour of operation.

2.1.2.8 NESCAUM, 1998

A recent study by the Northeast States for Coordinated Air Use Management (NESCAUM) evaluated in-use emissions from diesel-powered off-road construction vehicles and explored the effects of various emissions control devices [14]. To measure the on-board emissions data, a computer controlled sampling system was assembled using a mini-dilution tunnel. The system consisted of a heated, raw exhaust sample line to transfer a portion of the raw exhaust to a mini-dilution tunnel. A portion of the mixture was extracted through sampling lines to provide continuous emissions monitoring (using an MPSI five-gas portable gas analyzer) and bag (Tedlar) sampling. A 70-mm filter was placed at the outlet of the dilution tunnel for PM collection. Emissions analysis using the five-gas analyzer was found to be unreliable; NOx response time was inadequate and the concentrations of CO and total hydrocarbons (THC) were too low to be reliable. Only CO_2 was used to infer fuel consumption. Tedlar bags were also analyzed using an off-line Horiba laboratory emissions analyzer for determining emissions levels of NOx, CO and THC.

To verify the accuracy of the on-board system, one of the engines was tested on an engine dynamometer. It was found that there was a 27% difference between the field and laboratory collection systems for CO, a 12% difference for NOx, a 22% difference for HC, and a 9% difference for the fuel consumption calculation.

2.1.2.9 US-EPA, 1999

The Office of Mobile Sources at the US-EPA is currently developing a mobile measurement system, termed ROVER, for light-duty gasoline vehicles and is working to extend the system for use on heavy-duty vehicles. The ROVER system uses an Annubar with a differential pressure sensor for exhaust flow rate measurement, and a Snap-On MT3505 multi-gas analyzer for gas analysis. The vehicle speed and distance traveled is measured either by sampling the engine control module or using a global positioning system (GPS) receiver or a microwave speed and distance sensor. US-EPA has suggested that the Snap-On MT3505 gas analyzer will be replaced by a Sun DGA 1000 multi-gas analyzer. Currently, the ROVER determines exhaust emissions (CO, CO_2, HC, O_2 and NO) in grams per distance traveled. In addition to gaseous concentrations, the ROVER also records engine speed (using a read-out connected to the engine's ECU), air-to-fuel (A/F) ratio, and exhaust mass flow rate.

2.1.2.10 Ford Motor Company and WPI-Microprocessor Systems, Inc., 1999

Ford Motor Company and WPI-Microprocessor Systems, Inc. are developing a Portable Real-Time Emission Vehicular Integrated Engineering Workstation (PREVIEW) that will sample water-laden exhaust [15]. PREVIEW is reported to be a fully integrated, portable system that simultaneously measures exhaust mass emissions (CO, CO_2, NO and HC) and up to forty engine parameters (through the engine control module readout). Results comparing simultaneous concentration measurements from PREVIEW and those obtained from a light-duty chassis dynamometer laboratory with conventional instrumentation during FTP and Highway Fuel Economy tests showed agreement to within 1.5% for CO_2, 3.4% for CO, 12.3% for HC (comparing NDIR with FID), and 0.4% for NOx. It should be noted that these tests were conducted on exhaust from light-duty gasoline-fueled vehicles.

2.1.2.11 Horiba, Ltd., 2000

Horiba, Ltd. and NGK Insulators, Ltd have recently presented an on-board NOx emissions measurement system for diesel vehicles [16]. The system uses solid-state sensors made of zirconium (ZrO_2) and other ceramic materials to measure NOx and excess-air ratio. The system consists of a variety of sensors to measure NOx concentration (0-1000 ppm; ZrO_2 sensor), intake air flow rate (0 – 3.6 m^3/minute; Karman vortex volumetric flow meter), air-to-fuel ratio (1-10; ZrO_2 sensor), intake air pressure (50 – 110 kPa), intake air temperature (Pt resistor sensor); intake air relative humidity, boost pressure (80-240 kPa), ambient temperature (Pt resistor sensor), ambient pressure (50-110 kPa); vehicle velocity, engine rpm, and coolant temperature. The authors report that correlations with laboratory regulatory compliance tests showed discrepancies within 4% for NOx mass emissions measurements, within 3% for fuel consumption measurements and within 1% for distance measurements.

2.1.2.12 Honda, 2000

Preliminary work on an FTIR-based system was recently presented by Honda R&D Americas, Ltd., Honda R&D Co., Ltd, and Nicolet Instrument Corp. for measuring real-world emissions from light duty gasoline vehicles [17]. The target pollutants were non-methane hydrocarbons (NMHC), NOx, and CO. It appears that the authors have yet to resolve several issues including temporal resolution and vibration isolation.

3 MOBILE EMISSIONS MEASUREMENT SYSTEM (MEMS)

West Virginia University has completed the integration/construction and evaluation of a new on-road emissions measurement system, named MEMS. The system is capable of measuring in-use brake-specific mass emissions of NOx and CO_2 from heavy-duty vehicles driven over the road under real-world conditions. The major sub-systems of MEMS include:

i. Exhaust mass flow measurement system
ii. Engine torque and speed measurement system
iii. Exhaust emissions analyzers
iv. Exhaust gas sampling, and sample conditioning systems
v. Vehicle speed and distance measurement system
vi. Data acquisition, reduction, and archival system

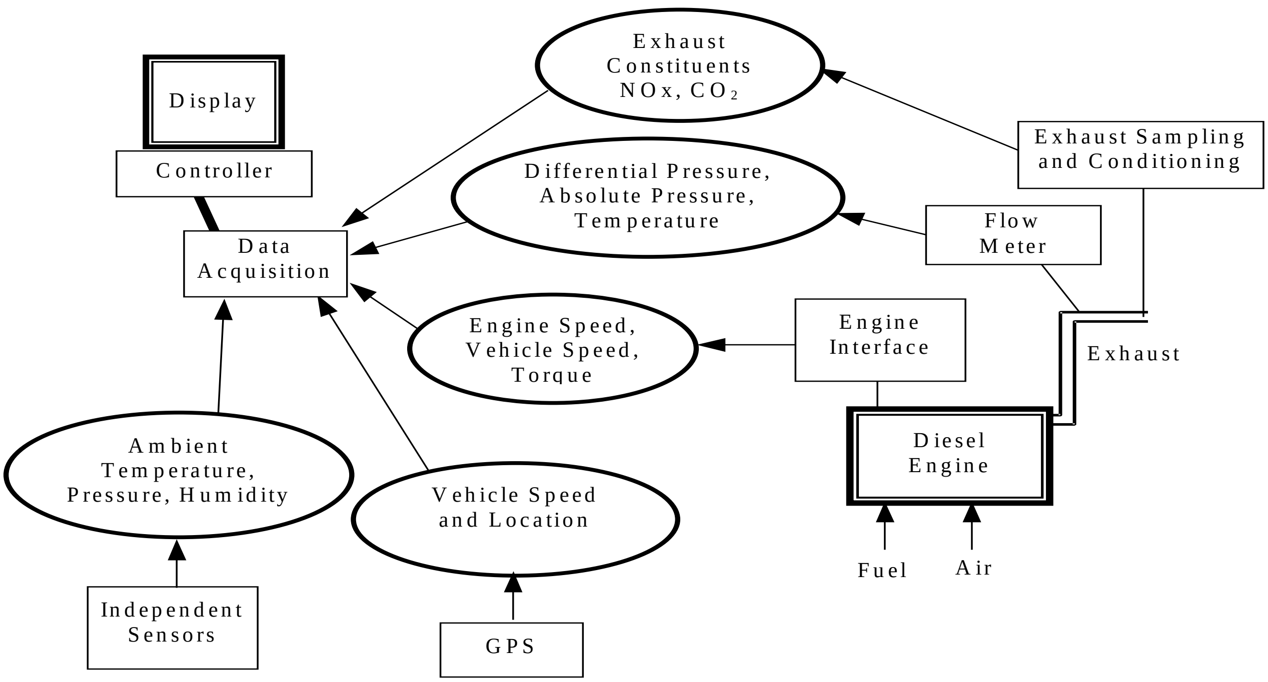


Figure 1 System integration of MEMS.

These subsystems are comprised of the components described below and represented above in Figure 1. Detailed discussion of component evaluation and selection criteria is given in Chapter 5.

3.1 Exhaust Mass Flow Rate

An accurate measurement of brake-specific mass emissions is directly dependent upon the accuracy of the exhaust mass flow rate measurement. The exhaust flow rate measurement system must be rugged, robust, and adaptable to a wide range of vehicle exhaust configurations. In addition, the selected flow meter should present a minimal amount of additional backpressure on the engine, so that total exhaust backpressure never exceeds the manufacturer's specifications. Selection of transducers used to measure the pressure drop across a flow meter is critical for an on-road measurement system.

Of all devices evaluated, the Annubar cross-sectional averaging flow meter was the best candidate for direct measurement of exhaust flow rate, since it can account for the effects of pulsation in the exhaust stream that are produced by an internal combustion engine. When used in the same nominal pipe size as the vehicle's exhaust system, a minimal additional backpressure is placed on the engine. It is anticipated that three different nominal flow meter sizes will be required to perform the in-use testing. A Validyne P365 differential pressure transducer, Omega PX176 or PX203 absolute pressure transducers and J-type thermocouples are recommended as transducers to interpret the Annubar signal for calculation of mass flow rate.

3.2 Engine Torque and Speed

Engine torque and speed are available via an ECU protocol adaptor through an RS232 interface with the data acquisition system. Engine torque is inferred from the ECU's broadcast signal of the percent load, the measured curb no-load percent load, and the manufacturer's supplied lug curve. Engine speed is available directly from the ECU broadcast and is a reliable measurement within the NTE zone. Engine load and speed data are available at least on a 10 Hz rate.

3.3 Emissions Analyzers Component

At the onset of the project, WVU identified that there were no manufacturers marketing portable emission analyzers that were specifically designed to sample diesel exhaust emissions. It should be noted that "inspection-grade" and "garage-grade" emissions analyzers for gasoline fueled vehicles are commonly available. Although the primary emissions species (CO, CO_2, HC, and NO) are present in the exhaust of spark-ignited (gasoline) engines, the concentration levels and specific constituents (e.g. heavy-ended hydrocarbons and NO_2) are quite different from those found in diesel exhaust streams. Since this study was intended to evaluate the currently available technologies, and not to develop new products, WVU integrated the best available components in order to accommodate the additional requirements of diesel emission sampling, and quantified the measurement errors inherent in their current design. Throughout the course of the project, several manufacturers have indicated their intent to provide specialized products in the future. However, no prototype models or detailed information were available during the course of this study.

The WVU MEMS employs an NDIR solid-state detection device for the measurement of CO_2, (as well as CO and HC), whereas a ZrO_2 sensor is used for NOx determination. An electrochemical cell is employed as a quality control/quality assurance (QC/QA) measure, due to the limited in-field performance data associated with the ZrO_2 sensor that serves as the primary NOx measurement device. It should be noted that although the NDIR system is capable of measuring HC and CO, the resolution of the microbench is substandard for diesel applications.

3.4 Emissions Sample Conditioning System

A basic MEMS sampling system addresses three key design parameters: removal of particulate matter, sample temperature control, and minimization of water interference. Water interference may be minimized by preventing condensation or by removing the water vapor present in the sample stream. Currently employed practices (based upon Code of Federal Regulations (CFR) 40) do not make use of chemical drying for exhaust emissions sampling streams; therefore, condensation prevention may be afforded by either diluting the exhaust sample (hence lowering sample dew point) or by heating the sample stream. Dilute emissions measurement schemes add to system complexity and cost. Therefore, such systems were not investigated. In order to prevent sample stream condensation, heated sampling lines were incorporated into the MEMS. In addition, a thermoelectric chiller was placed immediately before the emissions measurement devices in order to remove water from the sample stream and lower the sample temperature to manufacturer's specifications.

A schematic of the proposed sampling system for MEMS is shown in Figure 2. The generalized system consists of a sampling probe, a heated line, a heated filter, a heated-head pump, an external NO_2 converter, and a thermoelectric chiller. The MEMS sampling probe is designed in accordance with the CFR 40 Part 89.412.96. Specifically, it is recommended that a 0.25-inch diameter stainless steel tube with nine sampling holes be used, as shown in Figure 3. The multiple sampling ports on the probe provide a means of averaging the exhaust flow composition, which helps to reduce the dependency of the sampling accuracy on the specific flow rate regime. Differential pressure regulators, used in conjunction with flow meters, provide for stable flow rate control. System components were sized according to the specific requirements of the emissions analyzers that are employed. It should be noted that the pump should be capable of providing flow rates in excess of those required by the analyzers. Such a practice increases the sample flow rate of the system prior to the NO_2 converter, which minimizes the residence time of the sample within the heated sampling line. This, in turn, improves the transient response of MEMS. The excess flow is by-passed upstream of the NO_2 converter. Elaboration of the base system should also include implementation of sample pressure, temperature, and humidity measurement devices. Such instrumentation would provide for improved correction of concentration data, as well as improved assurance of overall sample conditioning system performance.

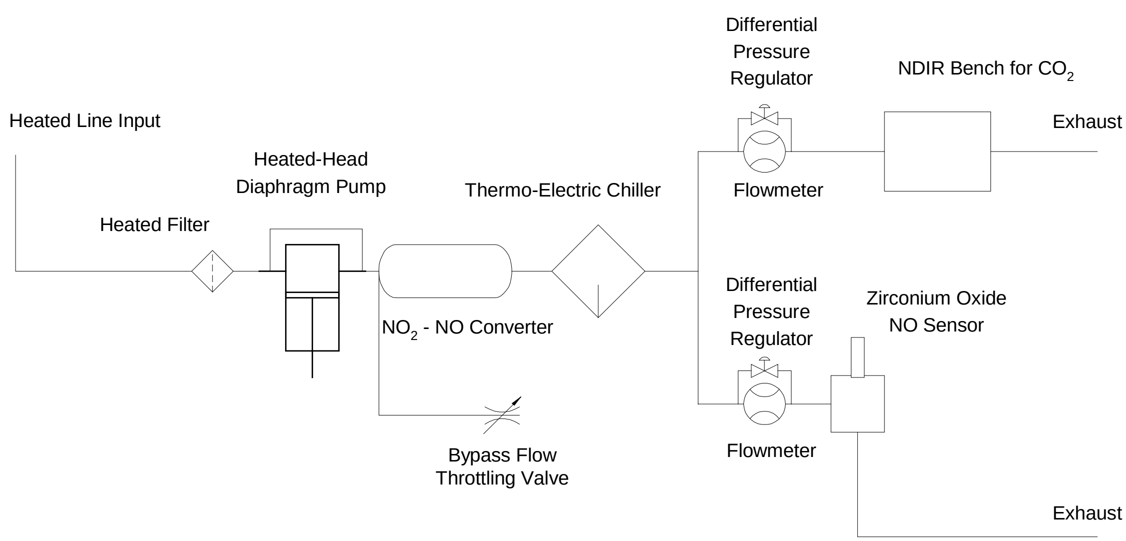


Figure 2 MEMS exhaust sampling system.

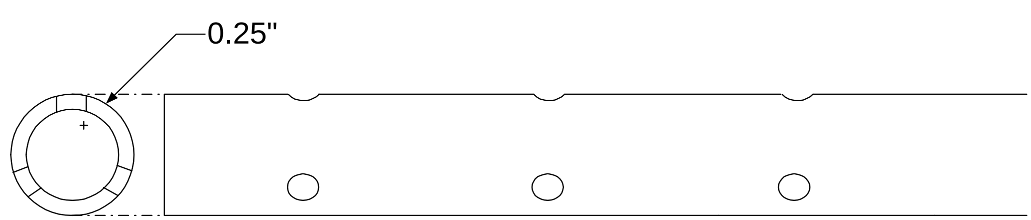


Figure 3 MEMS sample probe.

3.5 Vehicle Speed and Distance

Vehicle speed is available via ECU broadcast, which permits the inference of vehicle distance traveled. However, due to the variety of in-field arrangements of drivetrain components, a GPS should be used to provide a QC/QA measure for ECU-inferred vehicle speed measurements. Testing experience has suggested that the GPS signal provides an accurate and precise means of measuring vehicle speed.

3.6 Data Acquisition, Reduction, and Archival System

The data acquisition system employed in the MEMS is compact, due to the limited space in the cab of many HDDE vehicles. The system is rugged and capable of withstanding vibrations encountered during on-road testing. The data acquisition system is also able to adapt to a wide range of test vehicles and is flexible in its ability to measure a wide variety of signals. The associated software for control, data acquisition, and data analysis has been designed to accept a wide range of transducers and interfaces.

WVU selected a National Instruments PXI-1025 as the computer platform for MEMS, due to its inherent ruggedness and expandability. The configuration consisted of a National Instruments multifunction 6071E data acquisition card that interfaced to a signal conditioning box, a National Instruments Temperature/Voltage 4351 card, and a RS-232 serial card. The platform also employed a National Instruments PXI-8156B embedded computer, which allowed access to two serial ports, a USB port, a GPIB interface, as well as hard, floppy, and CD drives. The portable platform utilized a built-in monitor and keyboard, which was attached to the chassis, and required minimal setup effort.

WVU chose the National Instruments system over an in-shop design for several reasons. The National Instruments design was field-tested and proven. It was available with a minimum two serial ports, fulfilling the requirements associated with retrieval of ECU data as well as GPS information. Although modification of a standard laptop to accommodate multiple serial ports is possible, the robustness of a laptop is questionable for on-road testing.

An OREMS may require external power sources to operate. External power sources include heavy-duty, 12 or 24-V batteries or a generator set. If batteries are used, an inverter can be used for the AC powered equipment. Likewise, if a generator is used, transformers can be used to power the high amperage equipment. Currently, the WVU MEMS employs a portable generator set.

A completed MEMS has been successfully evaluated in engine and chassis dynamometer-based laboratories, as well as on-road tests. Results of laboratory and in-field testing, including comparative tests with the ROVER, are presented in the following chapters.

4 SUBSTANTIATION OF INTEGRATED OREMS PERFORMANCE

All engine dynamometer comparison tests were performed at the WVU Engine and Emissions Research Laboratory (EERL) using a GE DC dynamometer and full-flow double-dilution (CFV-CVS) system. This facility has been operating according to the procedures set forth by the CFR 40, Part 86, Subpart N, since 1993. Results generated by the laboratory have provided satisfactory comparative data for previous Round Robin testing. In addition, systems verification procedures, including the use of standard reference materials as well as CFR systems integrity tests, are continuously performed to ensure the highest possible accuracy level of emissions reporting. At the onset of the study, correlation with laboratory data established by Mack Trucks, Inc. (Mack) on an E7-400 engine, as well as a laboratory inspection by Mr. Dave Perkins of the US-EPA provided a means of substantiating the level of data integrity produced by this facility.

4.1 Correlation and Inspection of WVU-EERL

A series of heavy-duty diesel engine tests was conducted at the EERL to provide a laboratory-to-laboratory comparison between the WVU EERL and Mack. The Mack E7-400 engine employed in this study is not a typical production engine and was provided by Mack solely for correlation purpose. Mack provided WVU with a research level access to the ECU so that the engine could be locked in a fixed injection-timing map, thus preventing injection timing excursions.

The laboratory comparison consisted of running two different tests - the heavy-duty certification test (FTP) cycle and a European steady-state test (ESC) cycle. For all tests, the engine control map was configured to operate on the fixed injection timing map via software provided by Mack. The tests performed for this work included a cold-start plus two hot-start FTP runs, per CFR 40, Part 86, Subpart N. Two 28 minute ESC steady-state tests were performed, per the Commission of the European Communities regulations along with a 78 minute ESC, which is an extended version of the 28 minute ESC. The 78 minute ESC allowed the engine to reach thermal steady-state in each mode. Although US-EPA certification fuel was used throughout the course of the testing present herein, it was not the same batch of certification fuel that was used by Mack.

4.1.1 Examination of the WVU EERL by US-EPA

Mr. Dave Perkins of the US-EPA visited WVU and conducted an inspection of the EERL. Mr. Perkins reviewed WVU's testing procedures and the calibration records. Additionally, a short report of recent calibrations (gas analyzer calibrations; dynamometer torque arm load cell calibration; dynamometer angular velocity calibration), CO analyzer water interference check data sheet, NOx efficiency test data sheet, HFID burner peaking data sheet, list of equipment and facilities in the EERL, and QC/QA plans were also submitted to Mr. Perkins.

Mr. Perkins also reviewed the exhaust sampling, conditioning, and analysis equipment, the data acquisition system, and dynamometer operation in the laboratory. A Mack E7-400 engine was operated through the FTP schedule for Mr. Perkins to witness. As a final test of data integrity, Mr. Perkins provided lecture bottles for WVU to read. In a letter to Mr. R. E. Kleine, Cummins Engine Company, Inc., Mr. Bruce Fergusson, Air Enforcement Division, US-EPA documented that US-EPA had found no problems with the WVU facility. Upon completion of the checkout, Mr. Perkins told WVU that he had found no problems with the WVU's EERL maintenance protocols or the test procedures.

4.1.2 Test Setup

The Mack E7-400 was tested in the transient DC dynamometer test cell at the WVU-EERL. A total exhaust, double dilution full-scale CFV-CVS system dilution tunnel was incorporated into the emissions measurement system. Prior to testing, a detailed laboratory check was performed along with the routine calibration and performance evaluation of the dynamometer and emissions measurement equipment.

4.1.3 FTP Results

The FTP test consisted of mapping the engine with the ECU injection timing locked to one map to obtain the required speed-load points for the cycle. Practice FTP cycles were performed to verify span gas ranges, to obtain throttle set point positions, and to verify regression. A 12 hour soak period was used prior to the cold start FTP run.

The results from the FTP tests are shown in Table 1. The WVU FTP results were calculated from the reduction program at the EERL which analyzes the data in accordance with the requirements of CFR 40, Part 86. As illustrated in the table, WVU and Mack results for integrated work and brake-specific fuel consumption were in good agreement with one another. These minor differences may be attributed to different mapping procedures and throttle control routines used by the two laboratories. The NOx (6.93% differences) and CO_2 (-3.96% differences), measurements from WVU were in good agreement with the Mack data. CO and HC measurements differed by 8.84% and 1.36%, respectively. It is well documented that accurate quantification of CO and HC emissions is more elusive than accurate measurement of NOx and CO_2 from diesel engines, especially when only two laboratories are compared (two data points).

Table 1 FTP cycle laboratory comparison between WVU and Mack for the Mack E7 engine.

Parameter	Mack	WVU	Per. Diff. (%)
Integrated Power (HP-HR)	27.38	27.92	1.93
BSFC	0.382	0.371	-3.00
BSHC	0.073	0.074	1.36
BSCO (Corrected)	0.652	0.712	8.84
$BSCO_2$	573.7	551.4	-3.96
BSNOx (Corrected)	4.405	4.721	6.93

4.1.4 ESC Results

The ESC cycle consists of 13 steady-state modes with the first mode being an idle condition and the remaining 12 modes occurring at different speed-load points. Two different ESC cycles were used, a 28-minute version and a 78-minute version. The 28-minute ESC consisted of a four minute idle duration for the first mode with the remaining 12 modes each being two minutes in duration. For the 78-minute ESC, each mode was six minutes long. The data collection was performed towards the end of each mode and the sampling times are listed in Table 2. For example, Mode 3 in the 78-minute ESC would run for 260 seconds before data collection would commence. The data for the remaining 100 seconds of this mode was collected and the last 30 seconds was averaged and used for the calculations. Speed-load points for the ESC cycles were taken from the data supplied by Mack in lieu of calculation from the maximum torque curve. Only NOx data was provided to WVU and are shown in Table 3 and Table 4 on mode-by-mode basis and integrated cycle basis. As shown in these tables, the mode-by-mode

BSNOx differed by as much as 11.75% but the integrated cycle percent difference varied by less than 7%.

Table 2 ESC data collection time for the 28 and 78 minute cycles.

Mode	Sample Time (s)
1	150
2	80
3	100
4	100
5	50
6	50
7	50
8	90
9	100
10	80
11	50
12	50
13	50

Table 3 NOx 28 minute ESC laboratory comparisons between WVU and Mack for the Mack E7 engine.

Mode	Set Speed (rpm)	Set Load (ft-lb)	Mack BSNOx	WVU BSNOx	Per. Diff. (%)
1	Idle	0			
2	1193	1476	4.1504	4.3962	5.75
3	1437	740	4.0128	4.0937	2.00
4	1437	1110	3.7229	4.0016	7.22
5	1193	738	4.6131	5.0573	9.19
6	1193	1107	3.9763	4.3347	8.62
7	1193	369	4.9526	5.2392	5.62
8	1437	1480	4.0236	4.1913	4.08
9	1437	370	4.1585	4.5153	8.23
10	1681	1302	4.8627	5.2016	6.73
11	1681	326	4.0152	4.2881	6.57
12	1681	977	3.5386	3.8412	8.20
13	1681	651	3.1199	3.4175	9.10
		Cycle	4.1328	4.3977	6.21

Table 4 NOx 78 minute ESC laboratory comparisons between WVU and Mack for the Mack E7 engine.

Mode	Set Speed (rpm)	Set Load (ft-lb)	Mack BSNOx	WVU BSNOx	Per. Diff. (%)
1	Idle	0			
2	1193	1476	4.1593	4.6558	11.27
3	1437	740	3.7026	4.0347	8.58
4	1437	1110	3.7426	4.0652	8.26
5	1193	738	4.6722	4.9744	6.27
6	1193	1107	3.8501	4.3308	11.75
7	1193	369	5.0948	5.2532	3.06
8	1437	1480	4.1786	4.2903	2.64
9	1437	370	4.3151	4.5176	4.59
10	1681	1302	4.7792	5.1508	7.49
11	1681	326	4.2055	4.3139	2.54
12	1681	977	3.5929	3.9172	8.64
13	1681	651	3.3302	3.3360	0.18
		Cycle	4.1461	4.4444	6.95

4.1.5 Laboratory Comparison Conclusions

NOx correlation data between WVU and Mack should be viewed in the light of “Round Robin” data acquired from comparisons of emissions from major test facilities and manufacturers in the US and Canada. Results from the 1994 Round Robin test of a DT446 Navistar engine on a Phillip fuel for the FTP cycle show that the between-laboratory differences for NOx, expressed as two standard deviations, are 8% for cold start, 11% for hot start, and 9% for the combined sevenths-weighted cold and two hot starts. The NOx mass emissions between Mack and WVU differed by 6.93%, which compares favorably to the similar round-robin correlation results. It should be noted that Round Robin testing usually calls for a target of the more rigorous spark ignited heavy-duty engines FTP regression criteria, which was not imposed for the WVU and Mack comparison presented in this report.

4.2 Engine Dynamometer Tests

Presented below are representative emissions data, generated by a Cummins ISM-370 research engine. Reported herein are raw exhaust measurements that were made with the ROVER and the MEMS, and dilute exhaust measurements made with the CFV-CVS system using laboratory-grade instruments. The engine was operated over the following test cycles, using fuel that is consistent with current on-highway standards:

1. two FTP test schedules (hot starts only)
2. two steady-state cycles that traversed the NTE region, dubbed the MEMSCYC cycle
3. a transient cycle that was developed by sampling speed/load data from on-road Mack tractor vehicle testing, dubbed the SAB2SW cycle.

The transient SAB2SW cycle was derived from on-road Mack tractor data, and then applied to the Cummins ISM-370. Standard practices used for the conversion of on-road cycle measurements into engine dynamometer operation schedules entail the use of ECU load data from the route as well as lug curves and zero-flywheel load curves. A thorough transformation could not be accomplished, since ECU-reported load data could be significantly different for a Cummins-powered vehicle operating over the same route. Hence, for the testing, the dynamometer speed-load set points were merely adapted to the Cummins engine. Increased idle speeds were used to accommodate differences in curb-idle, and some peak commanded torque values were not achieved. Nonetheless, the SAB2SW cycle provided for the best simulation of on-road emissions events in the controlled environment of an engine-testing laboratory. More interestingly, the performance of an OREMS over this cycle which reasonably mimicked road use would be a good indication of its real-world measurement integrity.

Cycle-integrated brake-specific mass emissions recorded from the engine tests are tabulated in Table 5, while brake-specific mass emissions and associated measurement errors for 30 second NTE-region windows are presented in Figure 4 to Figure 25. Measurements with the MEMS, the ROVER, and the laboratory grade instruments were conducted simultaneously over each of the cycles. It should be noted that these figures incorporate expanded axes, emphasizing differences between the systems. In addition, it must be emphasized that ROVER does not provide for time alignment of power with emissions, nor does ROVER determine operation within the NTE zones. The authors were obliged to determine the NTE zones independently and align ROVER power and emissions data independently to allow these comparisons. The resulting ROVER data are therefore not a direct product of ROVER output. The NOx data presented in this report were not corrected for humidity conditions since ROVER does not account for ambient humidity in its analysis.

Table 5 shows that the integrated brake-specific mass emissions of NOx reported by MEMS were within 0.5% of the laboratory data over the FTP tests. It should be noted that only NTE emissions are to be reported by an OREMS and that cycle results are for information purposes only. Differences between the brake-specific NOx mass emissions from the laboratory and the ROVER for FTP A and FTP B were 7.9% and 6.6%, respectively. The cycles (MEMSCYC and the SAB2SW) yielded integrated brake-specific NOx mass emissions that were within ±4% of the laboratory values. It should be noted that the ROVER does not provide for NO_2 conversion (records NO only) or for appropriate water removal from the raw exhaust sample.

Table 5 Cycle integrated brake-specific mass emissions data from engine dynamometer tests.

Test Cycle	Measurement Device	CO_2		NOx	
		(g/bhp-hr)	(% diff.)	(g/bhp-hr)	(% diff.)
FTP A	Laboratory	548.00		4.397	
	MEMS	523.95	-4.39	4.389	-0.18
	ROVER	514.79	-6.06	4.050	-7.88
FTP B	Laboratory	538.47		4.405	
	MEMS	527.68	-2.00	4.383	-0.49
	ROVER	517.95	-3.81	4.114	-6.60
MEMSCYC A	Laboratory	492.65		5.803	
	MEMS	493.16	0.10	6.025	3.83
	ROVER	485.58	-1.44	5.939	2.34
MEMSCYC B	Laboratory	491.57		5.822	
	MEMS	495.45	0.79	6.025	3.48
	ROVER	491.07	-0.10	5.910	1.50
SAB2SW A	Laboratory	485.99		5.661	
	MEMS	445.68	-8.29	5.527	-2.37
	ROVER	441.22	-9.21	5.630	-0.55

The NTE zone 30 second window results for the FTP, MEMSCYC, and SAB2SW tests are summarized in Table 6. In this table, the percent differences between the OREMS (MEMS and ROVER) and laboratory measurements are shown for power, CO_2 mass emissions, NOx mass emissions, CO_2 brake-specific mass emissions, and NOx brake-specific mass emissions. The maximum, minimum, average and standard deviation for the results associated with each test summarizes the performances of the OREMS. Figure 4 to Figure 13 illustrate the NTE zone results for FTP A. For example, Figure 5 and Table 6 illustrate that the differences in 30 second integrated power window range from 3.4 to 6.0% for the MEMS with an average value of 4.45%. Likewise, differences in ROVER integrated power range from 3.1 to 6.0% with an average of 4.53%. It should be noted that ROVER and MEMS used the same ECU broadcast and the same algorithm to infer torque. The differences between MEMS and ROVER reported torque arise from data sampling frequency differences: 5 Hz for MEMS and a nominal 1 Hz for ROVER. WVU was obliged to convert ROVER's nominal 1 Hz data to 5 Hz data in order to permit the comparison with 5 Hz laboratory data. The transformation from 1 Hz to 5 Hz data required that the first and last two seconds of the "new" 5 Hz ROVER data be discarded to avoid large errors.

As illustrated in Table 6 and the following figures, the differences in the integrated 30 second windows for power ranged from –4.46 to 6.85% with an average range of 0 to 5% for the five tests. Integrated CO_2 mass emissions differences ranged from -11.12 to -0.89% for MEMS and -11.82 to -0.29% for ROVER. Integrated NOx mass emissions ranged from -7.79 to 2.94% for MEMS and -11.23 to 4.27% for ROVER. Integrated CO_2 brake-specific mass emissions ranged from -14.99 to 2.09% for MEMS and -11.84 to 1.18% for ROVER. Differences in integrated NOx brake-specific mass emissions ranged from -11.81 to 2.94% for MEMS and –13.75 to 4.87% for ROVER. The ROVER reported percent differences exclude the NTE zones that were not captured due to the nominal 1 Hz sampling rate. One such NTE exclusion by ROVER is shown in Figure 22 to Figure 25. It should be noted that the ROVER percent differences would generally span a larger range (from minimum to maximum) if the complete NTE zone were captured. This is due to ROVER's slower transient response and data sampling frequency.

Table 6 Summary of NTE zone integration from engine dynamometer tests. All values represent a percent difference (%) relative to the laboratory measurement.

		Power*		CO_2 Mass		NOx Mass		CO_2 Brake-Specific		NOx Brake-Specific	
		MEMS	ROVER	MEMS	ROVER	MEMS	ROVER	MEMS	ROVER	MEMS	ROVER
FTP A	Maximum	6.03	6.00	-6.29	-3.53	-1.57	-4.54	-9.41	-7.15	-5.45	-8.16
	Minimum	3.41	3.09	-11.12	-8.79	-7.79	-10.50	-14.99	-11.84	-11.81	-12.82
	Average	4.45	4.53	-8.17	-5.68	-3.52	-6.99	-12.08	-9.64	-7.63	-10.94
	Std. Dev.	0.72	0.85	1.02	1.07	1.42	1.15	1.35	1.50	1.35	1.54
FTP B	Maximum	6.44	6.85	-2.95	-2.47	-1.80	-4.78	-6.18	-6.27	-6.03	-8.48
	Minimum	3.07	3.25	-6.59	-7.02	-6.67	-9.76	-12.01	-11.42	-10.87	-13.75
	Average	4.57	5.03	-5.32	-4.47	-3.45	-6.88	-9.44	-9.00	-7.81	-11.32
	Std. Dev.	1.06	1.14	1.01	1.00	1.13	0.95	1.76	1.62	1.05	1.50
MEMSCYC A	Maximum	4.28	4.44	-2.11	-1.77	2.94	3.36	1.41	-0.09	4.81	4.87
	Minimum	-4.46	-4.45	-6.21	-7.29	-1.58	-3.50	-9.11	-9.17	-4.89	-5.97
	Average	0.12	0.22	-4.45	-4.45	-0.18	0.17	-4.50	-4.59	-0.25	0.03
	Std. Dev.	2.12	2.21	1.12	1.21	0.88	1.39	2.97	2.20	2.26	2.45
MEMSCYC A	Maximum	4.28	4.39	-0.89	-0.29	2.77	3.20	2.06	1.18	4.31	3.82
	Minimum	-3.58	-3.40	-5.44	-5.57	-2.37	-3.69	-7.83	-6.75	-4.89	-6.01
	Average	0.39	0.33	-3.62	-2.48	-0.34	0.14	-3.95	-2.79	-0.69	-0.19
	Std. Dev.	1.99	1.99	1.22	1.03	1.12	1.25	2.64	1.95	2.03	2.31
SAB2SW A	Maximum	5.11	4.83	-3.77	-1.12	2.23	4.27	-4.38	-1.21	1.80	3.27
	Minimum	0.13	0.23	-8.72	-11.82	-2.00	-11.23	-12.56	-11.05	-5.62	-10.15
	Average	1.75	1.85	-5.92	-4.38	0.51	-1.20	-7.53	-5.92	-1.21	-2.75
	Std. Dev.	0.96	0.92	0.81	1.63	0.67	2.49	1.24	1.61	1.29	2.33

* MEMS and ROVER incorporate ECU-derived power from the same algorithm. Differences between MEMS and ROVER power are due to different sampling rates (MEMS at 5 Hz, ROVER at ~1 Hz).

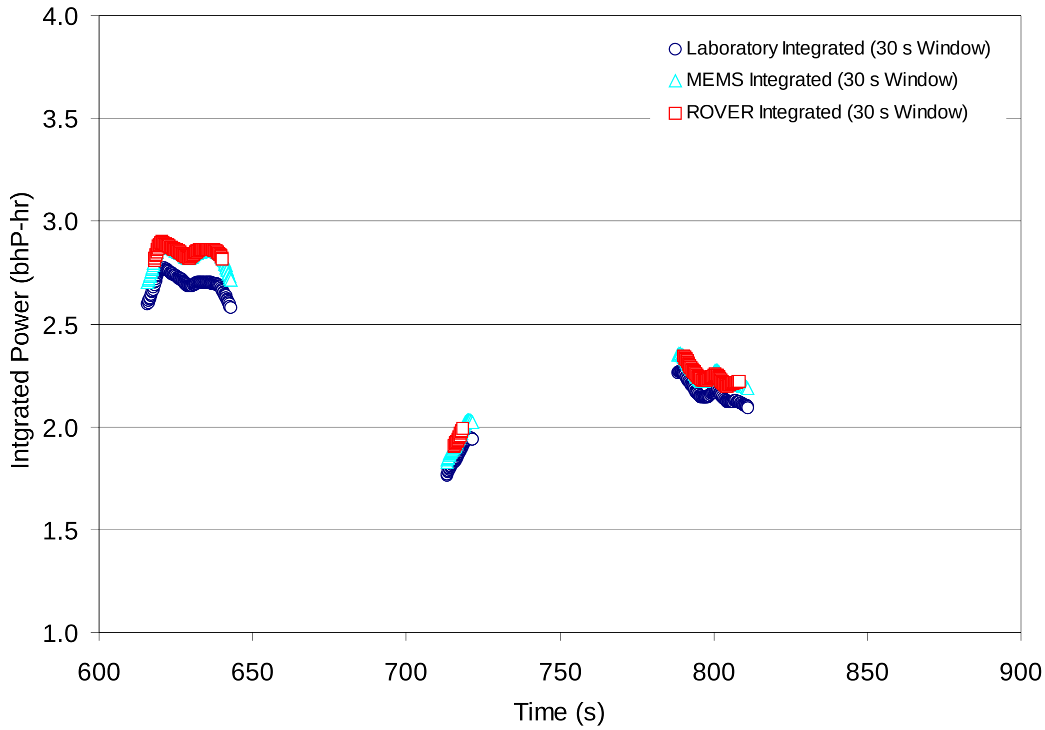


Figure 4 FTP A integrated 30 second power windows within the NTE zone.

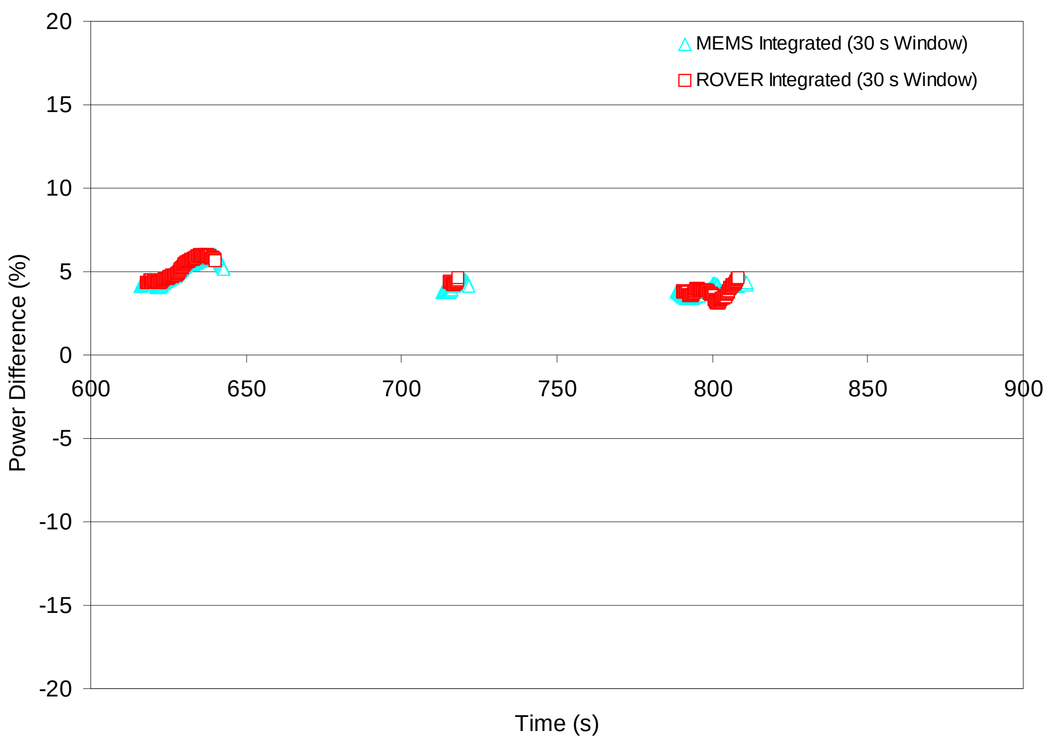


Figure 5 FTP A percent differences for integrated 30 second power windows within the NTE zone.

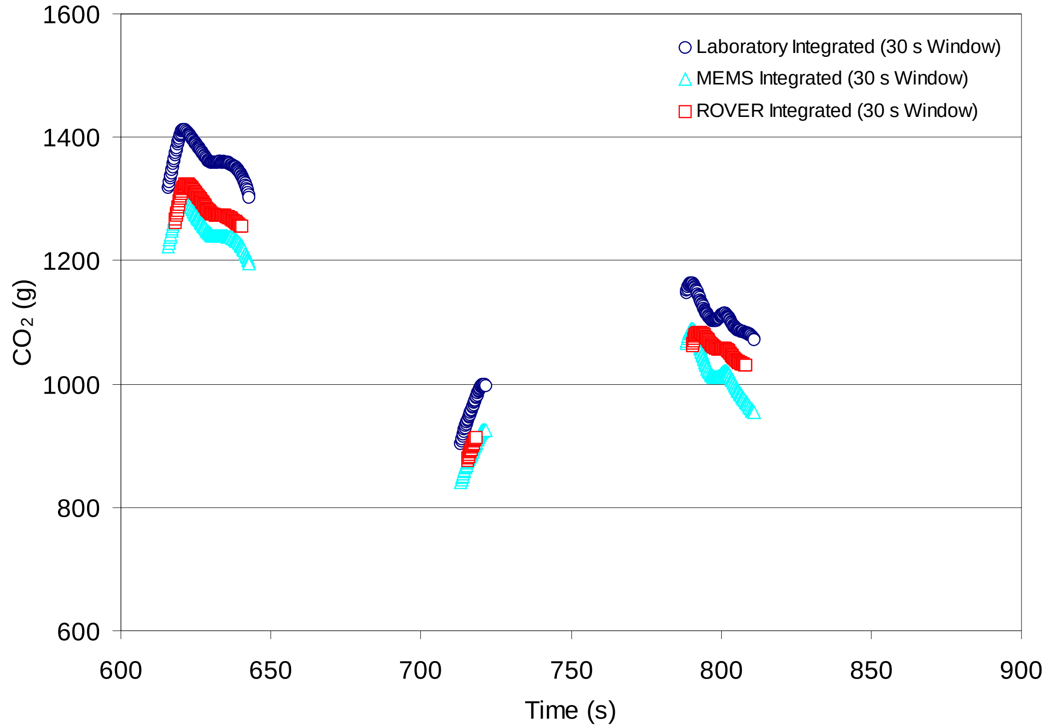


Figure 6 FTP A integrated 30 second CO_2 windows within the NTE zone.

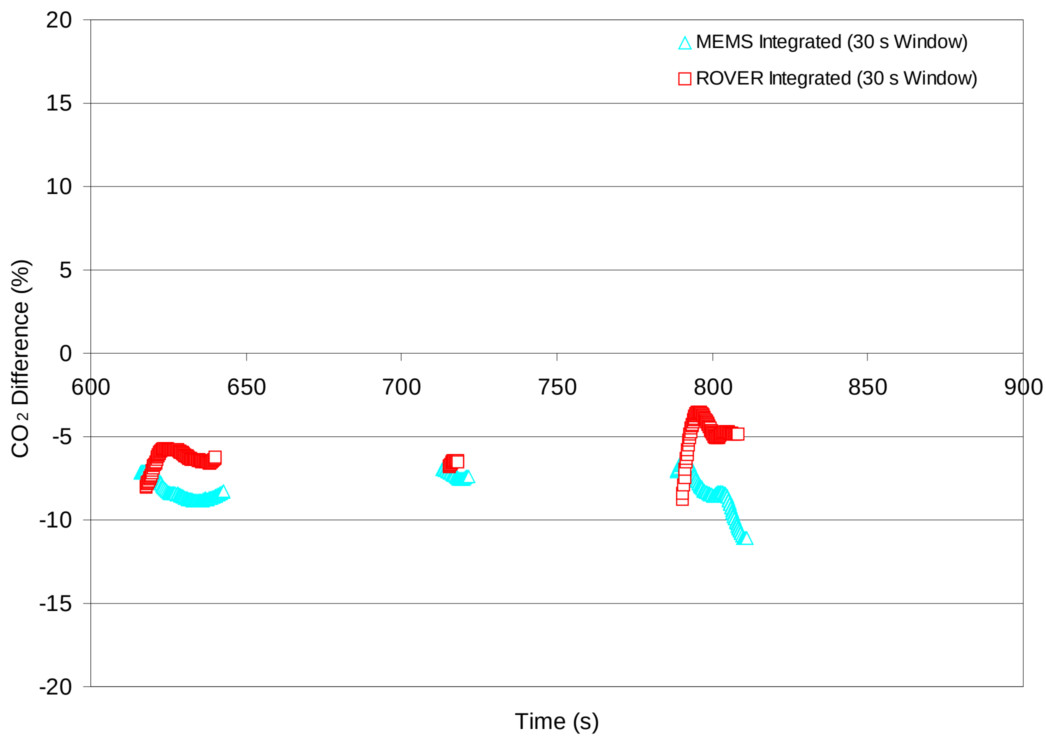


Figure 7 FTP A percent differences for integrated 30 second CO_2 windows within the NTE zone.

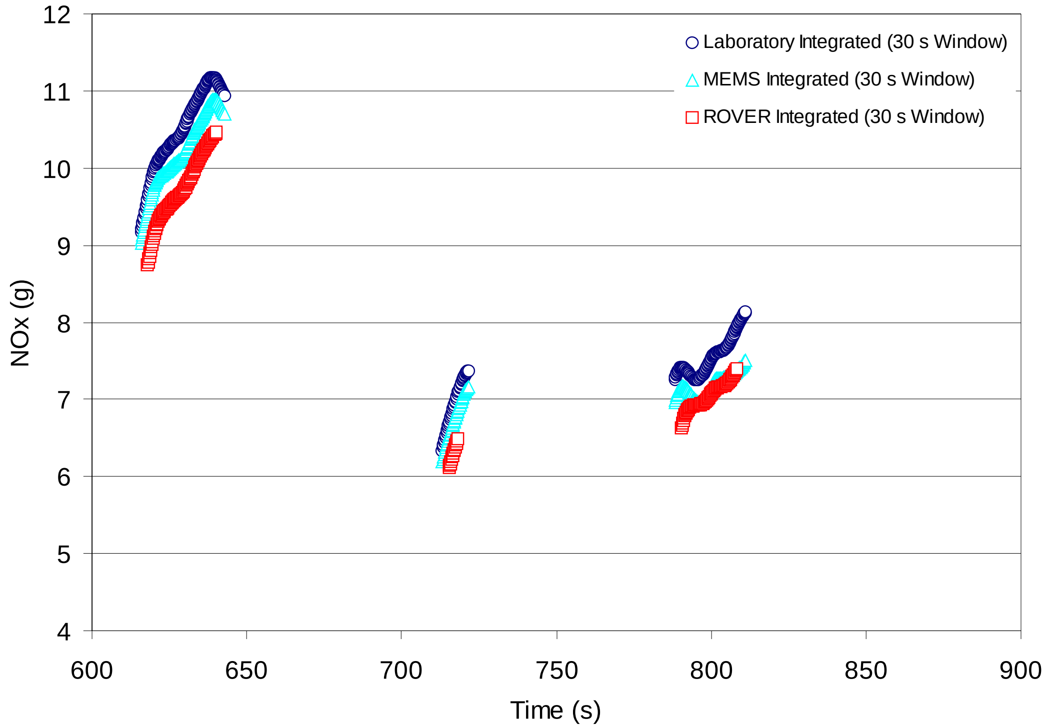


Figure 8 FTP A integrated 30 second NOx windows within the NTE zone.

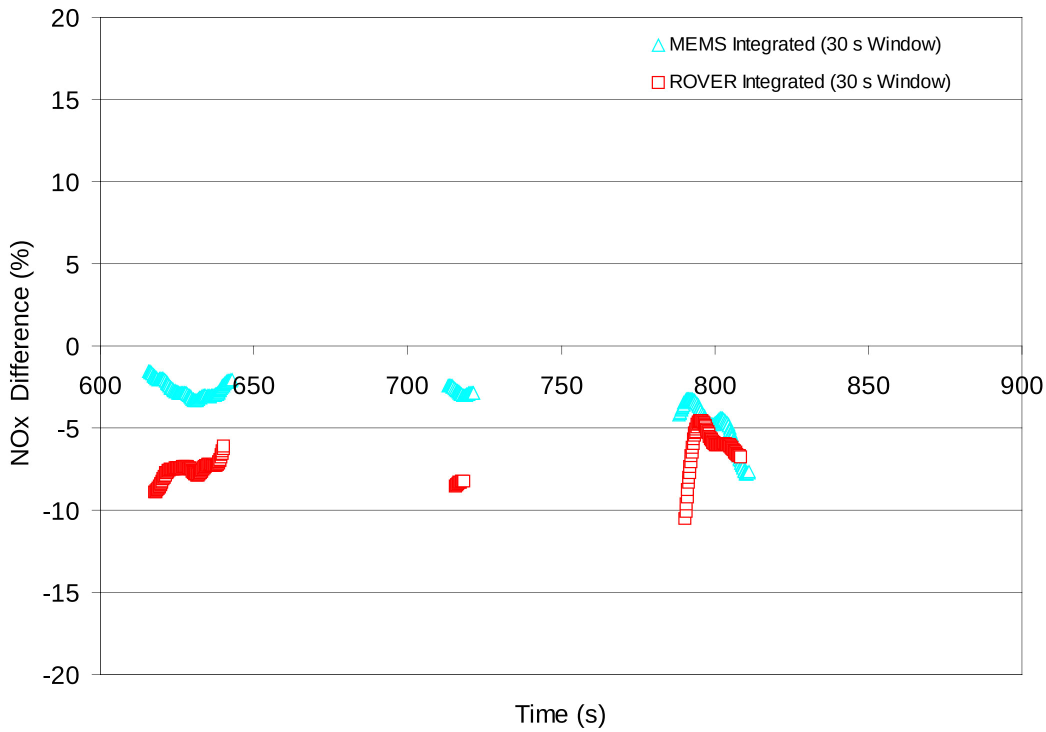


Figure 9 FTP A percent differences for integrated 30 second NOx windows within the NTE zone.

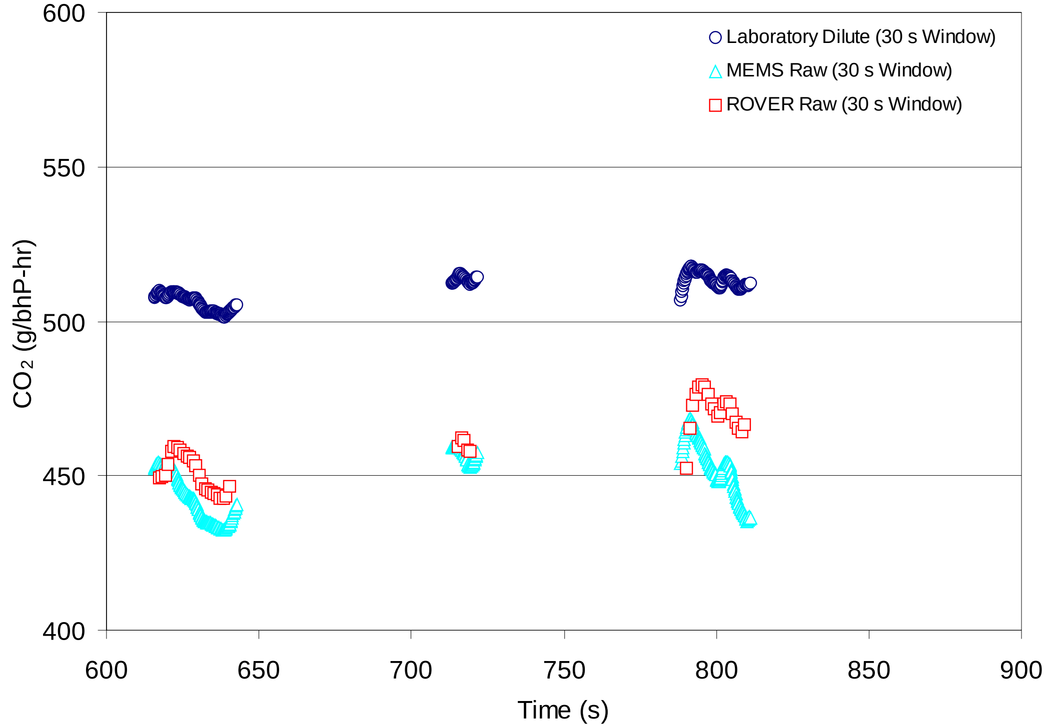


Figure 10 FTP A integrated 30 second windows brake-specific CO_2 emissions within the NTE zone.

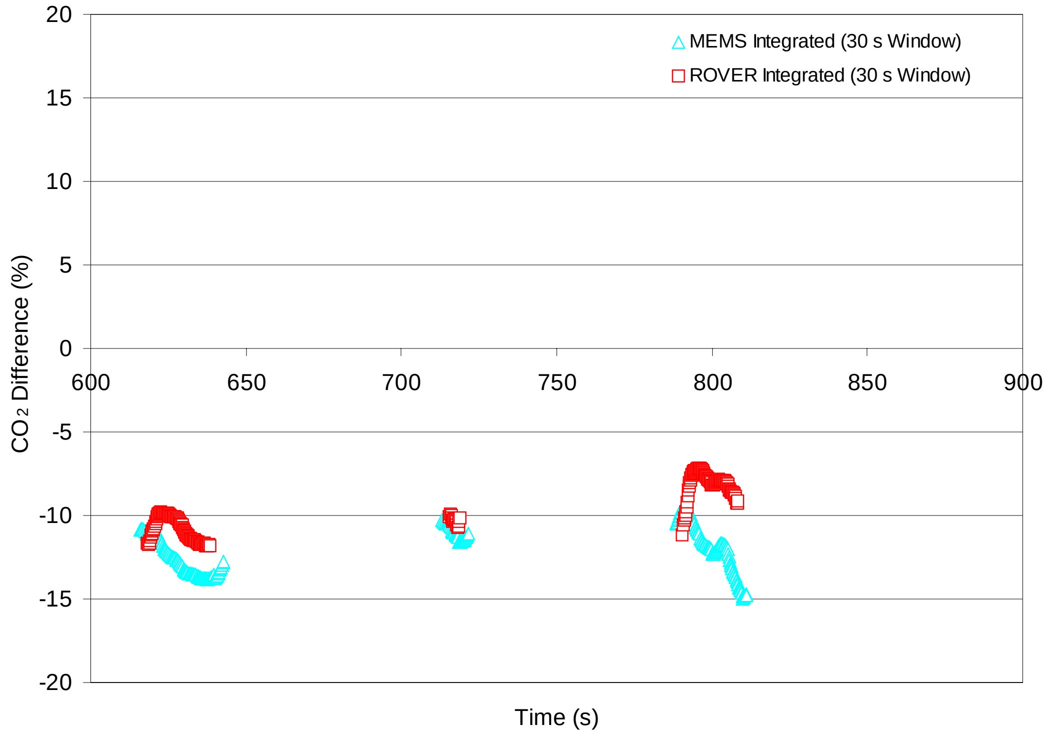


Figure 11 FTP A percent differences for integrated 30 second windows for brake-specific CO_2 emissions within the NTE zone.

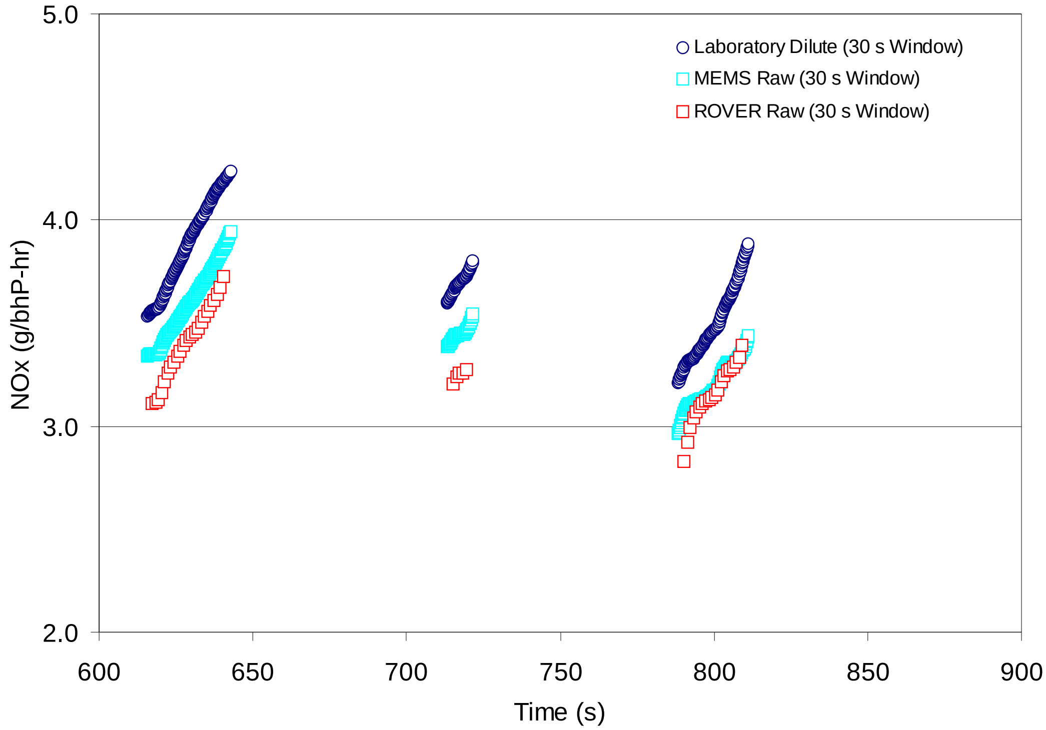


Figure 12 FTP A integrated 30 second windows brake-specific NOx emissions within the NTE zone.

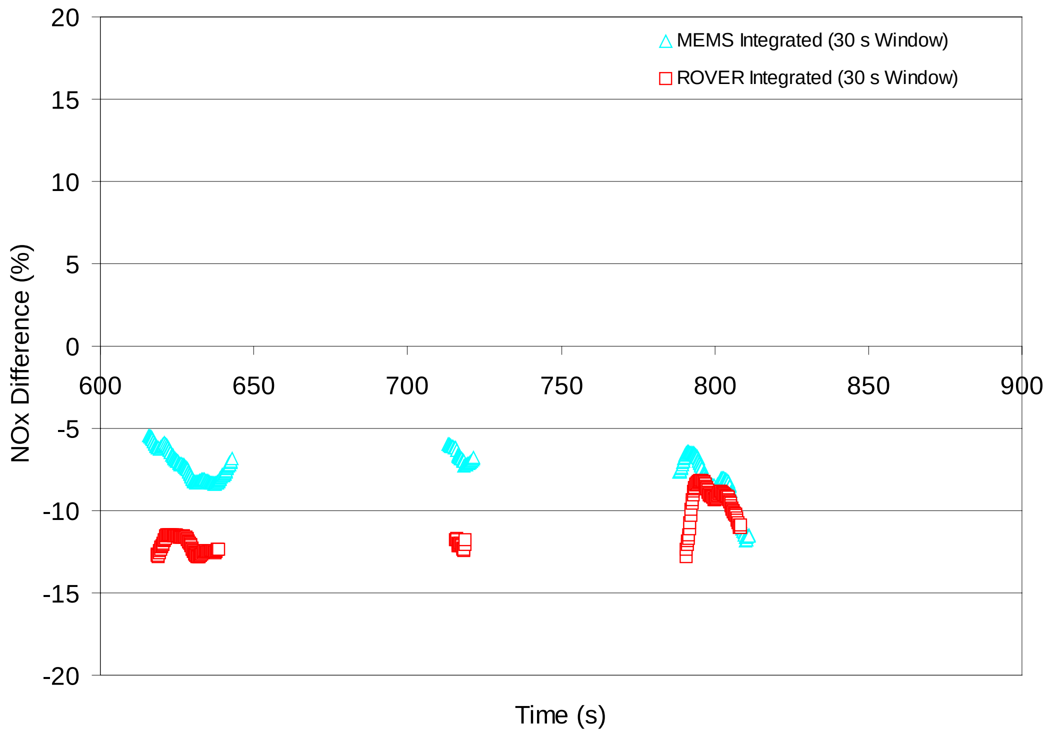


Figure 13 FTP A percent differences for integrated 30 second windows for brake-specific NOx emissions within the NTE zone.

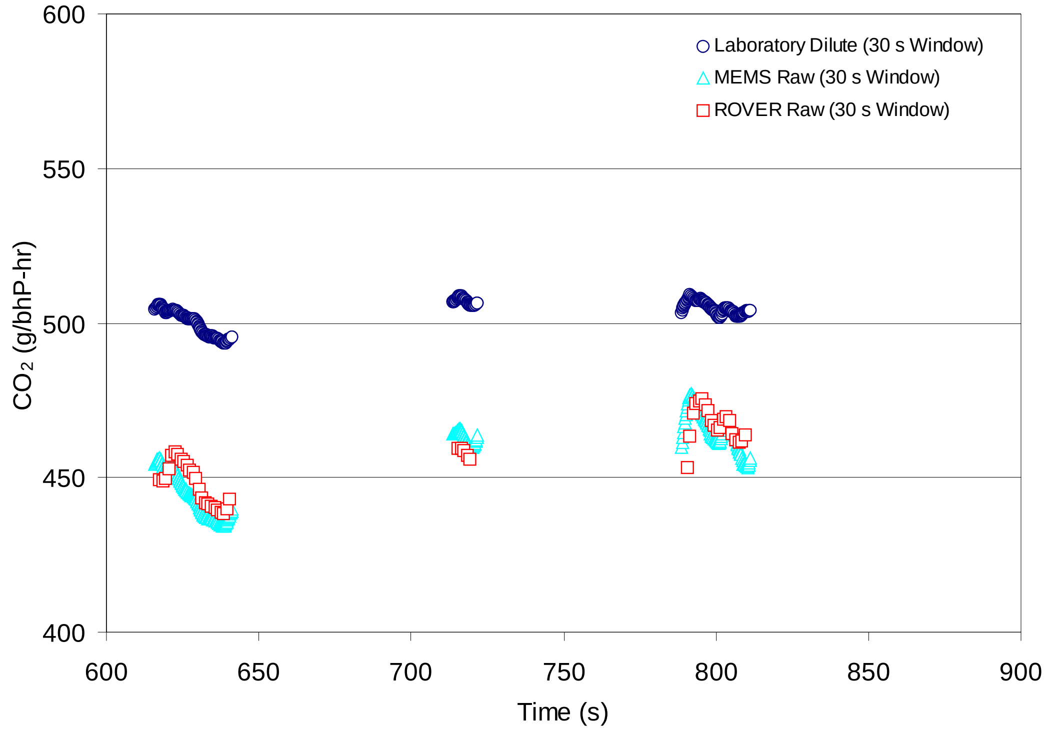


Figure 14 FTP B integrated 30 second windows brake-specific CO_2 emissions within the NTE zone.

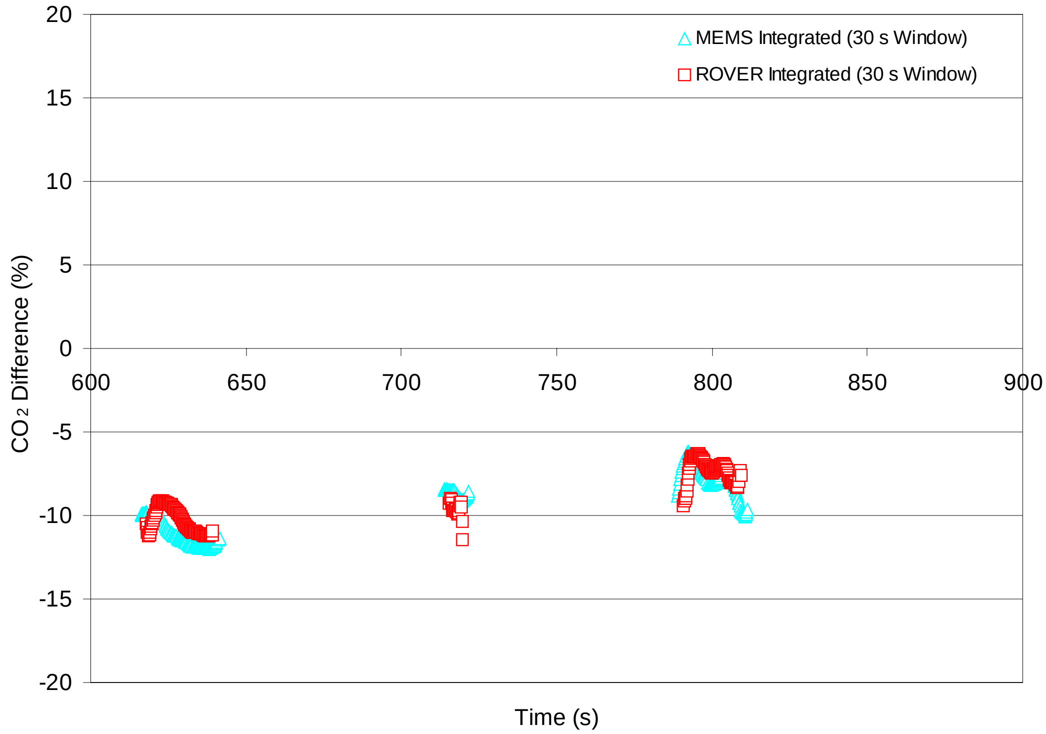


Figure 15 FTP B percent differences for integrated 30 second windows for brake-specific CO_2 emissions within the NTE zone.

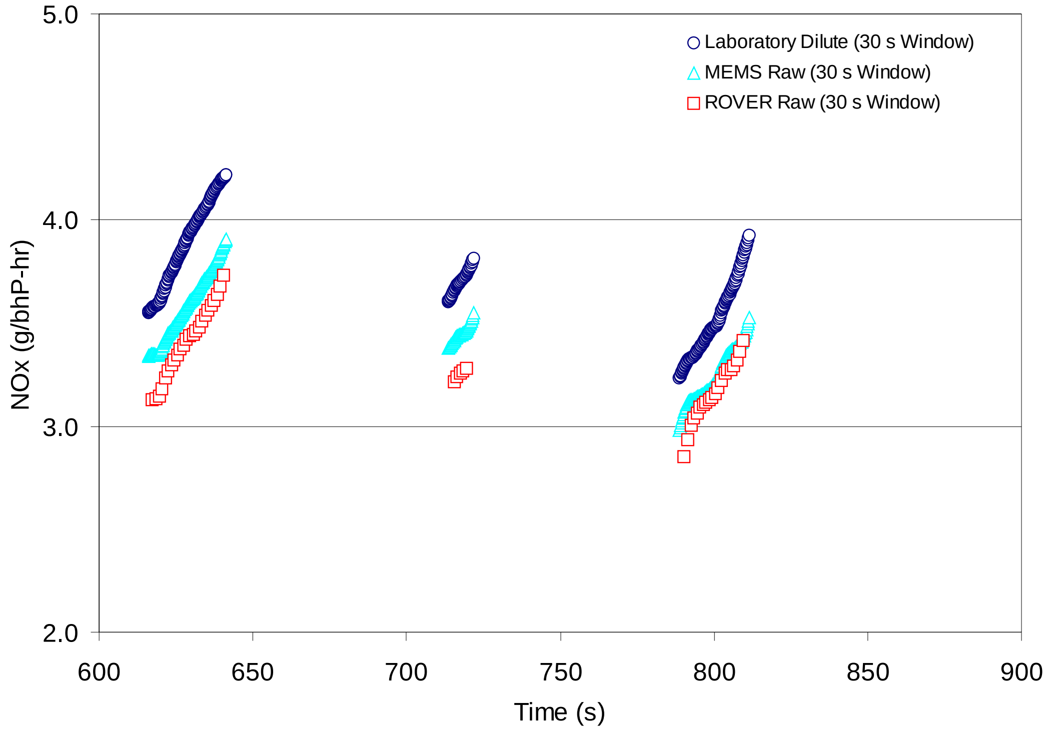


Figure 16 FTP B integrated 30 second windows brake-specific NOx emissions within the NTE zone.

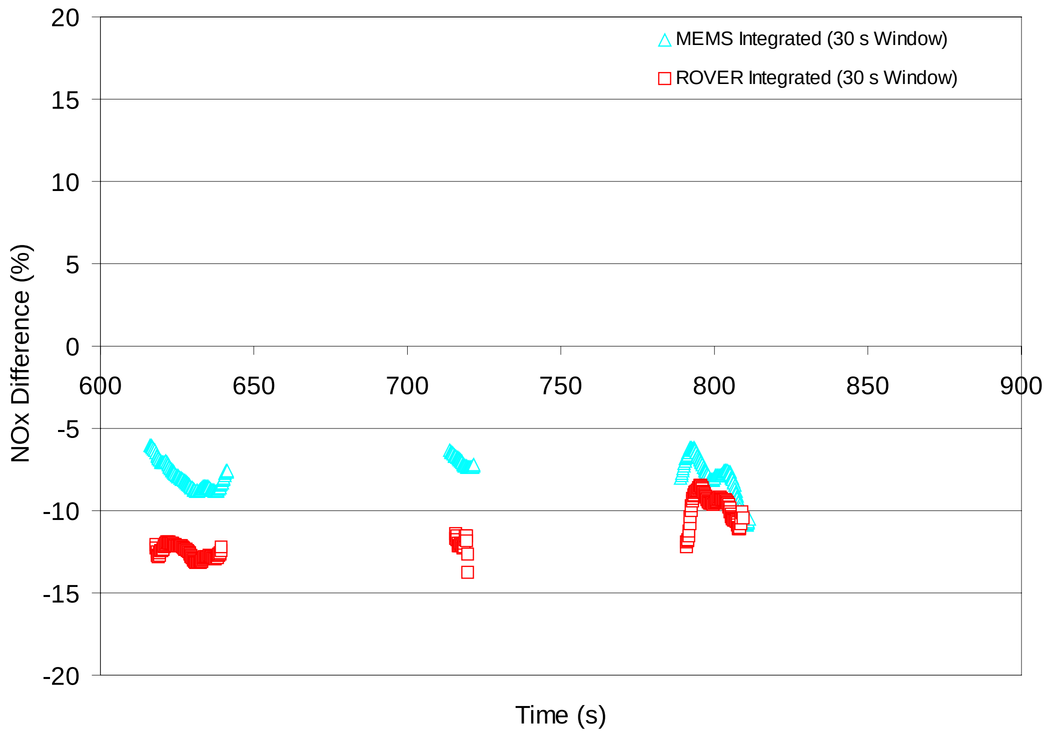


Figure 17 FTP B percent differences for integrated 30 second windows for brake-specific NOx emissions within the NTE zone.

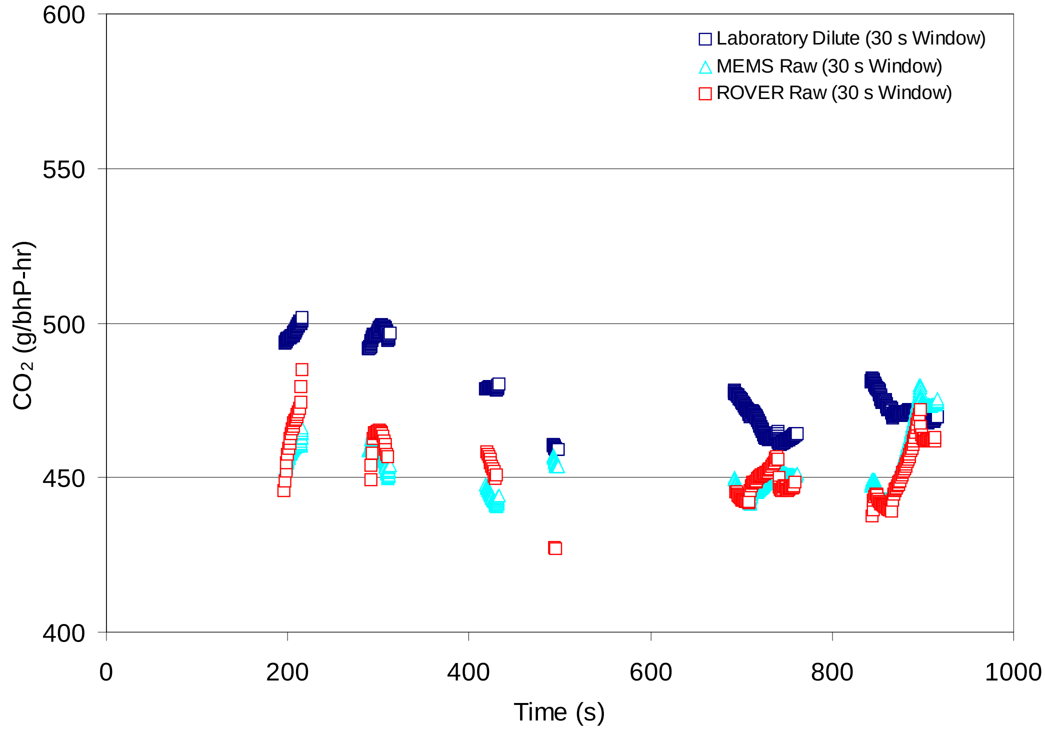


Figure 18 MEMSCYC A integrated 30 second windows brake-specific CO_2 emissions within the NTE zone.

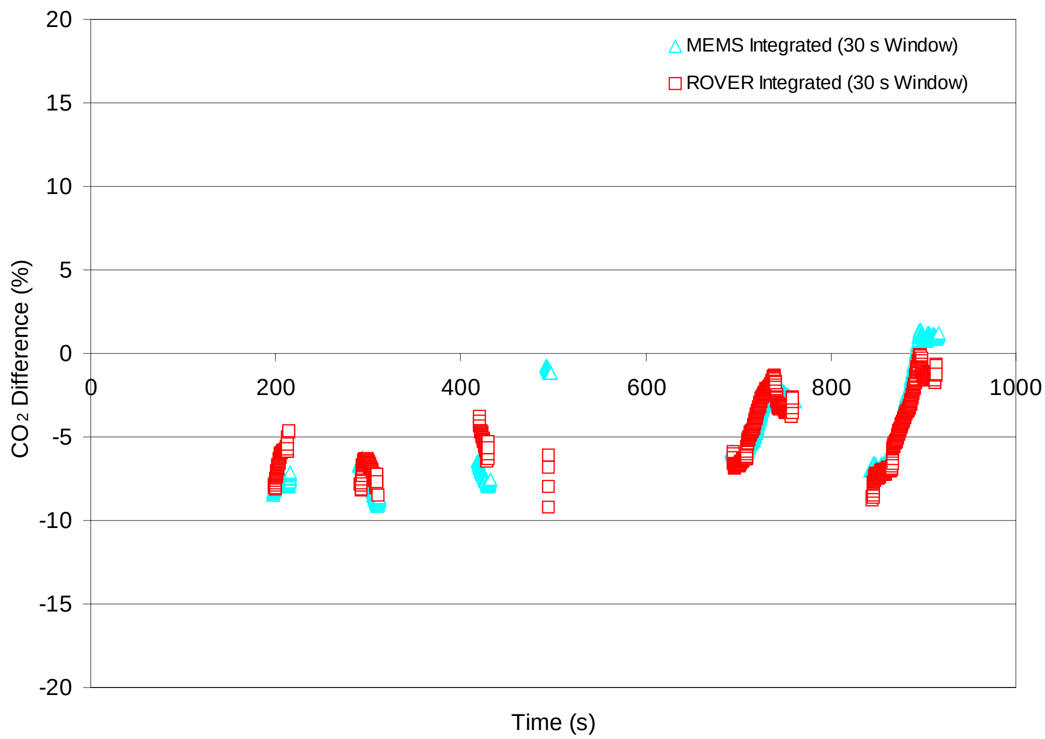


Figure 19 MEMSCYC A percent differences for integrated 30 second windows for brake-specific CO_2 emissions within the NTE zone.

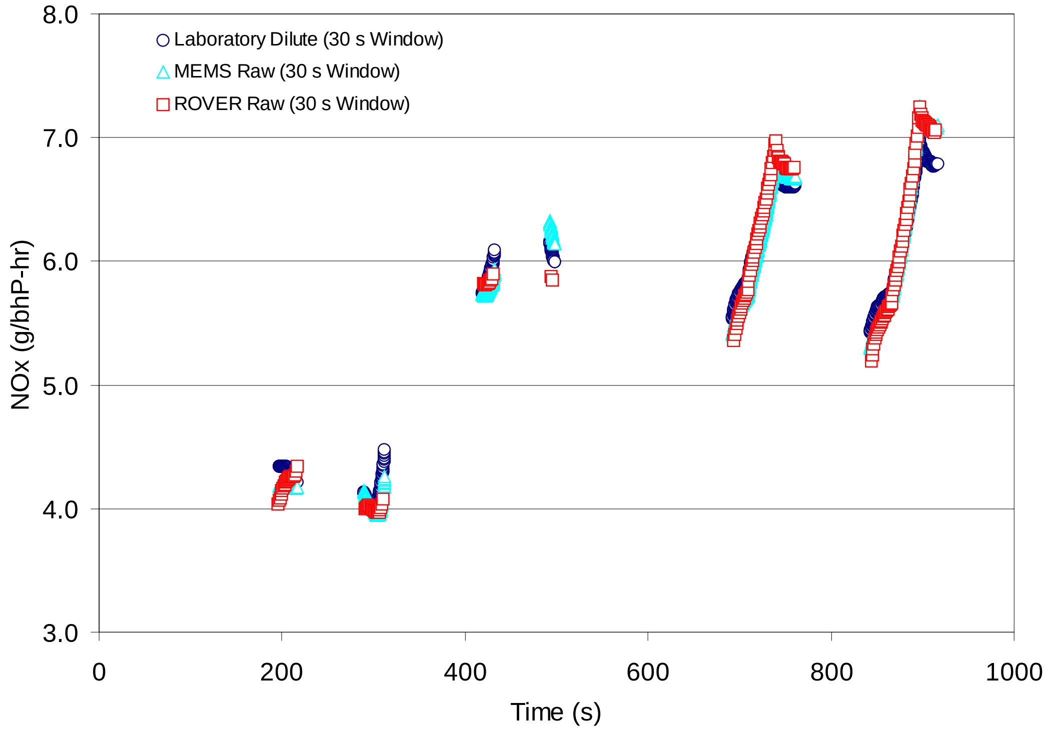


Figure 20 MEMSCYC A integrated 30 second windows brake-specific NOx emissions within the NTE zone.

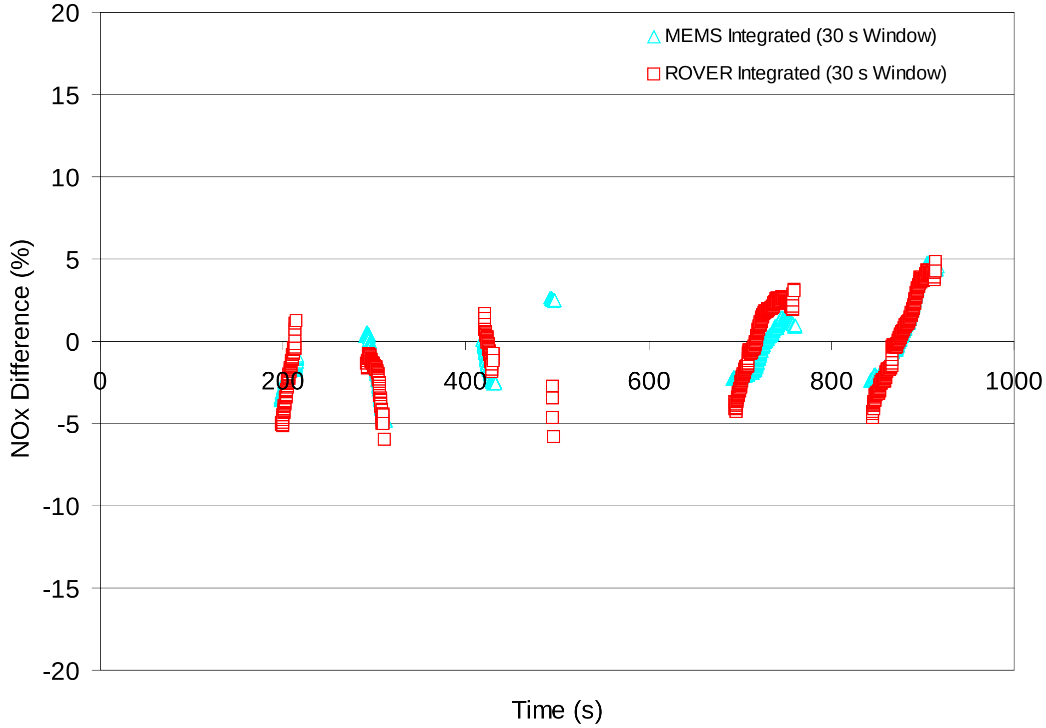


Figure 21 MEMSCYC A percent differences for integrated 30 second windows for brake-specific NOx emissions within the NTE zone.

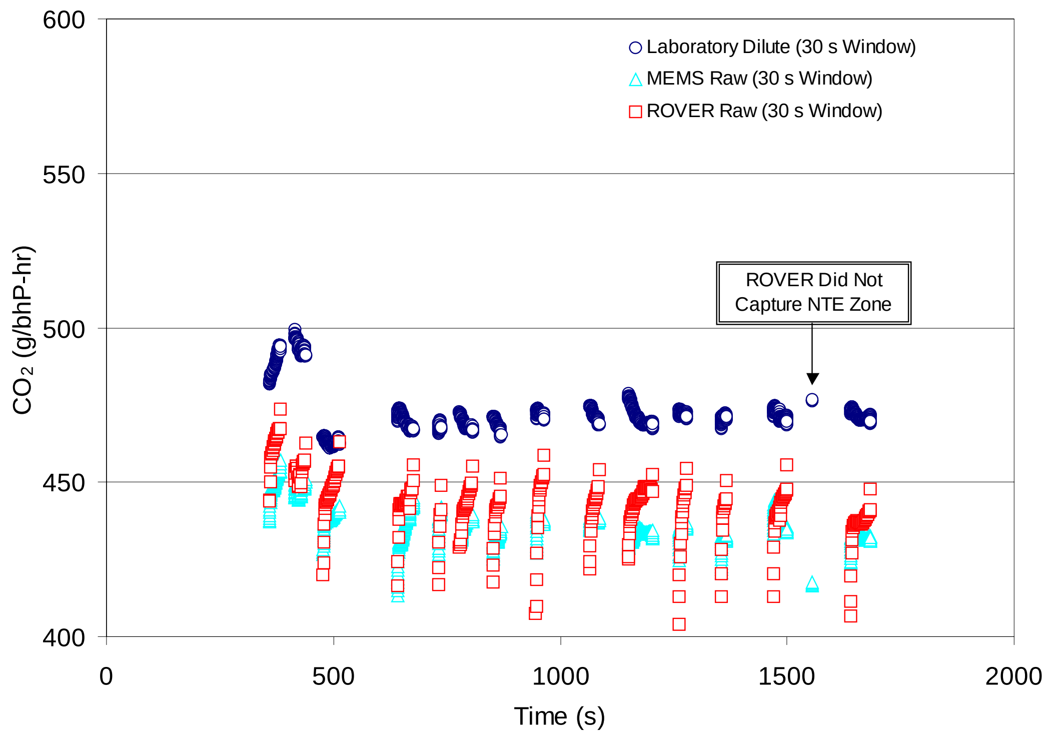


Figure 22 SAB2SW A integrated 30 second windows brake-specific CO_2 emissions within the NTE zone.

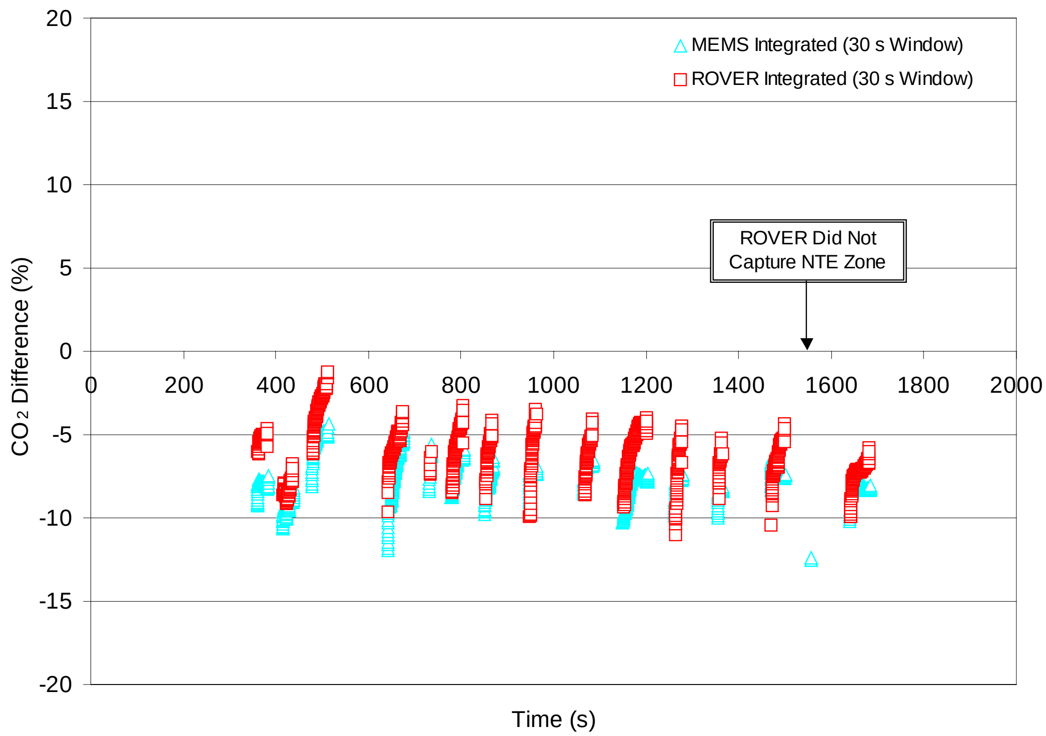


Figure 23 SAB2SW A percent differences for integrated 30 second windows for brake-specific CO_2 emissions within the NTE zone.

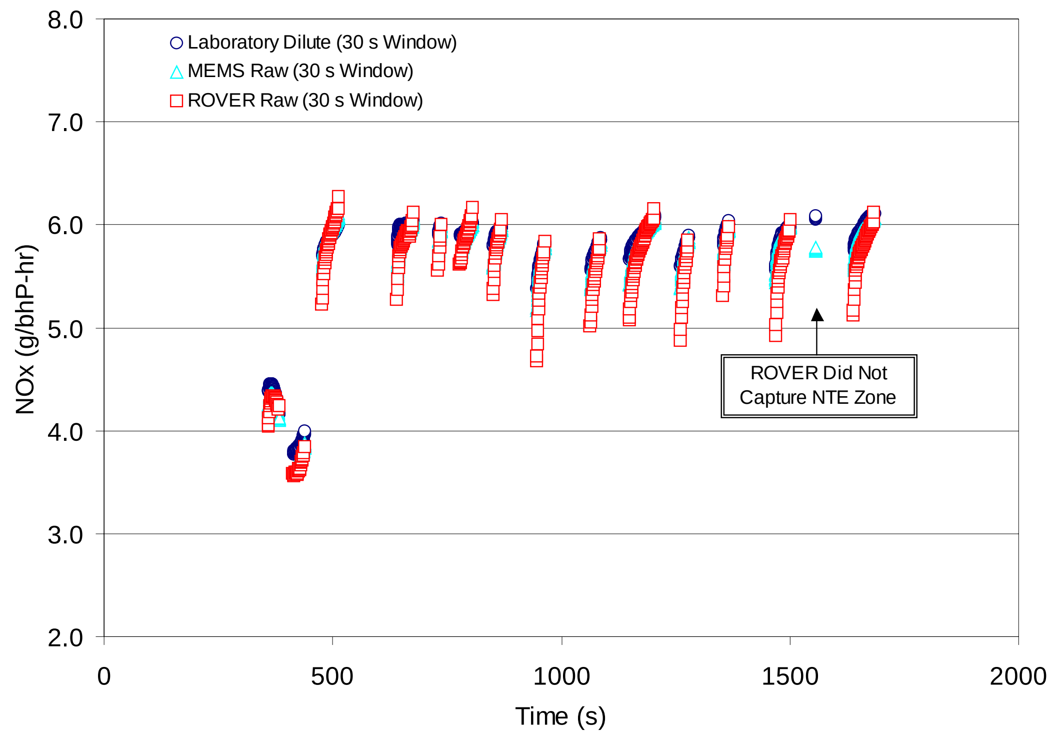


Figure 24 SAB2SW A integrated 30 second windows brake-specific NOx emissions within the NTE zone.

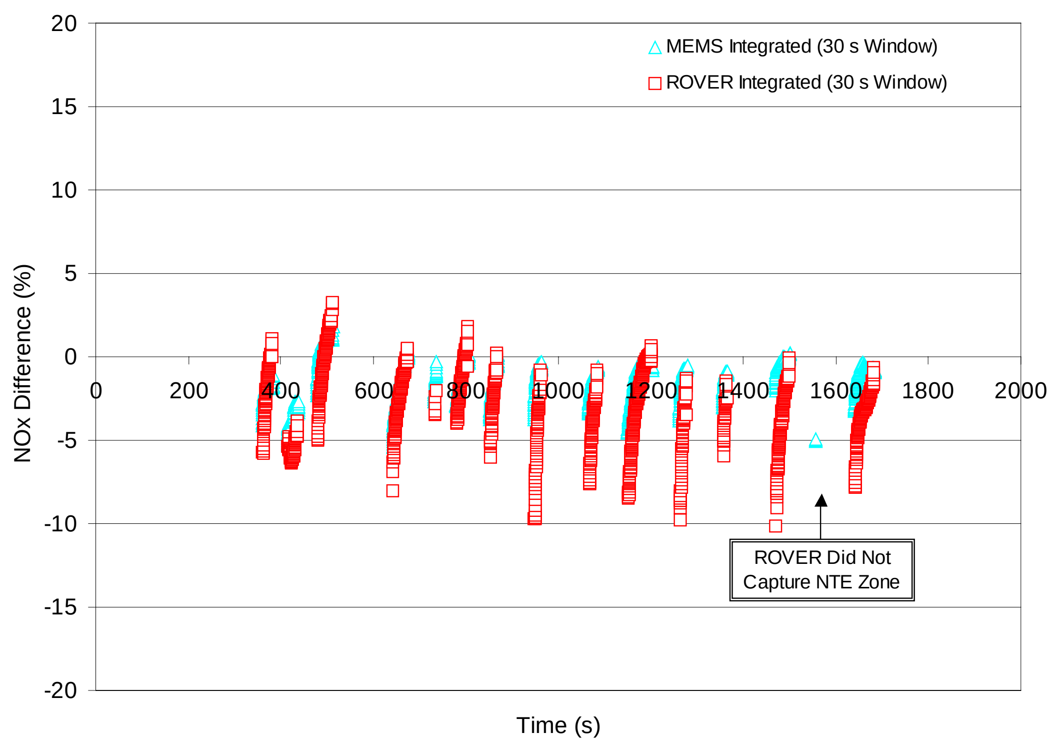


Figure 25 SAB2SW A percent differences for integrated 30 second windows for brake-specific NOx emissions within the NTE zone.

4.3 Vehicle Chassis Tests

Vehicle chassis tests were performed using the WVU Transportable Heavy-Duty Vehicle Emissions Testing Laboratory. This laboratory has been in full-time operation since 1992, and provides exhaust emissions measurements according to the procedures set forth by the CFR 40, Part 86, Subpart N. The emissions measurement systems and total exhaust double-dilution tunnel (CFV-CVS) system were designed coincident to those at the WVU EERL. With maintenance schedules, operation procedures, and system verification measures (for example the use of standard reference materials) that mimic those used at the EERL, the chassis laboratory is capable of producing emissions measurements at a level of accuracy equal to those made by the previously qualified EERL.

Both MEMS and ROVER were employed to measure the mass emissions rate from vehicles operating through chassis schedules (speed vs. time) using the WVU chassis laboratory. A steady-state cycle was used in order to quantify measurement errors while minimizing the smearing effects typical of transient vehicle emissions testing.

Presented in Figure 26 in Figure 27 are only the integrated 30-second window traces for CO_2 and NOx (in grams) for the steady state chassis cycle, as measured by the MEMS, the ROVER, and the laboratory-grade analyzers. Both the ROVER and MEMS yielded NOx mass emission measurements consistent with the EERL measurement system. It should be noted that 900 seconds into the driving schedule, the dilute exhaust NOx concentration exceeded the laboratory analyzer’s full-scale value. The other portable systems continued to record the emissions concentration for the remainder of the cycle.

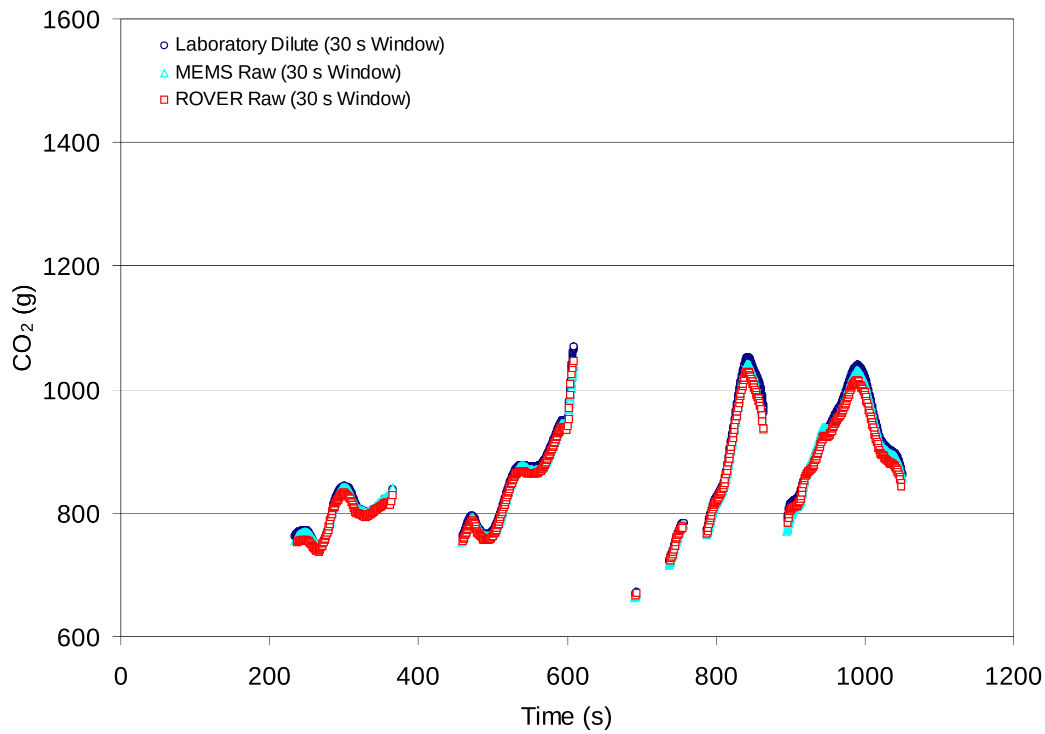


Figure 26 Mack tractor chassis dynamometer integrated 30 second NTE CO_2 windows.

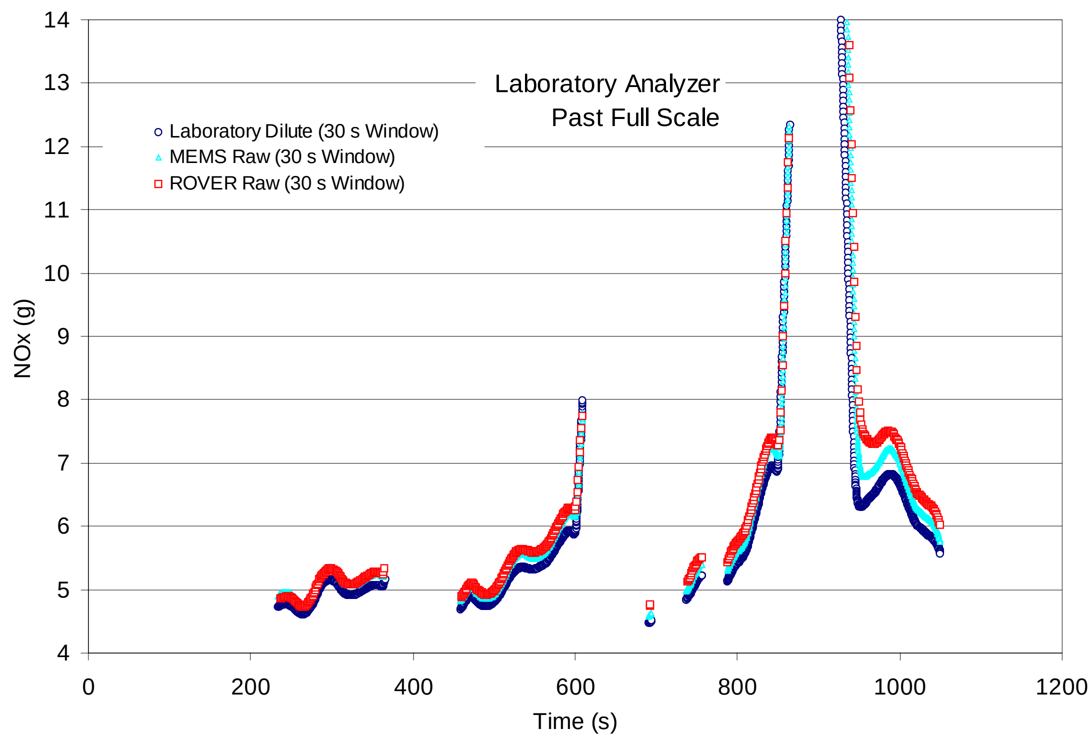


Figure 27 Mack tractor chassis dynamometer integrated 30 second NTE NOx windows.

5 EVALUATION AND SELECTION OF MEMS COMPONENTS

5.1 Mass Flow Rate

The accurate measurement of diesel engine brake-specific mass emissions using an OREMS is directly dependent upon the accuracy of the exhaust mass flow rate measurement. Of all devices evaluated, the Annubar and venturi are the two best candidates for measuring the exhaust flow rate directly. The Annubar is a cross-sectional averaging device that can account for the effects of pulsation in the exhaust stream of an internal combustion engine. A Validyne P365 differential pressure transducer, Omega PX176 or PX203 absolute pressure transducers and J-type thermocouples are recommended as transducers to interpret the Annubar signal.

5.1.1 Flow Requirements

There are several techniques that can be used to measure or infer mass flow rate of a gas in a pipe. Each method will have advantages and disadvantages that must be evaluated to arrive at a method that satisfies a set of requirements that is specific for on-road exhaust flow rate monitoring. First, the flow measurement system must have minimal intrusive effects; the device must offer a minimal pressure loss in the flow stream. The system must be robust and able to withstand on-road vibration. The flow measurement meter must withstand the exhaust gas temperature. The system must be able to measure the total exhaust flow directly or as the sum of the intake air flow rate and fuel flow rate. An on-board flow measurement system must be able to perform in a wider ambient temperature range (0 to 50°C) than is found in the laboratory. The system should be sized for the engine's displacement and vehicle's exhaust system (pipe size). The measurement system must establish a minimum zero drift between the start and end of the test. The system must be able to account for pulsating flow, and finally, the selected method should be based upon proven technology with sound engineering principles.

5.1.2 Flow Measurement Methods

A variety of methods were examined for potential application to measure or infer the exhaust mass flow rate. These methods can be divided between intake and exhaust stream placement. Intake methods include use of laminar flow element (LFE), hot wire anemometer, and tracer gas. Exhaust methods include use of venturi, Annubar, pitot static tube, reverse pitot tube, and air-to-fuel ratio sensors. It is recognized that except for air-to-fuel, the exhaust methods could also be used in the intake with knowledge of the fuel flow rate.

5.1.2.1 Intake Flow Rate

Intake flow rate measurement is not seen as a viable means to measure exhaust mass flow rate. First, intake methods are limited to packaging constraints of the available space found at the engine's intake; flow meters typically require a certain amount of straight upstream (10 diameters) and downstream distance (5 to 10 diameters) from the meter location. It is recognized that a flow meter can be calibrated for a specific non-ideal plumbing configuration but this is not feasible for the large number of vehicles that will be tested in the future per Consent Decrees requirements. Second, all of the intake flow rate measurement methods require the additional measurement of fuel flow rate either directly (via measurement) or indirectly (via ECU information). Additionally, knowledge of blowby past the rings would be required. However, the authors do recognize that fueling and blowby corrections are modest.

A LFE has the advantage that it has a near linear relationship between pressure drop and flow; however, a LFE is sensitive to pulsating flow and may not be rugged enough for on-road testing [18]. A hot wire anemometer is not an accurate method for this work. The tracer gas method may be an accurate means to measure exhaust gas flow [19,20]. However, a tracer gas approach is seen as technology that would require a significant development effort and packaging such a system for on-road testing would be a challenge.

5.1.2.2 Exhaust Flow Rate

Direct exhaust flow measurement was determined to be the best means to measure exhaust mass flow rate. The air-to-fuel method relies upon the accurate measurement of exhaust gas constituents to arrive at the air-to-fuel ratio. This method is used by the VOEM system that was developed by VITO. The total exhaust flow rate can be inferred from the calculated ratio and knowledge of the fuel flow rate. The VOEM system uses a laboratory-grade fuel counter to monitor fuel. Disadvantages of this approach include the deconvolution of the instantaneous emissions concentration to arrive at the instantaneous air-to-fuel ratio and the additional fuel flow rate measurement. Fuel flow rate can be measured with laboratory-grade equipment but is seen as too bulky and costly for on-road testing. Direct fuel flow rate measurement also requires intrusion into the vehicle's fueling system. Fueling estimation via ECU may not be available from all manufacturers and the accuracy of available ECU fueling information is questionable. However, this method may provide for a verification check during steady-state operating conditions of the selected flow measurement method when ECU fueling information is available.

The remaining potential candidates for exhaust flow measurements are all based upon the production of a differential pressure signal more or less proportional to the square of the exhaust volume flow rate. This results in a nonlinear relationship between the measured quantity and either volume or mass flow rate. The pitot static tubes and reverse pitot tubes are single point flow meter devices. The reverse pitot tube consists of two pitot tubes facing in opposite directions placed in the streamline of the flow through a pipe. Disadvantages of these two devices are that they probe the flow at a single point and rely upon an invariant, well defined velocity profile in the pipe. It is essential that this velocity distribution be similar during calibration and the actual test. Hence, when the flow pattern is different (pulsating) from the calibrated flow field, then the measured flow rate will be in error. Not only will pulsating flows cause transient flow measurement variations, but they will also generate time-averaged velocity profiles that differ from a steady state profile. Since pitot tubes are normally centrally located, and since a disproportionate quantity of the flow may be associated with velocities at outer radii locations, alterations of the velocity profile can cause substantial measurement error. The venturi is a well-defined device for measuring flow rate and is an accepted and accurate method for measuring turbulent flow rates. Extensive evaluation of the venturi was not performed due to time limitations. However, testing has indicated that the venturi warrants an additional evaluation before being discarded from potential application into the MEMS.

An Annubar is an averaging pitot-type device that can account reasonably for the pulsating flow since the resulting differential pressure that it provides is a weighted average of multiple points across the flow field. It is recognized that the Annubar is not removed from potential problems. The effects of the localized mass flow in and out of the multiple holes in the Annubar meter due to pulsating flow is not documented. An Annubar is sensitive to alignment within the flow stream and to the upstream piping layout. Since the Annubar has exposed ports to the diesel exhaust stream, blockage is a concern but can be addressed by purging the passages with compressed air prior to testing and cleaning the Annubar cylinder prior to installation. There are temperature limiting structural concerns of the Annubar flow meter that are specified for continuous operation but should not pose a problem if these limits are exceeded for short durations of the order of several minutes.

5.1.2.3 Pulsating Flow Commentary

Although pulsating flow is addressed in the CFR and referenced to a SAE standard [21], the actual process by which pulsating flow is analyzed is not well defined for steady-state engine operating conditions, let alone for transient operation. For any flow measurement system in which a pressure (absolute, gage, or differential) measurement is required, substantial analysis may be required to determine the time averaged flow rate. One of the best sources to examine the effects of pulsation on flow rate measurements is a 1998 ISO technical report [22]. A summary of flow devices with additional references concerning pulsating flow is found in Miller [18]. For any flow device, which has a square root relationship between the flow rate and differential pressure, an error is introduced by taking the mean of the pressure measurement as shown by

$$\left(\overline{\Delta p}\right)^{1/2} \neq \left(\overline{\Delta p^{1/2}}\right). \tag{1}$$

Although pulsating flow will greatly influence the flow meter selection process, other errors are introduced into an exhaust flow measurement system and include thermal growth (area change) of the exhaust pipe and flow meter, exhaust stream fluid properties, and transducer response.

It is difficult to identify a primary standard to compare the various exhaust mass flow measurement techniques. An LFE placed in the intake flow stream with surge tanks is limited to the design’s narrow steady state operating regime. The best method to compare one flow measurement system to another for this work was to compare the raw emissions mass rate (g/s) for CO_2 with the dilute emissions mass rate (g/s) via the CVS system. This approach was adopted since the raw CO_2 emissions measurement is seen as being accurate and the dilute CVS system is the method by which the final on-board measurement system will be compared. For a near steady-state engine operating point this method should provide for a good method to evaluate the given flow device. However, it does have the disadvantage that dispersion and diffusion of the emissions through the sampling system will impact this measurement.

An example of the effect of pulsation on an LFE in the intake, and a venturi and Annubar in the exhaust is shown in Figure 28. The given flow instrument was placed in the flow stream without any plenums or surge tanks. Each flow device consisted of temperature, absolute pressure, and differential pressure measurement transducers. The results from a FTP cycle between 600 and 1000 seconds into the cycle are illustrated. All data were reported at a 5 Hz frequency per minimum requirements set forth in the Consent Decrees. This sampling rate is too slow to derive any conclusions about the pulsating flow. As shown in this figure, the LFE in the intake flow stream yields a higher flow rate than either exhaust flow stream meters. The resulting exhaust flow rate inferred from the intake LFE plus fuel flow rate would be even higher. The venturi exhaust flow rate falls between the Annubar and LFE measurements.

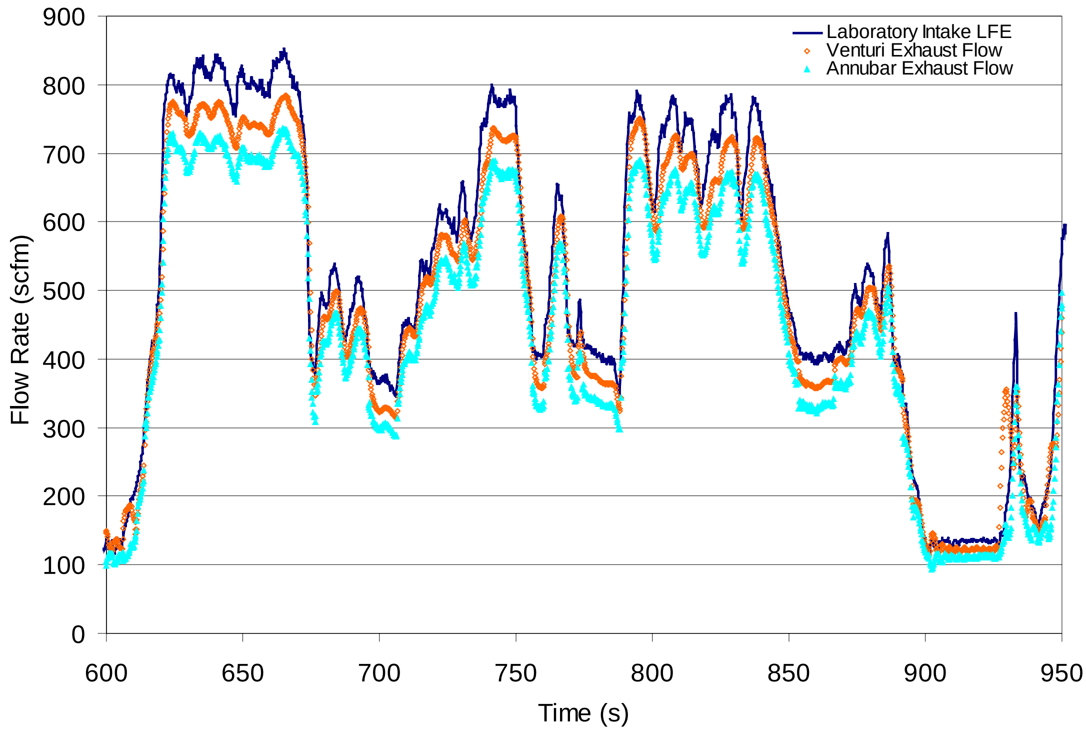


Figure 28 Comparison between intake LFE, exhaust venturi and Annubar flow rates for the FTP cycle from 600 to 950 seconds.

The CO_2 emissions mass rates are shown in Figure 29 for the raw exhaust measurement using the venturi and Annubar flow rates, and compared to the laboratory CVS emission calculation. Both venturi and Annubar mass emissions rates shown in this figure used the same raw concentration value as measured by the MEMS emissions system. The difference between the venturi and Annubar flow measurement is also evident in this figure, but a direct comparison between the mass emissions cannot be made on an instantaneous basis between the raw exhaust and dilute CVS system due to the dispersion and diffusion in the dilute CVS system. This figure does allow the instantaneous comparison between the venturi and Annubar since only the flow rate data are different; the same raw emissions are used to calculate the mass emissions rate.

When the mass emissions are integrated over the cycle, the venturi-derived and Annubar-derived values differ from the laboratory CVS system by 3.1% and -4.9%, respectively.

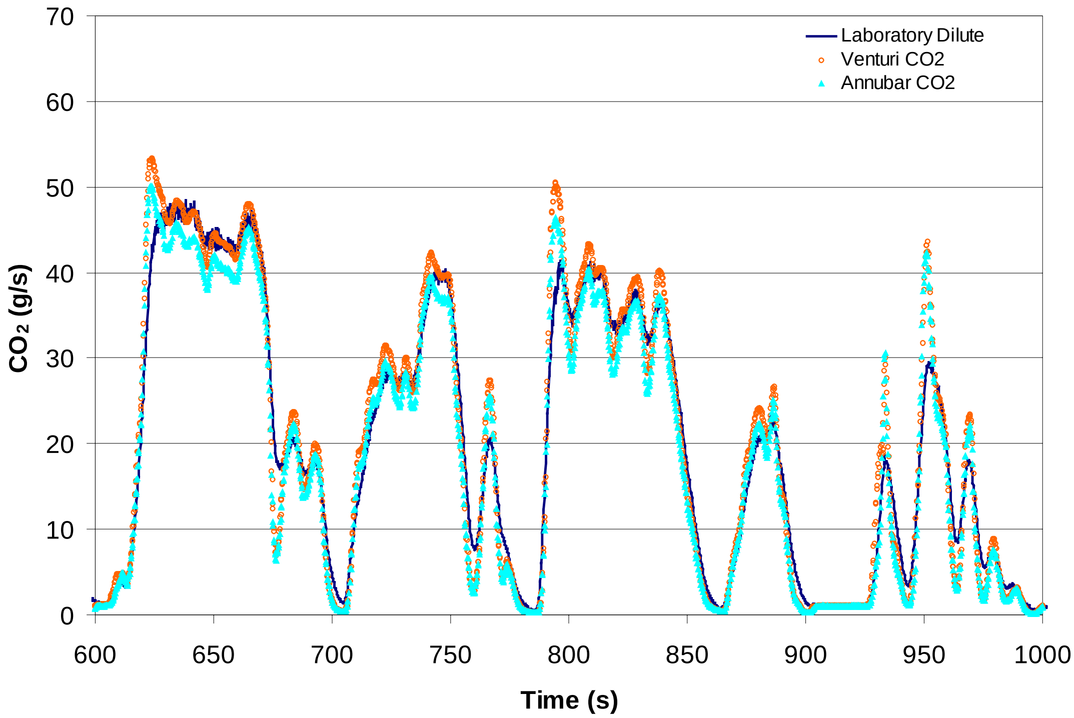


Figure 29 Comparison between CO_2 mass emissions for the WVU EERL dilute CVS and raw exhaust gas for a venturi and Annubar flow meter.

It should be noted that 5 Hz average data were used to determine exhaust mass flow rates presented above. As shown in this work, the Annubar averaging-type meter and venturi meter can measure the exhaust mass flow rates directly at the minimum sampling rate required by the Consent Decrees. The flow meters reviewed above or other types of flow measurement meters may be used if they account for the pulsations through pressure signal data acquisition rates that can capture the pulsations. For example, 2000 Hz pressure data may be adequate to capture the pulsations.

5.1.3 Transducer Selection

The selection of the transducers to measure the bulk flow temperature, bulk flow absolute pressure, and flow meter differential pressure are as important as the flow meter selection itself. The transducers must not only be selected to meet the expected range to be measured (temperature, absolute pressure, and differential pressure) with the highest possible accuracy, but must also meet the requirements that they can withstand the ambient environmental and vibration conditions that will be found in on-road testing. The transducers must also be able to withstand the exhaust gas environment.

5.1.3.1 Temperature

The most reliable method for measuring the bulk flow temperature is with a thermocouple. Although there is a wide range of thermocouple types and thermocouple designs, type J thermocouples provide for a wide temperature range and are readily available. The smallest diameter thermocouple that is sufficiently rugged should be used; however, there is a trade-off between sheath diameter, response time, and structural integrity. For a type J thermocouple, it is preferable that a 1/16" diameter, stainless steel sheath thermocouple be used, although a 1/8" diameter will provide for adequate response. At least two temperature measurements are used to average the flow temperature, one upstream and one downstream. Two temperature measurements will also provide an accuracy check in the temperature measurement. A thermocouple is not influenced by the vibration or ambient conditions if a cold junction compensation junction is incorporated into the data acquisition system.

5.1.3.2 Differential and Absolute Pressure

There are several different types of pressure transducers that can be used to measure the absolute and differential pressures accurately for mass flow rate determination. However, the final transducer selection must meet the requirements that it can withstand the corrosive environment of the exhaust stream, vibration typically encountered in on-road testing, and the ambient environment. In order to select a given transducer for application in an on-road flow rate measurement system, a series of tests must be performed to evaluate the transducer. The results from such a test series are reviewed below for a select number of transducers that were tested for this work.

For this work, four differential pressure transducers and the three absolute transducers were selected from a large number available on the market as being potentially suitable. These were evaluated and they are listed in Table 7. With the exception of the Omega PX654-25D5V, which would require a purge air supply, all of the listed transducers can be used in the exhaust stream. The Omega PX654-25D5V was selected for evaluation in the intake stream application but not in the exhaust.

Table 7 Selected transducers for on-road testing.

Type	Manuf.	Model	Range	Accuracy	Output	Response	Notes
Abs.	Omega	PX176-025A5V	0-25 psia	± 1.0%	1-6 VDC	20 ms	
Abs.	Omega	PX203-030G5V	0-30 psia	± 0.25%	0.5-5.5 VDC	1 ms	
Abs.	Viatran	1042ACA	0-15 psia	± 0.15%	0-5 VDC	1 ms	
Diff.	Omega	PX654-25D5V	0-25 in WC	± 0.25%	1-5 VDC	250 ms	Dry Gas Only
Diff.	Validyne	P365	0-20 in WC	± 0.5%	0-5 VDC	4 ms	Changeable Diaphragmas
Diff.	Viatran	2746	0-25 in WC	± 0.25%	0-5 VDC	50 ms	
Diff.	Omega	PX154-025DI	0-25 in WC	± 1.0%	1-5 VDC	250 ms	

Six tests were performed to evaluate the transducers and these included four on-road tests and two in-laboratory tests. The on-road tests consisted of driving through approximately 20 miles of urban, suburban on highway roads with a Mack CH tractor and trailer to evaluate the effects of vibration and temperature on the response of the transducers. For two on-road tests, the transducers were mounted horizontally and vertically, respectively, in the cab to evaluate their performance under "normal" ambient conditions of approximately 25°C. The third on-road test placed the transducers in a horizontal position outside the truck with an ambient temperature of approximately 5°C to examine a cold condition. The final on-road test examined the effect of increasing temperature with the transducers wrapped in heat tape to simulate a hot condition. The in-laboratory tests consist of the effect of temperature gradients (similar to the forth on-road test but without vibration) and the effect of inclination on the zero set point. For all tests, the differential pressure transducers' high and low sides were connected together to eliminate any influence due to air movement; the absolute pressure transducers were exposed to the ambient environment but the openings were shielded to minimize air movement effects. All transducers were zeroed prior to the start of the test.

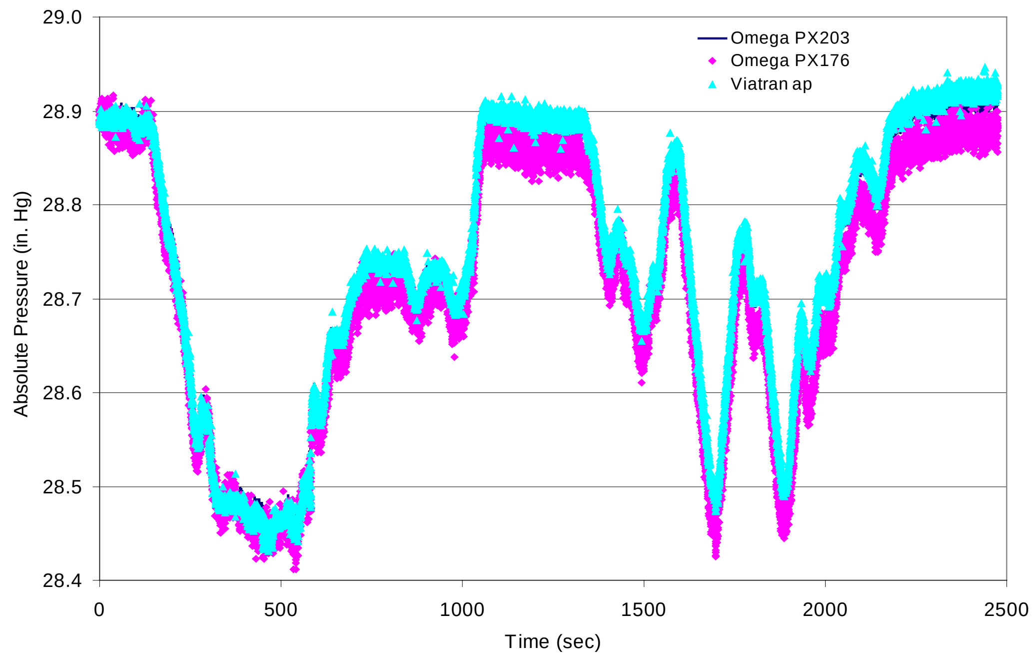


Figure 30 Absolute pressure transducers' response to on-road testing, horizontal in-cab run.

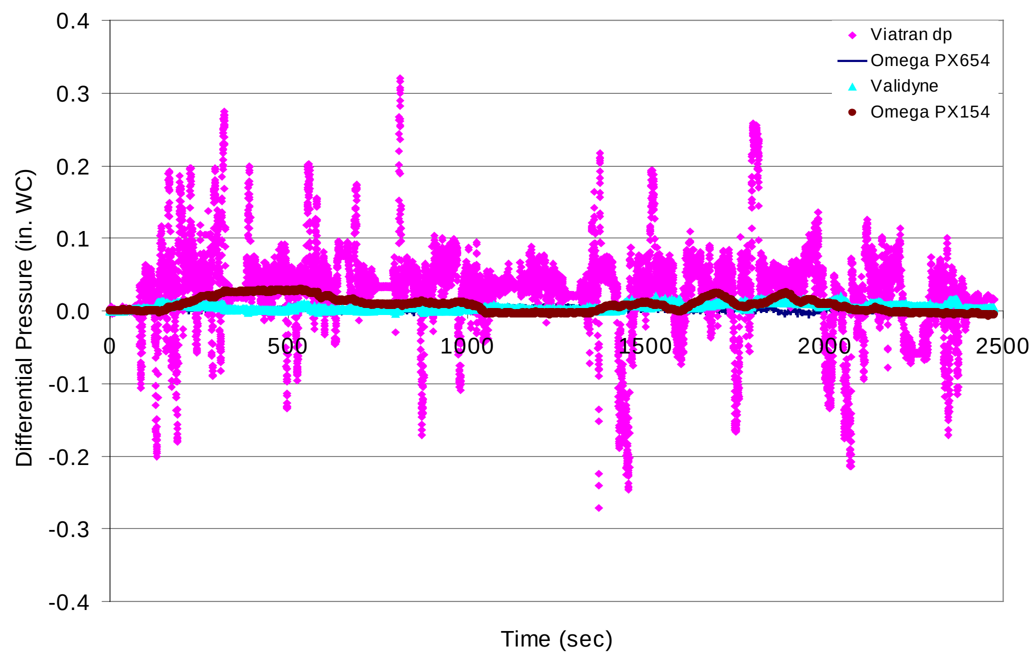


Figure 31 Differential pressure transducers' response to on-road testing, horizontal in-cab run.

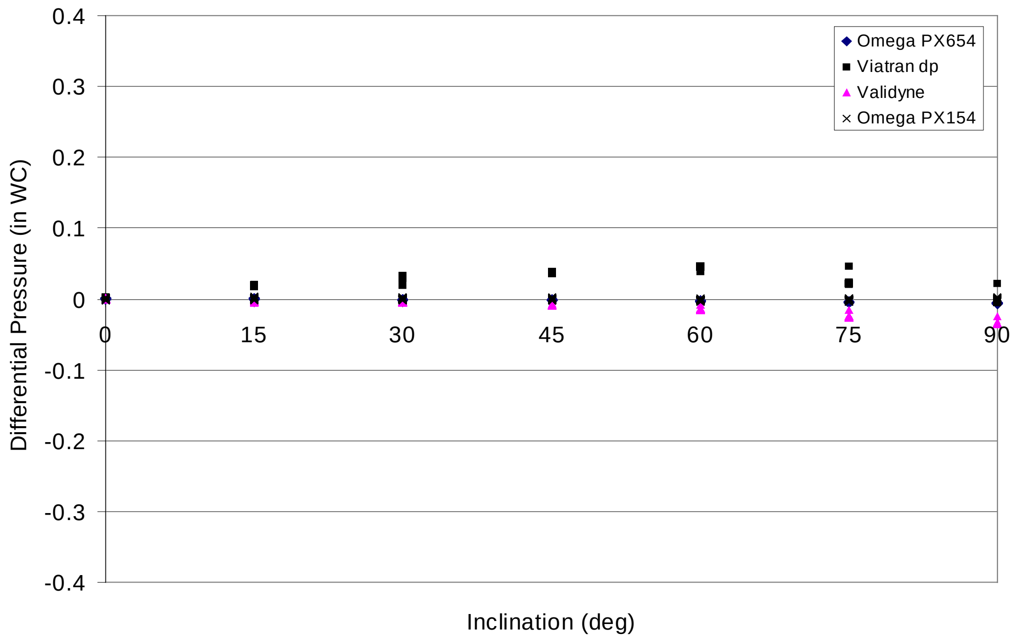


Figure 32 Differential pressure transducers' response to in-laboratory testing, inclination test.

The results from the on-road and in-laboratory testing are illustrated in Figure 30 to Figure 32 and summarized in Table 8 and Table 9. Table 8 shows the average values of the differential pressure and the standard deviation. Table 9 shows the percent difference between the start and end of a test for the absolute pressure transducers. Although the Omega PX654 is influenced the least by vibration, temperature, and inclination, it cannot directly be used to measure a flow meter's differential pressure in a raw exhaust gas stream since this transducer is designed for dry, non-corrosive gases. The PX654 results are given to illustrate the limit of a transducer's response.

Table 8 Differential pressure transducers testing results (in WC).

Transducer	Horizontal Inside Ave.	Horizontal Inside Std. Dev.	Vertical Inside Ave.	Vertical Inside Std. Dev.	Horizontal Outside Ave.	Horizontal Outside Std. Dev.	Heated Inside Ave.	Heated Inside Std. Dev.	Bench Temp. Increase Ave.	Bench Temp. Increase Std. Dev.	Bench Incline Ave.	Bench Incline Std. Dev.
Omega PX654	0.0025	0.0004	-0.0019	0.0002	0.0066	0.0008	0.0000	0.0046	0.0001	0.0001	-0.0024	0.0004
Viatran 2746	0.0283	0.0114	0.0111	0.0121	-0.1278	0.0267	-0.0154	0.0128	0.0037	0.0006	0.0214	0.0034
Validyne P365	0.0051	0.0011	0.0053	0.0011	-0.0192	0.0021	0.0129	0.0015	-0.0152	0.0033	-0.0132	0.0030
Omega PX154	0.0084	0.0016	-0.0030	0.0022	0.0383	0.0023	-0.0523	0.0056	-0.0082	0.0012	-0.0007	0.0002

Table 9 Absolute pressure transducers percent difference (%) results between test start and end.

	Horizontal Inside	Vertical Inside	Horizontal Outside	Heated Inside	Bench Temp. Increase	Bench Incline
Omega PX203 AP	0.0485	0.1099	0.0117	0.0571	0.3038	0.0401
Omega PX176 AP	0.0443	0.0496	0.0508	0.5860	1.5886	0.0221
Viatran 1042 AP	0.1119	0.0576	0.1270	0.5396	0.1479	0.0294

The Validyne P365 differential transducer and the Omega PX176 absolute transducer had the least signal drift during tests when the transducers were mounted either horizontally or vertically in the cab of the truck. The Validyne P365 also exhibited the least drift in the third test where the transducers were mounted outside the cab. The Omega PX203 had the least zero drift among the absolute transducers during this test. When the transducers were exposed to the temperature increase inside the cab of the truck, the Validyne P365 differential and the Omega PX203 absolute experienced the smallest drift between the mean and the zero, respectively. The fifth test showed that the Viatran 2746 differential and the Viatran 1042 absolute were influenced the least by increasing temperature. The final test showed that the Omega PX154 differential pressure transducer and the Omega PX176 absolute pressure transducer had the least drift among them when they experienced changes in orientation.

The overall goal of these tests was to select a differential and absolute pressure transducer that could be used over a wide range of operating conditions. Based on the least amount of drift, it was determined that the Validyne P365 and the Omega PX176 meet the criteria of minimum drift (less than 2% of full scale value). It should be noted that the Omega PX203 had the same response as the PX176 transducer during all of the tests and therefore it could be used as well.

5.1.4 Design Layout

The exhaust mass flow measurement design should consist of a flow meter and transducers that will have a maximum reading of 90% flow full-scale output for the engine to be tested. The flow meter should be sized to minimize any additional backpressure to the engine but fall in the highest accuracy of the flow measurement system. It is proposed that three different flow meter ranges be available, depending partly upon engine displacement. The flow meters should be targeted at three different exhaust flow rates: (1) up to ~500 scfm, (2) up to ~900 scfm, and (3) above ~900 scfm. The three ranges would nominally correspond to 4", 5", and 6" exhaust pipe sizes. Adaptors would handle any deviation of the pipe size found on the vehicle during in-use testing.

A proposed design layout of the flow meter and transducers is given in Figure 33. As shown in this figure, an Annubar is used in conjunction with a differential pressure transducer, absolute pressure transducer, and two thermocouples. Due to large axial temperature gradients in the exhaust stream, two temperature measurements are recommended in order to obtain an average temperature at the flow meter. The pressure transducers should be plumbed such that the transducers can be zeroed or spanned without the removal of lines connecting them to the exhaust tube. It may be necessary to duplicate the system shown below with an additional Annubar and transducers placed one or two pipe diameters away from the first Annubar. It is recommended that a minimum drift value of the flow rate measurement system of 2% of the full-scale value be used as the criterion for test validity.

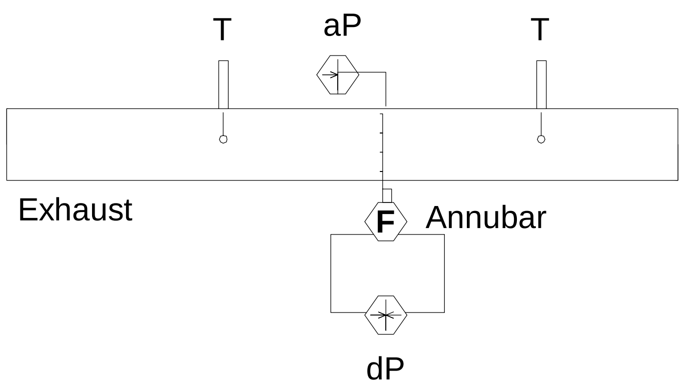


Figure 33 Annubar transducer layout.

5.1.5 In-Field Application

In-field testing of the emissions from heavy-duty diesel engines will require a significant effort to ensure the accuracy and quality of the data due to the nature (on-road, uncontrolled ambient conditions) of the testing. Since a wide variety of exhaust pipe sizes and plumbing configurations may be encountered, it will be necessary to have several flow tubes that match the engines' exhaust flow mass flow rates. The location of the connection in the exhaust system will be determined on a per vehicle basis. It is preferable to place the flow meter downstream of a continuous straight section of the vehicle's existing exhaust system in an effort to avoid any upstream disturbances. Split exhaust systems will have to be approached on an individual basis; if possible, the split system should be by-passed with the flow meter in its place. If the flow rate must be measured after a split exhaust system then both legs of the split should be rejoined and the total flow rate measured with one flow tube.

Tasks that will be required to be performed for each vehicle test include the inspection and leak check of the exhaust system. A system zero run should be performed over one of the routes at the onset of testing to ensure system and transducer integrity.

5.2 Engine Torque and Speed Measurement

Engine torque derived from ECU broadcast parameter is based upon fueling commands and assumed engine efficiency by the manufacturer. The ECU-derived torque approach is obtained from in-field measurement of the ECU data and from manufacturer's supplied data. The manufacturer-supplied data is for a typical engine for that engine series. The ECU broadcast speed and torque is reliable and can be employed directly for an OREMS measurement. The inference of power from broadcast of ECU engine speed and percent load can only be accomplished with accompanying manufacturer's lug torque curve and a curb-side no-load test. It is recognized that accessory loadings (which are not included during certification testing) are associated with the brake-specific mass emissions in an OREMS and must be minimized during on-road testing. This measurement was found to be in error by as much as 10% for a 30 second window average within the NTE zone.

5.2.1 Overview

Engine speed and torque are primary parameters that must be measured by an OREMS to meet the Consent Decrees requirements of reporting emissions data in brake-specific units while the engine operates within the NTE zone. On-road engine speed and torque measurements will differ from in-cell laboratory measurements due to the fundamental differences between the two types of tests. In-cell tests use a dynamometer to control and measure the engine speed and load on the engine to a high and verifiable accuracy. On-road tests will rely upon ECU broadcast load information and engine speed measurements provided by on-board sensors. Although in-line techniques (shaft collars) are available for measuring the torque directly, these methods fail to account for accessory work and are installed only with difficulty. The best method, therefore, to estimate output shaft power is via ECU broadcast. However, a disadvantage of relying upon the ECU data for shaft power estimation is that only electronically controlled vehicles with required signal output can be evaluated.

Engine speed and torque are required independently for the NTE zone determination and cannot be described using engine shaft power alone. Figure 34 illustrates the NTE area with the associated boundaries. The NTE zone is defined in the Consent Decrees and is bounded by engine speeds above the 15% ESC Speed,

$$n_{15\% ESCSpeed} = n_{lo} + 0.15(n_{hi} - n_{lo}), \qquad (2)$$

engine loads greater than 30% of maximum, and engine power greater than 30% of maximum. In Equation (2), n_{lo} is defined as the lowest engine speed at which 50% of the maximum power occurs, while n_{hi}, is defined as the highest engine speed where 70% of the maximum power occurs. The Consent Decrees requires that exhaust emissions be reported for engines operating within the NTE zone for at least 30 consecutive seconds.

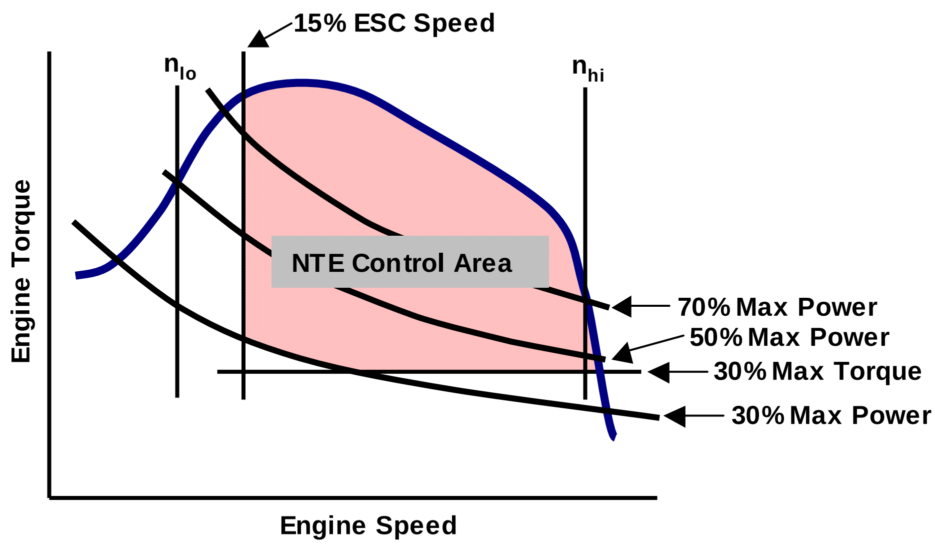


Figure 34 Example NTE area definition.

5.2.2 Available ECU Information

Currently, there are three standards that are used in ECU serial communication, namely, SAE Standards J1587, J1922, and J1939 [23,24,25]. Generally, a protocol adaptor (hardware), such as that available from the Dearborn Group [26], is required to communicate between the ECU and a computer via a serial (RS-232) interface. Protocol usage charts for the S-HDDE manufacturers are listed in Table 11 to Table 15.

Although SAE standards have provisions for a plethora of engine and vehicle information, not all of the information is broadcast through public packages. WVU has opted to use only publicly broadcast packets, thus alleviating the task of implementing each S-HDDE company's proprietary hardware into an OREMS. The various packets of information are broadcast at different rates. For SAE J1587, engine speed is broadcast at 10 Hz with a 0.25 rpm resolution, engine percent load is broadcast at 10 Hz with a 0.5% resolution, and output torque is broadcast at 1 Hz with a 20 lb-ft resolution. However, output torque was not a publicly broadcast parameter for the engines (Mack E7, Navistar T444E, and Cummins ISM-370) tested to date. Due to the unavailability of direct torque broadcast, an OREMS should be capable of inferring the instantaneous torque using the percent load broadcast in conjunction with a manufacturer's supplied lug curve and curb-side no-load data.

5.2.3 ECU Engine Speed Measurement

Engine dynamometer testing has shown that engine speed broadcast via the ECU correlates very well with laboratory grade equipment. Engine speed broadcast per SAE J1587 standard has a range of 0 to 16383 rpm with a resolution of 0.25 rpm. A comparison between measured laboratory and ECU broadcast engine speed is shown in Figure 35 for a Cummins ISM-370 engine. A Dearborn protocol adaptor was used to interface the ECU to a PC. As shown in this figure, the percent difference varies from –6.2% (during a steep deceleration) to 13.6% (during an aggressive acceleration). However, these points lie outside the NTE zone. It should be noted that these differences might be attributed to slight time alignment errors between the two different data acquisition computers and the 5 Hz data used to generate the chart. The average absolute percent difference between ECU broadcast and measured laboratory engine speed, over the FTP cycle, is 0.55%. This suggests that ECU broadcast engine speed is a very reliable and accurate measurement.

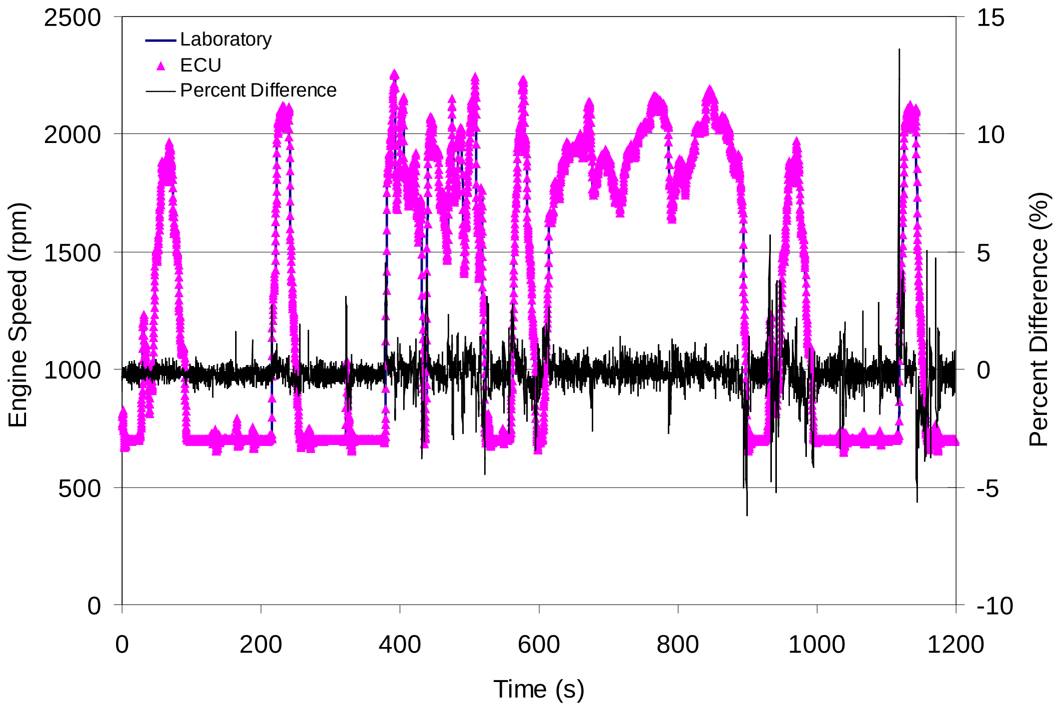


Figure 35 Comparison between measured laboratory and ECU broadcast engine speed for a Cummins ISM-370 engine exercised through the FTP cycle.

5.2.4 ECU Torque Estimate

The percent load generally varies from 0 (no fueling, friction load) to 100 (maximum torque) at a given engine speed, although there are provisions for the percent load to exceed 100%. It is recognized that torque, and hence percent load, will vary with engine operating temperature and that all work should be conducted at normal (hot) engine operating conditions. It is also recognized that the ECU-derived torque is engine total output torque and not merely the flywheel torque that is used for US-EPA certification tests. To arrive at an accurate estimate of engine output torque at a given engine speed, the lug curve (100% load) must be combined with either the friction torque (zero fueling) curve or the zero flywheel (zero output shaft load) percent load curve. The current approach involves measuring the no-load percent load (ECU_{noload}) through the speed domain at the curb and employing the lug curve (T_{max}) provided by the S-HDDE manufacturer. The resulting engine torque (T^{rpm}) at a given engine speed and percent load ($ECU^{rpm}_{\%}$) was obtained by

$$T^{rpm} = \left(\frac{ECU^{rpm}_{\%} - ECU^{rpm}_{noload}}{ECU^{rpm}_{\%\max} - ECU^{rpm}_{noload}} \right) * T^{rpm}_{\max} . \qquad (3)$$

It is stressed that the above equation is a function of engine speed, as indicated by the superscript “rpm,” for each of the parameters. Equation (3) assumes that the internal friction load is a function of speed only. However, friction load is also dependent upon the absolute engine load. Hence, the above relationship will overestimate the actual load.

A composite shaft torque and ECU percent load chart for a Navistar T444E engine is shown in Figure 36. The no-load percent load (P1) varies as a function engine speed, while the output torque (T1) is constant. For the lug curve, the percent load (P2) is constant at 100% up to approximately 2670 rpm while the torque (T2) varies throughout the speed domain. At engine speeds above 2670 rpm, the percent load drops sharply from 100% down to the no-load percent load level. The lower NTE torque limit is also illustrated in this figure for the percent load (P3) and torque (T3). A Mack E7 engine tested at WVU showed a similar torque-percent load relationship over the speed domain at no-load conditions and along the lower NTE curve, and the lug curve. However, a Cummins ISM-370 engine tested at WVU displayed a somewhat different no-load and lug curve percent load as shown in Figure 37. For the ISM-370, the lug curve percent load (P2) is 100% across the speed domain. However, the no-load percent load (P1) is 0% up to 2000 rpm and then steadily increases to approximately 22% thereafter. The lower NTE curve percent load (P3) mirrors the no-load percent load curve. Figure 36 and Figure 37 indicate that the implementation of the percent load definition differs from one manufacturer to another.

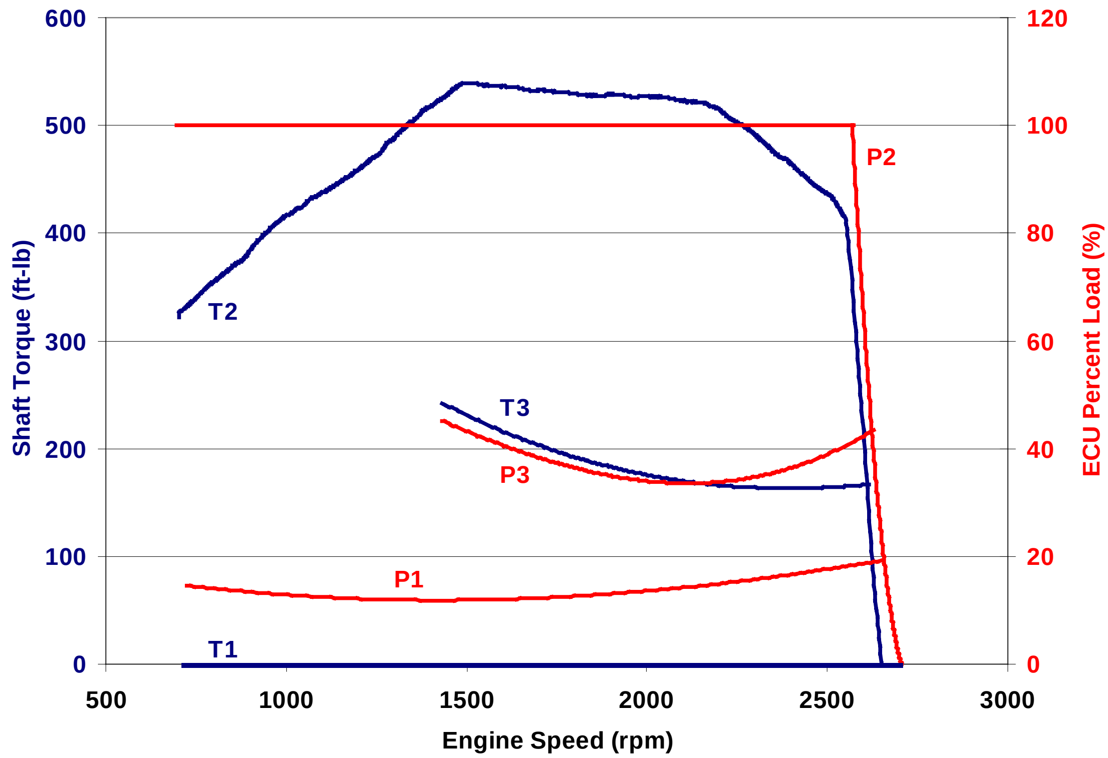


Figure 36 Shaft torque and ECU percent load variation for a Navistar T444E.

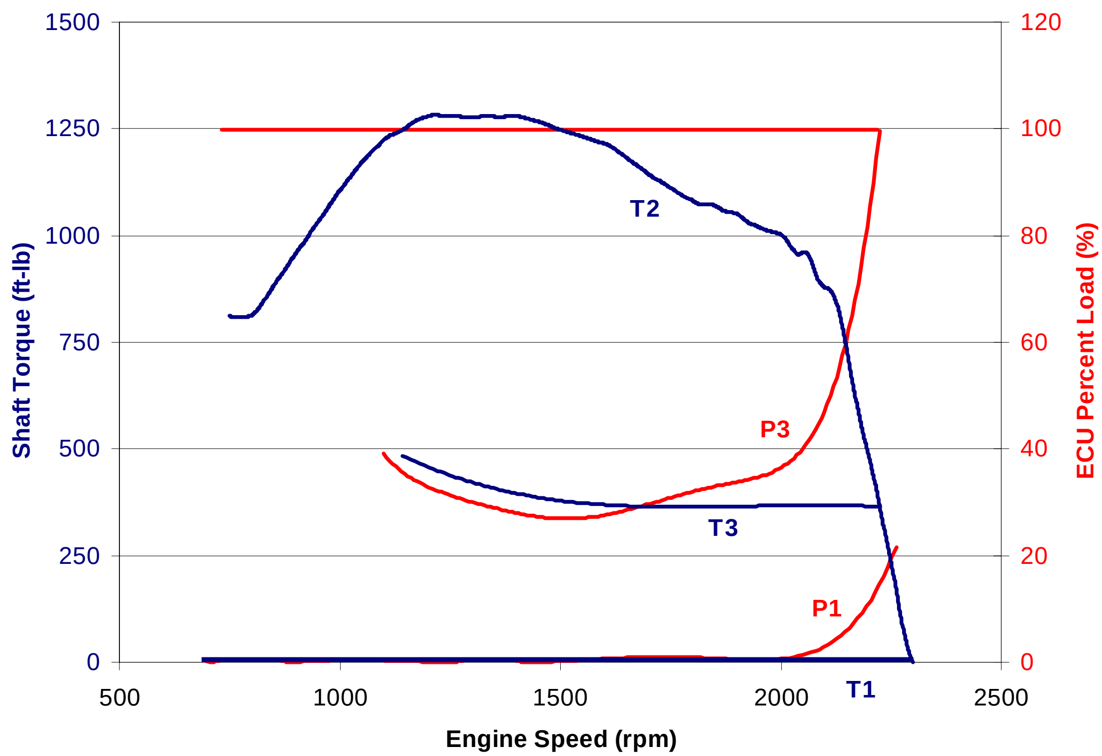


Figure 37 Shaft torque and ECU percent load variation for a Cummins ISM-370.

The accuracy of the torque inferred from ECU data is limited by three parameters: the no-load percent load, the measured percent load value, and the lug curve. Figure 38 illustrates the error in the torque when the no-load (ECU_{noload}) percent load in Equation (3) is assumed to be 14%. The family of curves shows the error in the estimated torque value as a function of the actual no-load percent load deviation above or below the assumed/measured value. At low load conditions the error is greatest and asymptotically approaches zero at 100% load conditions. For example, an error of one percentage point (±1) in the no-load ECU load reading will result in a 4% error in the torque estimation at a 33% ECU percent load measurement. Likewise, a two percentage point error will result in an 8% error at the same point.

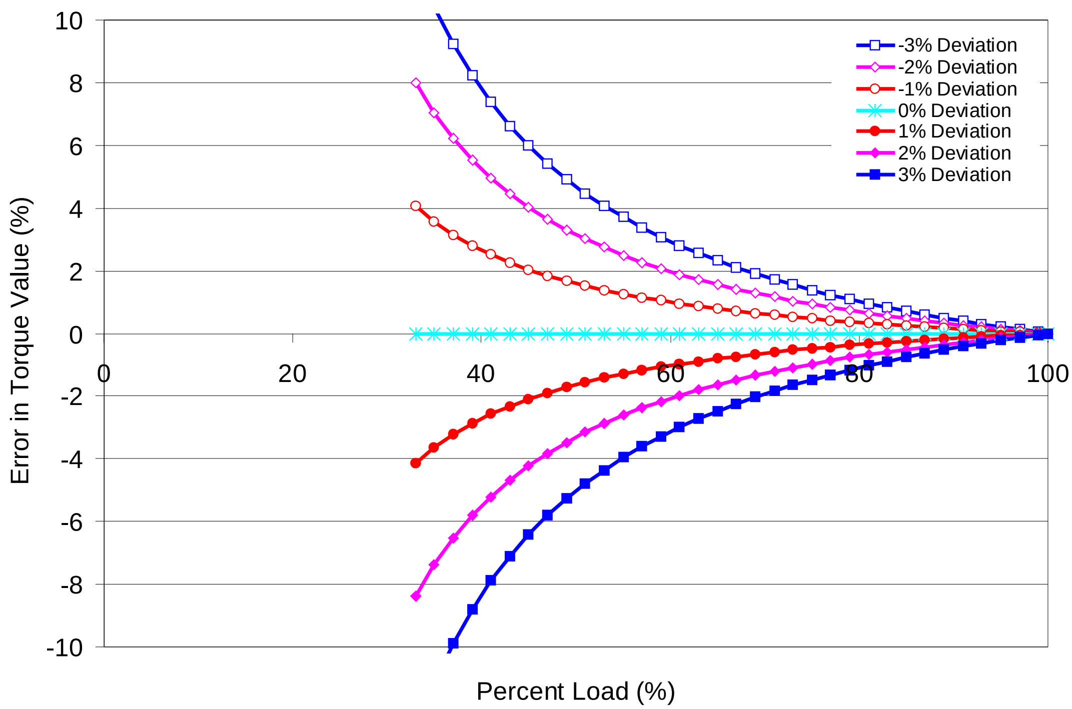


Figure 38 Error in torque due to error in no-load ECU load reading.

Figure 39 illustrates the error in torque determination resulting from various errors in the percent load. The family of curves shows the error if the measured percent load is above or below the measured value. At low load conditions the error is greatest and asymptotically approaches a minima at 100% load conditions. An error of one percentage point (±1) in the measured ECU load reading will result in a 5.3% error in the torque estimation at a nominal 33% ECU percent load measurement.

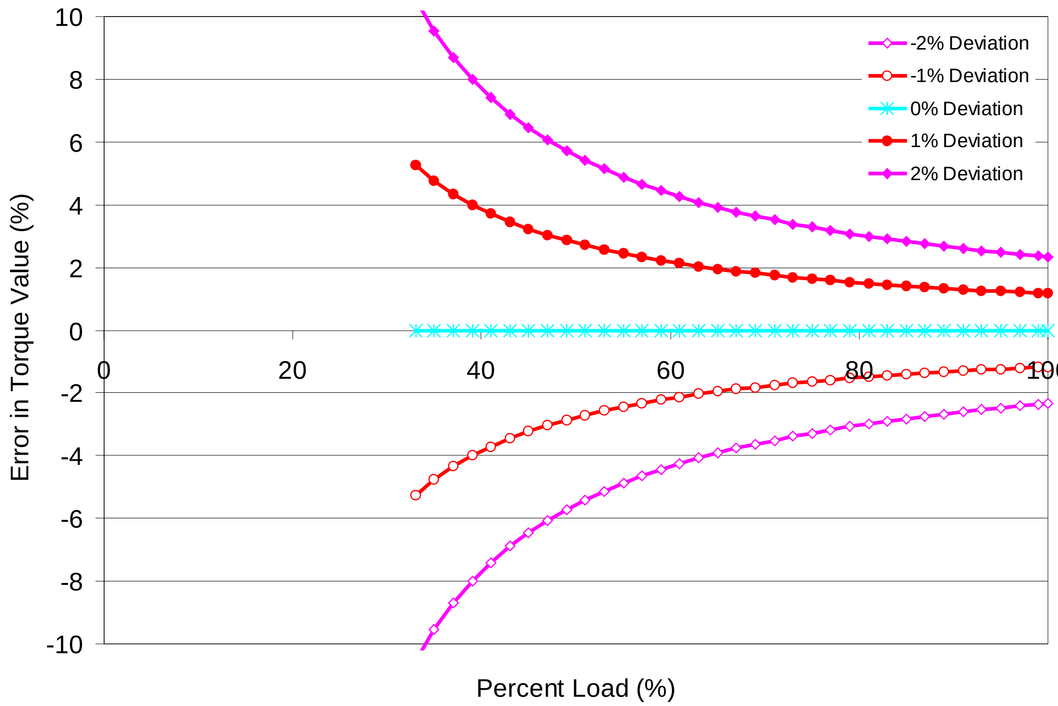


Figure 39 Error in torque due to error in measured percent load.

The third parameter that contributes to an error in inferring torque, via the ECU broadcast percent load data, is the lug curve provided to the OREMS user. As shown in Equation (3), the ECU torque is directly proportional to the value of torque from the lug curve. For purpose of in-use testing, the lug curve will be obtained from the manufacturer for a typical production engine. It is not known how a typical HDDE lug curve will deviate from engine to engine or due to component deterioration over time. However, for the Cummins engine shown in Figure 37, the difference in the lug curve as measured at WVU and as reported by Cummins for a typical ISM-370 is shown in Table 10. As illustrated in this table, the average difference is –3.9%. It is noted that the Cummins ISM-370 engine tested at WVU was being used for other research at the time the testing occurred; the fuel used had properties similar to pump fuel. It is recognized that factors such as atmospheric conditions, injector wear, and intake and exhaust restrictions (all within prescribed testing regulations) will also contribute to differences in full-load torque.

The overall error associated with inference of load from the ECU broadcast percent load and engine speed for the Cummins ISM-370, exercised through the FTP cycle, is illustrated in Figure 40, Figure 41, and Figure 42. The Cummins supplied data and WVU measured data as labeled in the figures are from the lug curve listed in Table 10 and also in Figure 37. As shown in these figures, there is a discrepancy between the inferred and measured power. Generally, the power inferred from the ECU is greater than the laboratory reported power. This is also borne out in Figure 41 where the 30 second integrated power is higher for the ECU derived values compared to the laboratory values.

Table 10 Lug curve comparison between WVU and Cummins for a Cummins ISM-370.

Engine Speed (rpm)	Cummins Reported (ft-lb)	WVU Measured (ft-lb)	Percent Difference (%)
700	840	811	-3.5
800	871	820	-5.8
900	996	974	-2.2
1000	1160	1122	-3.3
1100	1285	1235	-3.9
1200	1350	1282	-5.0
1300	1350	1280	-5.2
1400	1350	1279	-5.3
1500	1307	1245	-4.7
1600	1264	1212	-4.2
1700	1189	1135	-4.6
1800	1123	1071	-4.6
1900	1057	1043	-1.3
2000	991	990	-0.1
2100	925	876	-5.3

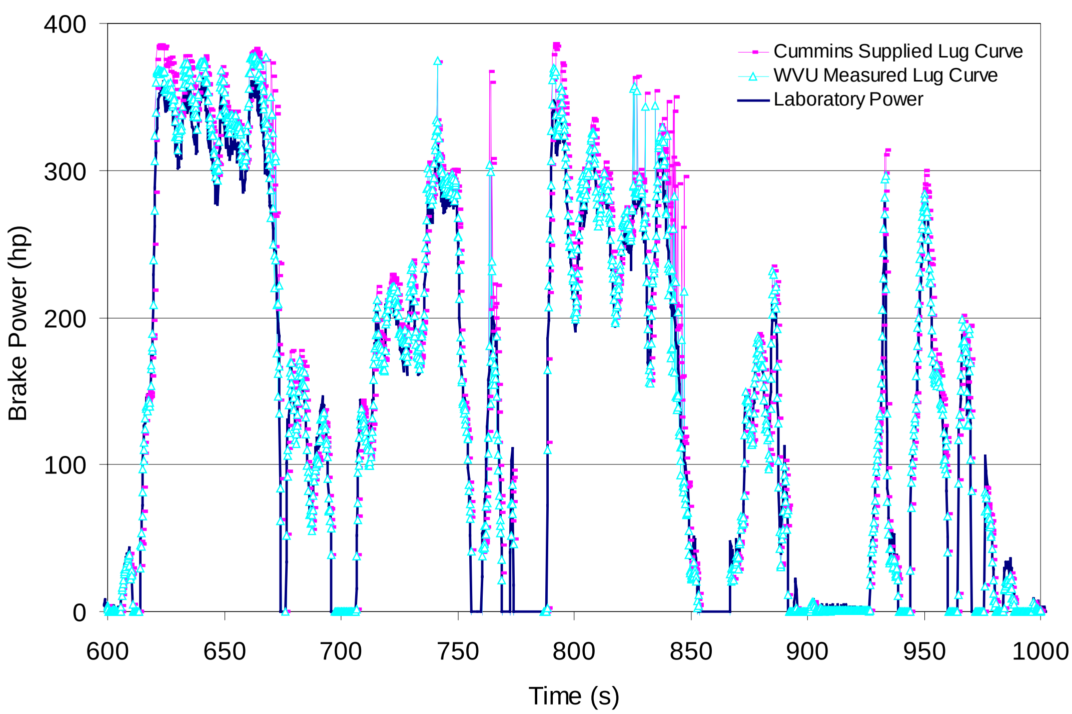


Figure 40 Instantaneous brake power comparison between laboratory and ECU inferred data for a Cummins ISM-370 engine exercised through the FTP cycle from 600 to 1000 seconds.

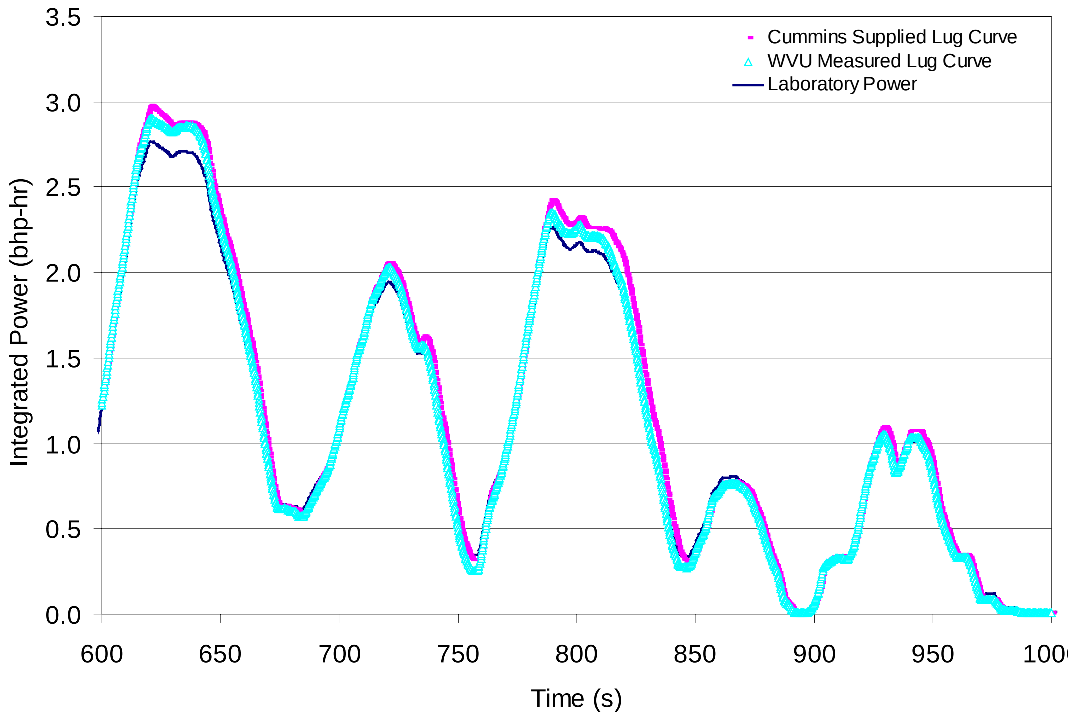


Figure 41 Integrated 30 second brake power windows between laboratory and ECU inferred data for a Cummins ISM-370 engine exercised through the FTP cycle from 600 to 1000 seconds.

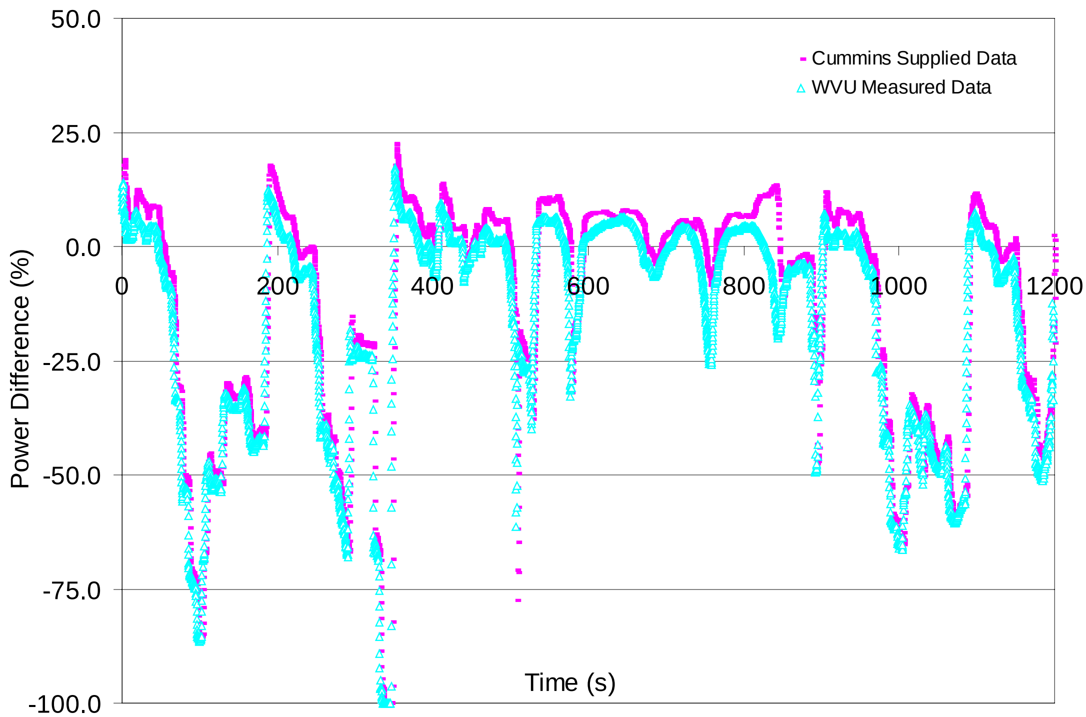


Figure 42 Integrated 30 second brake power windows percent difference between laboratory and ECU inferred data for a Cummins ISM-370 engine exercised through the FTP cycle.

As illustrated in the above figures, errors will become significantly greater outside the NTE zone. Within the NTE zone, the error in the inferred power, via the ECU percent load broadcast, is of the order of 10% for a 30 second window. Merely using a larger window can reduce this error. For example, in the limiting case of integrating the entire 1200 seconds, there is a 1% difference between ECU and laboratory integrated brake power when using the measured lug curve, and a 5% difference when using the lug curve supplied by Cummins.

5.2.5 Manufacturer's ECU Protocol Usage

Only engines with a SAE J1587 or J1939 interface can be tested for the Consent Decrees work due to the availability of the percent load signal from the ECU. As illustrated in the tables below, not all manufacturers' post 1988 model years can be tested per Consent Decrees requirements. The nomenclature used in Table 11 to Table 15 is as follows: A=SAE J1922, B=SAE J1587, C=SAE J1939. As illustrated in the tables, the earliest engine from Cummins that can be tested is a model year (MY) 1991; Caterpillar MY 1991, but may be difficult to find an engine until MY 1994; Volvo MY 1994; Mack MY 1995; and Detroit Diesel 1994.

Table 11 Cummins Engine Corporation protocol usage chart (A: SAE J1922, B: SAE J1587, C: SAE J1939).

	Engine								
Model Year	L10	M11	N14	Sig600	ISX	ISL	ISM	ISC	ISB
1988									
1989									
1990									
1991	A, B		A, B						
1992	A, B		A, B						
1993	A, B		A, B						
1994		A, B	A, B						
1995		A, B, C	A, B, C						
1996		A, B, C	A, B, C						
1997		A, B, C	A, B, C						
1998		A, B, C	A, B, C	B, C			B, C	B, C	B, C
1999		A, B, C	A, B, C	B, C	B, C	B, C	B, C	B, C	B, C
2000		A, B, C	A, B, C	B, C	B, C	B, C	B, C	B, C	B, C
2001		A, B, C	A, B, C	B, C	B, C	B, C	B, C	B, C	B, C
2002									
2003									

Table 12 Caterpillar, Inc. protocol usage chart (A: SAE J1922, B: SAE J1587, C: SAE J1939).

	Engine		
Model Year	3406	3176/C-10/ C-12	3100
1988*	B		
1989*	B	B	
1990*	B	B	
1991*	A, B	A, B	
1992*	A, B	A, B	
1993*	A, B	A, B	
1994	A, B	A, B	
1995	A, B	A, B	B
1996	A, B	A, B	B
1997	A, B	A, B	B
1998	A, B	A, B	B
1999**	A, B, C	A, B, C	B, C
2000**	A, B, C	A, B, C	B, C
2001**	A, B, C	A, B, C	B, C
2002**	A, B, C	A, B, C	B, C
2003**	A, B, C	A, B, C	B, C

* Sold mostly mechanical engines in this time period.

** GM chassis did not have the J1939 data link, non-GM did (3100 only).

J1587 has been installed in all electronic engines and chassis. J1922 and J1939 are in the ECU but not always used in the trucks.

Table 13 Volvo Truck Company protocol usage chart (B: SAE J1587, C: SAE J1939).

	Engine	
Model Year	12l	7l
1988*		
1989*		
1990*		
1991*		
1992*		
1993*		
1994	B	
1995	B	
1996	B	
1997	B	
1998	B, C	B, C
1999	B, C	B, C
2000	B, C	B, C
2001	B, C	B, C
2002	B, C	B, C
2003	B, C	B, C

* Sold only mechanical engines in this time period.

Table 14 Mack Trucks Inc. protocol usage chart (B: SAE J1587, C: SAE J1939).

	Engine Controller		
Model Year	V-Mac I(1)	V-Mac II	V-Mac III
1988	X		
1989	X		
1990	X		
1991	X		
1992	X		
1993	X		
1994	X		
1995		B	
1996		B	
1997		B	
1998		B	
1999			B, C
2000			B, C
2001			B, C
2002			B, C
2003			B, C

(1) V-Mac I did not include a percent load signal and cannot be used.

Table 15 Detroit Diesel Corporation protocol usage chart (A: SAE J1922, B: SAE J1587, C: SAE J1939).

	Engine Controller			
Model Year	*On-Highway DDEC® II*	*On-Highway DDEC® III*	*On-Highway DDEC® IV*	*On-Highway DDEC® V*
1988*	B			
1989*	B			
1990*	A, B			
1991*	A, B			
1992*	A, B			
1993*	A, B	A, B, C		
1994		A, B, C		
1995		A, B, C		
1996		A, B, C		
1997		A, B, C	A, B, C	
1998			A, B, C	
1999			A, B, C	
2000			A, B, C	
2001			A, B, C	
2002			A, B, C	B, C
2003				B, C

* Calibration of torque output signal not institutionalized prior to 1994. Prior years cannot be used.

5.3 Gaseous Emissions Analyzers

Throughout the study, WVU has maintained that portability and minimal power consumption were the key considerations concerning the selection of candidate emissions analyzers for the MEMS. Hence, laboratory-grade analyzers, as well as gas chromatographs and Fourier transform infrared spectroscopes, were not considered to be viable options. Similarly, "miniaturized" heated flame ionization detectors and chemiluminescent devices were not considered due to their complexity and lack of necessary robustness.

The MEMS must utilize an emissions measurement technique that is extremely robust and resistant to any problems associated with on-road vehicle operation. In addition, the device must be compact, and should provide for maximum detection range flexibility. Paramount to these qualities would be the ability of the unit to provide measurements at the highest possible accuracy, with the fastest possible response time, and the best possible resolution. Also, the MEMS should be capable of recording data at 5 Hz, per the requirements of the Consent Decrees.

Although laboratory-grade emissions measurement devices provide for the highest possible accuracy, such components are not well suited for implementation into the MEMS. Vibrations associated with the transport as well as on-board operations tend to qualify only solid-state or chemical-based detection schemes. The use of Luft-type detectors for an NDIR device can provide improved accuracy, but these units have poor resistance to vibration. Solid-state detection schemes provide acceptable accuracy and, by nature, are basically impervious to any vibration problems. Moreover, the system complexity necessary for the accommodation of laboratory-based analyzers prohibit the portability that is imperative to the MEMS. Finally, the implementation of the necessary fuel and operation gases required by devices such as flame ionization detectors and chemiluminescent detectors would significantly limit system flexibility, portability, and compromise on-board operational safety of the MEMS.

Since similar measurement schemes are employed, CO and CO_2 measurements should be comparable between the microbenches and the laboratory-grade instruments. However, there are no established correlations for hydrocarbon measurements made with the NDIR detectors and the HFID. Moreover, THC determination from diesel engines cannot be made with NDIR detectors. NDIR-based HC determination is very spectral sensitive, therefore multiple HC bands may need to be considered. Similarly, there are no established correlations for diesel exhaust measurements using NDIR or electrochemical detection of NO and total NOx using chemiluminescent analyzers. Moreover, sensor-to-sensor variability in accuracy, unit life, pressure sensitivity, drift, and response times for electrochemical sensors pose a serious problem in the development of the MEMS. The specific evaluation of the emissions measurement devices that represent currently-available technology is presented herein.

At the onset of the project, WVU secured four multi-gas microbenches in order to evaluate their performance and feasibility as MEMS components. As a result of the emissions measurement industry survey, the following four manufacturers were chosen: Siemens, Andros, Horiba Instruments, and Sensors, Inc. Although other systems are available, many are simply units that have been sourced from one of the above manufacturers. Moreover, in discussing the general OREMS concept with various field experts, these manufacturers were consistently earmarked as the most reputable. In order to document information concerning the specifics of each analyzer, and the subsequent selection criteria, the following overview has been provided.

In order to provide a thorough comparison of the various emissions measurement devices (microbenches) WVU proposed to divide the testing into four target areas: gas bottle tests, engine dynamometer tests, vehicles chassis-dynamometer tests, and on-road emissions measurement tests. For this battery of tests, the measurements made with the microbenches were compared to measurements made with common industry-accepted measurement devices, that is non-dispersive infrared determination of CO/CO_2, wet chemiluminescent determination of NOx, and heated flame ionization detection of total hydrocarbons.

5.3.1 Andros

An Andros 6800 multi-gas analyzer was secured by WVU. The unit is an NDIR-based device that uses fixed, non-scanning infrared light frequencies to characterize HC, CO, and CO_2 gas concentrations and electrochemical cells to determine O_2 and NO concentrations. A current-regulated infrared source, modulated at 1 Hz, provides a photon stream in the range of 2 to 5 microns through the sample cell and onto the optical block (detector). The source temperature is monitored and compensation is made in order to ensure that the infrared light is maintained within the specified frequency. An optical beam splitter divides the source beam into four discrete paths, one for each of the three constituent gas detectors and one for use as a reference value. The sample cells are constructed of gold-coated glass, and a microprocessor-controlled transducer and thermistor provide measurement compensation for sample gas temperature and pressure variances. The optical block receives the light energy that has been attenuated through energy absorption by the sample gas. Optical band pass filters are positioned between the sample cell and the detector block in order to increase resolution and minimize interference effects. The detector block itself consists of a thermopile window and collector and a detector substrate. The substrate has a light-sensitive coating, which produces a voltage that is proportional to light intensity. The output of the constituent gas detector blocks is compared with the output from the reference beam optical block in order to compensate for variations of the infrared source.

5.3.2 Horiba

WVU received a Horiba Instruments BE 140 Multigas bench and a BE 220 NO bench for evaluation purposes. The BE 140 is an NDIR device that utilizes solid-state infrared detectors. The detectors are dual, precision pyroelectric units, which incorporate built-in field-effect transistor (FET), in the detector enclosure. These detectors virtually eliminate the effects of thermal transients on the measurements by exposing only one of the two elements of each detector to the modulated light path, that is automatically compensating for common-mode temperature effects. The detectors also exhibit a high-level, low-noise signal over relatively wide temperature fluctuations. Four of these detectors are employed by the instrument, one for a reference path, and one for each of the three constituent gases. Broadband radiation is passed through the sample cell, and then sequentially onto each of the four detectors using a mechanical chopper. The BE 220 is an NDIR bench that uses a Luft-type detector, where diaphragm capacitance is used to deduce the absorption of infrared energy. Horiba has expressed limited concern with the vibration-resistance of the Luft detector. The unit presented by Horiba was a prototype, and little documentation was included regarding operating procedures.

A Horiba MEXA 120 Zirconium Oxide NOx detection system was investigated due to its robust characteristics. The sensor utilizes a ceramic material, ZrO_2, to determine the amount of NOx in a sample stream. The unit consists of two internal cavities. The first cavity receives the sample gas through the first diffusion path. At this point, the oxygen present in the sample is pumped out in order to insure a low oxygen concentration within the cavity. The sample stream then migrates to the second internal cavity, where the oxygen concentration is lower than it is in the first cavity. The sensor is heated to approximately 900°F to allow for the migration of the oxygen ions through the zirconium oxide material. The sample is then dissociated into nitrogen and oxygen. The oxygen generated in this reaction is then pumped out of this second cavity. The current generated by the removal of the oxygen is used to determine the NO concentration. Horiba has expressed concern that the MEXA 120 sensor is sensitive to ammonia, NH_4. However, ammonia is not a significant constituent of diesel exhaust, so it is not a main concern in developing an OREMS. It is assumed that even as SCR-Urea systems are adopted for exhaust aftertreatment, ammonia breakthrough will be low. Moisture in the sample stream is certainly a concern. If a large amount of water exists in the sample stream, then any moisture collected in the sensor could cause the ceramic material to cool rapidly and crack. By utilizing the thermoelectric chiller, an OREMS should be able to avoid this problem. The unit is capable of measuring NOx concentrations, in exhaust gas streams, ranging from 0 to 5000 ppm. Although the sensor permits direct installation into the engine exhaust system, this in-situ technique was not utilized due to particulate matter fouling concerns. WVU opted to design a manifold system and sample a slip-stream from the engine exhaust, in order to provide for increased sensor life as well as a more-direct integration into the current MEMS set-up.

5.3.3 Sensors

The Sensors, Inc. AMBII microbench is a 5-gas NDIR-based unit that relies upon solid-state detection devices. In theory, a single waveband within the infrared spectrum is selected for each gas to measure where its absorption is known to be substantial and where no other background gas absorbs significantly. Optical band pass filters, which transmit electromagnetic energies only within the waveband, are placed before the thermocouple detector. The effects of absorption spectrum overlap are accounted for by way of optical band pass filtering. This also increases resolution. When the sample cell is filled with sample gas, the IR detector measures the resultant reduction of transmitted IR energy within the waveband of each gas. The bench-mounted microprocessor compensates for temperature and pressure variation in the sample stream as well as variation in the infrared source. Gases that might have an absorption spectrum overlapping that of CO_2 are known *a priori* to be absent.

5.3.4 Siemens

The Siemens SIBENCH uses NDIR measurement techniques in order to quantify constituent gas concentrations by employing optopneumatic double layer detectors. Infrared radiation is emitted from a transmitter coil, which is heated to approximately 600°C. A diaphragm wheel (chopper) modulates the radiation, which passes on through the sampling stream. The sampling stream is comprised of an analysis chamber and a double layer detection chamber. Sample gas is used to fill the analysis chamber, and this media absorbs energy from the radiation source. The double layer detector chamber operates in a manner similar to those employed by “laboratory grade” analyzers. The sample stream is comprised of a detection cell that is mounted downstream of the sample gas cell. The detection cell is subdivided into two chambers. A pressure imbalance is measured by a microflow sensor and is correlated to the concentration of candidate gas levels in the sample cell. The imbalance results from the characteristically larger amount of absorption energy correspondent to the heavily absorbent “centered” wavelengths for a particular gas. If the candidate gas were present in the sample cell, IR radiation of the band-center wavelength would be absorbed. In such a case, the front chamber of the detection cell would absorb most of the “centered” bandwidth energy, leaving only the “fringe” wavelengths to be absorbed by the rear chamber. These detection cells are removable, resulting in a high level of measurement selectivity. This is very important to an OREMS device for use with heavy-duty diesel vehicles, since the broad hydrocarbon emission spectrum may be accounted for more directly. This measurement technique also prevents the band overlap interference caused by coexistent gas species that tends to be problematic with single layer or solid-state detectors. In addition, the technique innately compensates for changes in the infrared source, long-time drift, and sample cell contamination by zeroing the system (transmitter, analysis cell, detector, microflow sensor, and pre-amplifier) in its entirety. During every balancing (zeroing) operation, a system check is automatically made that ensures that full detection sensitivity.

Preliminary testing of the Siemens SIBENCH was encountered with countless problems associated with the manufacturer’s software. The second-generation OREMS device (ROVER II) from the US-EPA is scheduled to use a SUN DGA 1000, which relies on a Siemens Sibench for measurement of exhaust gas concentrations. Since ROVER II is intended to supercede the ROVER that was tested in this report, evaluation of a SIBENCH, or equivalently a SUN DGA

1000, was deemed crucial to the project. WVU purchased a DGA 1000 and attempted to evaluate the product. Measurement accuracy of the device was drastically affected by the analyzer's orientation, and the unit exhibited an inability to sample continuously for the required test time, due to an auto-zero feature that could not be disabled according to the manufacturer, for the work presented herein. As a result, it was determined that the current version of the SIBENCH was not suitable for implementation into an OREMS application.

5.3.5 HC Discussion/Conclusions

Current microbench technology employs NDIR detection of HC, exclusively. These units were designed to measure HC concentrations at levels typical of gasoline engines. Not only do diesel engines produce lower concentrations of THC than do their gasoline counterparts, but, more importantly, the spectrum differs significantly. NDIR devices provide adequate detection of most HC species produced by gasoline engines, but are very ineffective at accurately measuring all the species encountered in diesel exhaust streams (see Table 16).

Secondary to the inherent measurement errors associated with NDIR detection of HC are the sampling system problems that arise as a result of heavy-ended HC condensation issues. A large percentage of the hydrocarbons in diesel engine exhaust condense out at temperatures higher than the microbenches can tolerate. HC hang-up within the sampling system causes incorrect and unpredictable measurements, particularly if the analyzer's sample cell serves as a primary location for HC condensation. Unstable sample-stream temperatures will also result in vaporization of condensed species, which greatly skews the HC measurements related to transient emissions events. WVU recommends that an OREMS incorporates a thermoelectric chiller to remove most of the moisture from the sample stream. This device provides far superior reproduction of sample stream humidity control as compared to the simple water traps employed by repair-grade systems. In addition its usage greatly reduces buildup of hydrocarbons in the sampling stream, particularly in the analyzers, because the peristaltic pump removes most condensed hydrocarbons.

As a result of the two preceding paragraphs it is recommended that an OREMS not use NDIR detection of HC. Improvements in NDIR determination of HC could be realized if analyzers were capable of operating at elevated temperatures (a minimum of 375°F), but only through the adaptation of a mobile HFID would an OREMS be capable of providing an adequate correlation to HC data collected by laboratory-grade instruments. However, implementation of an HFID would significantly add to system complexity, and hence limit portability. Moreover safety issues associated with the carriage of necessary HFID burner fuel becomes a concern.

Table 16 NDIR vs. FID response to HC species [27].

Hydrocarbon	NDIR Response (Hexane=100)	FID Response (Hexane=100)
Paraffins		
Methane	30	104
Ethane	100	103
Propane	103	103
N-Butane	106	102
N-Pentane	104	102
N-Hexane	100	100
N-Heptane	97	100
Olefins		
Ethylene	9	104
Propylene	31	104
1-Butene	53	-
Acetylenes		
Acetylene	1	95
Methylacetylene	16	96
Ethylacetylene	32	96
Aromatics		
Benzene	2	105
Toluene	13	105

5.3.6 CO Discussion/Conclusions

Similar to their laboratory-grade counterparts, all of the microbenches that were evaluated employed NDIR techniques to measure CO emissions. However, poor measurement resolution at the low CO concentrations encountered in diesel exhaust, presented a problem. All of the currently available microbenches were designed to measure higher-level CO emissions, such as those typically produced from gasoline engines. The CO emissions from a diesel engine are much lower, resulting in large-scale emissions reporting errors.

5.3.7 Known Gas Bottle Tests

The first step in the performance evaluation of the four microbenches was to perform tests using known gas bottle concentrations. Each microbench was tested on various concentrations and blends of the candidate gases. A gas divider was used to provide concentrations from 10 to 100% of a component gas diluted with N_2. Differences between single- and multiple-point calibrations were investigated, where applicable, and water interference and orientation bias tests were performed. Spot checks were conducted with NIST traceable reference gases (NTRM's)

No testing was performed on the Andros 6800, due to complete unit failure. A replacement unit was not provided until January 2000, therefore further testing of the Andros unit was cancelled. WVU found the NO measurements to be very inaccurate on the Siemens SIBENCH. The bench exhibited dramatic orientation bias, likely due to temperature effects on the infrared source, and was very susceptible to vibration. WVU attempted to improve measurements by implementing shielding and vibration-isolation techniques. However, continued testing of the Siemens bench was cancelled due to numerous operation problems associated with the provided software. The second generation ROVER was to incorporate a Sun DGA1000 multigas analyzer, which uses the Siemens microbench. As discussed in Section 5.3.4, in an effort to facilitate a more thorough investigation of current emissions measurement devices, WVU purchased a Sun DGA1000. Preliminary laboratory and in-field testing resulted in termination of subsequent tests due to the inability to disable the auto-zero function. In light of the above findings, the Andros and Siemens benches were no longer considered by WVU as viable OREMS components.

The Horiba BE 220 and MEXA 120 units exhibited superior transient response, compared to the electrochemical cell measurements produced by the Sensors, Inc. AMBII and the Snap-On MT3505, employed by ROVER. The original BE 220 prototype exhibited substantial oscillations at steady gas concentrations, however an updated version showed improved stability. Accuracy, repeatability, and resistance to orientation bias of the Horiba BE 140, Horiba BE 220, Sensors AMBII, Horiba MEXA 120 and ROVER units were considered acceptable for an OREMS.

5.3.8 Response Times

Transient exhaust emissions measurements can be compromised by delays in the sampling system and because of distortion introduced by the analyzer's dynamics. While delays can easily be estimated and recovered off line, amplitude and phase distortion due to analyzer dynamics require attention. In order to qualify manufacturer's advertised response times, a test bed was developed (see Figure 43) to produce oscillations of analyzer input streams between a zero and span value. A sample bleed vent was positioned between a three-way solenoid valve and the analyzer input to prevent over-pressurizing units that incorporated built-in pumps. For each test it was verified that the device input flow rate was maintained per manufacturer's specifications. Time response characteristics of the various devices tested are presented in Figure 44 through Figure 50, for varying step input frequencies.

5.3.8.1 Horiba BE 140

Tests were conducted on the Horiba BE 140 microbench analyzer using a 15.0% volume CO_2 gas bottle. As described previously, the bench uses NDIR detection for CO_2. The results of this test are shown in Figure 44. The analyzer tends to overshoot the span value at the beginning of the test, but appears to be consistent for each of the step inputs throughout the test. It can be determined from the steady state pulse that the Horiba BE 140 has a T_{90} of approximately 5 seconds.

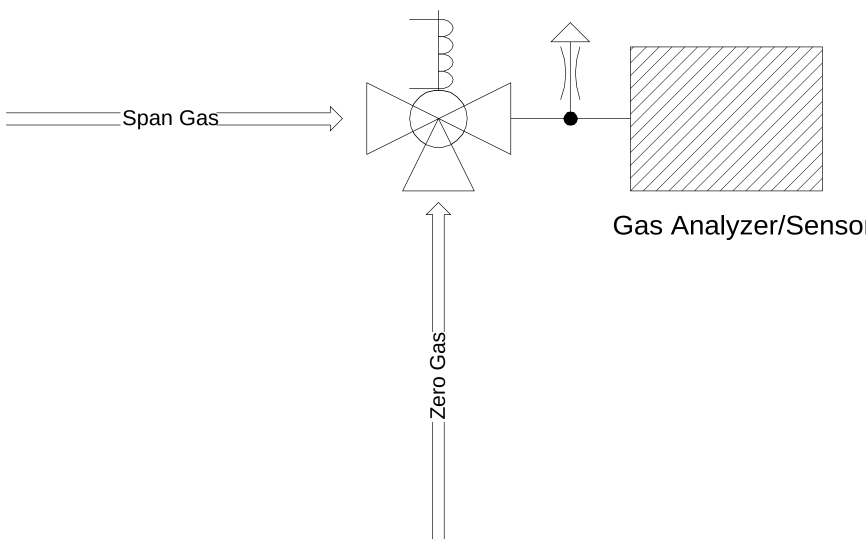


Figure 43 Test apparatus for analyzer/sensor response time evaluations.

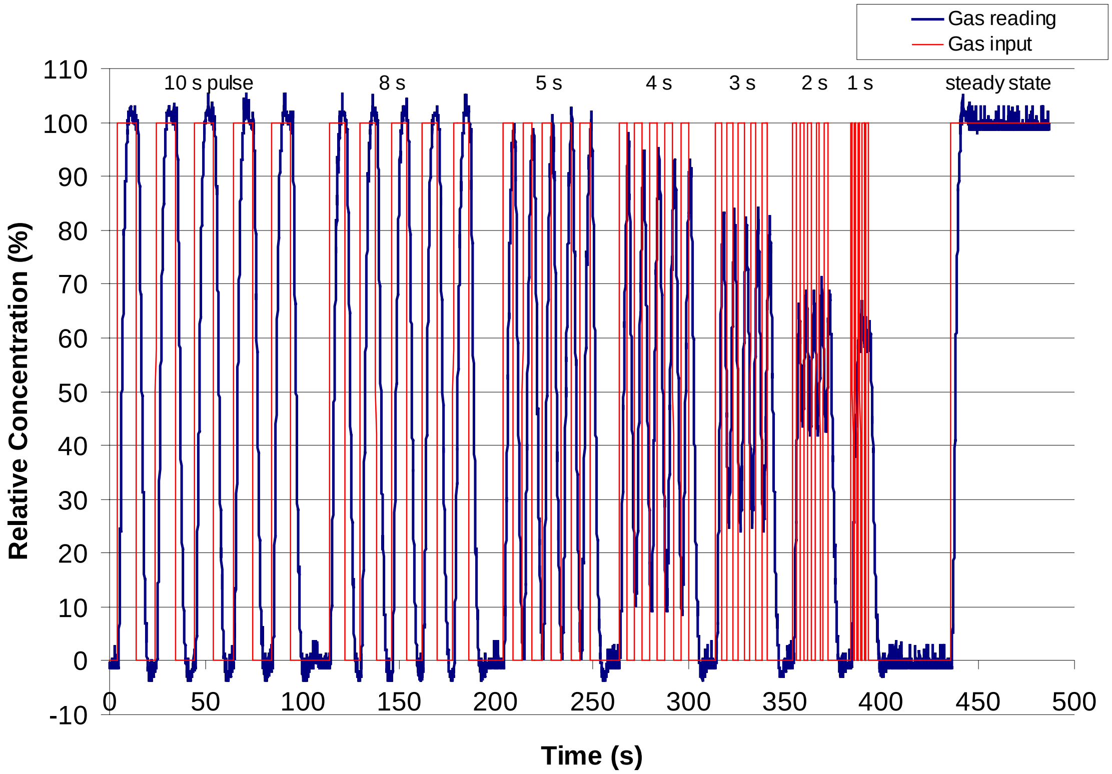


Figure 44 15.00% CO_2 step input test on the Horiba BE 140.

5.3.8.2 ROVER (Snap-On MT3505)

Gas analyzer calibration and response time tests on the ROVER were conducted with the gases specified by the US-EPA. The response time of the ROVER unit, which uses an electrochemical NO cell, was determined using a 4000 ppm NO gas bottle. The response time for CO_2, as measured by ROVER, was determined using a 12.1% gas bottle. As seen in Figure 45, the NO concentration never reaches the actual value of the gas flowing through it within the 10-second pulse at the beginning of the test series. The analyzer reading worsens as the test progresses. The T_{90} was determined to be 14.5 seconds from the graph with the actual gas value of 4000 ppm NO never achieved on the steady state test in the time allowed. The CO_2 measurements followed the step inputs much better than the NO measurements. The T_{90} for ROVER CO_2 was determined to be approximately 6 seconds. Results of the CO_2 step inputs are shown in Figure 46.

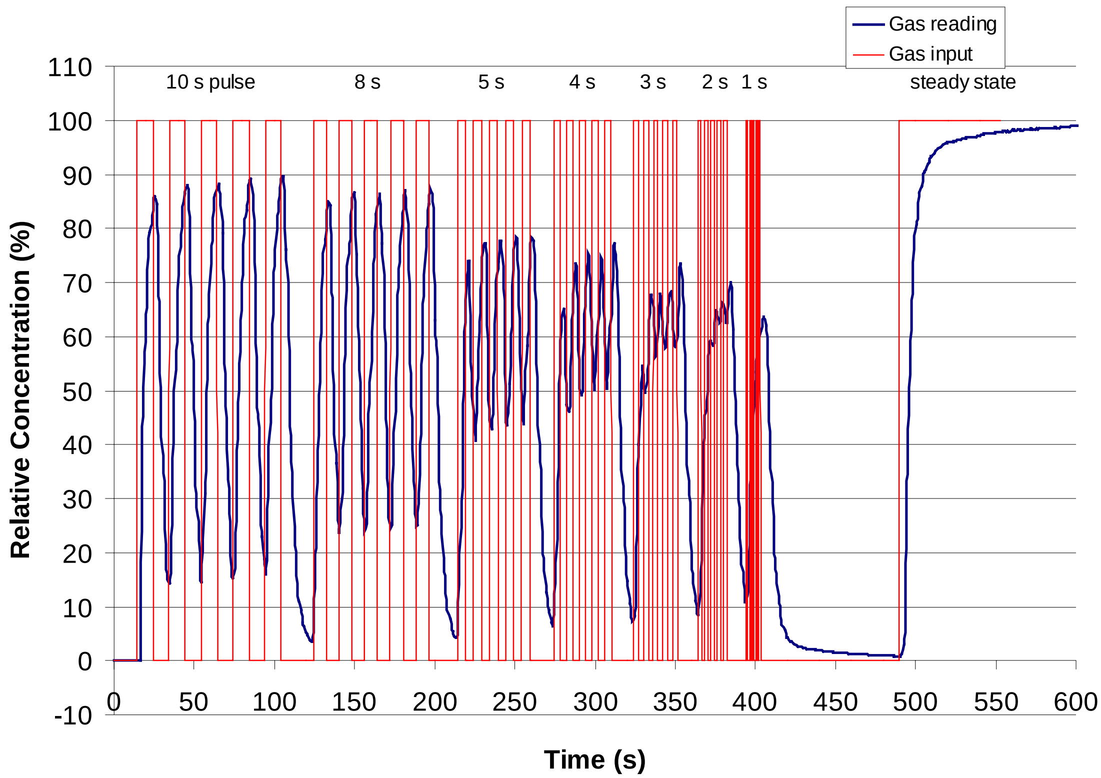


Figure 45 4000 ppm NO step input test on ROVER.

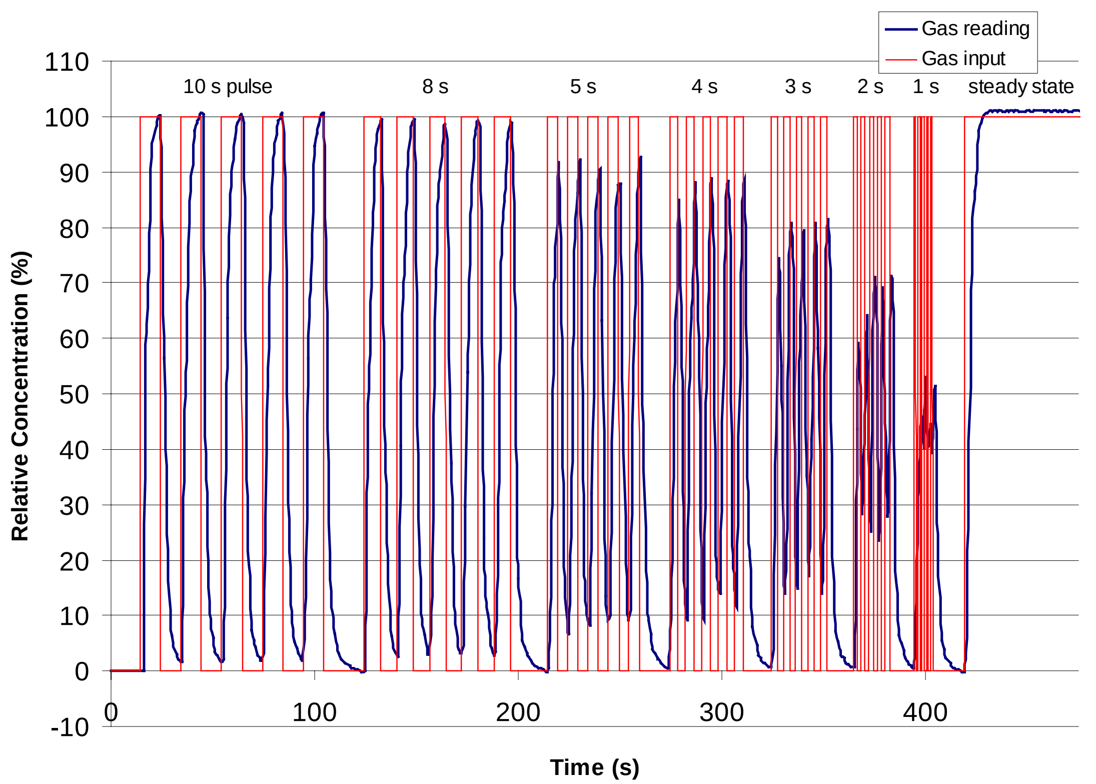


Figure 46 12.1% CO_2 step input on ROVER.

5.3.8.3 Sensors AMBII

The Sensors unit uses an electrochemical cell for NO detection and a NDIR solid-state detector for CO_2 concentrations. Step response experiments were conducted on the Sensors AMBII for both gases. The results for the test using 30.0% CO_2 are shown in Figure 47 while the results for the test using 4490 ppm NO are shown in Figure 48. The CO_2 concentrations reported by the bench follow the input quite well, even down to the 2-second pulse. The T_{90} was determined to be less than 1 second from the steady state input. However, the data was reported serially at a rate less than 5 Hz as required by the Consent Decrees. As expected, the NO data reported via the electrochemical cell did not follow the step inputs as well as the CO_2. However, this unit does tend to respond to the inputs better than the ROVER unit, as it has a T_{90} of about 5 seconds.

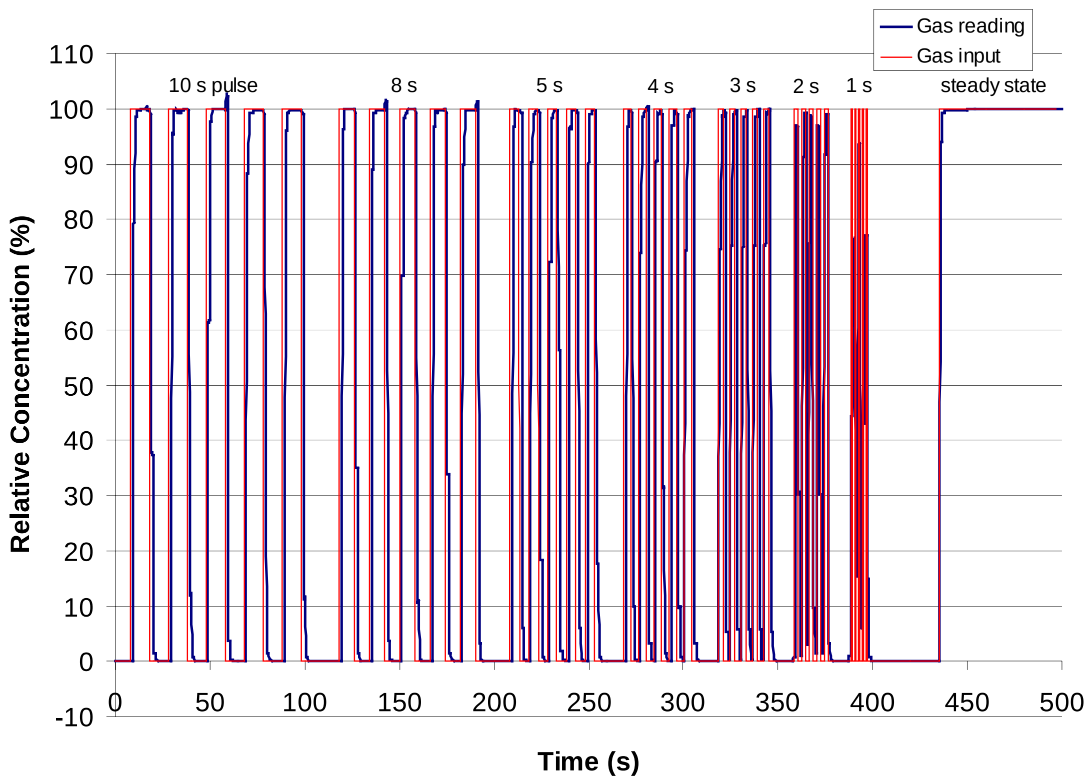


Figure 47 30.0% CO_2 step input on the Sensors AMBII.

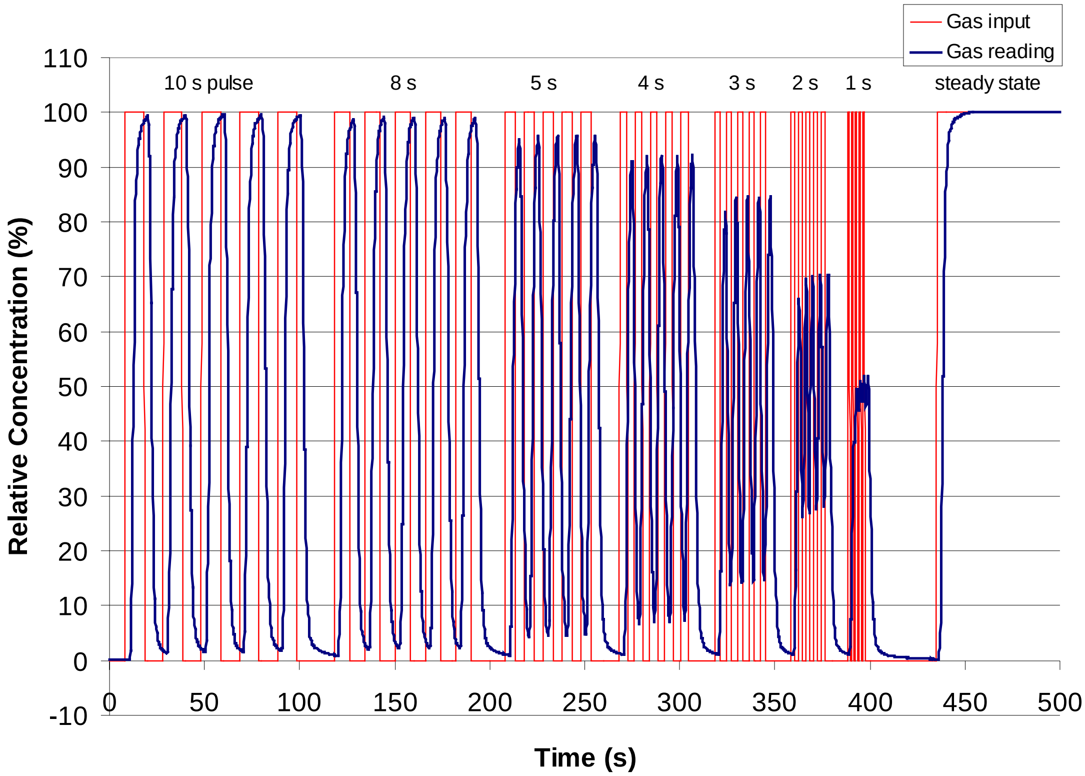


Figure 48 4490 ppm NO step input on Sensors AMBII.

5.3.8.4 Horiba MEXA 120 (zirconium oxide sensor)

The zirconium-oxide sensor from the Horiba MEXA 120 is used to determine NO concentrations in the sample stream. Analyzer step responses were performed using a 2500 ppm NO as the span value, and N_2 as the zero state. These test results are shown in Figure 49. The zirconium oxide sensor exhibited improved response over its electrochemical-based counterpart. From the steady state pulse, the MEXA 120 was found to have a T_{90} of approximately 5 seconds.

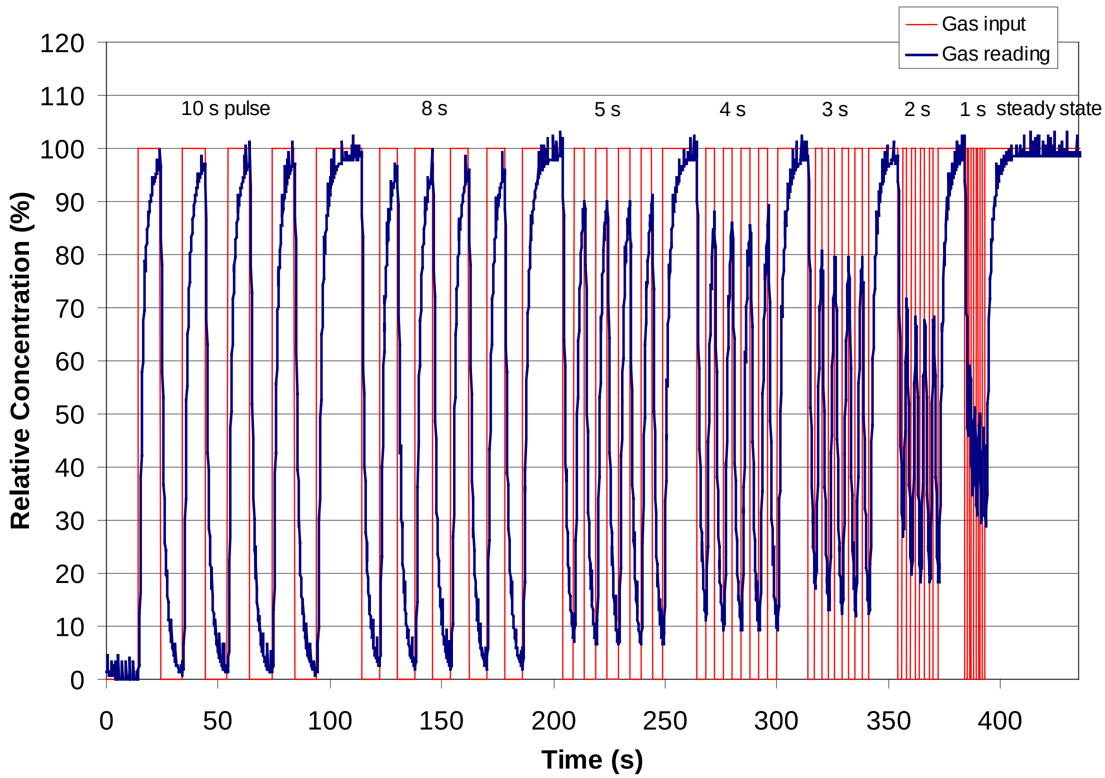


Figure 49 2500 ppm NO step input on the Horiba MEXA 120.

5.3.8.5 <u>Horiba BE 220</u>

The Horiba BE 220 NO analyzer uses a NDIR Luft-type detector to determine the NO concentration present in the sample stream. The step response test was performed on this analyzer using a 2000 ppm NO gas bottle. These test results are shown in Figure 50. Similar to the Horiba BE 140, the BE 220 tends to initially overshoot the concentration of the gas present. It is however, consistent across the respective step inputs. From the steady state pulse, the BE 220 was found to have a T_{90} of approximately 4 seconds. It should be noted that this test was performed on the original BE 220, which tended to vary considerably more about a given concentration than the BE 220 microbenches that was used for the engine and chassis tests. The new BE 220 exhibited an improved response compared to the original prototype unit.

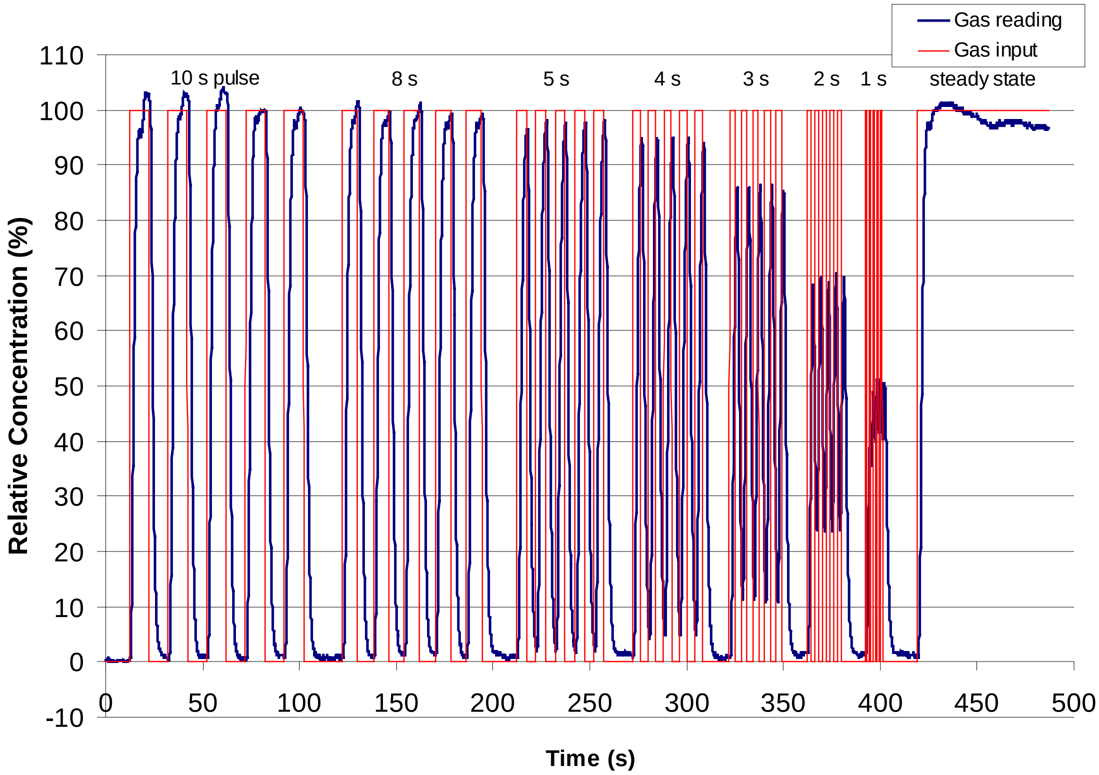


Figure 50 2000 ppm NO step input on the Horiba BE 220.

In order to quantify the performance of an OREMS, it is imperative that the system be correlated against laboratory-grade emissions measurement devices. Such comparisons provide the highest level of benchmark testing, under the controlled environment of a laboratory setting. During this study, comparisons were made between candidate OREMS and laboratory-grade analyzers for both engine dynamometer tests and vehicle chassis tests.

5.3.9 Exhaust Emissions Tests

Since neither the Siemens nor the Andros units were able to provide WVU with a stable, reproducible, and accurate means of monitoring emissions quantities, testing beyond the preliminary bottle benchmarks was not performed. The Sensors system could not provide a means of sampling the exhaust emissions constituents at a rate of 5 Hz, which is required by the Consent Decrees. Conversely, the Horiba BE 220, MEXA 120, and BE 140 could be configured to collect analog signals continuously throughout a test cycle. Consequently, all MEMS exhaust emissions testing was performed utilizing the Horiba units.

Engine dynamometer tests were performed on the following engines: Mack E7, Navistar T444E, and Cummins ISM-370. The engines were operated over the FTP and various steady-state and transient NTE-region cycles. Tests were conducted with the MEMS and ROVER.

5.3.10 Exhaust Sample Humidity Control

An OREMS utilizing an NDIR measurement scheme for determining CO_2 levels must provide for a means to remove the moisture that is present in the sampled exhaust stream. Without such provision, erroneous reports of exhaust mass emissions could result, due to NDIR interference issues as well as inaccurate determination of the volume displaced by water in the exhaust stream, i.e. incorrect reporting of "wet" emissions data. Experience has suggested that it is more accurate to establish a dry measurement and, from it, determine the gas concentration in the exhaust, via a dry to wet correction factor, than to directly report a wet concentration. Moreover, the removal of water reduces inherent absorption errors associated with the overlapping responses of NDIR devices to CO_2 and water. Common practices involve lowering the dewpoint of the sample to at least 44°F to make certain that the remaining water in the sample is at or below 1% of the total volume present. "Wet" reporting of emissions data necessitates elimination of water condensation throughout the sample stream. If the sample is dried, then this concern is no longer warranted, and a "dry-to-wet" conversion can be inferred from CO_2 measurements. As an example, when operating at high loads, a heavy-duty diesel engine exhaust stream can contain as much as 15% water, by volume. It is also during these points of high load operation that the engine emits the highest concentrations of CO_2.

A paramount issue that must be addressed when employing NDIR detection schemes is the restricted temperature ranges that these devices must operate within. Due to such restrictions, heated sampling systems must be coupled with some means of sample cooling. Water removal, therefore, must be employed only after NO_2 conversion, and could be accomplished by condensing the water vapor or by employing diffusion-drying techniques. For the determination of all regulated exhaust pollutants, with the exception of hydrocarbons, the water may be condensed out. However, unlike the exhaust streams of gasoline-fueled engines, diesel exhaust includes heavy-ended hydrocarbons, which can condense at lower temperatures. In addition, the levels of UHC associated with diesel exhaust are much lower than those produced by light-duty gasoline-fueled engines. Therefore, the inherent water interference issues coupled with the limited operating temperatures associated with the portable NDIR units tend to compromise the accuracy of NDIR-based HC measurements. Moreover, HC hang-up issues make continuous measurements very suspect, as condensation and vaporization integrate to skew cycle events. As a result, the sampling system needs to accommodate a water handling unit, but design temperatures need not be maintained at levels necessary for accurate HC determination.

For this study, three types of water removal techniques were evaluated – Nafion tube dryers, thermoelectric chillers, and simple water-trap reservoirs. Performance of the units was verified using bottled gas tests, as well as engine exhaust tests. The nafion-tube systems produced by Perma-Pure, commonly employed by FTIR-based systems, remove water without affecting exhaust gas species such as CO, CO_2, SO_2, and NOx. However, nafion-tube systems have limited operating temperatures that are situated below the condensation points of the heavier-ended hydrocarbon species. Testing experience suggests that the HC condensation inherent of these systems tends to saturate the nafion membranes, resulting in performance degradation, unsteady water removal rates, and hydrocarbon hang-up. Simple water trap devices, commonly used by the manufacturers of repair-grade emissions measurement systems, provide only for limited water removal, and, moreover, produce very inconsistent resultant humidity levels in the sample stream. Their performance depends heavily upon the ambient conditions present at the time of testing. In light of the above discussion, WVU opted to employ a sample-chilling unit. Such units provide adequate, reproducible water removal, thus minimizing NDIR interference issues, and decrease sample stream temperatures, to levels that are at par with manufacturer specifications. A Universal Analyzers model 1080 thermoelectric water condenser was used for the engine laboratory correlation tests. The unit provides for two parallel sample paths, with a total flow rate of 10 lpm. Humidity test results indicated that the unit provided stable humidity control of the sample stream to nearly 8% RH. The unit is relatively heavy, weighing nearly 33 lbs., and requiring 740 watts power. However, system flow optimization would permit the substitution of a model 530, which is approximately 50% smaller and requires only 175 watts of AC power. Implementation of this unit could be coupled with the use of a non-heated head pump, located downstream of the NO_2 converter and sample chiller, in order to reduce overall system power consumption.

In order to determine the amount of moisture in a sample gas in the MEMS system, tests were conducted to measure the relative humidity of the gas at the system's exit. Three methods for drying the gas were utilized: a water trap filter in ambient air, the same water trap filter cooled in ice water, and a thermoelectric chiller. The tests consisted of sampling a known gas concentration dry (straight from the bottle), and then bubbling that same gas through water before entering the MEMS system. The tests were performed for 5.00% CO_2 and 2463 ppm NO. The gas divider was used with N_2 as the diluent to examine the effects of moisture on the concentration measured by the MEMS system. The gas divider was set to 100, 60, 30, 10, and 0% of the component gas. After allowing for stabilization of the reading, the data was recorded. Humidity was measured at the exit of the system using a relative humidity sensor. The inlet temperature to the analyzer, as well as the water removal device, was maintained at a constant temperature. It is often more important to report the absolute humidity of the sample rather than the relative humidity, but since these experiments were conducted for evaluation purposes, and knowing that the absolute humidity can be determined from the relative humidity and temperature, using the relative humidity measurements as a method of evaluation was justifiable.

The first set of tests was conducted with 5.00% CO_2 gas. Figure 51 emphasizes that the dry bottle gas has nearly 0% relative humidity, since each drying method produced nearly the same results. However, when the gas was bubbled through water, it was seen that the thermoelectric chiller removed most of the moisture, drying the gas to about 10% relative humidity. The water trap in ice-water dried the gas to about 35-40% relative humidity, while the water trap in ambient air dried the gas to about 60-65% relative humidity.

The second set of tests was performed on 2463 ppm NO. For the dry bottle gas, only the thermoelectric chiller was used to establish that the gas was dry. These results are shown in Figure 52. Again, when the sample gas was bubbled through water, the chiller dried the gas the best to a relative humidity of 10-12%. The drying methods are repetitious as the water trap in ice water dried the sample to about 35% relative humidity, and the water trap in air dried the sample to slightly less than 70% relative humidity.

To further illustrate that the thermoelectric chiller is the best method for drying the sample gas in the MEMS system, tests were performed using the Cummins ISM-370 engine. The tests were developed so that the engine was operating within the NTE zone. Two wet measurements were performed for repeatability while a test using the water trap in ice water was omitted due to the difficulty of using ice water in an OREMS. The CO_2 measurement of the

Horiba BE 140 is based on volume. As the amount of moisture in the sample stream changes due to engine load, the actual volume of CO_2 entering the analyzer will change. If water is present in the sample stream, the actual gas concentration is decreased. Therefore, it is necessary to provide a method of maintaining the sample stream at a constant humidity, preferably drier, so that the analyzer will sample the correct volume of CO_2. As shown in Figure 53, the highest CO_2 measurements were measured using the thermoelectric chiller. The relative humidity measurements for these tests are shown in Figure 54. From this graph, it can be seen that the thermoelectric chiller were the most effective in removing moisture from the sample gas at each point in the test, and that it maintained the sample stream at a near constant relative humidity. These tests emphasize the need for an external chiller so that CO_2 emissions can be measured accurately.

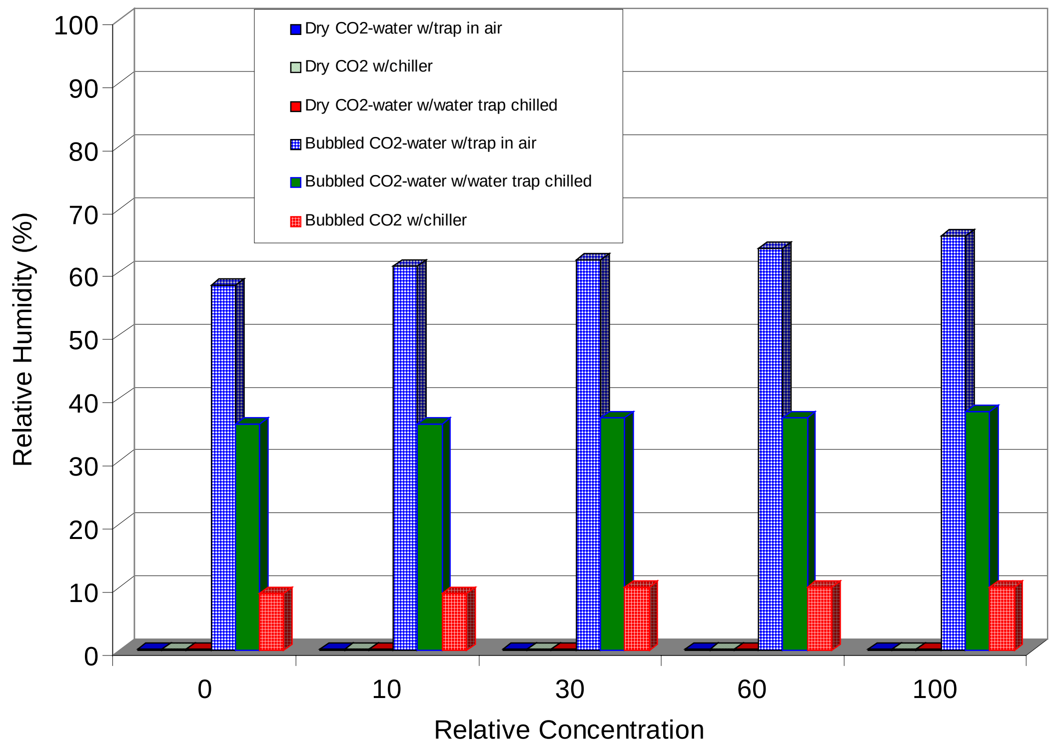


Figure 51 Relative humidity of 5.00% CO_2.

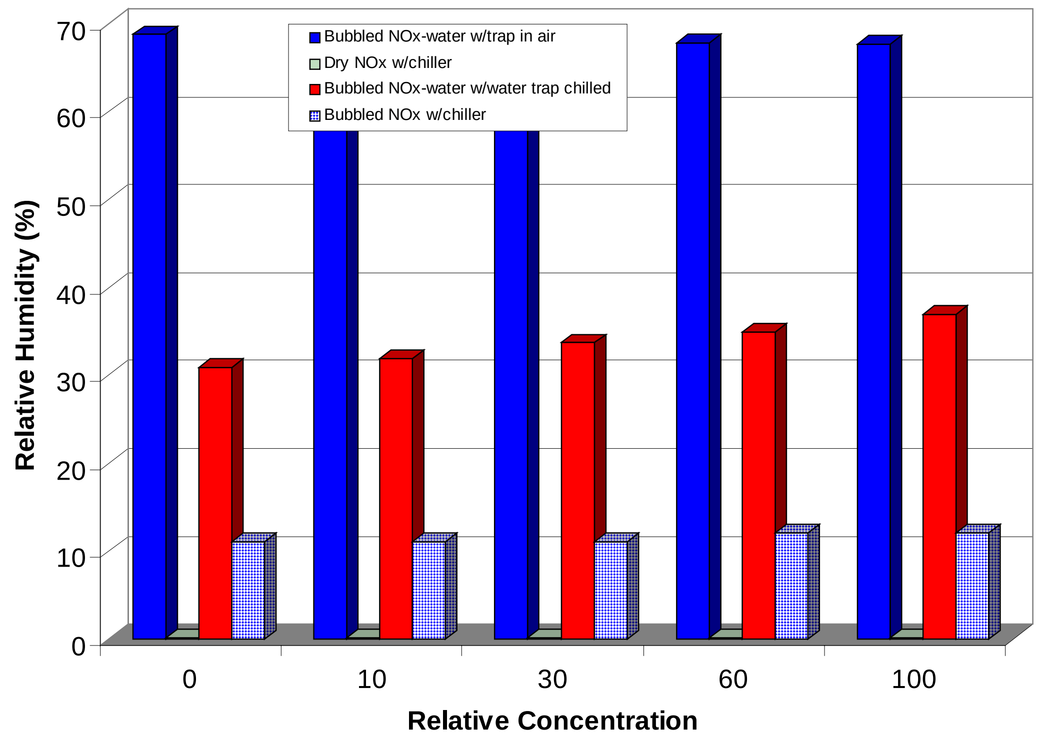


Figure 52 Relative humidity of 2463 ppm NOx.

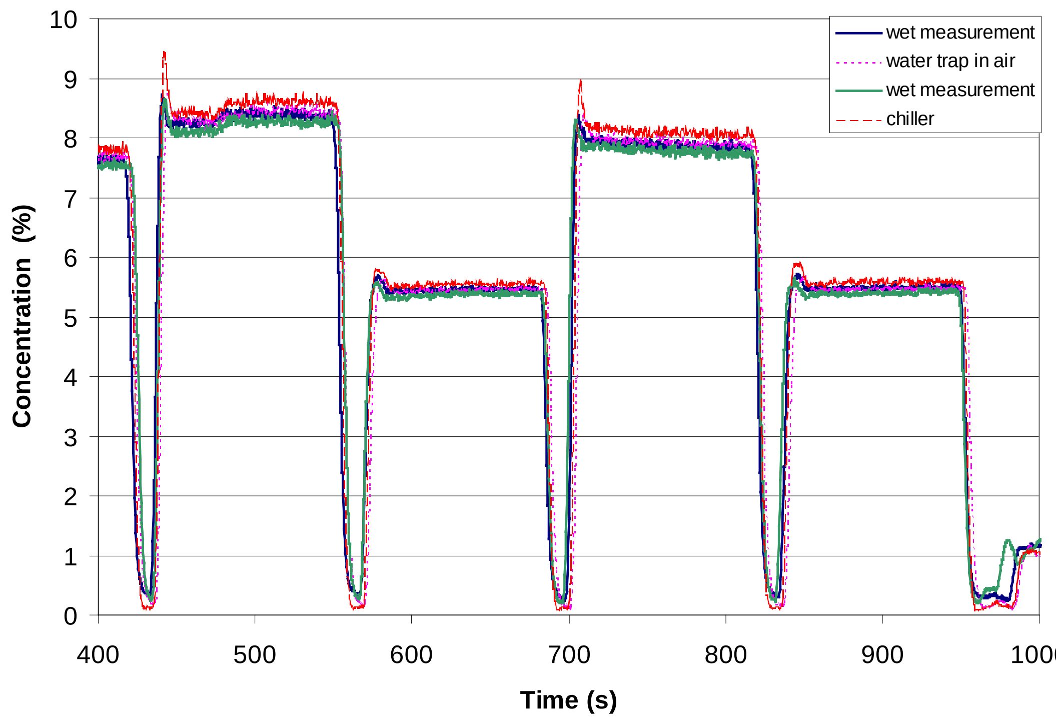


Figure 53 CO_2 measurements on a Cummins ISM-370 engine operating within the NTE zone.

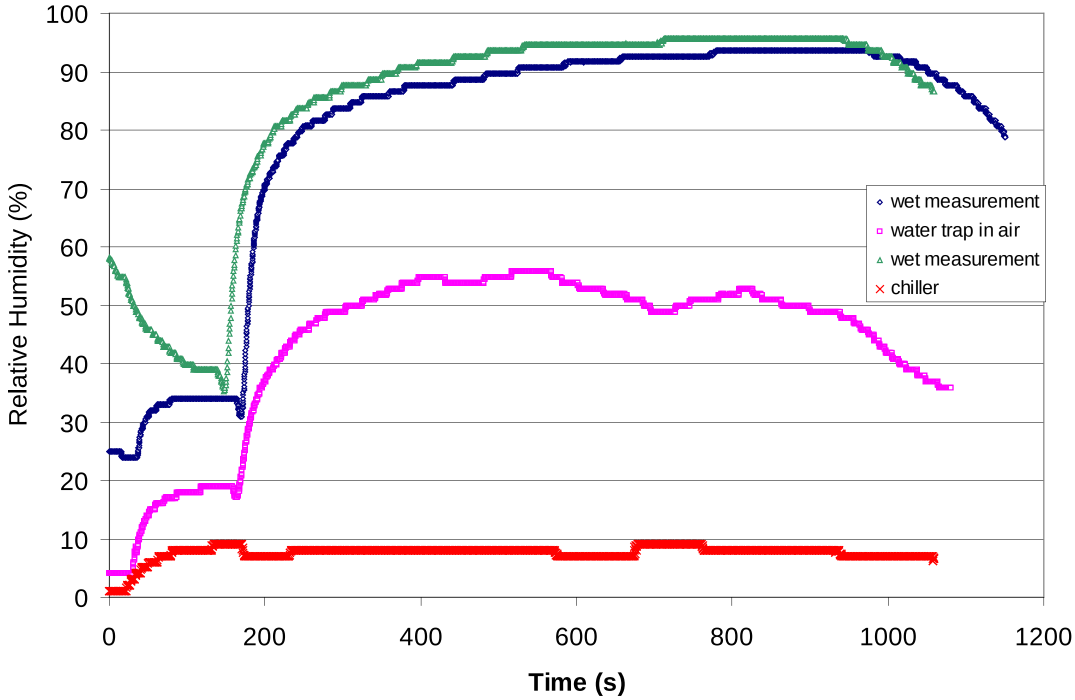


Figure 54 Relative humidity of the sample stream from a Cummins ISM-370 engine operating within the NTE zone.

5.3.11 NOx Measurement Requirements for MEMS

The MEMS was used to measure the raw emissions from a test engine that was operated over a steady-state test cycle (ESC 28-minute). Back-to-back tests were performed in order to qualify the need for an NO_2 converter in MEMS sampling system. The results of the test cycles are presented in Figure 55 and Figure 56. According to Horiba representatives, the MEXA 120 zirconium oxide-based sensor is a total NOx determination device. However, it is readily apparent that, although the sensor tends to have some response to components other than NO, it is necessary to incorporate a NO_2 converter into the sampling system. The differing response curves of the NDIR-based Horiba BE 220 illustrates the contribution of NO_2 to the total NOx during the test cycle, and, hence, further substantiating the need for implementation of a converter in MEMS.

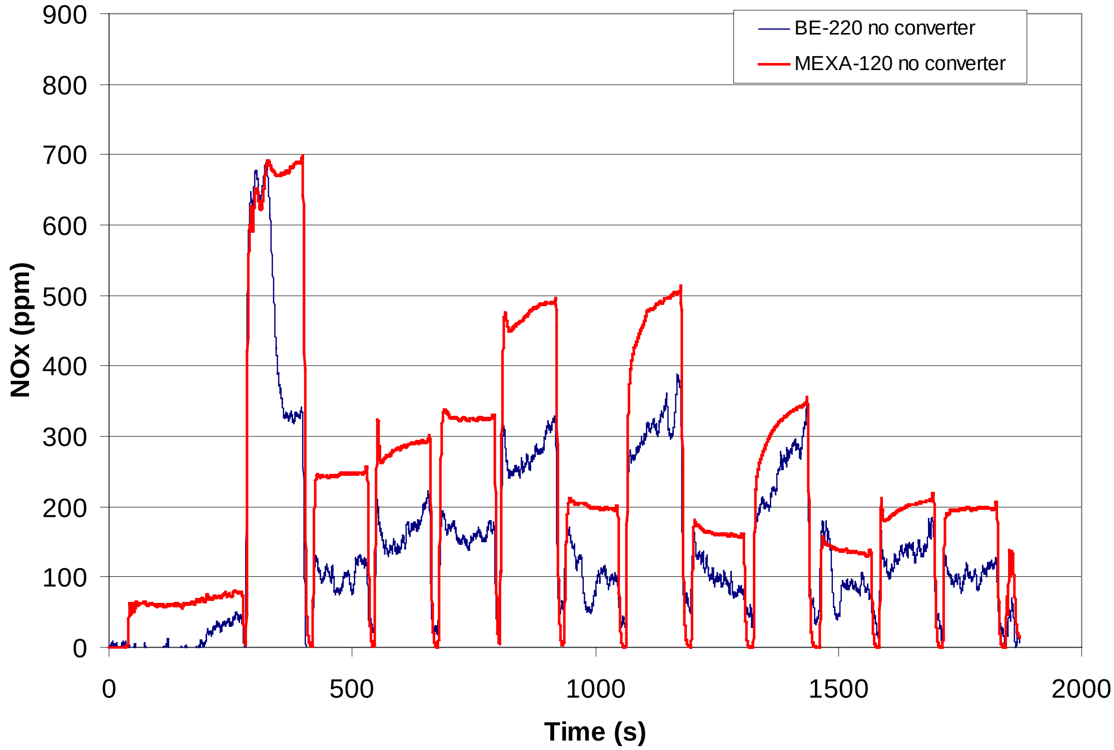


Figure 55 MEMS NO measurements – ESC 28 minute test cycle.

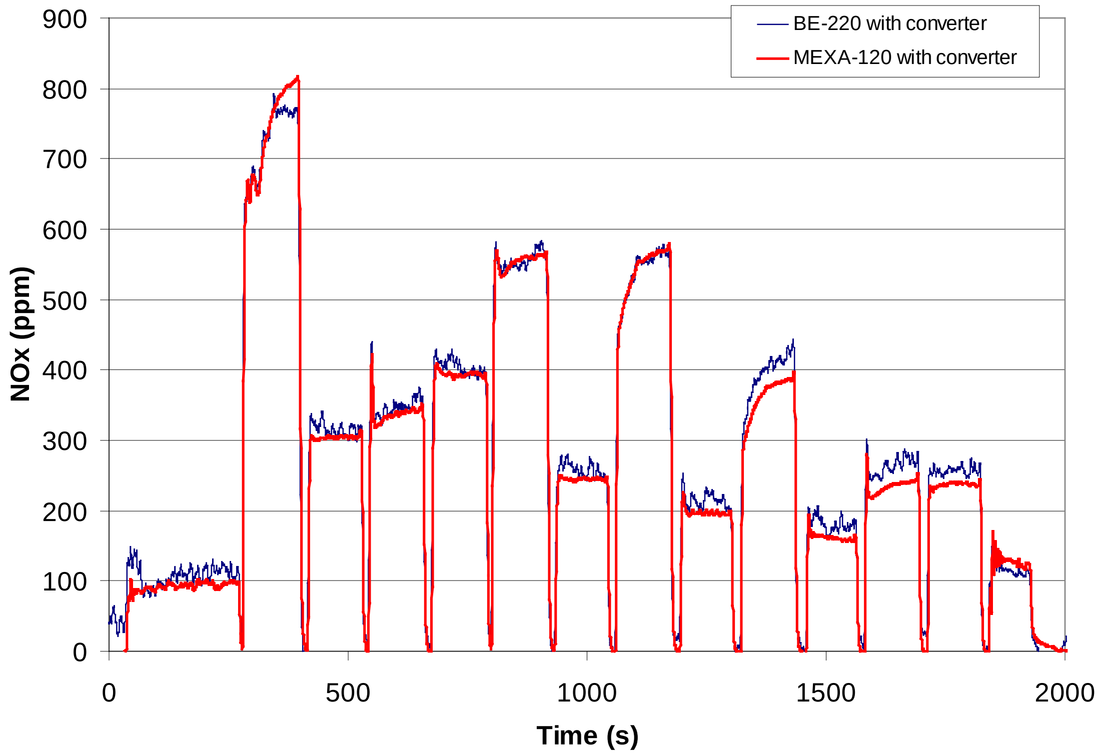


Figure 56 MEMS NOx measurements – ESC 28 minute test cycle.

In order to provide a comparison of current repair-grade components to laboratory-grade equipment, preliminary tests were performed using a Rosemount Model 955 Heated Chemiluminescent Detector sampling from the raw exhaust stream. The sampling line was maintained at 250°F and PM was removed from the sample stream via a heated filter located near the analyzer input, after the external NO_2 converter. A Horiba COM-11 NO_2 converter was used to assist the converter contained within the Rosemount 955 unit. Sample flow rates were controlled below 4 lpm so that adequate converter efficiencies could be achieved. In addition, optimization of the sample bypass flow rates and pressures were necessary for these tests to ensure that sufficient quantity of ozone was available for the reaction chamber.

Raw diesel exhaust streams are capable of containing up to 15% H_2O during high load levels (approximately proportional to CO_2 production). In addition to the sample volume displaced by water, water content can quench some of the necessary reactions used by chemiluminescent detectors to correlate NO concentrations. The chemiluminescent detection principle is governed by the following reactions,

$$NO + O_3 \rightarrow NO_2^* + O_2 \tag{4}$$

and

$$NO_2^* \rightarrow NO_2 + hv\,. \tag{5}$$

An interfering molecule, such as water, can collide with the excited NO_2 molecule (NO_2*). The colliding molecules move faster after their contact, but the additional energy, normally released as a photon, is dissipated during the collision. Therefore, if the water is not removed, measurements made with the chemiluminescent detector can be erroneously low.

In order to quantify the interference effects, back-to-back steady-state tests were performed with a Rosemount Model 955 a heated chemiluminescent detector (HCLD). For the first test, an external converter was utilized, but no water removal technique was employed. For the second test, a thermoelectric chiller was installed downstream of the external NO_2 converter, in order to remove water vapor that was contained within the sample stream. Figure 57 illustrates the combined humidity effects (volume displacement and quenching) encountered during the first test, by comparing the recorded back-to-back measurements.

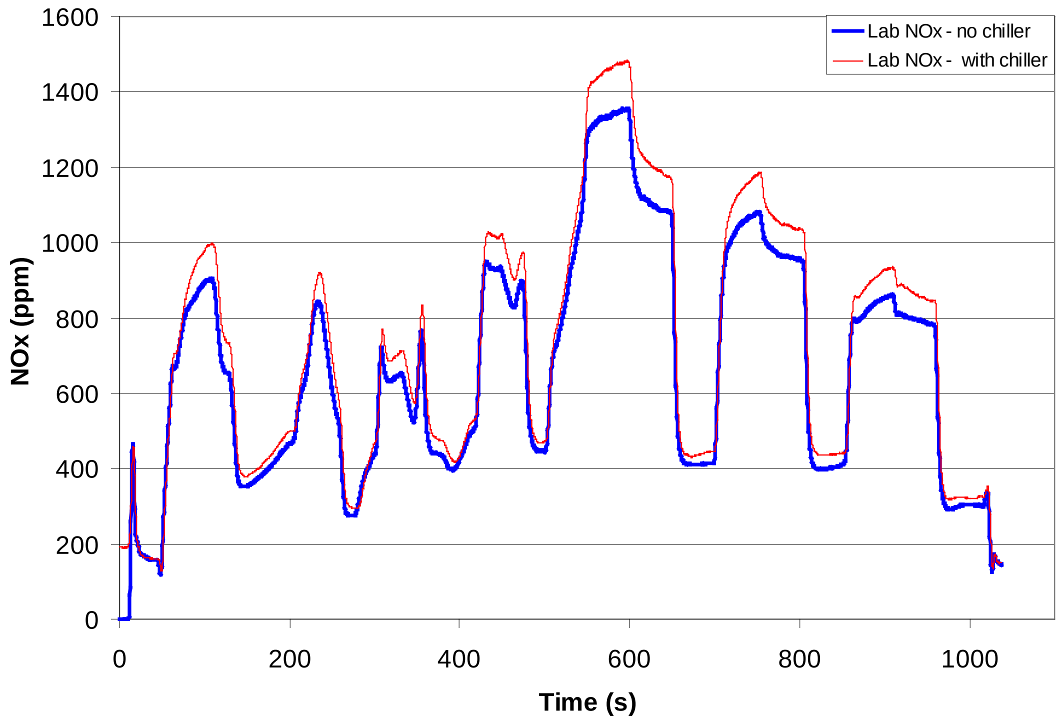


Figure 57 Effect of thermoelectric chiller on Rosemount 955 measuring raw exhaust samples.

The various OREMS candidate NOx measurement schemes were compared with the recorded response of a Rosemount Model 955 HCLD to raw exhaust concentrations. The OREMS candidate devices and the Rosemount Model 955 HCLD were coupled with a Horiba COM-11 NO_2 converter and a thermoelectric chiller (the internal NO_2 converter of the 955 was also used to ensure adequate converter efficiencies as well as to reverse any possible NO to NO_2 re-conversions). A Cummins ISM-370 was operated over a steady-state test cycle, dubbed the MEMSCYC; the recorded NOx emissions measurements obtained from two independent electrochemical cells are compared to raw laboratory NOx measurements in Figure 58. The electrochemical devices provide results almost identical to the laboratory analyzer when both sample streams are passed through a NO_2 converter and a thermoelectric chiller. Figure 59 and Figure 60 present transient engine test results in which a ZrO_2 sensor, employed by the Horiba MEXA 120, is compared to an electrochemical cell. During the first test (Figure 59) the MEMS thermoelectric chiller was deactivated, whereas the system was reconfigured to use the chiller for the second test (Figure 60). Results indicate that the electrochemical devices showed no apparent change in output due to variations in sample humidity, although higher concentrations should have been reported due to water displacement. The ZrO_2 sensor correlates well with the electrochemical cells when both are used to measure sample streams that are chilled and dried. However, similar to the response tests presented earlier, the electrochemical cells exhibited slower response to transient emissions events than did the ZrO_2 sensor.

As a result of the evaluations presented above, the MEMS utilized an NO_2 converter and a ZrO_2 sensor for NOx determination. Due to time limitations associated with the evaluation of the ZrO_2 sensor, an electrochemical cell was implemented as a QC/QA measure. Including an electrochemical cell in the system provided a means of ensuring that measurement problems, not detected during pre- and post-test procedures, did not manifest themselves during the test. Overall, data suggests that such an OREMS system yields good correlation with laboratory-grade raw HCLD NOx emissions data.

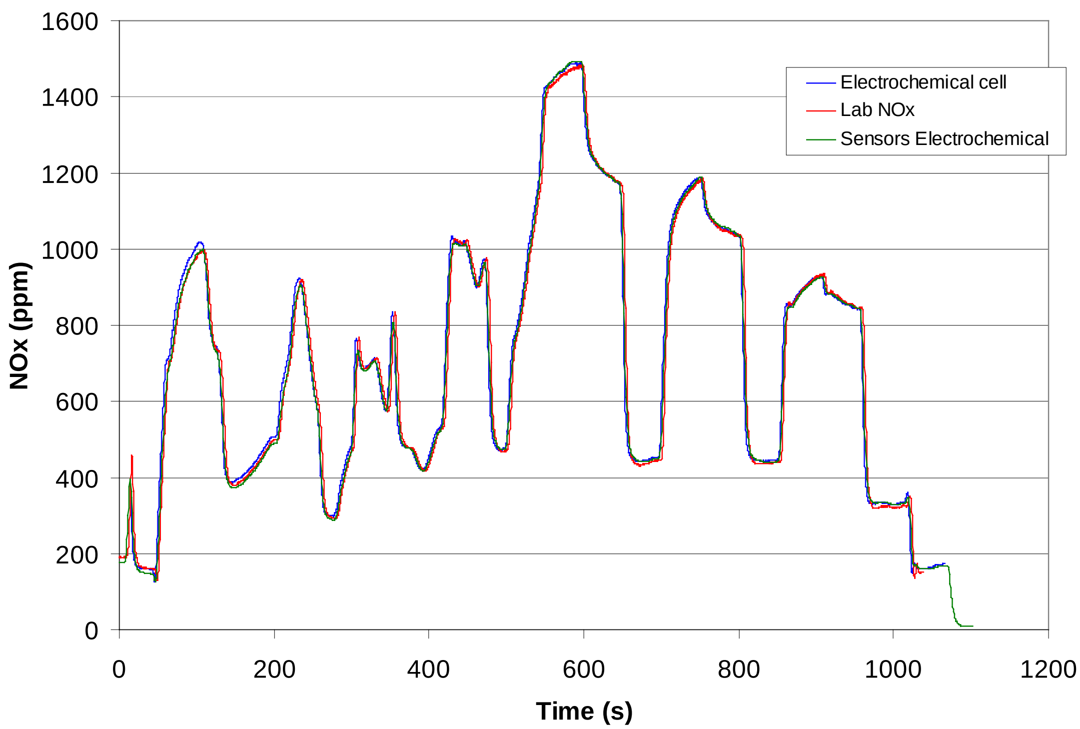


Figure 58 Raw NOx exhaust emissions comparisons of OREMS devices vs. laboratory-grade equipment.

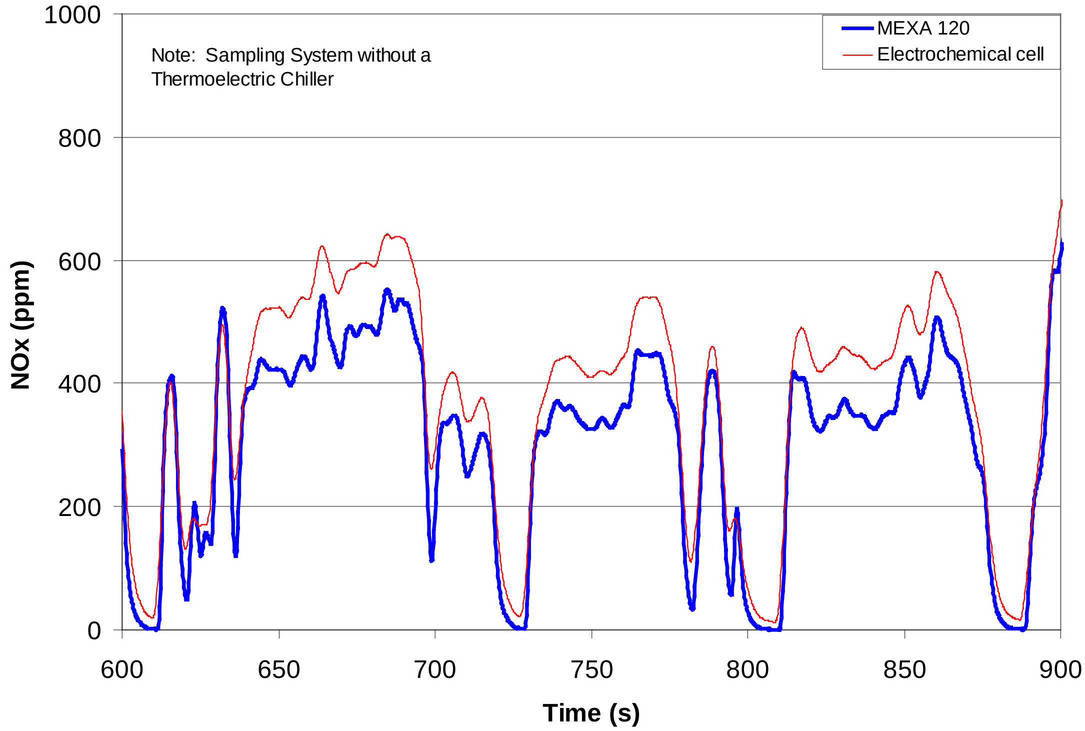


Figure 59 Wet transient NOx emissions comparison between electrochemical and MEXA 120 analyzers for the FTP cycle from 600 to 900 seconds.

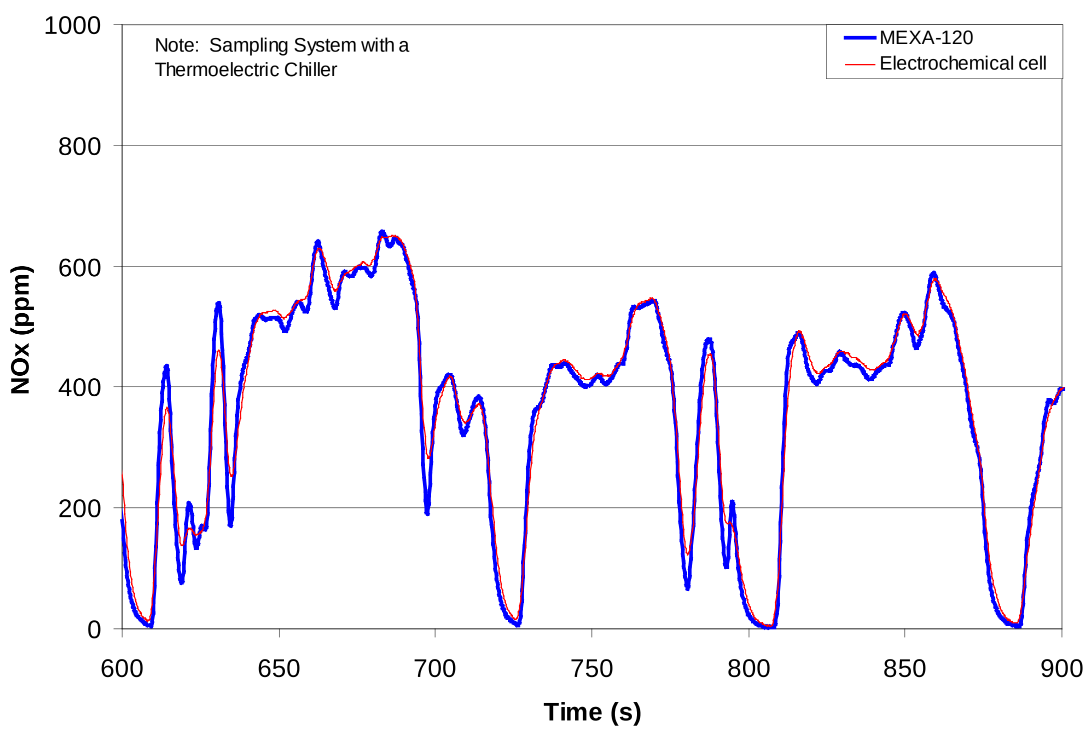


Figure 60 Dry transient NOx emissions comparison between electrochemical and MEXA 120 analyzers for the FTP cycle from 600 to 900 seconds.

5.3.12 On-Road Vibration Tests

Vibration is a major concern in the development of an OREMS. A limited number of tests were carried out to determine effects of vibration on the candidate microbenches and laboratory analyzers. The tests were performed by driving the class 8 Mack CH tractor on a route consisting of city and highway operation. Ambient air from inside the cab of the tractor was sampled throughout the test cycle. Some of the available analyzers exhibited unacceptable errors from vibration when subjected to this road test. The Rosemount Model 880 laboratory grade CO_2 analyzer and the Horiba BE 220 are both very sensitive to vibration. Figure 61 shows the vibration effects on the BE 220. The magnitude of the peaks is approximately half of the span value, which indicates that the instrument could not be used for on-road testing. Otherwise, the BE 220 performed well in a laboratory environment, especially on time response tests. Figure 62 shows the effects of the same test on the BE 140 CO_2 data. The variation in concentration over the test is significantly lower than that of the model 880 CO_2 analyzer. Some of the minor variations in these tests could be attributed to the actual sample concentrations (ambient air) changing inside the tractor cab during the route. The vibration test results for the Rosemount 880 CO_2 analyzer are shown in Figure 63. The 880 and BE 220 are Luft detectors, which consist of a diaphragm between two chambers. The diaphragm deflects based on the pressure differential between the two chambers. This deflection is detected by a capacitor between the moving diaphragm and a stationary mount. Vibration as well as pressure will cause the diaphragm to deflect. The BE 140 employs a solid state NDIR detector. Therefore, it is much less sensitive to vibration. As shown in Figure 64, the solid state Horiba MEXA 120 NOx analyzer shows very little fluctuation from zero over the test route. The higher concentration observed in the first 500 seconds are attributed to the relatively high ambient concentration (1 to 2 ppm) in the cab of the tractor prior to the start of the test.

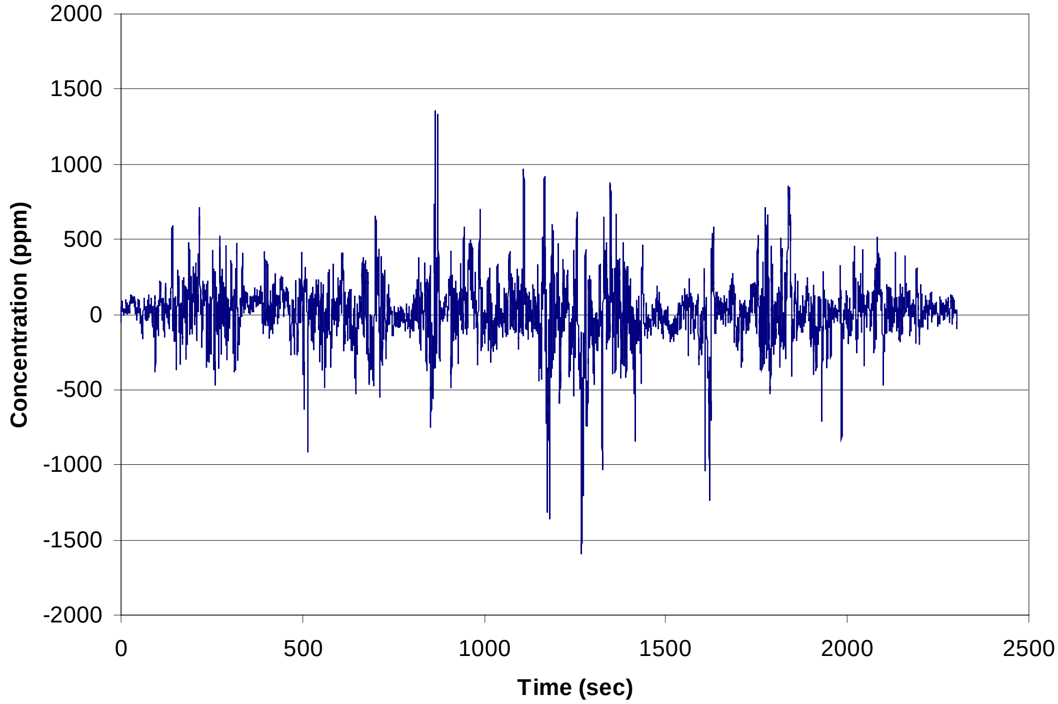


Figure 61 Vibration test on the Horiba BE 220 NO analyzer.

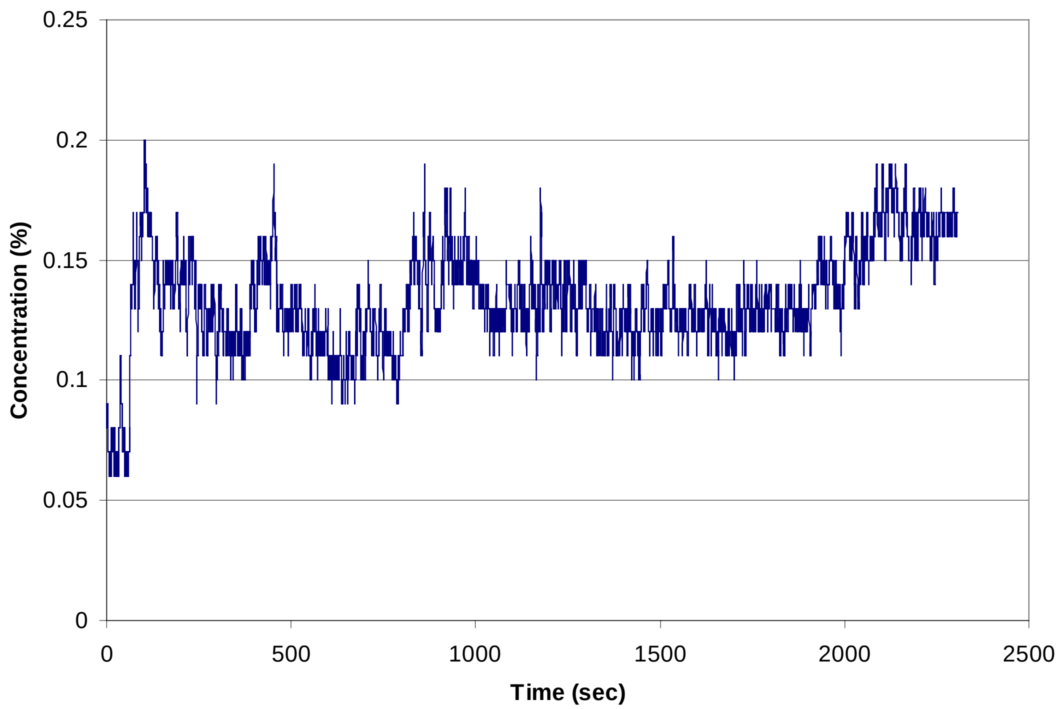


Figure 62 Vibration test on the Horiba BE 140 multi-gas analyzer for CO_2.

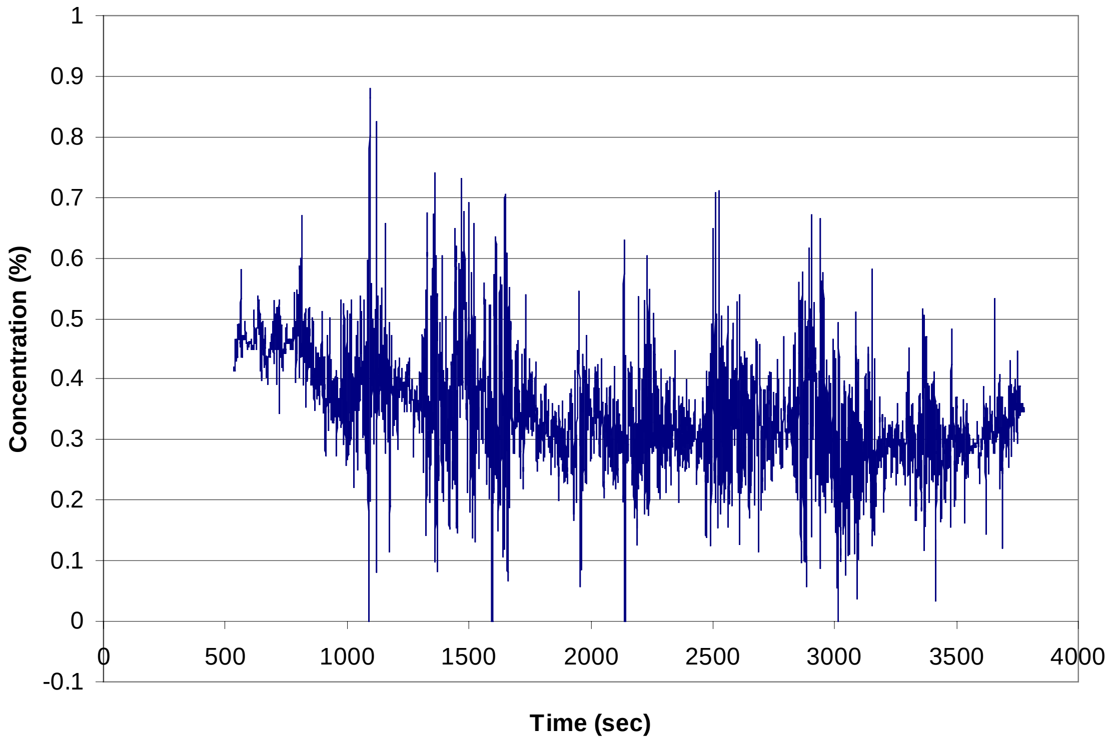


Figure 63 Vibration test on the Rosemount 880 CO_2 analyzer.

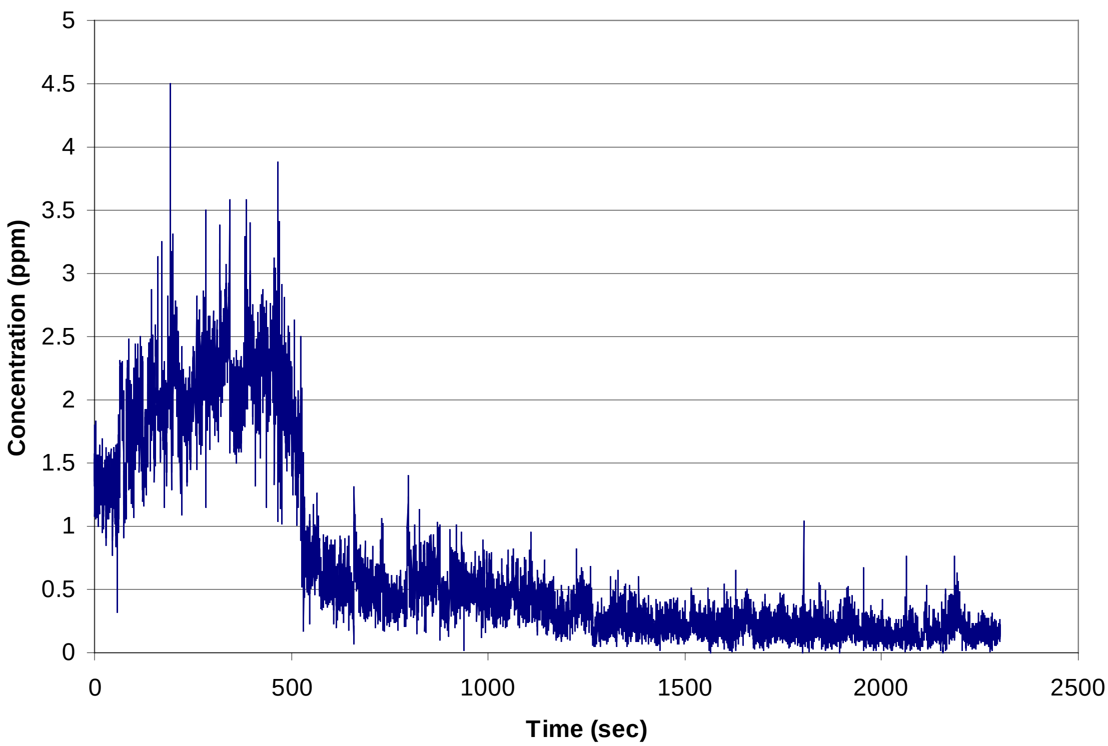


Figure 64 Vibration test on the Horiba MEXA 120 NOx analyzer.

5.4 Vehicle Speed and Distance Measurement

Measurement of vehicle speed and distance traveled are not critical for determining brake-specific mass emissions. However, it is anticipated that emissions with the OREMS may be examined in mileage specific units in the future and will require accurate measurement of a vehicle's instantaneous speed and distance traveled. Also, vehicle speed and distance traveled will be used in Phases III and IV, for in-use emissions measurements, to quantify the test routes.

Three measurement techniques were examined, namely the ECU broadcast signal, an external GPS signal, and an optical sensor from Datron Technology. The Mack CH tractor was used for the comparison study using the MEMS data acquisition system. The ROVER was not equipped with any sensors/devices to measure vehicle speed or distance.

The ECU signal was broadcast via the SAE J1587 standard. A Dearborn protocol adaptor was used to interpret the ECU broadcast with the MEMS data acquisition via the serial port. The SAE J1587 protocol requires data be broadcast at 10 Hz with a 0.5 mph resolution.

A J&S Instruments GPS/A receiver were also used with the MEMS to determine vehicle speed. The GPS data was broadcast through the NMEA standard and acquired at 1 Hz via the serial port. A unique feature of the J&S Instruments' receiver is that the speed and position information can be acquired at higher transfer rates through analog voltage output channels.

Further, a Datron DLS-2 optical speed and distance sensor was employed as a non-contact fifth-wheel measurement technique with a 1% accuracy. While both analog and digital outputs were available for the speed data, MEMS monitored the analog signal.

The comparative study consisted of driving the Mack CH tractor, without a trailer, on an interstate highway at a constant speed using the cruise control. The distance was measured using the mileage markers located along the road. This standard was determined to be the most accurate distance measurement method available for this study. The results for three separate tests are shown in Figure 65 to Figure 67 for three separate tests. The distance traveled and integrated results are shown in Table 17 for the three tests.

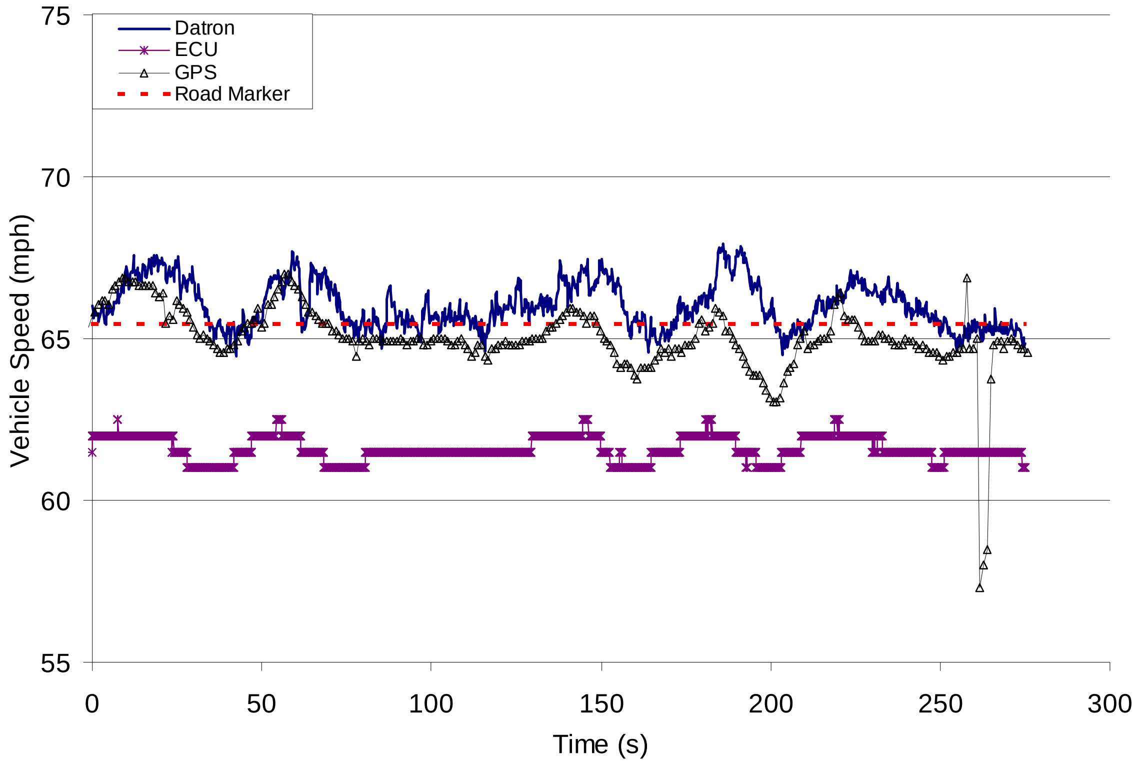


Figure 65 Vehicle speed comparison for Test A.

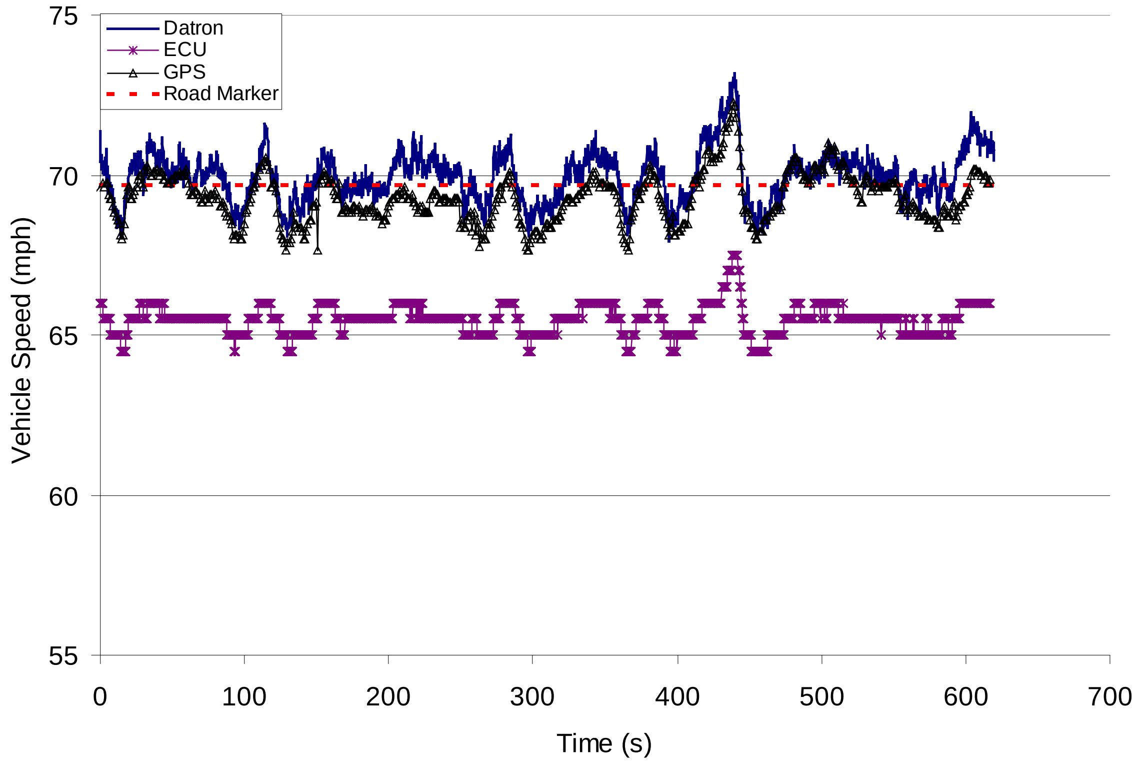


Figure 66 Vehicle speed comparison for Test B.

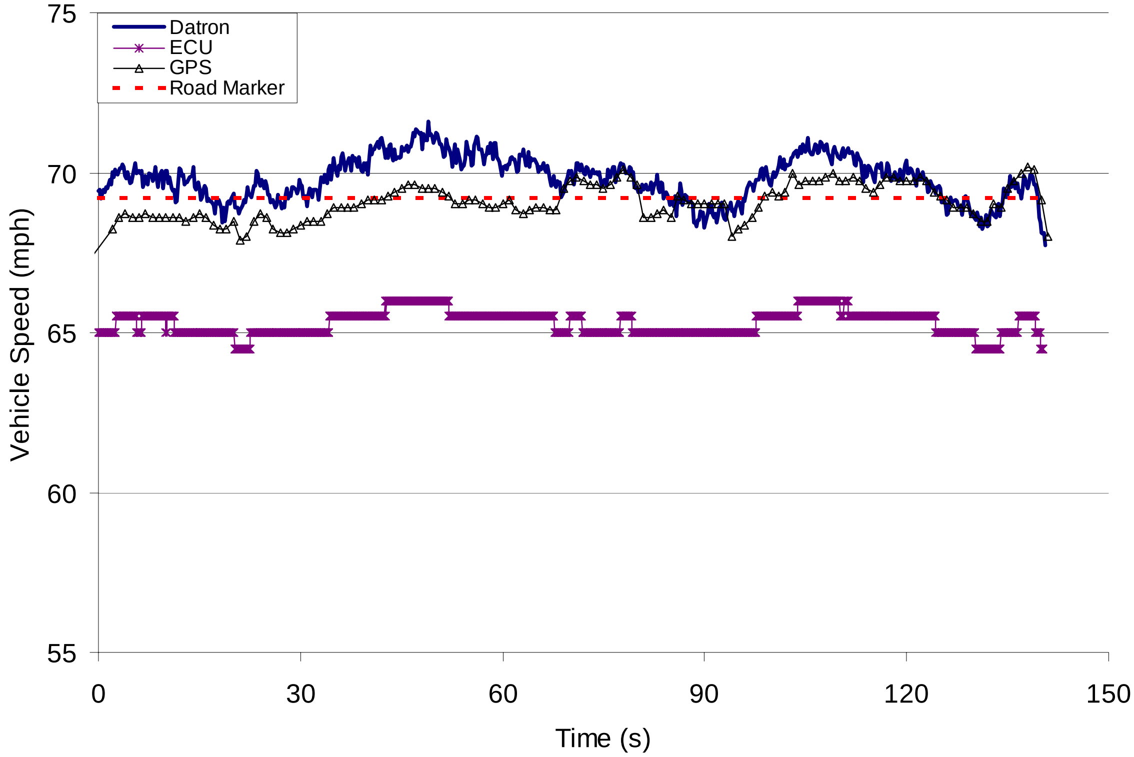


Figure 67 Vehicle speed comparison for Test C.

Table 17 Integrated vehicle speed measurement technique comparison.

	Road Marker (Miles)	Datron (Miles)	Per. Diff. (%)	ECU (Miles)	Per. Diff. (%)	GPS (Miles)	Per. Diff. (%)
Test A	5.0	5.04	-0.87	4.71	5.88	4.99	0.28
Test B	12.0	12.04	-0.32	11.22	6.47	11.88	1.03
Test C	2.0	1.96	1.80	1.84	8.19	1.95	2.33

As illustrated in the three figures, the Datron and GPS speed measurements are in very good agreement with each other. The speed data from these two measurement methods oscillate about the average Road Marker speed line. The oscillations are due to small speed variations resulting from the changing road grade and the corresponding response of the cruise control. The ECU measurement is approximately 6% lower than the average Road Marker measurement. It is noted that the Mack tractor tested is a research vehicle and may not be typical of an on-road tractor; however, it does illustrate that the ECU broadcast speed data should be compared against an independent measurement for each vehicle because in practice drivetrain or tire size changes may render the ECU signal inaccurate. The Datron and GPS sensors are within 1% of the integrated (distance) measurement for Tests A and B.

As illustrated in Figure 65, the GPS signal displays a sudden change in speed at 270 seconds. Although the GPS data did not indicate a loss of signal, there is an obvious error in the GPS signal at this point. Other on-road data has shown similar discontinuities for both the GPS unit and for the Datron sensor. It is recommended that for all vehicle speed and distance measurements, redundant systems should be employed to ensure data quality and validity.

A second series of tests was performed to examine the repeatability of the speed and distance measurement. Each test consisted of a 20 mile long route that included urban, suburban, and highway driving. The results from three replicates are illustrated in Table 18 along with the average and the coefficient of variation (COV) for each measurement method. It is noted that there will be minor differences in the distance due to test-to-test driving pattern (lane changing) differences. As shown in this table, the ECU output is approximately 5% lower than the Datron or GPS sensor, similar to the highway results above, but has the lowest COV (greater precision). The GPS COV is approximately twice that of the ECU while the Datron COV is approximately 11 times that of the ECU.

Table 18 Integrated vehicle distance reproducibility.

	Datron (Miles)	ECU (Miles)	GPS (Miles)
Test A	20.56	19.50	20.55
Test B	20.20	19.49	20.61
Test C	20.27	19.47	20.61
Average	20.34	19.49	20.59
COV (%)	0.961	0.087	0.164

The vehicle speed and distance measurements should be performed with at least two different methods. The ECU interface is the most cost effective although it may not be the most accurate. The GPS method entails an additional cost but provides for similar precision as the ECU and the accuracy of the Datron unit. The Datron unit was the most expensive of the three candidates tested, but provides a high degree of accuracy. However, the operation of the Datron unit may be affected by ambient conditions.

A GPS unit should be used as an independent measurement method to verify a vehicle's ECU speed measurement. It is recognized that most GPS units communicate via RS232 at 1 Hz or slower speeds and would not meet the Consent Decrees requirements of 5 Hz data acquisition rates; however, this measurement is not required per the Consent Decrees and is only being performed in the anticipation that this data will be useful in the future. The J&S Instruments GPS/A unit does provide an analog voltage signal at a faster rate than the serial connection if interface speed were to become an issue.

6 DISCUSSION AND RECOMMENDATIONS

6.1 Exhaust Flow Rate

The method of measuring the exhaust flow rate must be able to account for pulsating flow issues. It may prove advantageous to incorporate two flow meters in order to provide a redundant measurement. This can be accomplished within the existing packaging requirements for an Annubar flow meter by placing a secondary flow measurement device, either a second Annubar or a venturi, one-to-two pipe diameters downstream. Each meter section would require its own set of transducers. The redundant system would also provide a QC/QA measure that could be used to identify flow measurement errors that manifest themselves during on-road data collection.

A primary concern of any intrusive flow rate measurement is the associated effect on engine performance. It is imperative that the flow meter has minimal influence on the backpressure to the engine. For example, the ROVER flow tube is a nominal 4.5" diameter tube section. When tested on the Cummins ISM-370 with 5" exhaust pipe, the pressure drop across the ROVER flow tube was nearly 12" WC whereas the MEMS flow tube was approximately 3" WC at a rated set point.

6.2 Engine Torque and Speed

Engine torque inferred from ECU broadcast data is quite possibly the greatest source of error in reporting brake-specific mass emissions from in-use testing. ECU-derived torque must be limited to the NTE zone and to integration windows 30 seconds or greater. Torque inference errors related to ECU broadcast and manufacturer supplied lug data can be as large as 10% within the NTE zone. These errors may be greater than 10% under part load conditions and will become unacceptably large as the engine approaches and idle condition. ECU broadcast engine speed errors, however, are typically only a few percent within the NTE zone. The inferred ECU broadcast power, as a product of engine torque and speed, can be in error by as much as 15% within the NTE zone. It should be noted that the ranges of error listed above were derived from testing with new (<500 hours) engines and that in-use testing may result in increases of these errors, due to usage degradation.

6.3 Emissions

Variations in the test environment could prove to be an inherent problem to in-use testing. Although ambient air quality measurements generally produce very low concentrations of NOx, CO_2, CO, and HC, the emissions quantities sampled from the exhaust streams of heavy-duty diesel vehicles are the integration of test vehicle-generated combustion products, as well as these localized ambient air contributions. Thorough evaluation of on-road engine intake air has not been performed, but the topic does warrant investigation. The current system could be used to continuously monitor ambient intake air throughout a series of on-road tests. Potential problem areas include highly industrialized areas as well as regions of heavy traffic congestion.

At the onset of the testing, the S-HDDE prioritized the emissions that were to be measured by an OREMS as NOx, HC, CO_2, and CO. NDIR determination of HC has previously been discussed as a problematic area, and CO measurements made with currently-available technology, dedicated to gasoline exhaust characterization, seem to be limited by current design resolution. The low-levels of CO emitted by diesel engines typically require that longer sample cells be implemented in NDIR detection schemes in order to provide adequate residence time for the absorption of infrared energy by the exhaust gas sample. For a given gas detector being used in an NDIR detection scheme, low sample concentrations of a candidate gas require increased path lengths in order to provide measurement accuracy similar to that made for higher concentration levels. This is readily accomplished for laboratory-grade analyzers, where space requirements are not paramount. However, current portable emissions measurement devices have been designed to be extremely compact and were developed to make measurements of emission levels consistent with light-duty spark-ignited gasoline engines. Therefore, the software interfaces and suggested operating ranges of these devices have been designed to accommodate such operations. Although increased accuracy is likely afforded through implementation of longer sample cells, improved low-level performance may be provided by incorporating enhanced calibration techniques that use low-level gases as substitutes for the manufacturer's recommended calibration ranges. The serial output data could then be processed via calibration curves that produce low-level concentration "arrived-at" values from the seemingly high-level concentration output of the bench software data. This option has not yet been thoroughly investigated, however, it is not compatible with the current Sensors AMBII software (out of range error results).

The Horiba BE 140 was the only analyzer tested that provided 5 Hz serial port data, which is the data rate mandated by the Consent Decrees. Similar to the ROVER, the Sensors AMB II performed adequately from an accuracy standpoint, but the maximum data transfer rate of 2 Hz was insufficient. It is possible that data sampled at less than 5 Hz be transformed to 5 Hz data, but this would not correspond to sound engineering practices. From a systems integration standpoint, analog data collection is preferred over serial data collection, due to improved time stamping and increased data collection frequencies. However, analog data from the BE 140 microbench cannot be used until Horiba releases details concerning temperature and pressure corrections of the solid-state detector response.

The use of laboratory-grade NDIR-based equipment for on-board emissions measurements poses a problem due to the Luft-type detection schemes employed by most analyzer manufacturers. Implementation of such devices would require rather elaborate vibration-reduction techniques, and would obviously result in a system that would be rather cumbersome. Siemens and California Analytical Instruments both currently produce NDIR devices that infer sample cell concentrations from the output of microflow detection devices. This technology is a variation of the Luft-detector in that gas-filled detector cells are used to relate the amount of infrared energy absorbed by the gas sample. However, instead of using a diaphragm-based capacitance measurement of the pressure imbalances, a microflow sensor is used to measure the flow rate of candidate gas that accompanies the equilibration of the imbalanced detector cells as shown in Figure 68. This detection scheme may have better vibration resistance and should provide for increased accuracy and resolution, as compared to solid-state detectors. Current trends in the analyzer market have provided for significant reductions in overall unit size, therefore the feasibility regarding the implementation of such laboratory-grade analyzers in an on-board application should be investigated.

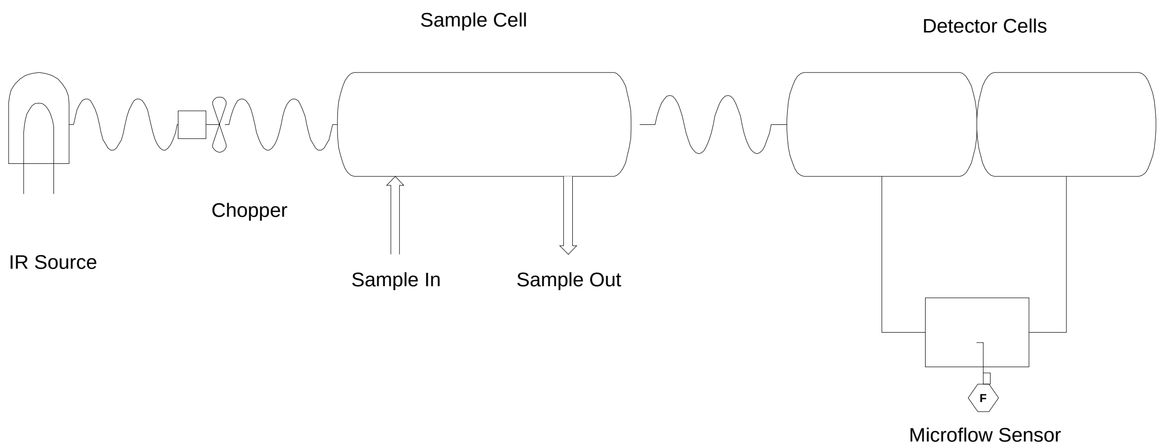


Figure 68 Microflow detection scheme for NDIR-based analyzers.

The use of electrochemical cells for the determination of NO is a very common practice for the manufacturers of repair grade gas analysis systems. The units are very compact, and replacement costs for the units are very reasonable. In addition, when the cells are operating correctly, they provide very accurate measurements of NO. However, there are serious problems associated with the exclusive use of electrochemical cells for the determination of NOx in an OREMS system. According to City Technologies, a large supplier of electrochemical cells, the sample stream for the cells should be humidified, in order to prevent depletion of the diffusion membrane. The performance of the units seems, therefore, to be affected by the relative humidity of the sample stream. The units are quite sensitive to sample stream pressure fluctuations. This could obviously pose problems during significant altitude variations, as well as in instances involving the implementation of such units in substandard sampling systems. Electrochemical cells, unlike NDIR-based systems, are known to have useful life spans, which vary significantly from sensor-to-sensor. Degradation of the cells, according to industry experts, is often very difficult to detect in the early stages. In addition, production variations do not readily provide for accurate “plug-and-play” replacement techniques.

6.4 Vehicle Speed and Distance

Vehicle speed can be measured from ECU broadcast data at a minimum of 5 Hz. Factory-calibrated ECU’s have shown to be very accurate. However, the accuracy of the ECU vehicle’s speed signal cannot be ensured, due to in-field modifications of associated chassis drivetrain parameters such as gear ratios, tire sizes, and even the amount of tire wear. The addition of a GPS unit will complement the ECU vehicle speed data and serve as a check for all vehicles operating in the field. Although vehicle speed is not directly required for the Consent Decrees' requirements of reporting the emissions in brake-specific units, it is important in evaluating the vehicle's test route and for identifying urban, suburban, and highway NTE zone locations.

Although data are not presented in this report, nor were they required for this work, it should be noted that any grade information inferred from elevation data from GPS data should not be used. It has been found in this work that the elevation data from the GPS broadcast is inaccurate. However, since an absolute pressure transducer is required to continuously monitor the ambient pressure for the NOx humidity correction factor, it may be possible to use this transducer to infer the gross changes in grade. An example of the change in ambient absolute pressure with a change in elevation is shown in Figure 30. It is noted that inclinometers are also available.

6.5 Sample Flow Rates Issues

On-board emissions testing of in-use heavy-duty diesel vehicles is largely comprised of transient emissions events. Obtaining accurate records of these events is a difficult task, due to the inherent "smearing" of exhaust emissions constituents from the time the combustion products exit the combustion chamber. Recreation of the emissions signals is a possible solution, but such reconstruction techniques often propagate errors rather than reduce them. High sample flow rates tend to enhance transient recording capabilities, but the flow rates must be controlled to prevent excess sample chamber fluctuations and excess flow rates through devices that have heavily flow-dependent performance, such as NO_2 converters.

The "smearing" of exhaust emissions events is a paramount concern to future correlation of raw exhaust measurement techniques to the "standard" dilute techniques that have provided the pre-dominant amount of the current emissions data base. Figure 69 illustrates the effects of sample flow rate on laboratory grade analyzers used to record transient emissions events produced from an engine operated over an FTP test schedule. Increased sample flow rates did visually improve transient records, but the dilute measurements exhibit significantly different trends, compared to the raw exhaust record. However, as indicated by the figure, integrated cycle concentration figures were quite comparable, begging recommendation for longer data comparison windows. In any event, "dead-on" instantaneous or limited-time integration windows should not be the ultimate measure of data integrity for a raw emissions measurement system.

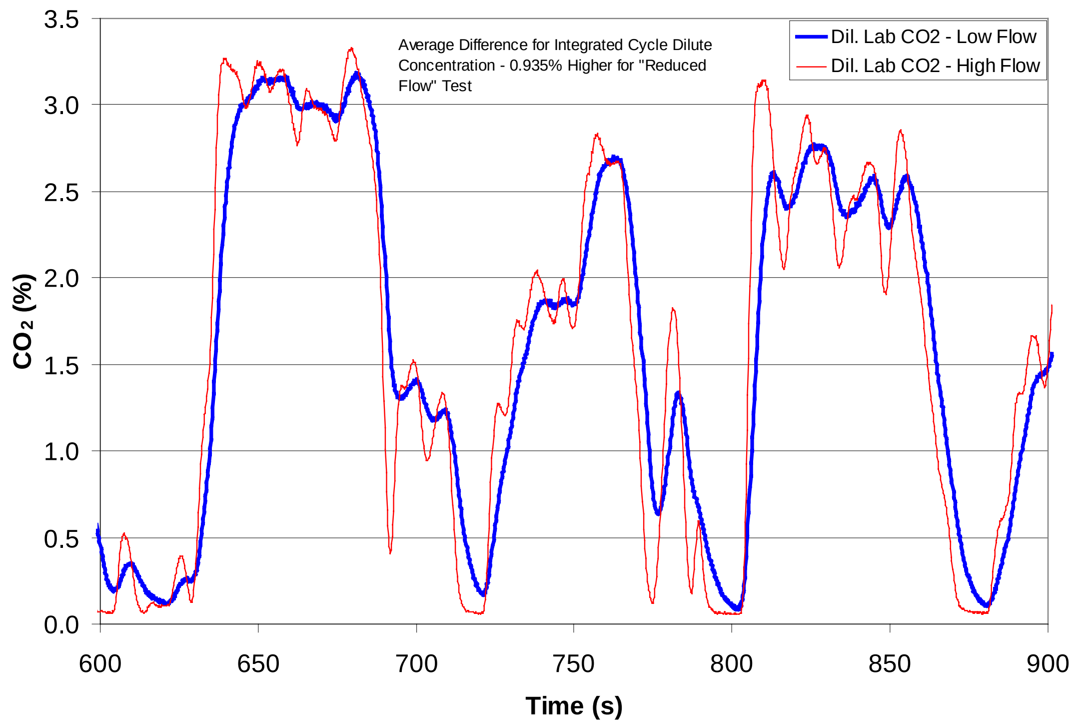


Figure 69 CO_2 Response for Rosemount Model 880 NDIR over the FTP test schedule from 600 to 900 seconds.

6.6 Alternative Emissions Reporting Techniques

The majority of current emissions databases is comprised of results in terms mass emissions and brake-specific mass emissions. Emissions data may also be presented on a fuel-specific basis; that is, the concentrations of CO, NOx, and UHC may be reported based upon fuel consumption that is derived from CO_2 concentration (with a given hydrogen-to-carbon ratio). This method eliminates the need for measuring instantaneous torque and exhaust flow rate, thereby reducing the uncertainties associated with measuring in-use brake-specific mass emissions. One possible criticism of fuel-specific measurements is that it would penalize engines with good fuel consumption [4]. However, engine manufacturers are committed to producing engines with the highest possible fuel efficiency for the customer. WVU is of the opinion that quantifying emissions on a fuel-specific basis is a promising alternative, in that it eliminates the problems associated with measuring torque and exhaust flow rate. This would significantly reduce the size and complexity of an OREMS.

6.7 Quality Control/Quality Assurance Procedures

A detailed presentation of QC/QA procedures associated with OREMS testing will be presented in a later report. This report has discussed very specific issues regarding the implementation of redundant measurements for NOx determination, vehicle speed, and exhaust flow rates. These measures have been afforded in order to identify problems that may manifest themselves during an on-road test, but could not be identified during pre- and post-test procedures. Such redundancy is further warranted due to the stand-alone nature of an in-use testing device, such as an OREMS, and would provide a comparative means of detecting sensor performance degradation during early stages.

QC/QA procedures that are customary to all WVU engine/vehicle testing programs were followed throughout the course of this study.

6.8 OREMS Commentary

Thorough evaluations of candidate OREMS have been presented in terms of measurement performance as compared to standard laboratory-grade devices. Such benchmark testing is important, but the resultant errors should not be the only means of performance assessment. For instance, if a “black box” evaluation is made, the final answer becomes the only measure of quantifying product performance. If the opportunity does not exist to integrate sound engineering judgment with a thorough understanding of the events that led to the final output, high confidence in performance cannot be justified. Measurement errors can often be blindly combined in such a manner as to cancel one another, thus reducing the overall measurement error associated with the “final answer.” Without a substantial amount of data collection, very little assurance can be gained by means such “black box evaluations.”

Testing procedures adopted for evaluating MEMS adhered closely to the recommendations found in CFR 40 Parts 86 and 89. Similarly, the data reduction techniques for this system mimic the raw sampling protocols presented in CFR 40 Part 89, governing raw exhaust emissions measurements for steady-state engine tests. Such sound engineering practices result in system errors that can be quantified, and measurement errors that can be explained.

The emissions data presented from the MEMS were analyzed according to CFR 40 regulations and SAE standards. It should be noted that there are no standards governing the analysis of transient raw emissions, let alone in-use, on-road, continuous raw emissions. The approach adopted by WVU was to measure the exhaust flow rate and raw emission concentration, and then to apply a constant shift in the measured emissions concentration, in order to align the calculated mass emissions data with engine power, since it is expected that NOx and CO_2 increase monotonically with power. The time shift for the emissions was performed on a test-by-test configuration basis (for example, engine test cell test and chassis test) to account for the variations in engine/vehicle exhaust systems. It is conceded that the issues of automated time alignment and diffusion in time merit future attention. The exhaust flow rate was calculated according to the Annubar manual and has the form

$$\dot{Q} = C' \sqrt{h_w * P}_{abs} \tag{6}$$

where C' accounts for the flow conditions and normalizes the actual flow rate to standard conditions. The emissions were converted from a dry to wet basis by using the dry CO_2 concentration and the known hydrogen to carbon ratio (y) of the fuel.

$$ppm_{wetbasis} = \frac{ppm_{drybasis}}{\left(1 + 0.5 * y * CO_2\right)} \tag{7}$$

The mass emissions were determined from CFR 89.419 on an instantaneous basis by

$$\dot{m} = const * \dot{Q} * ppm_{wetbasis}, \tag{8}$$

where the value of the constant (const) is dependant upon each specific emission constituent. The NO mass emission rate may be corrected on a continuous basis to account for ambient humidity levels. When this procedure is employed, ambient barometric pressure, dry-bulb temperature, and relative humidity are incorporated into the NO correction factor (K) to obtain the corrected NO mass emissions rate

$$\dot{m}_{NOcorr} = K * \dot{m}_{NOwet}. \tag{9}$$

Although in-use NOx data may be corrected in evaluating compliance, the results present herein are uncorrected (K=1) since ROVER reports uncorrected NOx.

The OREMS provided by the US-EPA (ROVER), regretfully, had to be evaluated using a "black box" approach. The system components could not be easily studied independently in order to permit accurate differentiation of various measurement errors. Moreover, the project objectives did not require or allocate resources for "reverse engineering" of the ROVER system. The operating procedures for ROVER (see Appendix A) were written by WVU and revised by Dennis Johnson, US-EPA. No documentation was provided by US-EPA regarding the necessary data reduction procedures that must accompany the ROVER output files in order to produce meaningful emissions reports. From the sample ROVER data file, included as Appendix B, it is apparent that the ROVER system merely reports mass emissions rates on a second-by-second basis. It does not produce brake-specific mass emissions. Moreover, all power inferences from ECU broadcasts that were used to produce brake-specific mass emissions ROVER data were provided by an interface developed exclusively for the ROVER by WVU. The ROVER-ECU interface was designed, according to US-EPA requests, to provide an analog input to ROVER that was proportional to ECU-derived power, using the same calculation methodology as the MEMS system. This analog input is proportional to the one-dimensional unit of engine power output rather than separate torque and speed. Hence it does not enable ROVER to identify NTE regions of operation, nor to calculate 30 second, brake-specific mass emissions within the NTE zone, which is a requirement mandated by the Consent Decrees. For NTE zone determination, engine speed and torque must be specified independently. However, the ROVER system that was evaluated was unable to process these required inputs. Although brake-specific mass emissions are reported herein for ROVER, all of the necessary data reduction required for the presentation of such data was afforded through the efforts of WVU and the results are not a unique product of ROVER. It also took significant effort, on the part of WVU, to translate the 5 Hz data from the laboratory-grade system and the MEMS into the non-uniformly spaced ROVER data, in order to provide for more equal comparison of generated results. From the above discussion, it must be concluded that ROVER cannot provide integrated 30 second windows of brake-specific mass emissions data. Moreover, ROVER is not suitable to assess the on-road emissions of heavy-duty diesel vehicles according to the requirements outlined by the Consent Decrees.

Documentation regarding the data reduction details for the ROVER system was not disclosed to WVU. Therefore, the only insight into this subject was afforded by means of inspecting the data output files. An analyzer correction factor is included in the output file, but the significance of the value has not been explained. However, when this factor was combined with the exhaust mass flow measurements and the cold, semi-dried, electrochemical cell NO measurements, the resultant NOx mass emissions that were reported were very comparable to those produced by the laboratory-grade analyzers and the MEMS. Considering the low sample flow rates used by ROVER and the lack of NO_2 conversion/determination, reported NOx measurements should have been erroneously low, due to the formation of NO_2 in the sample handling system. In addition, the water trap, which was located upstream of the gas analyzer in the ROVER sample stream, provided an absorption site for the NO_2 that would have formed throughout the sample line. It is suggested that this absorption should have further decreased the reported NOx emissions levels, as compared to those reported by systems that accommodate the presence of NO_2.

In addition to the problems encountered during data reduction, technological inadequacies of the basic ROVER design need to be discussed. The device uses cold sampling lines and employs a simple water trap, similar to the unit evaluated in Chapter 5. The system encountered flow rate faults during on-road testing, as a result of condensation saturating the sample probe filter. The system does not utilize a NO_2 converter, and does not provide for continuous measurements of intake air humidity. The dependence upon electrochemical NOx measurements is also a concern, considering the information gathered from industry experts during this evaluation. Close contact with the repair-grade analyzer industry as well as Bureau of Automotive Repair (BAR)-level industry experts, have provided numerous accounts of unacceptably high field failures and performance deterioration of electrochemical cells used for NO determination. Catastrophic failures would be detected in the field, but the degradation in response time, and hence overall measurement accuracy associated with transient emissions events, would be difficult to track considering the adherence to software-driven calibration procedures of currently available commercial multi-gas analyzers.

7 NOMENCLATURE AND ABBREVIATIONS

A/F	Air-to-Fuel Ratio
BAR	Bureau of Automotive Repair
bhp	Brake Horsepower
CFR	Code of Federal Regulations
CLA	Chemiluminescent Analyzer
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COV	Coefficient of Variation
DC	Direct Current
EAMP	Emissions-Assisted Maintenance Procedure
ECU	Electronic Control Module
EERL	Engine and Emissions Research Laboratory at West Virginia University
EGS	Electrochemical Gas Sensor
EMA	Emissions Measurement Apparatus
EPA	United States Environmental Protection Agency
ESC	European Steady-State Test
FET	Field-Effect Transistor
FID	Flame Ionization Detector
FTIR	Fourier Transform Infrared
FTP	Federal Test Procedures
g	Grams
g/bhp-hr	Unit of brake-specific mass emissions.
GPS	Global Positioning System
HC	Hydrocarbon
HCLD	Heated Chemiluminescent Detector
HDDE	Heavy-Duty Diesel Engine
HFID	Heated Flame Ionization Detector
hr	Hour
I/M	Inspection and Maintenance
LFE	Laminar Flow Element
lpm	Liters per Minute
MEMS	Mobile Emissions Measurement System Designed and Integrated by WVU
MTU	Michigan Technological University
NDIR	Non-Dispersive Infrared
NDUV	Non-Dispersive Ultraviolet
NESCAUM	Northeast States for Coordinated Air Use Management
NMHC	Non-Methane Hydrocarbons
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
NTE	Not to Exceed
O_2	Oxygen
O_3	Ozone

OBD	On-Board Diagnostic
OBE	On-Board Emissions System
OREMS	On-Road Emissions Measurements System
PM	Particulate Matter
ppm	Parts Per Million
PREVIEW	Portable Real-Time Emission Vehicular Integrated Engineering Workstation
QC/QA	Quality Control/Quality Assurance
RF	Radio Frequency
ROVER	Real Time On Road Vehicle Emissions Recorder
S-HDDE	Settling Heavy-Duty Diesel Engine
SO_2	Sulfur Dioxide
THC	Total Hydrocarbons
T_{90}	Time required for response to exceed 90% of final value given a step change input.
UHC	Unburned Hydrocarbons
US	United States
VOEM	Vito's On-the-Road Emission and Energy Measurement System
VITO	The Flemish Institute for Technological Research
WVU	West Virginia University
ZrO_2	Zirconium Oxide

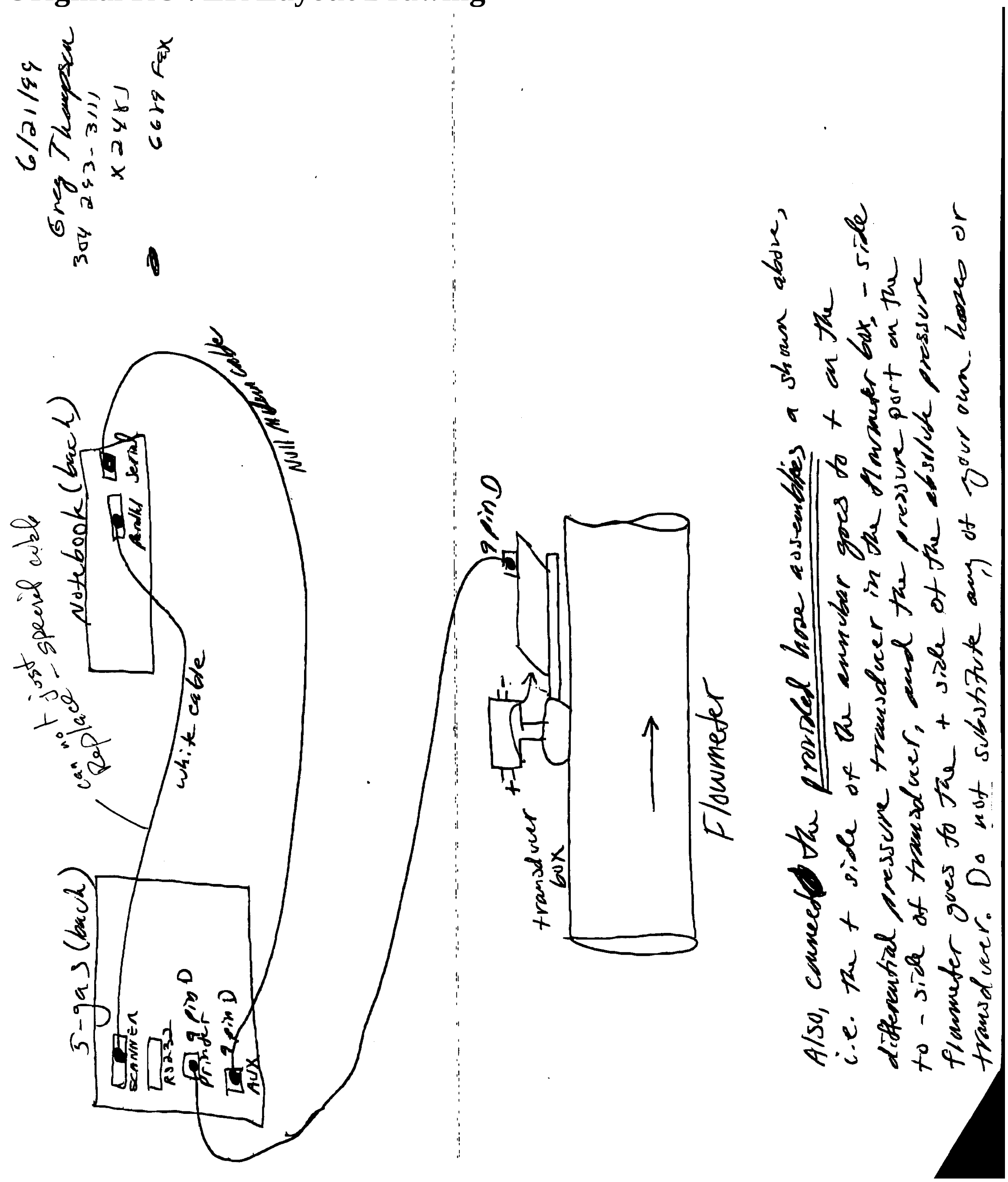
8 REFERENCES

1. Branstetter, R., Burrahm, R., and Dietzmann, H., "Relationship of Underground Diesel Engine Maintenance to Emissions," Final Report for 1978 to 1983 to the U.S. Bureau of Mines, Department of the Interior Contract H0292009, 1983.
2. Chan, L., Carlson, D. H., and Johnson, J. H., "Evaluation and Application of a Portable Tailpipe Emissions Measurement Apparatus for Field Use," SAE Technical Paper No. 921647, 1992.
3. Spears, M. W., "An Emissions-Assisted Maintenance Procedure for Diesel-Powered Equipment," University of Minnesota, Center for Diesel Research, Minneapolis, MN, 1997.
4. Englund, M. S., "Field Compatible NOx Emission Measurement Technique," SAE Technical Paper No. 820647, 1982.
5. Human, D. M. and Ullman, T. L., "Development of an I/M Short Emissions Test for Buses," SAE Technical Paper No. 920727, 1992.
6. Kelly, N. A. and Groblicki, P. J., "Real-world emissions from a modern production vehicle driven in Los Angeles," *Journal of the Air & Waste Management Association*, Vol. 43, No. 10, 1993.
7. Mackay, G. I., Nadler, S. D., Karecki, D. R., Schiff, H. I., Butler, J. W., Gierczak, C. A., and Jesion, G., "Dynamometer Intercomparison of Automobile Exhaust Gas CO/CO_2 Ratios and Temperature Between On-Board Measurements and a Remote Sensing Near Infrared Diode Laser System," Phase 1b Report to the Coordinating Research Council and National Renewable Energy Laboratory, 1994.
8. Mackay, G. I., Nadler, S. D., Karecki, D. R., Schiff, H. I., Butler, J. W., Gierczak, C. A., and Jesion, G., "Test Track Intercomparison of Automobile Exhaust Gas CO/CO_2 Ratios and Temperature Between On-Board Measurements and a Remote Sensing Near Infrared Diode Laser System," Phase 1c Report to the Coordinating Research Council and National Renewable Energy Laboratory, 1994.
9. Butler, J. W., Gierczak, C. A., Jesion, G., Stedman, D. H., and Lesko, J. M., "On-Road NOx Emissions Intercomparison of On-Board Measurements and Remote Sensing," Final Report, Coordinating Research Council, Inc., Atlanta, GA, CRC Report No. VE-11-6, 1994.
10. Gierczak, C. A., Jesion, G, Piatak, J. W., and Butler, J. W., "On-Board Vehicle Emissions Measurement Program," Final Report, Coordinating Research Council, Inc., Atlanta, GA, CRC Report No. VE-11-1, 1994.
11. Bentz, A. P. and Weaver, E., "Marine Diesel Exhaust Emissions Measured by Portable Instruments," SAE Technical Paper No. 941784, 1994.
12. Bentz, A. P., "Final Summary Report on Project 3310, Marine Diesel Exhaust Emissions (Alternative Fuels)," United States Department of Transportation United States Coast Guard Systems, Report No. CG-D-08-98, 1997.
13. Vojtisek-Lom, M. and Cobb, Jr., J. T., "On-Road Light-Duty Vehicle Mass Emission Measurements Using a Novel Inexpensive On-Board Portable System," Proceedings of the Eighth CRC On-Road Vehicle Workshop, San Diego, CA, April 20-22, 1998.
14. "Construction Equipment Retrofit Project," Northeast States for Coordinated Air Use Management, Boston, MA, 1998.

15. Butler, J. W., Kornisk, T. J., Reading, A. R., and Kotenko, T. L., "Dynamometer Quality Data On-board Vehicles for Real-World Emission Measurements," Proceedings of the Ninth CRC On-Road Vehicle Workshop, April 19-21, San Diego, CA, 1999.
16. Kihara, N., Tsukamoto, T., Matsumoto, K., Ishida, K., Kon, M., and Murase, T., "Real-time On-Board Measurement of Mass Emission of NOx, Fuel Consumption, Road Load, and Engine Output for Diesel Vehicles," SAE Technical Paper No. 2000-01-1141, 2000.
17. Jetter, J., Maeshiro, S., Hatcho, S., and Klebba, R., "Development of an On-Board Analyzer for Use on Advanced Low Emission Vehicles," SAE Technical Paper No. 2000-01-1140, 2000.
18. Miller, R. W., *Flow Measurement Engineering Handbook*, Third Ed., McGraw-Hill, New York, 1996.
19. Adachi, M., Hirano, T., Ishida, K., Cepeda, C., Nagata, Y., Kubo, A., and Nakamura, S., "Measurement of Exhaust Flow Rate: Helium Tracer Method with Mass Spectrometer," SAE Technical Paper No. 971020, 1997.
20. Herget, W. F., Staab, J., Klingenberg, H., and Riedel, W. J., "Progress in the Prototype of a New Multicomponent Exhaust Gas Sampling and Analyzing System," SAE Technical Paper No. 840470, 1984.
21. "Measurement of Intake Air or Exhaust Gas Flow of Diesel Engines," SAE Standard, SAE J244, 1992.
22. "Measurement of fluid flow in closed conduits – Guidelines on the effects of flow pulsations on flow-measurement instruments," International Organization for Standardization, ISO/TR 3313, Third Ed., 1998.
23. "Powertrain Control Interface for Electronic Controls Used in medium and Heavy Duty Diesel On-Highway Vehicle Applications," SAE Standard, SAE J1922, 1989.
24. "Joint SAE/TMC Electronic Data Interchange Between microcomputer systems in Heavy-Duty Vehicle Applications," SAE Standard, SAE J1587, 1996.
25. "Vehicle Application Layer," SAE Standard, SAE J1939/71, 1996.
26. Dearborn Group, Farmington Hills, MI, 1999.
27. Jackson, M.W., *Journal of Applied Chemistry*, Vol. 11, No. 12, 1962.
28. Jahnke, J. A., *Continuous Emission Monitoring*, Van Nostrand Reinhold, New York, 1993.

APPENDIX A ROVER OPERATING INSTRUCTIONS

Original ROVER Layout Drawing



Original ROVER Procedures

Laboratory Test Procedure for WVU

ROVER Flow Meter Installation

1) Install the proper diameter flow meter downstream of the muffler (if so equipped) with the exhaust flow in the direction indicated on the annubar flow element. The chosen flow meter diameter should not be significantly larger than the diameter of the majority of the *vehicle's* exhaust system between the engine and tailpipe. There must be no exhaust leaks in the exhaust system. Do not exceed an exhaust gas temperature of 850 F.

2)Install the transducer box on the flow meter. Check to ensure all hoses are tight. The transducer box must be installed with the hoses emanating downward or to the side, i.e. not tilted upward.

3)The transducer box does not reach high temperatures when installed on a moving vehicle. When installed on a stationary engine, the transducer box should not be installed such that large temperature increases will be experienced. Such a situation can arise from locating the transducer box above the hot flow meter with restricted air flow.

Analyzer Installation and Setup

1)Perform a gas calibration check each day, before testing begins and document the results. All gases must read within +/- 1% of calibration gas values.
2)Connect the sample line filter assembly to the sample line nipple on the flow meter and place a new filter element in the housing before **each** test *phase*.
3)Connect the 9 pin data cable to the transducer box.
4)Perform the analyzer zeroing procedure immediately before each test phase commences.

Computer and Software Setup

1)Turn on computer and boot up ROVER software.
2)Enter the flow meter constant supplied with the chosen flowmeter.
3)Enter the calibration constants supplied with the chosen flowmeter transducer box.
4)Run the ROVER software.
5)Under zero-flow conditions, note any non-zero values associated with the annubar_dP value and check the exhaust temperature reading. It is not sufficient to turn off the CVS blower to ensure a zero-flow condition. The flow must be blocked, or the CVS system disconnected from the flowmeter.
6)Stop the program and perform the manual zeroing process based on the results of step 5.
7)Restart the program and perform the test. Leave the program running during hot soaks and during analyzer zeroing.
8)Continue to run for at least 60 seconds after completion of the test.

If you have any questions regarding these instructions or other aspects of running the Rover system, please call Leo Breton at (202) 564-9245 or Dennis Johnson at (202) 564-9278.

WVU Developed Procedures for ROVER

ROVER Test Procedures

Greg Thompson and Dan Carder
Mechanical and Aerospace Engineering
West Virginia University
August 25, 1999

Emissions

Emissions are measured with a Snap-On MT3505 analyzer.

Snap-On analyzer must be on for at least 3 hours.

Filter housing located at the flow tube must be at least at 45°. This is to prevent water condensation on the filter.

Water condensation in the sample line has led to HC hang-up issues.

Panel mounted filters located on the back panel of the Snap-On MT3505 should not require frequent changing due to the implementation of the primary sample line filter.

Change the sample line filter frequently whenever the engine is off, i.e., in soak and as needed when road testing (every 20-30 minutes) depending on the engine and operating conditions.

Plugged sample line filters can lead to increased delay times, which, in turn, lead to inaccurate compensation of measured emission events (phasing).

Sample line connects to back panel filter inlet.

Electrochemical O_2 cell replacement is “plug and play”, requiring no special updating. This sensor should be replaced every 6 months [according to Leo Breton]. The NO cell replacement is not “plug and play” – it has a special start-up procedure in the **Options** menu, **Service** submenu.

Check filter life by visual inspection.

Do not block or modify any hoses or vents.

Be careful not to over-tighten sample line at the analyzer.

For the leak test, disconnect sample line from the flow tube and block with finger or other suitable device.

The Snap-On bench will shut the pump off after 7-10 minutes if the CO_2 is less than ~3%.

The auto zero should be set to "OFF."

The Scotty bottles used for calibrations should be checked for listed concentration values prior to use.

A one point gas calibration is used.

The calibration gas should be set to 10 psi when flowing in calibration.

If CO_2 level in the sample falls below a predetermined amount for 7 or 10 minutes [3% according to Leo Breton], the Snap-On unit will exit the gas measurement mode, and the unit must be reactivated. If this occurs, ROVER will continue to log data, but until reset, the SUN will be reporting inaccurate results. It should be noted that this fault occurred during the initial FTP performed by Dr. Thompson. If the analyzer is zeroed and the exhaust measurement mode is entered immediately prior to starting a test, there should not be a problem. The analyzer will continue to measure emissions (even with low CO_2) for a period of time before shutting off the pump.

Flow Tube

Annubar temperature limit is 950 °F.

The Annubar does not need serviced (cleaned).

Interface Box

When testing in the lab, direct a fan at the box.

Pressure lines must point down (to create a water trap) to prevent water from entering the pressure transducer.

The red LED should be lit when operational.

Pressure lines from the flow tube to the transducers have flow restrictions built into them to dampen oscillations.

Annubar pressure transducer tube connections need to be oriented at least 45° upward in order to prevent condensation from reaching the diaphragms.

Keep temperatures less than 950°F for the test section.

No lines should be altered.

For the annubar pressure transducer enclosure, the live side of one pair for the absolute measurement is marked "+", the other is plugged. The upstream side of the Δp measurement is to be attached to the "+" side, the downstream side should be connected to "-."

The thermocouple in the test section is [according to Leo Breton] a 1/16" J-type ungrounded unit.

Only one of the absolute pressure transducers is active.

Thermocouple tends to be one component that may fail, particularly if bent or hit. TC response should be observed before and after each test to verify proper operation. It is a 1/16", ungrounded, J-type thermocouple.

Data Acquisition

All cables are incorporated into the data acquisition system. Do not change any cables.

The ROVER software is a LABVIEW executable named ROVER_6.00b. Use the default settings when the program starts. However, if the software does not find the analyzer, check the COM port setting (it should be set to Port 0 for COM1). In addition, the intercept values for the pressure transducer linear fit must be changed to zero the readings before each test.

Port Settings:

Analyzer 1 is Port 0 (Corresponding to COM 1)

Scantool is Port 1

Baud Rates should remain at the 19.2 default value.

Sampling frequency for the emissions analyzer is 1 Hz; the interface box (absolute pressure, differential pressure, and temperature) is collected at 25 Hz and averaged to 1 Hz. All data is reported at 1 Hz and cannot be changed.

Computer parallel port to Snap-On Scanner port.

Computer serial port to Snap-On auxiliary port.

Snap-On printer port to test section (annubar pressure transducer box)

Snap-On port marked RS-232 is left vacant.

From the data file EVERY entry (line) has been phase adjusted (in time).

The OTC Scan Tool is not installed.

The GPS unit is not installed.

Operating Procedures

1. Connect all lines and cables per the drawing by Leo Breton.
2. Boot the computer.
3. Run the program ROVER_6.00b that is located on the Desktop.
4. The emissions analyzer must be on for at least 3 hours before testing; however, it can be unplugged and moved with only a 30 minute warm-up time.
5. Install a new filter into the filter housing. This should be performed prior to each and every test, as well as in soak.
6. Disconnect the emissions sample line from the flow tube and perform a leak check (Options → Service → Leak Check). Proceed if passed, otherwise determine where the leak is located and fix. This step must be performed each time the filter is changed.
7. Perform the gas calibration.
    - Connect the Scotty bottle, with a regulator set to 10 psi, to the calibration port on the analyzer. Do not turn on the bottle.
    - Enter into the calibration menu (Options → Service → Gas Calibration).
    - Enter in the concentration values.
    - Press the calibrate button.
    - After the zero is completed, turn the Scotty bottle on at 10 psi while flowing and continue.
    - After the calibration is completed, Press F1 to continue. Turn the Scotty bottle off and disconnect.
    - The Snap-On MT3505 utilizes a 1-point calibration (span and zero) for all channels. The Snap-On DGA1000 utilizes a 2-point calibration for the NDIR channels and a 1-point for the electrochemical cell channels [according to Leo Breton].
8. Have power to the box for at least 10 minutes prior to zeroing. Perform the pressure transducer zeroing. This must be done prior to each test.
    - Turn off the engine and prevent any potential flow through the flow tube. If performing an engine test in the test cell with the blower on and the air handler unit on then the flow tube may need to be disconnected from the exhaust system and the end capped.
    - Observe the values in the ROVER software relating to the absolute and differential pressure transducers.
    - At the onset, the units flow measurement should be zeroed. The units in the onscreen menu correspond to slopes and intercepts of the individual response curves. The slopes must not be altered, but the intercepts must be varied to obtain "zero" values. These values would be 0" H_2O for Δp, barometric (corrected) pressure in "Hg for the total pressure, temperature of the test section (to correct the temperature, not to zero it), and 0.100 as the last entry (auxiliary input). Adjust the intercept values so that readings will be within 0.000±0.002. This is accomplished by adding (subtracting) the "zero" value to (from) the intercept value.
    - The slope values must not be altered from the default values. A list of the "correct" values may be found on the inside cover of the Snap-On manual.
    - Stop the data collection ("Stop" button) and then restart to observe the new "zero" values.
    - Repeat the above two steps until the "zero" value is 0.000±0.001.
    - Use the "Stop" button to end the zeroing test.
9. Immediately before the test, re-zero the analyzer (F4).
10. Make sure that the auto zero is "off."
11. Start the data collection by pressing the "⇒" icon in the ROVER software.

12. Enter in any information that you want to appear in the output file header.
13. Verify proper system operation.
14. At the end of a test, wait 30 seconds before stopping the data collection. Click on the "Stop" button. If the data collection continues depress the stop button for a longer period of time.
15. Additional information can be entered as a footer to the output file.
16. The output file will use a time stamp as the filename. A copy of the file can be saved to a different filename, also stored in the default directory.
17. With the sample line off the analyzer and filter removed, blow out the sample line (from analyzer end) with dry shop air after testing to remove condensation.

APPENDIX B EXAMPLE ROVER OUTPUT FILE

Wednesday, February 16, 2000
8:28:17 PM
Test No:021600 MEMSCYC01
Vehicle:
Notes :
Analyzer Delays HC, CO, and CO2 by 9 seconds
25 readings averaged for analog inputs
Scan Tool Cartridge Used: Not Used
OPEN=0;CLOS=1;OFF=0;ON=1;NO=0;YES=1;MPH= ; V= ;IHG= ;PSI= ;MS= ; F= ;RICH=1;LEAN=0; %= ; =; =;
Log file name is c:\rover\data\Feb16_8.28P
1.000 Hz data
Analog Inputs: Annubar_dP = voltage x 4.394+-5.100; Exh_P = voltage x 4.929+-6.680; Exh_Temp = voltage x 1000.000+0.000; Power (hP) = voltage x 80.000+0.000;
Fuel Economy Constants: HC = 0.869; CO = 0.429; CO2 = 0.273; g/gal = 3197.157;
Flow Meter Calibration Constant: 798.000
Vmix not adjusted for condensation
Analyzer Concentrations adjusted for condensation (below 140F) by divisor: [1-0.82*[0.1057624 + (0.0020185*Texh(F)-0.0000195*Texh(F)^2)]]

Seconds	Delta t (s)	Annubar_dP	Exh_P	Exh_Temp	Power (hP)	Vmix'(scfm)	Vmix_CF	HC(ppm)	CO(%)	CO2(%)	O2(%)	NOx(ppm)	TEMP	Lambda(B)	A/F	Lambda	AnalCorFac	miles driven	HC(mg)	CO(mg)	CO2(mg)	O2(mg)	NOx(mg)	mpg	mgal
0.000	0.000	0.2860	29.1907	152.9053	0.0801	124.9870	1.0000	8.0000	0.0100	1.0400	19.2200	136.0000	81.900	13.45	197.22	13.54	1.0014								
1.040	1.040	0.2860	29.1907	152.9053	0.0801	124.9870	1.0000	8.0000	0.0100	1.0500	19.1300	137.0000	81.900	13.28	195.38	13.41	1.0015	0.000300	3.3912	7.1320	1176.7734	15592.5026	16.0505	2.551	0.11779
2.049	1.009	0.2859	29.0908	152.4597	0.0977	124.7965	1.0000	8.0000	0.0100	1.0400	19.3200	137.0000	81.900	13.52	197.22	13.54	1.0014	0.000574	3.2854	6.9095	1129.2039	15256.0987	15.5498	5.080	0.11305
3.036	0.987	0.2858	29.1089	152.0813	0.0684	124.8521	1.0000	9.0000	0.0100	1.0600	19.2200	137.0000	81.900	13.22	193.46	13.28	1.0016	0.000832	3.6164	6.7606	1126.1185	14850.0843	15.2147	7.377	0.11283
4.035	0.999	0.3177	29.1700	152.4475	0.0654	131.7342	1.0000	8.0000	0.0100	1.0500	19.2200	137.0000	81.900	13.34	195.38	13.41	1.0015	0.001120	3.4333	7.2206	1191.4032	15860.6176	16.2501	9.389	0.11926
1066.035	0.994	0.3047	29.1538	516.7236	0.6826	102.1199	1.0000	11.0000	0.0100	0.9400	18.7500	164.0000	81.900	14.40	217.36	14.92	1.0005	0.294344	3.6449	5.5751	823.5149	11946.5408	15.0194	3549.742	0.08292
1067.035	1.000	0.3462	29.2080	515.9180	0.7109	108.9985	1.0000	11.0000	0.0100	0.9400	18.7500	164.0000	81.900	14.40	217.36	14.92	1.0005	0.296399	3.9139	5.9865	884.2909	12828.2051	16.1278	3328.847	0.08904
1068.036	1.001	0.2983	29.1761	514.3738	0.6289	101.2022	1.0000	11.0000	0.0100	0.9400	18.7500	164.0000	81.900	14.40	217.36	14.92	1.0005	0.296973	3.6376	5.5639	821.8616	11922.5578	14.9892	3588.654	0.08275
1069.036	1.000	0.2969	29.1702	513.4277	1.0142	101.0033	1.0000	11.0000	0.0100	0.9300	18.7500	164.0000	81.900	14.54	219.65	15.08	1.0004	0.296954	3.6272	5.5479	810.7846	11888.3371	14.9462	3636.508	0.08166
1070.035	0.999	0.3396	29.1956	512.6770	0.6968	108.1113	1.0000	10.0000	0.0100	0.9400	18.7500	164.0000	81.900	14.41	217.50	14.93	1.0005	0.296935	3.5256	5.9318	876.2161	12711.0662	15.9806	3369.813	0.08812
1071.035	1.000	0.3226	29.1883	511.5662	0.4468	105.4176	1.0000	11.0000	0.0100	0.9400	18.8400	164.0000	81.500	14.46	217.44	14.93	1.0009	0.297510	3.7839	5.7876	854.9123	12461.5459	15.5920	3456.149	0.08608

8:47:14 PM
End of test

Problems:

A/C Setting:Off
Economy/Performance Switch:Economy
Windows:Open
Highway Cruise Control:Off
Driver:Fred Parks
Fuel Type:Cert. Fuel
Route Driven:"Cadillac"
Traffic Conditions:Medium

ATTACHMENT 1 WHITE PAPER

ASSESSMENT OF MOBILE MONITORING TECHNOLOGIES FOR HEAVY-DUTY VEHICLE EMISSIONS

Developed By

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Nigel N. Clark
Gregory J. Thompson
Donald W. Lyons

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March 10, 1999

FOREWORD

This report was prepared by the Department of Mechanical and Aerospace Engineering, College of Engineering and Mineral Resources, West Virginia University, Morgantown, WV with funding provided by the Settling Heavy-Duty Diesel Engine (S-HDDE) manufacturers (Caterpillar, Inc.; Cummins Engine Company, Inc.; Detroit Diesel Corporation; Mack Trucks, Inc.; Navistar International Transportation Corporation; Volvo Truck Corporation). This report is the first step of a workplan, submitted to the S-HDDE manufacturers, that is aimed at meeting the requirements of Phases I and II of the Consent Decree entered into by the United States and the S-HDDE manufacturers

The objective of this report is to consolidate information that will enable the selection of analyzers, sensors, exhaust sampling systems and other sub-systems and the subsequent integration of a state-of-the-art Mobile Emissions Measurement System (MEMS).

The authors express their sincere appreciation to all those who have provided technical data and information regarding previous in-field emissions testing efforts and emissions measurement instrumentation. A number of faculty, staff, and students at West Virginia University contributed to this report. Special recognition for their significant contribution goes to Dan Carder, Engineering Scientist, and Robert Craven, Research Associate.

TABLE OF CONTENTS

1 INTRODUCTION AND BACKGROUND

1.1 Introduction and Objectives

Heavy-duty vehicles are normally powered by diesel-fueled engines and contribute a substantial fraction of urban emissions inventories. In order to minimize the effect of the operation of heavy-duty vehicles on the atmosphere, the United States Environmental Protection Agency (US EPA) has mandated that engine manufacturers design engines that will produce low levels of regulated exhaust emissions constituents. To assure that this objective is achieved, it is necessary to measure the levels of these constituents in the exhaust stream of engines operating in a vehicle under realistic operating conditions.

The objective of this paper is to discuss the design features and practicality of a Mobile Emissions Measurement System (MEMS) which can be used to measure exhaust emissions from heavy-duty vehicles operating in the field. It is desirable to develop an on-board portable instrument system which can be used to measure the levels of certain regulated exhaust constituents. The levels measured by the MEMS should be representative of the levels which would be measured if the engine were removed from the vehicle and tested in accordance with the federal test procedures for engine certification which are prescribed in government regulations and further prescribed in the recent "Consent Decree" between the government and six settling heavy-duty diesel engine (S-HDDE) manufacturing companies. In order to examine the practicality of MEMS, West Virginia University has gathered and consolidated information on the currently available emissions measurement technologies and their ability to provide accurate, repeatable, and reliable mass emissions rates of gaseous exhaust pollutants (oxides of nitrogen, carbon monoxide, total hydrocarbons, and carbon dioxide) of heavy-duty vehicles.

In the 1970's, the EPA in cooperation with the engine manufacturers developed a test method and procedures for measuring the emissions from heavy-duty engines. This procedure is generally identified as the Federal Test Procedure (FTP) for heavy-duty engine emissions certification. The FTP has been published in the Code of Federal Regulations (CFR) Title 40 Part 86. Since the establishment of this test procedure, the EPA (and some state governments) has promulgated emissions standards which require that all heavy-duty on-road engines introduced into commerce in the United States operate in a manner so as to not produce levels of certain emission constituents which are in excess of those specified in the standard when measured using the FTP. Over the years, the acceptable levels of emissions specified in the regulations have been lowered and the engine manufacturers have greatly reduced the levels of the regulated emissions constituents.

The Consent Decree requires the engine manufacturers to produce engines that will meet the weighted average emissions limits applicable to the Euro III test procedure that incorporates the steady state test and emission weighting protocols identified as the "ESC Test" in Annex III to the Proposal adopted by the Commission of the European Union on December 3, 1997. In addition, the engine manufacturers agreed that engines will meet Not to Exceed limits, Smoke or Alternative Opacity limits, and Transient Load Response limits. Engines must meet these limits when new and during in-use operations throughout their Useful Life. These new requirements explore an engine operating envelope that extends beyond that of the FTP.

1.2 Engine Emissions Testing Methods

The FTP specifies that the engine be placed on an engine test stand and coupled to a dynamometer which applies torque to the engine and allows the engine to be loaded during operation. The engine is operated through a prescribed cycle of speed and torque for a test period and the amount of various constituents of emissions as well as the speed and torque are measured. From the measured results, the amount of each regulated emission constituent can be calculated relative to the energy output of the engine. The emissions constituent levels are normally reported in units of mass of emissions per unit of engine energy output averaged over the test period. In the United States, the usual units are grams per brake horsepower hour (g/bhp-hr). The specific constituents which are normally measured and controlled are carbon monoxide (CO), oxides of nitrogen (NOx), total hydrocarbons (THC), non-methane hydrocarbons (NMHC), and particulate matter (PM). Other emissions constituents may be measured and may be regulated for certain specific situations or may be controlled in future regulations. The amount of each constituent which is emitted is normally determined by measurement of the total diluted exhaust emission mass flow and the concentration of each constituent in the diluted exhaust. The energy output of the engine over the cycle can be determined by measuring the instantaneous speed and torque and integrating their product over the test.

There are three major components to the measurement system used for heavy-duty engine certification, namely the dynamometer component for applying a controlled load and for measuring the engine speed and torque, the exhaust collection and flow measurement component, and the emissions measurement instrumentation component.

The dynamometer component applies a controlled programmable torque and speed profile to the engine in order to establish operation under load. In normal operation, the level of exhaust constituents emitted from diesel engines varies greatly depending upon the speed and load and also upon the rate of change of the speed and load. In order for the emissions measured during the test to be representative of normal in-use operations of the engine, it is necessary to load the engine during the test and to operate the engine over a number of different changing conditions of speed and load. The dynamometer component provides the capability to apply a controlled load to the engine and also to provide a measurement of the speed and torque output of the engine.

The second component of a heavy-duty engine emission measurement system is the exhaust collection and flow measurement component. All of the exhaust from the engine is collected and diluted with clean air in a dilution tunnel. The dilution of the exhaust allows cooling of the exhaust so that reactions which naturally occur in the atmosphere can take place. The volume flow of the diluted exhaust is measured using either a positive displacement pump or a critical flow venturi and the temperature and pressure of the flow are measured allowing computation of the total mass flow of diluted exhaust.

The third component of the emissions measurement system is instrumentation for measuring the levels of the emission constituents. Heated probes extend into the dilution tunnel to sample a small amount of the diluted exhaust on a continuous basis over the period of the test. These samples of the exhaust are either stored in a gas-tight bag for analysis after the completion of the test or are directed to gas analysis instruments for continuous measurement of the concentrations of the constituents. The mass flow of the emissions constituents is computed as the product of the mass flow of the total diluted emission stream multiplied by the concentration of each particular constituent in the stream.

The FTP and Euro III procedures prescribe the use of precision laboratory-grade gas analysis instruments and instrumental methods. Several instrument manufacturers have developed precision instruments suitable for obtaining reliable, accurate and repeatable measurements of the constituents of the exhaust. The levels of carbon dioxide (CO_2), and CO are generally measured using non-dispersive infrared spectral analysis techniques, NOx using a chemiluminescent method, and THC using a flame ionization detection technique. For measurement of PM, the sample stream is usually further diluted and passed through a filter which is weighed before and after the test to determine the mass of particulate collected on the filter. The FTP and Euro III test methods require elaborate calibration and quality control procedures which include extensive and frequent zeroing, spanning, and calibration of the instruments with laboratory-grade calibration gases.

1.3 Vehicle Emissions Testing Methods

To demonstrate that the actual levels of exhaust emissions are below the prescribed standards, engine manufacturers test a specified number of engines which they produce before they are put into service and installed in a vehicle. However, the in-use testing of engines after they have been installed in vehicles and put into service poses a difficult problem. It is expensive to remove an engine from a vehicle in order to place the engine on a test stand to perform the prescribed exhaust emissions measurements. For this reason, alternative methods of testing which allow the engine to be tested while mounted in the vehicle are desirable.

When testing an engine in a vehicle it is necessary to load the engine during the test and to operate the vehicle so that the engine operates over varying speed and load conditions. There are two practical ways to apply a load on an engine which is mounted in a vehicle. The first is to place the vehicle on a chassis dynamometer which loads the vehicle and the engine while operating in place. The second is to load the engine by driving the vehicle on the road while measuring the emissions as the vehicle travels. The use of a chassis dynamometer allows the use of a laboratory-grade emissions measurement system in conjunction with chassis dynamometer and the use of measurement technologies which are already well developed. Measurement of the emissions while a vehicle is driven on the road requires the development of a new MEMS.

Chassis dynamometer systems have been developed and used for many years. Through extensive use it has been demonstrated that they are a reliable tool for studying vehicle emissions. The chassis dynamometer provides a method for applying a dynamic programmable load to the drive-train of the vehicle, and thus to the engine, while the vehicle is operated in place, and also of measuring the load and speed so that the engine power output can be computed. The existing chassis dynamometer laboratories can be used to make measurements of in-use engine emissions over the lifetime of the vehicle and can also be used to study the performance and reliability of MEMS which are the focus of this paper.

Most heavy-duty chassis dynamometers are permanently installed in a laboratory at one location. Vehicles to be tested are transported to the location of the laboratory for testing. West Virginia University has developed and operates two transportable heavy-duty vehicle chassis dynamometer systems which can be transported to a location near the home base of vehicles that are to be tested.

With a chassis dynamometer, the engine is loaded by applying a load to the drive train of the vehicle. The drive wheels of the vehicle are placed on a roller or set of rollers. Most chassis dynamometers are designed to apply the load to the roller(s) and the load is transmitted to the driveline of the vehicle via the tires. The West Virginia University transportable heavy-duty chassis dynamometers couple the load directly to the drive axle by coupling through the wheel lug bolts. This approach bypasses the concern that the actual torque applied to the vehicle may be different from the programmed torque to the rollers because of tire slippage or tire dynamics which might be peculiar to the roller design and not representative of actual road and tire interactions.

While connected to the dynamometer, the vehicle is operated by a driver or an automatic controller through either a pre-selected or random test cycle. Although the dynamic torque or load applied to the vehicle may be controlled over a wide range of selectable speed-torque cycles, it is generally not possible to apply to the engine the same speed-torque cycle of operation prescribed by the FTP heavy-duty engine certification test. The FTP certification test was developed for an engine test stand dynamometer where the load to the engine is coupled directly to the engine drive shaft. The engine is operated through a very aggressive operating cycle with numerous rapid accelerations and decelerations occurring across a very short duration. Very few heavy-duty vehicles can actually be driven in a manner which corresponds to this aggressive cycle. West Virginia University researchers, with funding from the California Air Resources Board, have developed a procedure which produces a close approximation of the FTP engine loading cycle by operating the vehicle in a single gear. This procedure is described in a SAE technical paper [1].

The heavy-duty chassis dynamometer systems can use the same emissions measurement instruments and instrumental methods as are prescribed for the FTP or Euro III procedures for engine certification, that is, precision laboratory-grade gas analysis instruments and instrumental methods and the careful zero, span, and calibration of the instruments using laboratory-grade calibration gases. The accuracy, reliability, and repeatability of these laboratories are comparable to the engine test stand dynamometer systems used for engine certification testing.

1.4 Mobile Emissions Measurement Systems

The second method that can be used to load a heavy-duty vehicle for testing is to drive the vehicle on the road. This method requires a MEMS which can be transported along with the vehicle as it is driven on the road during the test. A MEMS procedure has several advantages. One of the major advantages is that it may be possible to conduct emissions tests at low cost. MEMS based systems have been developed and demonstrated for a number of specific emissions measurement objectives. The use of a MEMS has been shown to be useful for monitoring the emissions from light-duty gasoline fueled vehicles and obtaining measurements of the emissions which are comparable to those obtained when the vehicle is tested on a chassis dynamometer in accordance with the FTP for light-duty vehicle testing. The most extensive MEMS is a recent development by Leo Breton and Dennis Johnson and others with the Office of Mobile Sources of the EPA. They generally refer to their system as ROVER (Real-Time On Road Vehicle Emissions Recorder). The emissions limit standards for light-duty vehicles are based upon units of mass of exhaust constituent per distance traveled. This approach thus requires measurement of the actual distance traveled but does not require measurement of engine output energy.

However, a reliable and accurate MEMS for heavy-duty vehicles has not yet been demonstrated. There is a number of difficult issues which must be resolved in order for a MEMS to obtain measurement results which are comparable to the heavy-duty engine FTP, the Euro III, other specific speed load cycles, or representative of in-use operations. One factor which makes the design of a MEMS system for heavy-duty vehicles more difficult than for light-duty vehicles is that the emissions limit standards are based upon units of mass of exhaust constituent per energy output of the engine rather than mass per distance traveled (g/mile or g/km). Therefore, it is necessary to measure or estimate the energy output of the engine, which is more difficult to measure than distance traveled by the vehicle. Brake specific units for reporting emissions levels include g/bhp-hr (or g/kW-hr). Emissions levels may also be reported on a fuel specific basis, such as mass of emission per mass of fuel consumed (g/kg of fuel), or on an emissions basis, such as mass of emission per mass of carbon dioxide (g/g CO_2). Reporting of emissions levels in various formats will provide confidence in the reported brake specific emissions values.

A MEMS must have certain operational characteristics in order to be practical for in-use vehicle testing. Foremost, the system must accurately and reliably measure the levels of certain constituents of the exhaust. The measurements must be repeatable, and correlate with measurements which are made in an engine laboratory or with a chassis dynamometer laboratory using laboratory-grade instruments and instrumental methods. It would be desirable for a MEMS to measure each and all of the regulated constituents of engine exhaust or additional constituents which might be harmful to the atmosphere. However, it essential that the system be capable of reliably measuring NOx emissions levels. It is essential that the instruments and methods used to measure the levels of exhaust constituent be reliable and accurate in field use. It is also essential that accurate calibration methods and procedures be incorporated as part of the measurement system.

The MEMS must be portable. There is not much room in many heavy-duty vehicles to place on-board the emissions measurement instrumentation, so the unit must be compact in size and lightweight enough to be easily placed in or on the vehicle. The MEMS system will need to attach to the exhaust pipe of the vehicle and must be capable of accommodating the very broad variety of exhaust pipe designs typical of heavy-duty vehicles. The exhaust pipes of heavy-duty vehicles may exit from the rear, the top, the side or the middle of the vehicle. Some vehicles have dual exhaust and some single exhaust, utilizing a variety of exhaust pipe diameters. Frequently, heavy-duty vehicle exhaust pipes have a permanently attached mechanical device or deflector on the end of the pipe.

Diesel engines for heavy-duty vehicles are produced in a very broad range of engine displacement. The range of mass flow from the exhaust varies greatly over this broad range. The MEMS must be capable of accommodating and reliably measuring exhaust flow rates over this broad range. In addition, it is essential that the installation of the MEMS on the exhaust pipe have no influence on the exhaust back pressure as this affects engine operation. The possibilities of inferring exhaust flow from intake flow also exists, but must first be proven as a reliable alternative.

The time lags and response function in each instrument system component must be understood and accounted for in the analysis of the test results. Some measured parameters, such as speed and torque may be measured instantaneously on the engine itself, while other parameters, such as the exhaust flow or concentration level of exhaust constituents, may be significantly delayed by the time it takes for the engine exhaust to travel from the engine through the exhaust pipe and then through probe lines to the analyzers. In addition, some types of gas analysis sensors utilize measurement technology which results in a finite response time between changes in constituent concentration and output reading of the analyzer. During transient operation of the vehicle the measured exhaust emissions are compared to the power output of the engine at any particular time and it is essential that the time lags in the measurement system be accounted for and understood.

In addition, the MEMS, with its associated sensors and sampling lines, must be expected to function accurately over a wide range of weather conditions and varying altitudes.

On some heavy-duty vehicles, there will be a very long distance from the most practical location of the instrument unit of the MEMS and the exit of the exhaust pipe. On these vehicles the exhaust sampling probe lines will be long and the heating of the lines may be necessary to prevent water and exhaust constituents from condensing on the walls of the sampling lines. In addition, since the length of exhaust pipes and sampling lines may vary greatly from vehicle to vehicle, the MEMS must be able to reliably accommodate the variable sampling lag times related to different exhaust flow line lengths.

Most heavy-duty vehicles can supply a limited amount of electrical power which could be used to power the MEMS. The available power would be either 12 or 24 volt direct current with a current probably limited to less than 50 amperes. If a MEMS requires additional power, a power supply will need to be provided as part of the device.

In order to determine or estimate the level of emissions constituents for heavy-duty vehicles it is necessary to measure several parameters including engine speed, engine torque, exhaust stream mass flow, and exhaust constituent concentration in the exhaust stream. Procedures which might be used for a MEMS to measure or estimate each of these parameters are discussed in individual sections which follow in this paper.

2 PRIOR PORTABLE IN-FIELD EMISSIONS MEASUREMENT SYSTEMS

2.1 Introduction to Prior Systems

In-field emission 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. A review of the work performed for portable and mobile emissions measurement systems over the last 20 years follows.

2.2 In-Field Measurements

2.2.1 Southwest Research Institute, 1983

Work was performed by Southwest Research Institute from 1978 to 1983 to develop a system to test diesel engines in a mine for an I/M program [2]. The transportable system consisted of a portable engine dynamometer, laboratory-grade emissions instruments, volumetric fuel flowmeter, and a laminar air meter. The emissions measurement system consisted of a heated flame ionization detector (HFID) for HC, non-dispersive infrared (NDIR) analyzers for CO and CO_2, a heated chemiluminescent analyzer (CLA) for NOx, and a polargraphic analyzer for oxygen (O_2). Calibration gases for these analyzers were carried along with the unit. The PM measurement system included a mini dilution tunnel. Although this system was transportable, the level of portability was minimal and therefore, could not be used for on-board vehicle emissions measurements.

2.2.2 Michigan Technological University, 1992

Michigan Technological University (MTU) researchers developed an Emissions Measurement Apparatus (EMA) system and reported results from underground mining equipment tests [3]. The EMA was designed to measure both PM and gaseous emissions. It consisted of a dilute bag sampling system, a mini-dilution tunnel for gravimetric analysis of PM, battery powered portable emissions analyzers (for off-line bag analysis), and heated sample lines (to avoid thermophoresis and condensation related problems). A comparison of the portable emission analyzers with the laboratory-grade analyzers on steady-state engine dynamometer tests showed that the results for CO_2 were within 5%, CO within 10%, and NO within 5%. The PM emission results were within 7% of the laboratory equipment. However, the EMA system was too bulky and labor intensive to use as a MEMS for on-board vehicle measurements.

2.2.3 University of Minnesota, 1997

The emissions-assisted maintenance procedure (EAMP) for diesel-powered mining equipment was developed by the University of Minnesota [4]. The EAMP system was designed to be far more portable than the prior systems developed by Southwest Research Institute and MTU, but still very capable of detecting engine faults. Assessments of portability were made for various instruments including NDIR, Fourier transform infrared (FTIR) spectrophotometer, and electrochemical gas sensors (EGS) were examined for portable use. EGS sensor technology was determined to be rugged and portable. In addition, accuracy to within 5% of the measured value was obtained by using a single EGS-based instrument that measured NO, NO_2, CO, CO_2, and O_2. The Ecom-AC and Ecom-E analyzers by ECOM America Ltd. were found to be portable, rugged, and inexpensive. A comparison of the portable system and laboratory-grade instruments, for a diesel engine on a dynamometer, showed that the Ecom-AC analyzer emissions readings were within 5% of the laboratory-grade instruments. The Ecom-E error was slightly higher when compared against the laboratory equipment. A curve fit to known gases was employed to minimize measurement errors. The EAMP was designed to measure on-site emissions concentrations from vehicles that were loaded by stalling either their torque converters or hydrostatic transmissions.

2.3 On-Board Measurements

2.3.1 Caterpillar, 1982

A portable bag collection system was developed by Caterpillar to quantify fuel specific NOx emission levels from in-use diesel engines [5]. A two bag collection system was designed with the capability of removing water vapor before the bags. The system was powered by an on-board supply and could be operated remotely by the driver. Moreover, the collection system could fit in a "small suitcase." Engine testing showed that the portable system collected bag samples which gave results that were accurate to within 10% of laboratory-grade equipment on a parts per million (ppm) concentration basis.

2.3.2 Southwest Research Institute, 1992

A portable system was developed by Southwest Research Institute to measure exhaust emissions from diesel buses and to compare the data against EPA's database of transient engine emissions [6]. The system was designed to collect information regarding emissions without the use of a chassis dynamometer. Several test cycles were developed to exercise the engine while the vehicle was parked. The cycles ranged from idle, no-load testing to loading the engine against the transmission through prescribed accelerator pedal positions. The prescribed test procedure could only be performed on vehicles with automatic transmissions. An Enerac 2000E was used to measure undiluted concentrations of CO, NOx, O_2, and CO_2 from a bag sample, and a mini dilution tunnel was used for the PM measurement. Exhaust emissions concentrations measured using the portable ("suitcase" size) Enerac 2000E were within 5% of laboratory-grade instruments. However, this system, being based upon an integrated bag approach, was not used to measure continuous on-board exhaust emissions from any vehicles.

2.3.3 General Motors, 1993

A 1989 gasoline fueled passenger vehicle was instrumented and driven through city and highway routes to obtain real-world emissions data [7]. The 180 kg (400 lbs) data acquisition system (housed in the trunk of the vehicle), consisted of five 12 volt batteries, inverters, computers, and five different emissions analyzers. The analyzers included a Horiba MEXA 311GE for CO_2 and hydrocarbon (HC), a Horiba MEXA 324GE for HC and CO, a Siemens Ultramat 22P for HC and CO, a Siemens analyzer for NO, and a Draeger analyzer for ambient CO. Redundant measurements of CO and HC were made in order to accommodate different emissions levels. Ambient CO measurement were made to monitor the passenger compartment concentration levels.

The exhaust flow was inferred from the intake flow. Exhaust flow rate measurements, made with a Kurz flowmeter, were correlated with the intake flow rates, derived from stock mass flow meter signals. The resultant relationship enabled inference of exhaust flow rates from intake flow rates. Some measurements were discounted due to time alignment problems associated with synchronizing the laptop and the diagnostic port. Concerns were also reported regarding the data collection rate (one sample per second) and its subsequent inability to capture transient events. However, the system did provide some in-use emissions data for spark ignited passenger vehicles.

2.3.4 Ford Motor Company, 1994

The emissions results from three different instrumented gasoline-fueled passenger vehicles are detailed in several reports [8,9,10,11]. The impetus of the study was to compare on-board measurements to remote measurement techniques. An On-Board Emissions (OBE) system, housed in an Aerostar van, consisted of an FTIR, and a dilution tunnel. The OBE was compared against Horiba laboratory-grade equipment for the vehicle on a chassis dynamometer. The comparison showed that the OBE system was within (on average) 2% for CO_2, 3% for CO, 10% for NOx, and 7% for HC. The on-road test showed that the OBE system was within (on average) 10% for CO, 1% for CO_2, 6.6% for NOx, and 1% for HC when compared against laboratory-grade equipment. However, the FTIR-based system has very slow transient response and may not be suitable for on-board emissions measurements of transient vehicle operations.

A Ford Taurus was instrumented with infrared-based analyzers (manufactured by MPSI) for measuring CO, HC, O_2, and CO_2, and an unspecified fast response (1.1 seconds) non-dispersive ultraviolet (NDUV) system for measuring NO. Comparisons were made between the on-board NDIR analyzers and laboratory-grade equipment for measuring NO. However, a correlation of 0.97, with a slope of 0.8, was found between the fast response NDUV analyzer and a conventional chemilumenscent instrument. All the above systems were designed for gasoline-fueled vehicles.

2.3.5 U.S. Coast Guard, 1997

A 1992 SAE paper and a 1997 report describe the on-board testing of U.S. Coast Guard Cutters to assess the emissions as part of the 1990 Clean Air Act for non-road air pollution [12,13]. Although the system was recognized as being too bulky and lacking portability, it demonstrated that emissions tests could be performed on-board a ship. The emissions of CO, NO, NO_2, sulfur dioxide (SO_2), O_2, and HC were monitored with an Energy Efficiency Systems, Inc., Enerac 2000E. CO_2 was inferred from the measured emissions. The monitoring system incorporated air and fuel flow measurements and provided for inference of engine-out torque via driveshaft mounted strain gauges. Radio frequency (RF) transmitters were used to record the shaft torque and speed via Wireless Data Corporation power metering equipment.

2.3.6 University of Pittsburgh, 1997

An on-board emissions measurement system for I/M was developed for natural gas-powered passenger vans at the University of Pittsburgh [14]. A RG240 five-gas analyzer from OTC SPX was used to measure the undiluted gas concentrations of HC, CO, CO_2, NOx (actually NO), and O_2. Engine data were collected via the OBD-II plug with third-party diagnostic equipment. The emissions measurement equipment was designed for gasoline-fueled vehicles, thus, the HC results were biased. It was reported that the system did fulfill some of the goals of providing an inexpensive, portable system capable of measuring real-world, in-use emissions from natural gas-fueled vehicles. However, some issues remain unresolved, for example, determination of mass emission rates, time alignment of signals, and analyzer (and the system) response times.

2.3.7 Flemish Institute for Technological Research, 1997

VITO, The Flemish Institute for Technological Research, performed on-board emission measurements with a system called VOEM (Vito's On-the-road Emission and Energy Measurement system). The system used NDIR analyzers to measure CO_2 and CO, an FID to determine HC concentrations, and a chemiluminescent analyzer to measure NOx. A nitrogen-driven ejector was used to draw a portion of the tailpipe exhaust and dilute it in order to prevent water condensation. A high temperature sampling line (190 °C) prevented the loss of heavy hydrocarbons that are associated with diesel exhaust. Partial dilute exhaust measurements were combined with fuel consumption, engine speed, and lambda value determination (to derive total exhaust flow quantities) in order to present gaseous emissions on a g/km and g/s basis. Tests were performed on both gasoline cars and diesel buses. Data generated by the VOEM was compared against a fixed chassis dynamometer. All errors were reported to be below 10%, with the exception of 20% for CO and 25% for HC for the diesel engine vehicles. The weight of the unit was 230 kg (500 lbs). The unit was powered by a 12 volt battery which provided one hour of operation.

2.3.8 NESCAUM, 1998

A recent study by the Northeast States for Coordinated Air Use Management (NESCAUM) evaluated in-use emissions from diesel-powered off-road construction vehicles and explored the effects of various emissions control devices [15]. To measure the on-board emissions data, a computer controlled sampling system was assembled using a mini dilution tunnel. The system consisted of a heated, raw exhaust sample line to transfer a portion of the raw exhaust to a mini dilution tunnel. A portion of the mixture was extracted through sampling lines to provide continuous emissions monitoring (using an MPSI five-gas portable gas analyzer) and bag (Tedlar) sampling. A 70-mm filter was placed at the outlet of the dilution tunnel for PM collection. Emissions analysis using the five-gas analyzer was found to be unreliable; NO_x response time was inadequate and the concentrations of CO and THC were too low to be reliable. Only CO_2 was used to infer fuel consumption. Tedlar bags were also analyzed using an off-line Horiba laboratory emissions analyzer for determining emissions levels of NO_x, CO and THC.

To verify the accuracy of the on-board system, one of the engines was tested on an engine dynamometer. It was found that there was a 27 percent difference between the field and laboratory collection systems for CO, a 12 percent difference for NOx, a 22 percent difference for HC, and a 9 percent difference for the fuel consumption calculation.

2.3.9 US EPA, 1999

The Office of Mobile Sources at the EPA is currently developing a mobile measurement system, termed ROVER, for light-duty gasoline vehicles and is working to extend the system for use on heavy-duty vehicles. The ROVER system uses an Annubar with a differential pressure sensor for exhaust flow rate measurement, and a Snap-On MT3505 multi-gas analyzer for gas analysis. The vehicle speed and distance traveled is measured either by sampling the engine control module or using a global positioning system (GPS) receiver or a microwave speed and distance sensor. EPA has suggested that the Snap-On MT3505 gas analyzer will be replaced by a Sun DGA 1000 multi-gas analyzer. Currently, the ROVER determines exhaust emissions (CO, CO_2, HC, O_2 and NO) in grams per distance traveled. In addition to gaseous concentrations, the ROVER also records engine speed (using a read-out connected to the engine's electronic control module (ECM)), A/F ratio, and exhaust mass flow rate.

2.3.10 Ford Motor Company and WPI-Microprocessor Systems, Inc., 1999

Ford Motor Company and WPI-Microprocessor Systems, Inc. are developing a Portable Real-Time Emission Vehicular Integrated Engineering Workstation (PREVIEW) that will sample water-laden exhaust [16]. PREVIEW is reported to be a fully integrated, portable system that simultaneously measures exhaust mass emissions (CO, CO_2, NO and HC) and up to forty engine parameters (through the engine control module readout). Detailed results of a comparative study between simultaneous measurements from PREVIEW and those obtained in the laboratory with conventional dynamometer instrumentation will be presented at the 9th CRC On-Road Vehicle Emissions Workshop, April 19-21, 1999 in San Diego, CA.

3 MEASUREMENT OF ENGINE SPEED AND VEHICLE SPEED

3.1 Engine Speed

The measurement of rotational engine speed can be accomplished with great accuracy, and is a trivial task relative to the other MEMS measurements. Speed is best measured by either a variable reluctance pickup or a Hall effect sensor, both of which can be used to detect individual flywheel teeth. Given that the variable reluctance pickups are much less expensive, are more robust, and operate passively, they will be the sensor of choice. Typically a time interval is established and the number of flywheel teeth passing the sensor is counted during this interval. By knowing the number of flywheel teeth a precise measure of engine speed is obtained. The only characteristic error for these devices is the uncertainty of whether a tooth is present at the sensor at the beginning and end of the time interval and this is termed jitter. By choosing a time interval of several engine revolutions this error is quite low (jitter of +/- 1 tooth/interval). The signal can be fed into a standard data acquisition system via a frequency-to-voltage converter and into the analog-to-digital converter port. However, additional error is introduced in this manner. A preferred technique is a timer/counter chip or port to count the pulses for a given time interval. Accuracy is typically within 10 rpm.

Present day electronic engines are equipped with such sensors, so that speed is obtainable in broadcast mode of the ECM. Speed may also be measured directly using such sensor's output.

3.2 Vehicle Speed and Distance

Measurement of vehicle speed can be accomplished using several methods. The simplest method being, obtaining the signal from the speedometer. For electronically controlled vehicles, this would involve obtaining the signal via broadcast mode from the ECM. For an older style vehicle, an inductance-type pickup could be used with the cable system with the distance traveled calculated from the vehicle speed. A disadvantage of using the vehicle's speed measurement method is that there is no verification that the speedometer is accurate and that there is no information on direction. It is also noted that tire diameter can vary by up to 5% due to wear and through variations from nominal size.

Alternative methods for measuring speed include fifth-wheel, optical, microwave, and GPS approaches. A fifth-wheel is very accurate when used under controlled environments such as a test track but is inadequate in rough terrain where slippage can occur. Link Engineering is a manufacturer of high performance fifth wheel assemblies that range from $1,000 to $5,000. Optical and microwave sensors are non-contact measurement methods which attach to the exterior surface of the vehicle under test. These measurement methods are similar in that a signal is transmitted to the road and reflected back to the sensor using the Doppler principle. However, they differ in the signal source. The optical sensor may be sensitive to weather conditions with wet or dirty environments posing problems to this sensor. Optical sensors have an error of less than 0.2% and have to be mounted within 20 inches of the ground. Microwave transducers are similar to optical sensors except they use RF energy which is not affected by wet or dirty environmental conditions. Microwave sensors can also incorporate multiple sensors to compensate for pitch of the vehicle. Microwave sensors have an accuracy of ±0.25% and can be mounted up to 47 inches from the ground. DATRON Technology is a supplier of optical and microwave speed and distance measurement systems that can measure from less than 1 mph to over 200 mph and are specifically designed for vehicle testing (with vibration compensation). Optical and microwave sensors range in price from $5,000 to $10,000. A limitation of the fifth wheel, optical, and microwave sensors is that they provide only speed and distance information and do not give directional information.

A GPS-based system will give speed and position information but may not give adequate spatial resolution or response time. Available commercial units are accurate to approximately 1 to 4 m (3 to 12 ft) for differential tracking and from 30 to 90 m (100 to 300 ft) for absolute tracking for horizontal "X-Y" position. The GPS systems are inaccurate for vertical "Z" position, and therefore, grade determination would be unreliable. GPS systems are greatly influenced by the surrounding terrain. When the system is used in an urban (tall buildings) or in a suburban (overpasses or tunnels) setting, the GPS data may be unreliable. J & S Instruments, Inc. is one supplier of GPS units with analog output capabilities for the position. GPS units can range in cost from $200 to $2000. Even if a MEMS utilized an optical or microwave sensor to obtain reliable speed and distance data it may be useful to use a GPS unit to obtain position data.

4 MEASUREMENT OF TORQUE

Direct measurement of torque at the flywheel is impractical for application in a MEMS system. In-line torque transducers are available for installation in vehicle drivelines, but the inefficiency of the vehicle transmission must be taken into account in order to compute flywheel torque. It is possible to instrument vehicles to measure the torque at the flywheel or clutch pressure plate, but only at substantial cost and with removal of the transmission. As sensor technology and signal technology improves, it may become possible to infer torque from instantaneous flywheel acceleration, as is presently considered for spark ignited engine misfire detection. However, this technology is too immature for immediate application.

Engine output torque must therefore be inferred from engine control parameters or feedback measurements. From first principles, torque can be computed with a knowledge of the quantity of fuel injected and the injection timing, the combustion duration and efficiency, and the mechanical efficiency of the engine. In practice, engine manufacturers are able to relate output torque to control parameters empirically, and are able to broadcast torque from the engine controller for electronically controlled engines.

Traditionally in evaluating energy-specific engine emissions, the brake torque at the flywheel is used to compute the reference energy. However, in the Consent Decree, the term "output torque" is favored. In-use engines supply power not only to the flywheel, but also to accessories such as the vehicle air conditioner, alternator, air brake compressor, and cooling fan. These accessories may load the engine intermittently. In truck applications, the compressor may account for approximately two horsepower of shaft load, the air conditioner may account for four horsepower, the alternator may draw up to two horsepower, and the fan will draw over ten horsepower when engaged. In city buses, the air conditioning load is prodigious and may exceed the brake power of the engine during much of the duty cycle. It is assumed that the reference energy (based on broadcast torque) used in the MEMS application will include accessory loads, and is therefore crankshaft work rather than brake work. In other words, for MEMS calculations, it will remain transparent as to how the work was proportioned between the flywheel and the accessory drives. In this way, use of accessories will introduce no error to inferred torque values. Conversely, the flywheel torque, if it were directly measured, would not faithfully represent the reference work used in MEMS calculations. In a similar fashion, the broadcast torque must include the contribution used to accelerate or decelerate the internal components of the engine during changes in engine speed.

The torque that is computed and broadcast by the engine control module will have accuracy and precision that depends directly on the complexity of the algorithm used for calculation and on the available sensor inputs used for calculation. The precision and accuracy also rely on the reproducible mechanical condition of the engine and will be influenced by factors including wear, environmental conditions, and fuel and lubricant properties.

In the simplest case, engine torque may be inferred from the fuel quantity injected and the speed of the engine. These two variables define closely all other operating parameters of a conventional open loop control diesel engine. The fueling rate per injection event provides a first estimate of the engine torque and the engine speed can be used to correct this estimate for changes in the mechanical efficiency with speed, the variation of programmed injection timing with speed, and the influence of speed on combustion and hence, in-cylinder pressure. For greater accuracy, under steady state conditions, computations should also include corrections for the following independent variables:

- Intake (after the turbocharger and intercooler) pressure and temperature (this will account properly for the influence of air filter pressure loss, loss in turbocharger performance, or intercooler leaks and atmospheric effects).
- Exhaust back pressure (which controls internal exhaust gas recirculation).
- Fuel temperature (which influences ignition and combustion).
- Coolant temperature (the algorithm may need to employ a recent history of coolant temperatures or loads for greater accuracy, to infer cylinder wall temperatures)
- Humidity of intake air.

It is assumed that the engine control module will, within its own control algorithms, take control action based on these variables. Therefore dependent variables, such as injection timing variations, external exhaust gas recirculation rate and the nature of split or rate shaped injection have not been included in the list, even though they influence the engine efficiency and hence the broadcast torque.

With the variables presented above employed in an appropriate algorithm or in a thorough empirical map, inaccuracy in torque prediction due to controllable factors will be small. At the present time the engine control modules for different engines are designed to utilize various combinations of measurements of these independent variables and to use differing algorithms to compute an estimate of engine torque. Therefore, the accuracy of the broadcast torque will differ from engine-to-engine.

Further factors will influence the accuracy of torque prediction but these factors are beyond the control of the ECM and could prove problematic in the use of broadcast torque. The cetane rating of the fuel in open loop control will influence the initiation of combustion and can change output torque. The fuel cetane rating, coupled with the fuel volatility (distillation range) will influence the combustion duration and the ratio of premix to diffusion burn in the cylinder, which will also influence both torque and efficiency. However, it is likely that these factors will cause a small, perhaps only 2%, variation in actual versus predicted torque.

Variation in engine oil viscosity, due to oil grade, age and temperature, will affect engine efficiency. It would be advisable to include oil temperature as a correction in the broadcast torque computation, but the viscosity effects cannot be measured on line. Oil viscosity effects independent of oil temperature may account for up to 2% error in broadcast torque.

Variation in fuel viscosity and density can affect the mass of fuel injected, and the volumetric energy content of the fuel can affect the delivered torque. Variations up to 5% can be expected considering the typical variations between diesel #1 and diesel #2, and the effect of paraffinic content versus aromatic content, and of oxygenated additives in the fuel. Changing fuel formulations over the life of the engine will render originally programmed broadcast torque inaccurate.

Engine wear will produce errors in the broadcast torque. Although heavy-duty diesel engines enjoy a long life, specific instances of neglect can lead to cylinder liner erosion, wear of rings and bores, valve damage, camshaft lobe loss, and bearing wear. These factors can influence the accuracy of broadcast torque by altering the engine volumetric efficiency, increasing blowby and changing frictional mechanical losses. In extreme cases, such as in the instance of a holed piston or dropped valve seat, broadcast torque will typically be in error by over 25% for a six cylinder engine, whereas effects of blowby without catastrophic failure may reach the 5% level before poor operation demands rebuild.

Wear of the fuel system components will cause broadcast torque errors. In particular, fuel leakage due to injector wear can decrease the quantity of fuel injected relative to that inferred by either the pulse width delivered to the injector or feedback information from the injector.

The broadcast torque computations should be capable of dealing with performance that is atypical of operation in a new engine. For example, a decline in turbocharger efficiency, or a leak or blockage in the intake system, or a blocked catalytic converter may cause "off-map" behavior. The advent of variable geometry turbochargers, electronically controlled wastegates, and EGR valves will increase the potential for flawed torque prediction. If the algorithm to calculate torque is too simplistic, or is predicated on perfect engine auxiliaries, the torque will be overestimated in these circumstances.

The precise effects of the variables discussed above will be influenced by the type of injection. Even though broadcast torque will be associated only with electronically managed injection systems, it is necessary to consider that there are three systems in current use in diesel engines. Most present day heavy-duty engines rely on cam-actuated electronic unit injectors, although Navistar employs the hydraulically actuated, electronically controlled unit injector (HEUI) system, where the actuation force is generated hydraulically. In this case the quantity of fuel injected is governed primarily not only by a pulse width, but also by an activation pressure, which must be monitored to predict the quantity of fuel delivered. Errors are associated with this oil pressure measurement for the HUEI system. Emerging technology in the heavy-duty engine arena employs common rail injection, where the torque delivered relies on a governed rail pressure, as well as pulse width. Newer combustion control approaches encourage the use of rate shaping in managing the injection: in these circumstances broadcast torque calculations must be more carefully formulated than with single pulse, fixed rate injection.

In summary, for an engine in usable condition and with a sufficiently sophisticated algorithm to measure broadcast torque, the error between computed and actual torque output could be as much as 10%. If some components of the fuel system change during engine use or if catastrophic failure occurs, the error could be greater.

It is possible that the accuracy of engine output torque prediction might be enhanced by the measurement of CO_2 levels in the exhaust. This would obviate many of the errors associated with the prediction of fuel quantity injected. However, it would require a knowledge of fuel properties such as the carbon to hydrogen ratio and energy density. It is possible that CO_2 levels may provide a level of redundancy in determining whether broadcast torque from a specific engine is reasonable in value.

5 MEASUREMENT OF EXHAUST MASS FLOW RATE

5.1 Flow Rate Measurement Requirements

Reporting exhaust mass emission rates in brake specific units (such as g/bhp-hr) using instruments that measure emission concentrations requires the mass flow rate through the engine to be known. An accurate and reliable measurement of exhaust mass flow rate is one of the major challenges for the design of a MEMS. Mass flow rate can be measured directly using momentum devices, or inferentially through volumetric flowmeters and separate density measurements or computations. This section will discuss problems associated with measuring gas flow rate through a heavy-duty diesel engine including the wide range of measurements necessary, contrast advantages and disadvantages of intake measurement versus exhaust flow rate measurement, discuss various instruments for their applicability, and make recommendations for both sensor placement and sensor choice.

Flow rate measurement of the exhaust stream or the intake air stream in a moving vehicle is complicated by conditions not found in stationary power systems. An on-the-road test will suffer the variabilities of changing traffic patterns, weather conditions, and the unpredictable usage of auxiliary equipment like air compressors. The Coriolis effect on the fluid by a vehicle changing direction could introduce a small error into fluid flow rate measurement systems that depend on a specific velocity flow profile. Road vibrations and other acceleration effects could likewise introduce errors. Vehicle speed and ambient conditions could affect intake air velocity profiles unless care is taken in pre-sensor flow stabilization. The space requirement to install piping sections to allow the flow profile to become fully developed is another factor to consider. In addition, as with stationary systems, care must be taken not to degrade engine performance or exceed allowable intake and exhaust absolute pressure requirements through instrumentation choices. Each of these complications must be considered in the selection of an instrument.

The mass flow rate could be measured in one of three general areas on the vehicle:

- The intake, prior to any compressor (along with knowledge of the fuel flow rate),
- After the compressor and inter-cooler but before the engine,
- In the exhaust stream.

Each location has advantages and disadvantages. The exhaust is an obvious choice since it is the flow of this section that will contain the emissions to be monitored. Coupling of a MEMS to the exhaust is usually simple except in the case of twin stack trucks or low discharge transit buses. However, the types of instruments that can be employed in this section are limited due to the elevated temperature (~420 °C) and presence of particulates in the exhaust. The intake location is a cleaner, cooler environment, but for accurate exhaust flow rate prediction, care must be taken to estimate blowby effects and mass of fuel added through the injectors. In the unlikely case that the assumption of complete combustion is not adequate, then percent combustion may be inferred from the emissions data. Another issue between intake and exhaust placement is the permitted in-line pressure drop. Typically, the intake can tolerate a total loss of about 18 inches of water while the exhaust may have about 40 inches of water pressure loss without dramatically affecting engine performance. The location between the intercooler and the engine is the least likely to be favored from an instrument installation perspective but has the advantage of a smaller range of fluid velocities between idle and full speed of the engine, thereby permitting a very precise but limited range instrument to be employed. If the advantage is substantial enough, perhaps it could be integrated into future engine designs.

The time delay during transient mass flow variations between a change in intake flow and the corresponding change in exhaust flow is of little concern, being at worst approximately 0.1 seconds.

The accurate and precise measurement of exhaust mass flow rate is a daunting task. In the following paragraphs, typical operating parameters are summarized and different measurement technologies are reviewed.

5.2 Typical Operating Parameters

The exhaust flow rate may be measured directly at the tailpipe, or may be inferred from measurement of intake flow, with minor adjustments for blowby and fuel addition. Both cases are considered below.

Consider a typical four stroke heavy-duty engine, with a 12 liter displacement and 400 horsepower rating. The range of engine speed, as a ratio of rated speed to idle speed, is about three. The range of turbocharger boost pressures, as a ratio of minimum to maximum absolute pressure delivered, is about three. If one assumes that the volumetric efficiency is invariant with load and speed, this implies that intake mass air flow will vary nine-fold over the full operating range of the engine. The Consent Decree limits the range that may be explored for emissions characterization, but the range of intake mass flow rates in this range will still exceed a factor of seven. Since the intake pressure and temperature will be more or less constant over the duration of any given test, the velocities in the intake will vary by the same amount as the mass flow rates, nine-fold for the full range and seven-fold for the Consent Decree zone.

In the exhaust, absolute temperatures can vary by a factor of over 2 between idle and rated conditions. In this case, exhaust velocities can vary by a factor of 16 to 20. The Consent Decree limits will reduce this exhaust velocity ratio to about 12. The range between minimum and maximum flow rate is important in discussing the dynamic range of the flow measurement instrumentation.

The case of measurement of mass flow at the engine intake manifold, after the turbocharger compressor and the intercooler (if present), has also been considered. In this case mass flow rate varies by a maximum ratio of nine, as discussed above, but the velocity is reduced to a ratio of about four or five, since the pressure in that region varies in sympathy with mass flow (due to turbocharger boost).

The values for flow ratios presented above are typical, rather than conservative. Smaller displacement heavy-duty engines have higher ratios of rated to idle speed, and boost pressures of Class 8 tractor engines have been steadily increasing by the year. It is conceivable that some future engines may have an exhaust velocity ratio exceeding 30, which would make accurate measurement over the entire range of flow rates rather difficult. Intake flow measurement is therefore an attractive option both to reduce the measurement range and to explore a more benign fluid environment than is present in the exhaust.

The flow measurements must be made using the MEMS system over a wide range of atmospheric conditions, with varying temperatures and altitudes. Also the MEMS system must be configured to deal with a range of engine sizes, and not with one engine. Even if the system has several different interchangeable flow measurement units, each unit will need to serve a range of engine sizes. Therefore, a MEMS mass flow measurement system may need to measure flow at the exhaust over a 35-fold range in velocity, or possibly a lesser range at the engine intake. If a measurement system is employed in the exhaust that utilizes differential pressure measurement to infer velocity measurement (as in the case with venturis or pitot tubes), then differential pressures must be measured over a 1200-fold range. It is unlikely that accuracy can be preserved at low flow rate measurements when the flow measurement device must have a span that caters to the largest anticipated flow.

5.3 Sensors

The field of choices of common sensors may be narrowed by eliminating non-feasible technology. Direct mass flow sensors like Coriolis devices may be eliminated without further discussion due to their inherent sensitivity to vibration. Magnetic metering devices can be eliminated due to the non-conductive nature of the fluid. Sensor technologies which are discussed below include pressure drop (through a venturi), pitot tubes (both single and averaging), hot wire, turning vanes, and vortex shedders.

Repeatability and range are the most important attributes of a sensor. However, pressure loss in the fluid stream resulting from the addition of instrumentation should be minimized and rate of response to transient conditions should be maximized. Temperature and PM sensitivity and to some extent the measurement range will determine if the instrument may be used in the exhaust or if it is restricted to intake usage. Many of the sensor technologies discussed below require accompanying pressure and temperature measurements to compensate for varying density effects.

Most flow sensors require a consistent velocity profile free from swirl effects. Ordinarily, this is achieved through a long section of pipe to permit fully developed flow. In a mobile application straightening vanes could be employed to shorten the lead pipe section. Calibration over the full range of the device can account for nonlinearities associated with upstream obstruction effects.

Many flow sensors employ a differential pressure measurement to sense the flow rate. During transient operation, systems that employ differential pressure transducers fed via probes and lines may fail to respond accurately to changing flow. Firstly, if the "dead volume" of the transducer, probe, and connecting tubing is too large, the response times of these systems will be slow. Secondly, if the two halves of the probe, tubing and dead volume associated with differential pressure measurement are mismatched, then the resulting signal will not faithfully represent differential pressure, but instead will be a corruption of absolute pressure and differential pressure during transients.

If instantaneous flow rate is to be calculated using three sensors to measure simultaneously differential pressure, absolute pressure, and temperature, the three sensor systems must be matched in frequency response, or their differing responses must be considered in calculating the flow. A first order approximate correction may be considered using time lags, but the true behavior is more complex. This issue is compounded further when instantaneous emissions levels are required, because there will be lag times and residence time distributions for the gas analyzers that must be correlated in time with the mass flow rate and torque measurements.

Although it is desirable to consider the composition of the exhaust gas in computing thermodynamic gas properties, these properties do not vary substantially from those of air in the exhaust of a diesel engine. This statement assumes that no substantial condensation of water occurs in the exhaust, which may prove false under cold operating conditions. The most significant variation is in specific heat, which would be of interest only in addressing compressibility effects. Density and viscosity variations are dominated by temperature rather than by composition.

5.3.1 Pressure Measurement

Since some instrument strategies are based on pressure measurements and others must be compensated for varying density using pressure measurements, a discussion of pressure sensors is appropriate. A very common, inexpensive, yet precise pressure sensor is based on the concept of piezoresistivity. Sensing elements are printed on wafers and mounted for use as strain gauges. These sensors exhibit quick response with negligible hysteresis. Typically, a single sensor element is used in a family of sensors where only the electronics are changed. This gives sensors with different measurement ranges the same effective overpressure limit thereby permitting several sensors to be employed to cover multiple pressure ranges. The net increase in rangeability of these types of sensors may be important for flow rate measurements using MEMS.

As an example, Model MPX210 from Motorola has a range of 0-10 kPa but an overpressure limit of 75 kPa, permitting it to be used for low differential pressures at low flow rates in conjunction with another sensor for the higher flow rates. Motorola is currently developing systems with much lower pressure ranges utilizing pulsed techniques which may provide additional precision at very low flow rates. The sensors have a response time of 1 ms. Their maximum temperature tolerance of 120 °C (250 °F) would require remote placement for exhaust measurement thereby reducing response time. For inlet placement, the sensor could be mounted very close to the pressure port.

5.3.2 Temperature Measurement

Precise linearized temperature measurements for the intake air temperature could include semiconductor sensors like the National Instruments LM35. The LM35 does not require any external calibration or trimming to provide typical accuracies of ±0.25 °C at room temperature and ±0.75 °C over a full -55 to +150 °C temperature range. For exhaust gas temperature measurements, a robust thermocouple with a linear range should be employed. An appropriate sensor would be one that ranges up to 540 °C (1000 °F) with a resolution of 0.5 °C (1 °F). Thermocouples are available in a 1/16-inch sensor that will be physically robust though a smaller shield package may be employed if quicker response is required.

5.3.3 Humidity Measurement

Gas composition, and hence density and compressibility relationships for the intake air, will change due to relative humidity changes but this may be neglected in MEMS since it will contribute less than 0.5% error. In other words, humidity measurements, for flow rate determination, will not be required for MEMS flow rate measurement.

5.3.4 Pressure Head Flow Sensors

There are many types of pressure head flow sensors including orifices, flow nozzles, and venturis. The principle behind these pressure differential devices is that the conservation of mass will hold true even when the geometry of the flow passage is changed. The fundamental equation for these types of devices is

$$q_m = CYA\sqrt{2g_c\rho_f\Delta P}\ .$$

For an adiabatic expansion from P_1 to P_2, the expansion factor is

$$Y = \sqrt{r^{2/k}\left(\frac{k}{k-1}\right)\left(\frac{1-r^{(k-1)/k}}{1-r}\right)\left(\frac{1-\beta^4}{1-B^4r^{2/k}}\right)}\ .$$

Though specific devices may have a slightly different form of the algebraic equation, all devices are similar in behavior and share a square root relationship between mass and pressure drop. It is important to note that for an engine application this is a complex relationship due to the changing temperature, pressure, and gas composition of the fluid stream. Intake placement has the advantage over exhaust placement in that it has the lesser variation in these fluid properties.

Of these types of devices, the venturi has the advantage of the lowest total in-line pressure drop while providing a high measurement pressure drop which improves instrument sensitivity. The permanent pressure loss of a "Herschel type" venturi can be 10-15% of the pressure differential for discharge cone angles of between 5 and 7 degrees or as much as 10-30% for a large discharge cone angle of 15 degrees. The pressure sample points for the venturi are in the sidewalls, upstream of the venturi and in the narrow throat, making for a robust self-cleaning instrument. The typical industry venturi/pressure transducer system has a rangeability of about 3/1. The insufficient range favors intake placement and probably requires multiple pressure sensors with different operating ranges but similar overpressure limits to achieve the necessary full range.

5.3.5 Pitot Tubes

The principle of the pitot tube is that the difference between the impact pressure in a flow stream and the static pressure in the flow stream is proportional to the velocity squared as expressed by the equation

$$V_o = C\sqrt{\frac{2g_c(P_1-P_2)}{\rho_o}}\ .$$

From the measured velocity, the mass flow rates can be computed using cross-sectional area, fluid density and a velocity profile correction factor. Compressibility may be ignored below 60 m/s (200 ft/s) and this is a valid assumption for MEMS. The very low differential pressure drop for gases at low velocities may require dual pressure transducers one set for improving precision of the low flow rates and another for full-scale measurements. Rather than base the measurement on a single point sample in the flow stream which is sensitive to a uniform velocity profile, commercially available instruments favor an averaging multiport sensor such as those produced by Annubar, Omega, and Kurz. The FPT 6000 series by Omega reports a repeatability of 0.1% of flow rate with a pressure drop of only 2.75 inches of water. The 93 °C (200 °F) maximum specification limits the use of this probe to the intake. The low sensitivity in the flow rate regime is a limiting factor. It is unknown at this time if a dual set of pressure transducers, each to cover part of the range, can satisfactorily address this concern. The transient time response due to the dead air volume between the ports and the sensors is of additional concern. Placement of pitot tubes in the exhaust has the further concern of PM blockage of the pressure ports. Since port to port flow is possible in these devices, blockage could be a significant source of measurement error.

5.3.6 Turbine Sensors

The turbine is a multi-vaned device occupying either the full pipe cross section or a small sampled location within it. The rate of spin is determined through a magnetic type pickup. Turbines are fairly linear with respect to fluid flow rate. Though their rangeability is about 100/1 for gas streams at high pressure, it is only 10/1 near atmospheric pressure. They are limited to intake air flow measurements due to elevated temperature and particulate sensitivities. Larger sensors will not have transient response and could cause pressure loss while smaller sensors may not be as accurate. Since the turbine is not a low insertion pressure drop device it could cause intake pressure drop for engines on the order of 18 inches of water.

5.3.7 Ultrasonic Flow Sensors

There are two types of ultrasonic flow sensors, one is a Doppler device relying on reflections from PM in the flow stream and the second is a time-of-flight type device which requires a transmitting and receiving transducer on opposite ends of a path at an acute angle to the moving fluid. The time of the propagating acoustic wave is proportional to the speed of the medium. Though literature indicates that this technique can be employed for gas streams, there are no commercially available instruments for high temperature exhaust gas streams. Ultrasonic meters enjoy the advantages of no pressure loss, a 25/1 range and 0.5% repeatability. Though the precision of ultrasonic meters may ultimately make it a good calibration tool, elevated temperature near the Curie point of the exhaust gases excludes it from exhaust usage. It should be noted that Flow Technology, Inc. has introduced an exhaust mass flow measurement system, Vertical E-Flow, that reflects the efforts of American Industry/Government Emissions Research (AIGER) group. However, the vertical E-Flow system is limited to gasoline exhausts and can be used only in a test cell because of its large size.

5.3.8 Vortex Shedding Sensors

A bluff body in a flow stream will shed vortices alternately on either side at a frequency proportional to the fluid velocity. This is a principle known as the Van Karman effect. A vortex shedding meter measures the slight vibrations of the carefully designed bluff body to produce a wide range, linear flow measurement instrument.

Vortex shedding sensors are sensitive to vibration induced errors near their natural oscillation frequency. However, a frequency of about 160 kHz is reported for one commercially available vortex shedding sensor and the only typical sources of vibrational noise in this frequency range would be turbocharger vane transients or turbocharger shaft speeds.

A commercially available product for engine exhaust streams is available from J-TEC and can tolerate temperatures up to 538 °C (1000°F). This company currently only produces 2" and 3" devices with a maximum throughput of 450 ACFM, but they have demonstrated the feasibility in an exhaust stream device with a range of 45/1. The device's rated repeatability of +/- 1% of full scale could indicate significant errors at the lowest flow rates. It has a 300 ms response time for analog output or 10 ms response time for frequency output.

A general vortex shedding sensor from Omega Engineering requires that the minimal flow velocity corresponds to a Reynolds number of 5,000. This should be sufficient for MEMS use since the Consent Decree lower limit on Reynolds number is estimated to be in excess of 10,000. The repeatability is 0.2% of reading but the maximum temperature of 300 °C (572 °F) restricts usage to the air intake.

A second vortex shedding sensor from J-TEC which has not been hardened for use in an exhaust stream characterizes itself as "Lo-flo." Its rangeability is 70/1 going from 43 m/s (140 ft/s) down to 0.6 m/s (2 ft/s). With repeatability of 0.5% of reading this is an excellent candidate for MEMS air intake measurement.

5.3.9 Hot Wire Anemometers

A wire heated by electrical current in a flowing stream of cold fluid will tend to be cooled, thereby changing the resistance of the wire. Through the use of an electrical circuit, either the current through the wire is maintained constant and the resistance is measured or the resistance (and hence the wire temperature) is maintained constant and the current is measured; either result can be related to velocity of the fluid stream. The rangeability can vary from 0.15 m/s (0.5 ft/s) to supersonic with transient responses of about 10 μs. The response time and the ruggedness of the sensor represent a trade-off since a very thin wire is necessary for the highest response times. Fairly rugged quick response systems are commercially available with the latest trend being toward mass integrated flow sensors that already compensate for varying temperature and pressure. The cooling principle limits the usage of hot wire anemometry to the intake.

A very precise instrument with pressure and temperature options is available from Omega with a repeatability of 0.2% of full scale. It has a fairly quick response time of 500 ms. It is currently packaged as a portable instrument that would need to be modified for mounting in a pipe.

5.4 Summary and Recommendations

The measurement of the intake air flow offers several advantageous features for sensor selection over the measurement of exhaust flow. The intake air has a smaller velocity rangeability requirement, lower temperature, absence of PM, and a more consistent gas composition than the exhaust. Placement of the flow sensor in the intake will require additional consideration in the form of mass of fuel injected and engine residence time (about 0.1 s). The recirculation of blowby around the pistons, through the crankcase, and back into the intake will also be considered. Since emissions will be measured in the exhaust, the intake placement has the disadvantage of additional connection requirements. Either the "Low-flow" vortex shedder instrument or a hot-wire anemometer based system might be used for intake mass flow.

The measurement of exhaust flow requires the identification of a sensor which can withstand the harsh environment and will accommodate the broad range of flow rates typical of diesel engine exhaust streams. It is possible that a vortex shedding sensor may be used. A multiport averaging pitot tube sensor such as that produced by Annubar may also be used. If this type of sensor is used, multiple pressure transducers would be required to ensure accurate measurements throughout the range of the pitot tube, as no single pressure transducer have the resolution necessary to span the expected broad range of pressures. A similar sensing challenge must be accommodated for use of a venturi type sensor.

6 MEASUREMENT OF EMISSIONS

6.1 Categories of Emissions Measurement Instrumentation

The available technologies that can be used to monitor the on-road exhaust gas emissions of heavy-duty diesel vehicles can be divided into two categories: garage-grade I/M analyzers and laboratory-grade analyzers. The former is perhaps best represented by the multi-gas microbench units that are typically designed in order to comply with the California Bureau of Automotive Repair (BAR)-97 Emissions Inspection System Specifications. These units are quite compact, and have been designed to withstand the harsh environments associated with portable emission measurements. Laboratory-grade analyzers are accepted as the standard means for precision measurement of emissions from all types of combustion sources. However, these units are not compact and may not have the ruggedness required for on-the-road emission measurements. A review of different emissions measurement sensors which are available from various manufacturers is presented below. Before reviewing specific sensors, a brief summary of measurement principles and techniques is presented.

6.2 Polarographic Analyzers

Polarographic analyzers, also called voltammetric or electrochemical analyzers, use chemical reactions and associated electron flow to deduce the concentrations of candidate gases in sample streams. These analyzers utilize an electrochemical transducer, which consists of a semipermeable membrane, a porous sensing electrode, an electrolytic solution, and a counter electrode. The sensing and counter electrodes are separated by a thin layer of electrolyte and are connected by a low resistance external circuit. Gas diffusing into the sensor is reacted at the surface of the sensing electrode, by oxidation or reduction, causing a current to flow between the electrodes through the external circuit. The current is proportional to the concentration of the candidate gas species and can be measured across a load resistor in the external circuit. Selection of the counter electrode and sensing electrode is governed by their respective electric potentials, so that the oxidation-reduction reaction takes place at the sensing electrode. As the candidate gas concentration increases, so does the current flow, causing a change in the potential of the counter electrode, that is, polarization. If the candidate gas concentration is too high, the sensing electrode potential will move outside its designed range. In such a case, the sensor will become nonlinear. In order to overcome this effect, sensor manufacturers have implemented a third reference electrode. Such a design enables the sensing electrode to be held at a fixed potential, relative to the reference electrode. Since no current is drawn from the reference electrode, both maintain a constant potential. If the candidate gas concentration causes the counter electrode to polarize, the sensing electrode is not affected, and thus the sensor does not move into a nonlinear region of operation. A potentiostatic operating circuit has also been used in order to provide greater selectivity and improved response [17].

Polarographic analyzers have been developed to measure a variety of gases, including SO_2, NO, NO_2, NOx, CO, O_2, and CO_2. They are inexpensive and portable, which obviously qualifies them as a candidate technology for a MEMS. The operation of the electrochemical cell is very sensitive to temperature variations, so that the system should be designed to maintain cell temperature within certain limits. In addition, due to the delicate nature of the membrane, care must be taken to remove PM from the exhaust stream, else fouling would likely occur. The response times of electrochemical cells is quite long and has been a limiting factor in their usage for measuring the instantaneous emission concentration levels in transient exhaust streams. However, there have been some recent improvements in response time for the sensors used for the detection of some gas species. Currently, NO sensors are available with a response time to measure 90 percent concentration levels (T_{90}) of less than 4.5 seconds. However, sensors used for measuring other gases, such as NO_2 and CO, still have response times of more than 30-40 seconds. Another factor that may restrict the use of electrochemical cells is that their inlet temperatures are generally limited to 50 °C. Such limitations require that the sample stream be cooled, which would likely result in the loss of some heavy-end HC compounds due to condensation. Lastly, like any chemical-based system, the cells will eventually be consumed, requiring either refurbishment or replacement.

6.3 Electrocatalytic Analyzers

Electrocatalytic analyzers utilize sensors that were developed as an outgrowth of fuel cell technology, and are commonly used to detect concentrations of O_2 in sample streams. These sensors use a solid catalytic electrolyte to aid the flow of electrons from a sample gas cell to a reference gas cell. In practice, catalyst-coated ceramic materials (such as ZrO_2) separate the reference cell (containing a high concentration of O_2) and the sample stream. When heated, the electrolyte allows transfer of ionic oxygen components from the reference cell to the sample cell. The surface of the electrolyte has a special electrocatalytic coating that catalyzes the transfer process and serves as an electrode surface in order to attract released electrons. The ions migrating from the reference side to the sample side release electrons on this surface. The process tends toward equilibrium. However, since the sample is continuously replenished, a continual flow of electrons is induced across the measurement load resistor. The current flow is then used to infer the concentration of oxygen in the gas sample stream [17]

Analyzers of this variety have been developed to measure the concentrations of O_2. The electrocatalytic transducers are inexpensive, portable, and quite small, making such systems very well suited to MEMS. The presence of other species in the sample gas stream may interfere with the response. Interference is caused by the oxidation reaction of gas species such as CO and HC. This oxidation process would cause a decrease in the oxygen concentration of the sample cell, which in turn would yield erroneously low readings of oxygen concentration levels in the sample stream.

A variation is used to produce catalytic oxidation sensors for CO and HC, commonly referred to as pellistors. These sensors consist of a matched pair of elements – detector and compensator. Each of these elements is comprised of a coil of platinum wire embedded within a catalytic bed. An electrical power source is used to heat the elements to a point where the active detector is capable of oxidizing combustible gases. Due to oxidation, the detector element experiences a rise in temperature, which is associated with an increase in element resistance. The compensator element, on the other hand, is poisoned so that it is inert to the presence of the same gas. Changes in the temperature of this element, therefore, are only indications of sample stream temperature variations. The compensator arms correct the resistance changes of the detector elements that are caused by sample stream conditions. The pairs are placed as opposite arms on a Wheatstone bridge circuit, so that an out-of-balance voltage across the bridge can be used to detect a change in the resistance of one element with respect to the other. When no combustible gas is present, the bridge is balanced, and a zero gas signal is registered. However, the introduction of a combustible gas will result in an imbalance and trigger a response. For low concentrations, the signal response is linear. Therefore, by calibrating with a gas of known concentration, the magnitude of the imbalance can be used to infer candidate gas concentration.

Catalytic oxidation sensors have been developed to measure a variety of combustible gases, including CO and various HC species. One application where these devices are used is for sensors to indicate dangerous exposure limits of the candidate gas.

6.4 Chemiluminescent Analyzers

Chemiluminescent analyzers can infer/determine the concentration of NO by observing a narrow band of the infrared emission spectrum that is produced as NO reacts with ozone (O_3). NO components of the sample gas stream are quantitatively converted into NO_2 by gas-phase oxidation with molecular ozone. When this reaction takes place, approximately 10% of the NO_2 molecules are elevated to an electronically excited state, followed by immediate reversion to the non-excited state. This conversion process produces a photon emission. A photon detector (multiplier tube) is then used to produce an instrument response that is proportional to the NO present in the original sample. The operation for NOx is identical to that of NO except that the gas sample stream is first passed through a converter which converts the NO_2 in the NOx into NO. In this case, the instrument response is proportional to the NO present in the original sample plus the NO produced by the dissociation of NO_2 [17].

Chemiluminescent analyzers offer the benefits of a fast response time and a linear response over 90% of the output range. They are currently considered the most accurate method for the determination of NOx. The presence of ammonia or other oxides of nitrogen may bias analyzer response, however these components may be scrubbed from the sample line by utilization of molybdenum converters. Another associated problem involves the quenching/absorption of the released photons by other sample gas components while the sample stream is in the excited state. The effects can be minimized by operating the reaction at lower pressures and by flowing O_3 into the sample chamber to dilute the sample gas stream. Due to the necessary ozone supply, the packaging requirements of the reaction chamber, and the associated need for the sample stream conditioning, chemiluminescent analyzers are not ideally suited as candidates for a MEMS.

6.5 Fluorescence Analyzers

Currently used only for the measurement of SO_2, fluorescence analyzers are based upon a photoluminescent process. In principle, the operation of these analyzers involves irradiating a gas sample containing SO_2 with UV light. The impinging light initiates the fluorescence process, in which SO_2 is elevated to an excited state. Accompanying this elevation in energy state is a release of longer-wavelength fluorescent radiation. This radiation is then measured via a photomultiplier tube, and the collected details of the released energy spectrum are used to infer SO_2 concentrations in the gas sample stream. In order to prevent interference, commercially available units implement band pass filters to narrow the fluorescence emission spectrum [17]. The released photons can be absorbed by other sample components, such as water, O_2, CO_2, nitrogen, and HC and this effect must be minimized. Commercially available systems have addressed this problem by using lower wavelength UV light, in order to reduce the time for fluorescence to occur, lowering the pressure of the sample cell, and diluting the cell with air, so as to minimize the effects of interfering components in the sample stream

6.6 Flame Photometric Analyzers

Using a principle similar to the chemiluminescence technique, these analyzers detect candidate gas concentrations by measuring the light energy released by excited gas molecules. A hydrogen flame is used to excite the sample gas molecules. As with other luminescent technologies, filters and scrubbers may be implemented in order to reduce interference effects generated by photon release from sample constituents other than the candidate gas [17].

Flame photometric analyzers are currently used for the detection of sulfur compounds. For detecting SO_2, they offer improved response times over NDIR analyzers which are discussed below. However, the hydrogen gas requirements for the excitation flame tends to disqualify them as a viable option for a MEMS.

6.7 Heated Flame Ionization Detectors

Heated flame ionization detectors, HFID, are currently used for the detection of HC. Exhaust HC levels are measured by counting elemental carbon atoms detected in the sample gas stream. A regulated flow of sample gas is ionized by heating it with a hydrogen/helium fuel gas flame (FID fuel). The flame ionization process involves a release of electrons, which are collected by polarized electrodes. The ion absorption produces a current flow, through an associated electronic measuring circuitry, that is proportional to the rate at which carbon atoms enter the burner [18,19].

Benefits of the HFID analyzer include the capability of measuring HC concentrations over the broad range of 50 ppm to 250,000 ppm with an associated full-scale linear output. However, the HFID is not ideally suited for a MEMS due to the problems associated with accommodating the need for the FID fuel and the fact that HFID's are very sensitive to vibration.

6.8 Non-Dispersive Infrared Analyzers

Non-dispersive infrared analyzers, NDIR, operate upon the principle of selective absorption. Loosely stated, the infrared energy of a particular band of wavelengths, specific to a certain gas, will be absorbed by that gas, whereas the gas will transmit infrared energy of other bands. The NDIR determines gas concentration by the amount of transmitted (or absorbed) energy in the selected band of wavelength. The transmission (or absorption) is directly proportional to the concentration of the component gas that is being measured. Detection of the amount of transmission (or absorption) is accomplished by one of two methods. The first simply involves the direct measurement of the emerging light from a single sample cell. A reference level of measured infrared energy is obtained by flooding the measurement cell with zero gas. The zero gas is selected so as to transmit the infrared energy of the candidate gases' absorption band. This energy value can be compared to the attenuated value obtained from the detection of gas exiting the sample cell when the candidate gas is present. In portable units, a solid-state measurement device typically performs infrared energy detection. This detection scheme is robust and enables the NDIR instrument to be packaged for limited space applications. However, such a detection scheme may be susceptible to absorption interference by some other component that coexists in the sample stream with the candidate gas.

In order to minimize such interference effects, the second method employs three measurement cells: a sample cell, a reference cell, and a detection chamber. The infrared source beam is alternated between two paths via a chopper-wheel assembly. The reference cell path is configured in parallel to the sample detection cell path and uses a quantity of zero gas in order to establish the reference amount of transmitted energy. The zero gas is chosen so as to transmit energy in the absorption band that is characteristic of the candidate gas. A detection cell is mounted downstream of the sample gas cell. The detection cell is subdivided into two unequal length chambers. Concentration levels of the candidate gas in the sample cell is inferred from the pressure imbalance that develops between the front and rear chambers of the detection cell. The front chamber is shorter than the rear chamber, and is used to absorb the light energy at the center of the absorption band. The infrared energy passed onto the rear chamber of the detection cell is primarily comprised of radiation with frequencies at the fringes of the absorption band. Since energy at fringe frequencies is not as efficiently absorbed, the rear chamber must be longer in order to achieve a balance of absorbed energy between the two cells. Detection of absorbed energy is accomplished via a microflow sensor that measures the pressure differential between the front and rear sections of the detection cell. If the candidate gas is present in the sample cell, infrared radiation of the band-center wavelength is absorbed. In such a case, the front chamber of the detection cell does not absorb as much energy as would the rear chamber. The differential pressure is used to determine the concentration of candidate gas in the sample cell. If, however, interference gases were present in the sample cell, the interference will present itself as a broadband absorption of infrared energy. This will not produce a measurable pressure differential in the detection cell. Thus, the absorption effects of interference gases will be minimized. Such a detection scheme is employed in most laboratory-grade analyzers [17]. Although very accurate and quite reliable, the instruments using this second method require considerable space which tends to disqualify this detection scheme as a possible candidate for a MEMS.

NDIR analyzers are currently used to measure CO, CO_2, SO_2, and HC. The units designed utilizing the first method described above tend to be quite compact in nature, which helps to qualify them as a candidate technology for a MEMS. Instrument size and accuracy have been improved with the implementation of solid-state detectors, used to replace the photomultiplier tubes. NDIR analyzers not only require the removal of PM from the sample exhaust stream, but also require that the sample be conditioned in order to limit the effects of water interference. Water interference may be minimized by heating to prevent condensation, condensing and removing the water vapor, or lowering the sample stream dew point. For the measurement of CO, CO_2, SO_2, and lighter-end HC, the water may be condensed out. However, unlike gasoline exhaust streams, diesel exhaust includes heavy-end HC that will condense along with the water vapor. Therefore, in order to reduce water interference, the use of heated lines or dilution air to lower the dew point must be implemented. Typical CO analyzers have ranges of 0-2 percent and 0-10 percent while the low CO analyzers have ranges of 0-1000 ppm and 0-5000 ppm. Typical CO_2 analyzers have ranges of 0-5 percent and 0-20 percent.

6.9 Non-Dispersive Ultraviolet Photometers

Non-dispersive ultraviolet photometers, NDUV, are similar in operation to NDIR analyzers. An ultraviolet source is used to radiate sample gas streams, and then a photomultiplier tube or, more recently, solid-state detectors are used to monitor the amount of absorption of light energy. Light in the ultraviolet region is characteristically shorter in wavelength, but higher in energy, than in the infrared spectrum. Therefore the absorption of energy is much greater, and the subsequent detection and, hence, correlation to candidate gas concentration is much easier. In contrast to NDIR methods, instead of comparing the transmitted energy of a reference gas cell and the candidate gas sample cell, a differential absorption technique is employed. This process involves the comparison of light energy transmitted by the candidate gas sample cell for two distinct narrow UV bands. Two band-pass filters are chosen, one that passes light energy of the absorption bandwidth of the candidate gas, and one that passes light energy of a wavelength that the candidate gas cannot absorb. Utilizing a chopper-wheel mechanism, the differential absorption is measured and correlated to the concentration of the candidate gas in the sample stream. Sample conditioning for NDUV analyzers require the removal of PM, but do not require the removal of water vapor. NDUV analyzers may operate on a hot-wet basis, since water vapor does not absorb light appreciably in the regions of the UV spectrum used for analysis. Thus, heated lines may be employed in order to prevent water condensation interference.

6.10 General Commentary on Available Sensors

A summary of available emissions measurement sensors available from various manufacturers is summarized in Table 1 and reviewed in the following paragraphs. The primary suppliers of component-level NDIR benches for the industry are Androse, Horiba Instruments, Inc., and Sensors, Inc., and the primary source for electrochemical sensors is City Technology Limited. It is intended that the entries in the table be used to represent various levels and technologies, instead of specific company offerings. In addition to the measurement specifications for the various measurement systems, there are special features and unique requirements for these devices that deserve discussion.

Currently, there are no portable analyzers available for THC measurements. It is recognized that the CFR 40 Part 89 permits NMHC estimations at 98% levels of the THC measurement. In the absence of a reliable portable sensor for THC, the approach found in CFR 40 Part 89 may be employed.

6.11 Inspection and Maintenance-Level Emissions Analyzers

6.11.1 Overview

A number of emissions measurement sensors and analyzers were developed by various instrument manufacturers to be used in the field for I/M of light-duty vehicles. Portability and minimal power consumption are a characteristic of these types of devices. Typically these units involve NDIR determination of CO, CO_2, and HC (hexane band), with NO being measured by electrochemical sensors. Many of the units of this class were developed to meet the requirements set forth in the State of California BAR-97 Emissions Inspection System Specifications.

BAR-97 specifications set standards for instruments primarily used to measure the exhaust emissions of gasoline-fueled automotive applications. These standards do include opacity standards for measuring diesel smoke levels, but no gaseous emission measurement specifications are included for diesel exhaust monitoring systems. There are currently no commercially available portable emission analyzers that are specifically designed to sample diesel exhaust emissions.

6.11.2 CO and CO_2 Determination

For CO and CO_2 the I/M level technology is based upon the same basic measurement principles as laboratory-grade analyzers. The major difference between the portable units and their laboratory counterparts is the manner in which the absorption (transmission) of infrared energy is detected. However, Stephens et al. [20] compared mobile NDIR-based CO and CO_2 measurements with those obtained from laboratory-grade instruments and reported a very close correlation. In addition, the use of solid-state detectors and the elimination of mechanical chopper units make the mobile units very resistant to vibration, a quality very desirable for a MEMS. However, current I/M instruments were designed to measure the levels of CO and CO_2 which are typical of gasoline exhaust samples. For instance, the SUN unit was designed to measure CO concentrations of up to 10% by volume - typical levels for rich operation of gasoline engines. Most diesel engines produce exhaust concentrations of CO that are less than 100 ppm, which would entail instrument operation in the lowest region of total response. Obviously, such practice is not conducive to accurate reporting of exhaust samples.

Determination of exhaust CO and CO_2 concentrations by electrochemical means is not recommended for a MEMS. ECOM reports (see Table 1) that its CO measurement has a T_{90} response time of approximately 38 seconds. Such a substantial lag in instrument response is not acceptable for a MEMS unit that would be used for transient on-road exhaust measurements.

6.11.3 HC Determination

The majority of the commercially available I/M-level analyzers use an optical NDIR technique for the determination of exhaust gas HC. However, since most of these units were designed under BAR-97 specifications, instrument response has been tailored to the HC spectrum produced by gasoline engines. Most of the NDIR bench-type instruments are limited to detection of HC in the hexane band and may be calibrated with hexane or propane. Detection of heavy-ended HC is not guaranteed. The spectral sensitivity is what dictates the instruments' measurement ability, and generally, these instruments utilize narrow infrared bands in order to improve accuracy and minimize interference of other components that coexist in the diesel exhaust stream. For instance, for the instruments available from Horiba Inc., HC determination using NDIR will likely not include HC groups above the C8 to C9 level. Since diesel exhaust streams generally comprise a large percentage of higher end HC, the measurement error associated with HC detection by an NDIR is expected to be unacceptably high unless the unit is tailored to identify larger molecules of HC.

City Technology markets a miniature catalytic oxidation sensor, or pellistor, that is used by ECOM in their SG portable emission analyzer. These sensors were designed to measure the concentration levels of combustible gases (or vapors) present in an environment. The sensors are used to provide a warning of an explosive buildup. ECOM lists accuracy of 2% by volume, with associated resolution of 0.1% by volume. However, these sensors respond to any combustible gas, and do not directly determine HC content. No specialized electrochemical sensors currently exist for the detection of individual HC species or families.

An experimental study was conducted by Stephens et al. [20] to compare FID measurements with other instruments for HC measurement. Stephens et al. compared HC measurements performed by a number of different instruments: a GC, an FID, an FTIR, a commercially produced NDIR, and two remote sensors. General Motors NAO Research and Development Center conducted a study in collaboration with the US EPA, Research Triangle Park, comparing HC measurements made with a GC, an FID, an FTIR, a NDIR, and two remote sensors (NDIR-based). HC concentrations in a variety of samples (individual HC species; 12 different gasoline-vehicle exhaust samples; three different volatilized fuel samples) were measured. To quantify the degree to which the various instruments agreed with the FID, a parameter called the response factor was used. The response factor was defined as the HC/CO_2 ratio measured by each instrument divided by the HC/CO_2 ratio measured by the FID. Of the various instruments, only the GC yielded response factors that were consistently at or close to unity. Stephens et al. reported that the NDIR analyzers currently have poor accuracy for quantitative determinations of exhaust HC concentration. The NDIR techniques agree well with FID for alkane compounds and poorly for olefinic and aromatic compounds. The ability to measure complex mixtures accurately improves with the amount of alkane species present in the mixture. NDIRs measured between 0.23 and 0.68 of the values reported by the FID.

6.11.4 NOx Determination

Most of the portable I/M instruments utilize an electrochemical cell for the determination of NO. To sample the exhaust of gasoline vehicles, no provisions are required to account for the presence of NO_2 in exhaust samples as little NO_2 is expected. For diesel vehicles, NO_2 is expected and the use of such devices would necessitate either the implementation of an external converter to convert NO_2 to NO or the addition of a separate NO_2 electrochemical sensor. ECOM reports NO sensor response times to be in the sub-4.5 second range. The NO_2 sensor used by the ECOM instrument has a T_{90} greater than 40 seconds, which is too low for a transient MEMS device that would be required to record transient emission values. Field tests conducted by a state agency responsible for roadside audit programs resulted in the determination of substantial sensor-to-sensor variability in accuracy, sensor life, pressure sensitivity, drift, and response times for the electrochemical sensors currently used for determination of NO concentrations in BAR-97 certified devices. Water and CO interferences were also identified as substantial problems with these instruments. The results of these field surveys and subsequent manufacturer consultations recently led to tighter specifications and required improvements to such NO detection cells. However, the field tests also indicated that properly functioning electrochemical NO sensors did produce surprisingly accurate results. Horiba markets an improved NDIR instrument for the determination of NO. The device uses a Luft-type detector, where diaphragm capacitance is used to deduce the absorption of infrared energy. These units have been reported to exhibit improved response times, increased accuracy, and reduced unit-to-unit variability. However, their cost has prevented widespread implementation by the secondary analyzer market. In addition, there is a concern for the resistance of the Luft detector to withstand the inherent vibrations possible in a MEMS operating environment.

6.12 Fourier Transform Infrared Spectroscopy

Fourier transform infrared spectroscopy, FTIR, provides an advancement in this emission measurement technology. A limitation is the high price of the commercially available models. Nicolet currently offers an FTIR priced in the $45,000 range. FTIR devices have some published correlations to the industry-accepted HC measurements made by the HFID. They have been used for measurement of on-road exhaust emissions of gasoline vehicles. However, the units tend to be rather large and quite susceptible to vibration.

6.13 Miniature Gas Chromatographs

Hewlett Packard currently markets the HP P Series Heated Micro Gas Chromatograph, which was formerly offered by Microsensor Technology Incorporated. The unit is advertised as being a self-contained portable analysis unit, capable of analyzing gas samples consisting of multiple compounds with boiling points up to 220 °C. Carrier gases are housed in an internal rechargeable tank. The unit includes a rechargeable 12 V lead-acid battery, providing up to 4 hours of operation. Its size is 6"x14"x16", and weight is 10 kg (23 lbs) which makes it portable. Unfortunately, the response time of the instrument, approximately 180 seconds, does not meet the demands of transient analysis that would be required by a MEMS.

6.14 Laboratory-Grade Analyzers

Laboratory-grade analyzers have well documented performance concerning the measurement of constituent gases found in diesel engine exhaust. They have proven reliability and reproducibility and are established and accepted by the heavy-duty diesel industry and the regulatory agencies worldwide. The units are not well suited for a MEMS because of their size, although various research-level programs have outfitted vehicles for collecting on-road emissions data. Rosemount Analytical has provided such systems for aircraft, with HFID and unheated chemiluminescent measurement technology. Rosemount NGA series analyzers were used, each housed in a robust aluminum case. The actual Rosemount NGA series analyzers are shoebox sized, operate on 24 VDC, are modular in design, and are daisy-chained together and connected to a common host computer. Horiba is working toward miniaturizing their MEXA 7000 series lab-grade emissions analyzers. Tentatively, the unit will be available in approximately one year, and will consist of two or three separate enclosures each measuring 19"x12"x7" plus a laptop. The 7000 series units use non-Luft type detectors and gold plated sample cells that are longer in length than those utilized by the I/M-level NDIR units.

6.15 Integrated Bag Sampling and Analysis

Several research teams have developed and used bag sampling systems to measure diesel exhaust emissions in the field. While all these systems had several shortcomings, they have contributed a wealth of information to assist in the development of an improved on-board bag sampling system. It is possible that a MEMS could include a heated bag sampling system with proportional sampling. The bag sample would be returned to a laboratory for analysis of the levels of various exhaust constituents. Bag sampling could be used as the only method for emissions measurement or used in addition to equipment that will measure exhaust emission concentrations on a continuous basis. The bag sampling and analysis system would provide a measurement of the concentration of exhaust constituents that would serve as a check on the emission rates obtained with the continuous emissions measurement analyzer system.

Bag sampling of raw diesel exhaust offers several challenges. Any bag system would consist of a heated sampling line, a heated filter, a sampling pump with a heated and insulated head, and a black Tedlar bag in a heated enclosure [21]. The raw exhaust sample would be analyzed at the end of a on-road test. The bag sample could be analyzed by a MEMS either on-board or at a fixed site, or with laboratory-grade analyzers located at a fixed site or in a trailer brought to the testing site. Black Tedlar bags, with an inner clear Tedlar lining, are available through SKC, Inc. for sampling gases that are reactive in presence of ultraviolet light. In the case of diesel exhaust, the black Tedlar film will preserve the integrity of hydrocarbons and NOx samples inside the bag. A heated sampling system and a heated container for the bag will prevent condensation of higher hydrocarbons and water. Many of the currently available portable analyzers which might be potential candidates for a MEMS have slow response times. The analysis of the heated bag exhaust sample using the MEMS analyzers or laboratory-grade analyzers could provide method to overcome the need for fast response time instruments.

6.16 Sample Conditioning Issues

Unlike gasoline exhaust, diesel exhaust samples have to be conditioned before they are analyzed. The foremost reason for sample conditioning is to avoid condensation of water and higher HC in the sampling lines. The design and operating conditions of the typical gas analyzers also dictate the nature of sample conditioning.

On-board emissions measurement systems, developed in the recent past, for gasoline vehicles have diluted the sample in ratios of 1:10 (Ford Motor Company) and 1:15 (VITO) to prevent water condensation in the sampling lines. Water condensation in diesel exhaust sampling lines will result in the loss of water-soluble NO_2. Additionally, diesel exhaust samples have to be maintained above 190 °C (375 °F) to prevent condensation of heavy HC. Heating the sampling lines will also prevent HC deposition in the measurement systems.

In addition to conditioning the exhaust to prevent condensation of water and heavy HC, limitations imposed by the various emissions measurement analyzers and sensors have to be taken into account. Any NDIR sensor output will be compromised by the presence of water vapor in the exhaust sample. Hence, for units such as the City Technology electrochemical cells or the Andros 6800, the exhaust sample temperature has to be lowered to below 50 °C and 40 °C, respectively. The ECOM SG Plus is one of the few emissions measurement units that is available with a heated sampling line. The system also employs a Peltier thermo-electric cooler, which is located directly upstream of the electrochemical cell in the sample stream, which is used to remove water vapor. ECOM implements this sampling procedure in order to prevent the loss of water-soluble NO_2 compounds.

6.17 Calibrations

Generally speaking, most I/M-level analyzer manufacturers will report that instrument calibration is necessary, at most, on a weekly basis. However, individuals who have done in-field testing report that systems require a more frequent schedule for leak-checking, instrument calibration, and verification of zero and span response. The rigors of an on-road-testing program entail a considerable amount of general wear-and-tear. In accordance with BAR-97 Emissions Inspection System Specifications and industry-accepted laboratory standards, MEMS gas analyzers should be calibrated using gases traceable to NIST, with blend tolerance and accuracy specified. It is understood that transportation and storage provisions for such calibration gases may pose a challenge to the portability of a MEMS, but without such requirements, the collected results will suffer a substantial loss of credibility.

It should be stressed that portable measurement systems should be correlated with laboratory-grade analyzers. Instrument accuracies reported in Table 1 are primarily derived from laboratory measurements of known component gas concentrations. This is standard practice, used to establish the measurement accuracy of a device, but such validation does not necessarily qualify the accuracy associated with real-world measurement of diesel engine exhaust streams. Most optical NDIR devices utilize narrow band-pass filters in order to reduce interference and improve instrument response. Such practices could limit the ability of these instruments to accurately detect the wide range of hydrocarbon species inherent to diesel exhaust streams. Such factors, in addition to interference effects caused by water and co-existent gas species, must be identified and qualified.

Table 1 Manufacturer specifications for emission analyzers.

Manufacturer	Analysis Method	Gas Species	Accuracy	Resolution	Response Time	Sampling Rate	Inlet Temperature	Physical Dimensions	Power Requirement
Siemens Ultramat 23	NDIR	Multi-Gas, (1-3): CO, CO_2, NO, and NO_2	1% Full Scale		3 – 5 s	1 lpm	< 50° C	19x7x14 (in)	120 VAC
	EC	O_2							
Siemens Ultramat 6	NDIR	Multi-Gas (1-4): CO, CO_2, SO_2, NO, NH_3, HC	1% Full Scale		3 – 5 s	1 lpm	< 50° C	19x7x18 (in)	120 VAC
Environment SA MIR 9000	NDIR	Multi-Gas (1-8): SO_2, NO, NO_2, CO, CO_2, N_20, NH_3, HC, CH_4, TOC, H_2O,	2% Full Scale					19 in Rack Mount	5 NiCad Batteries (8 – 10 hrs)
	ECat	O_2							
Enerac	EC	CO	2% Reading		T_{95} = 30 s		-5° C - 40° C	N/A Sensors	
		NO	2% Reading		T_{95} = 30 s				
		NO_2	2% Reading		T_{95} = 100 s				
		NO/NO_2	2% Reading		T_{95} = 5.5 s				
Sensors, Inc.	NDIR	HC	4 ppm or 3% Reading	1 ppm; 0.1 ppm High Res.	T_{90} = 3.5 s	0.3–6 lpm	Ambient Temperature + 5° C		5 VDC, 2A typical, 3A max.
		CO	0.02% Full Scale or 3% Reading	0.01%; 0.001% High Res.					
		CO_2	0.3% Full Scale or 3% Reading	0.1%; 0.01% High Res.					
		O_2	0.1% Full Scale or 5% Reading	0.01%					
	EC	NO_x	25 ppm or 4% Reading	1 ppm					

Table 1 Manufacturer specifications for emission analyzers (continued).

Manufacturer	Analysis Method	Gas Species	Accuracy	Resolution	Response Time	Sampling Rate	Inlet Temperature	Physical Dimensions	Power Requirement
SUN (Snap-On)	NDIR	HC	5-10%		11 – 14 s	5 – 8 lpm	< 45° C		115 VAC
		CO	3-5%		10 – 13 s				
		CO_2	5%		10 – 13 s				
	EC	NO/NO_2	5%		12 – 15 s				
Andros	NDIR	HC: n-Hexane		1ppm	T_{90} < 8 s	6 lpm	< 50° C	W = 12.6(in) D = 4.3(in) H = 3.9(in)	
		< 2000 ppm	±4 ppm or ±3% Reading						
		2001-15000 ppm	± 5% Reading						
		15001-30000 ppm	± 8% Reading						
		HC: Propane							
		< 4000 ppm	±8 ppm or ±3% Reading						
		4001-30000 ppm	± 5% Reading						
		30001-60000 ppm	± 8% Reading						
		CO		0.001% Reading	T_{90} < 8 s				
		< 10.00%	±0.02% Full Scale or ±4% Reading						
		10.01 – 15.00%	± 5% Reading						
		CO_2		0.01% Reading	T_{90} < 8 s				
		< 16.00%	±0.3% Full Scale or ±3% Reading						
		16.01 - 20.00%	± 5% Reading						
		O_2		0.01% Reading	T_{90} = 40 s Fall Time				
		< 25.00%	±0.1% Full Scale or ±3% Reading						
	EC	NO		1 ppm	T_{90} < 12 s				
		< 4000 ppm	±25 ppm or ±4% Reading						
		4001 – 5000 ppm	± 5% Reading						

Table 1 Manufacturer specifications for emission analyzers (continued).

Manufacturer	Analysis Method	Gas Species	Accuracy	Resolution	Response Time	Sampling Rate	Inlet Temperature	Physical Dimensions	Power Requirement
Rosemount	HFID	HC	1%	< 1% Full Scale	$T_{90} < 1.5$ s	0.5 lpm	200° C	5.3x9x18 (in)	24 VDC, 100W
	FID	HC	1%	< 1% Full Scale	$T_{90} < 1.5$ s	0.5 lpm	Ambient Temperature	5.3x9x18 (in)	24 VDC, 100W
	NDIR	CO/CO_2				0.5 lpm		5.3x9x18 (in)	24 VDC, 100W
		< 100 ppm CO	1%	< 1% Full Scale	$T_{90} < 3$ s				
		> 100 ppm CO	1%	< 1% Full Scale	$T_{90} < 1.5$ s				
	CLD	NO/NO_2				0.5 lpm		5.3x9x18 (in)	24 VDC, 100W
		< 25 ppm NO	1%	< 1% Full Scale	$T_{90} < 3$ s				
		> 25 ppm NO	1%	< 1% Full Scale	$T_{90} < 1.5$ s				
	WCLA	NO/NO_2	1%	< 1% Full Scale	$T_{90} < 1.5$ s	0.5 lpm	60° C	5.3x9x18 (in)	24 VDC, 100W
Monitor Labs	CLA	NO_x	0.005 ppm or 1%	0.001 ppm	$T_{90} = 30$ s	0.7 lpm		5x19x24 (in)	12VDC, 15A or 115 VAC, 4A
	GFC(1)	CO	1 ppm or 1%	0.1 ppm	$T_{90} = 40$ s	1 lpm		5x19x24 (in)	12VDC, 15A or 115 VAC, 4A
		CO_2	2 ppm or 0.2%	1 ppm	$T_{90} = 40$ s	1 lpm		5x19x24 (in)	12VDC, 15A or 115 VAC, 4A
	ECat	$CO/NO_x/O_2$	2 ppm	1 ppm	$T_{90} = 30$ s	3 lpm		24x36x12 (in)	115VAC, 10A
Horiba	NDIR	HC	±5%		$T_{90} < 5$ s	2 – 4 lpm	≤ 50° C		12 VDC, 20W max.
		CO	±5%						
		CO_2	±5%						
		NO			$T_{90} < 4.5$ s	2 – 3 lpm			12 VDC, 30.5W max
		0 – 625 ppm	±25 ppm						
		626 – 5000 ppm	±4% Reading						

Note: (1) GFC is an NDIR technique.

Table 1 Manufacturer specifications for emission analyzers (continued).

Manufacturer	Analysis Method	Gas Species	Accuracy	Resolution	Response Time	Sampling Rate	Inlet Temperature	Physical Dimensions	Power Requirement
Bacharach Model 300	ECat	O_2, CO, CO_2, NO_x, SO_2	5% Reading				< 1093° C	8x3.5x4.5 (in)	
SPX	NDIR	HC	±3%	1 ppm					120 VAC, 7 amps
		CO	±3%	0.01%					
		CO_2	±3%	0.1%					
	EC	NO	±4%	1 ppm					
ECOM	Pellistor	HC	2%	1 ppm	$T_{90} < 20$ s	5 lpm		19x23x8 (in)	
	EC	CO	2%	1 ppm	$T_{90} < 38$ s				
		CO_2	2%	1 ppm	$T_{90} < 10$ s				
		NO/NO_2	2%	1 ppm	$T_{90} < 35$ s				
		O_2	2%	0.1%	$T_{90} < 20$ s				
Vetronix	NDIR	HC-Propane	6 ppm greater than absolute or 5% of reading	1ppm	8.5 sec	0.6 s		13"x6.5"x7.3"	42W
	NDIR	CO	0.06% greater than absolute or 5% of reading	0.01%	8.5 sec	0.6 s		13"x6.5"x7.3"	42W
	NDIR	CO2	0.5% greater than absolute or 5% of reading	0.1%	8.5 sec	0.6 s		13"x6.5"x7.3"	42W
	EC	O2	0.01% greater than absolute or 5% of reading	0.01%	15 sec	0.6 s		13"x6.5"x7.3"	42W
	EC	NO	32 ppm	1 ppm	12 sec	0.6 s		13"x6.5"x7.3"	42W
	EC	NO	60 ppm	1 ppm	12 sec	0.6 s		13"x6.5"x7.3"	42W
	EC	NO	120 ppm	1 ppm	12 sec	0.6 s		13"x6.5"x7.3"	42W
Nicolet	FTIR	THC			Acquisition rate is 1 sample per second	20 lpm	100 - 185° C		120 VAC, 410W
		CO							
		CO_2							
		NO_x							

7 SYSTEM INTEGRATION AND DATA ACQUISITION

The system integration component consists of the computer, data acquisition and signal conditioning hardware, and software for control and data acquisition. The system must be rugged but portable and must therefore be powered with a portable energy supply such as a battery or the vehicle's supply.

The sensors have been discussed in the previous sections. A simplified schematic of a MEMS is shown in Figure 1. Rectangular boxes represent hardware and ovals represent the anticipated measurements. Typically, the sensors have analog voltage outputs, which can be read by standard data acquisition boards. Some sensors may also have digital outputs such as the RS-232 serial protocol to communicate with a computer for data transfer and control. For example, a GPS requires up to nine analog channels and four digital channels to record data whereas a single two wire digital interface using a serial protocol can be used to interrogate the unit. Multiple serial devices could be accommodated with a single RS-232 port on a computer through port extenders.

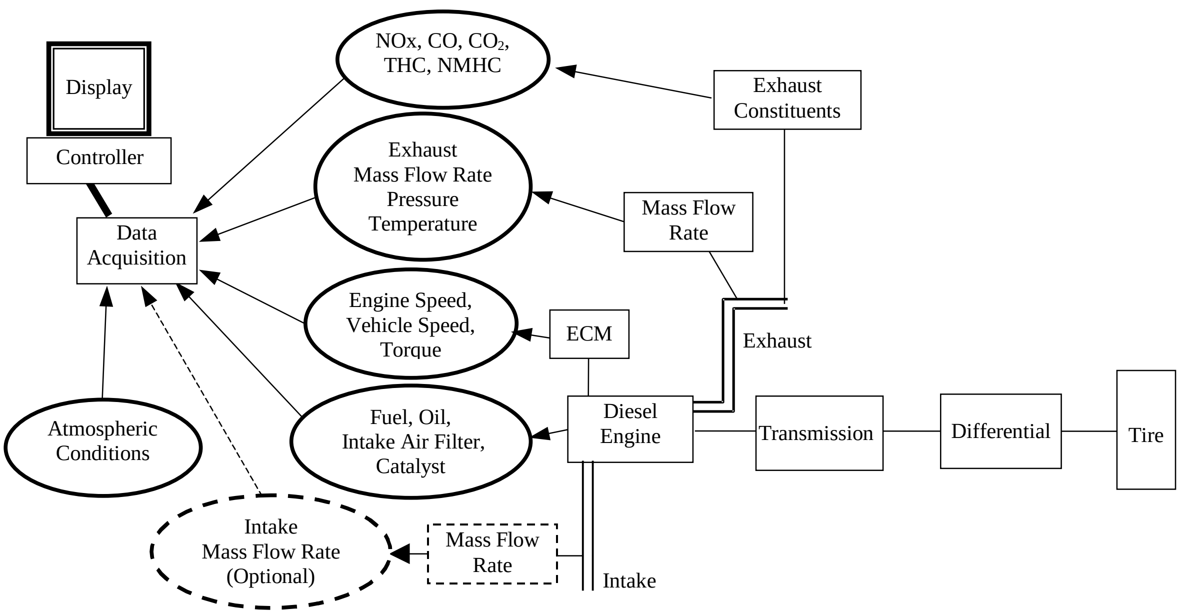

Figure 1 Vehicle test schematic.

7.1 Computers

A wide variety of computers are available to interface the data acquisition system hardware and software. The use of a "lunchbox"-style portable computer has the advantages of being similar to a regular desktop personal computer (PC) with ISA, EISA, PCI, PCMCIA (PC Card), USB, GPIB-IEEE488 and IEEE1394 interfaces in addition to a parallel line printer port. However, the system is bigger and bulkier than a laptop computer and may require 110V AC for its standard power supply, although the power supply could be adapted to employ DC power.

A non-portable VXI-systems are likewise rugged and has a high-speed interface bus. There is proper electro-magnetic interference/radio frequency (EMI/RF) shielding with reliable connector and module access. The system is suitable for more than 100 channels and high acquisition speeds. However, it is restricted to using VXI modules, needs a dedicated VXI controller computer or interface to PC (MXI-Controller, GPIB), and generally requires an AC supply. These systems are expensive, starting at about $25,000 and currently there are only a few vendors.

The semi-portable Compact PCI/PCX system has the advantages of being rugged with a 32 bit PCI bus architecture and supports several plug-in modules, including a PC module. It can be viewed as the industrial, modularized version of the "lunchbox"-style computer. The Compact PCI/PCX system is suitable for an intermediate number of data acquisition channels of around 64 analog inputs and has proper EMI/RF shielding. The system incorporates reliable connectors and easy module access, exchange and mounting, and is compatible with available PC software. Disadvantages of this system, which uses only Compact PCI modules, include limited interface options, a limit of up to 6 Compact PCI Cards in one system. Compact PCI/PCX systems with starting prices of around $15,000, are generally more expensive than conventional PC systems, and have a limited number of suppliers.

A laptop portable computer has the advantages of being compact and lightweight, but is more fragile and has fewer interface options. There are usually no ISA or ESIA slots. Though the original PCMCIA cards were much slower than PCI the advent of a new standard named CardBus allows for the full PCI bus speed to be realized. The parallel interface port is not well suited for fast high data throughput and the newer universal serial bus (USB) does provide for an improved interface, but has limited support with regard to peripherals and drivers. Associated vendor-software may not be reliable. Present laptop interfaces are well suited for a low number of data acquisition channels.

7.2 Operating System

DOS is well established, easy to interface to hardware, and has inexpensive development tools. However, disadvantages of DOS include the 640 kiloByte (kB) memory barrier and it may disappear as an operating system (OS) in the future. Manufacturers supporting the ISA and EISA style bus under the DOS platform are becoming fewer, and software support for the older hardware may become unavailable. Networking and programming for networks may have to rely on custom-written software.

The Windows 95/98 OS includes many programming tools for 32-bit operation, has no 640 kB memory barrier for software, and is a "current" OS that is fairly well established. Unlike the Windows NT OS, there is no hardware abstraction layer that prevents direct access to hardware. Networking is fairly trivial and there is substantial support amongst software and hardware developers. The 32-bit programming will cause incompatibility issues with non-32 bit software.

The Windows NT OS also includes many programming tools for 32-bit, and similarly has no 640 kB memory barrier for software. Again, it is a "current" OS that is fairly well established, networking is readily available, and there is support from many software and hardware developers. It is a stable preemptive multitasking OS for software so user written applications do not generally crash the entire system. This also means that each program gets a specified slice of

CPU time, which makes execution time more predictable. The hardware abstraction layer prevents easy access to low-level hardware input/output (I/O).

7.3 Data Acquisition Hardware

The choice of data acquisition hardware is somewhat dependent on the computer choice and sensor requirements. Most commonly available hardware for desktop computers includes 8 differential or 16 single ended, 16 bit analog-to-digital converter (ADC) inputs at 100 kilo-samples/sec (kS/sec). In higher end boards faster sampling rates up to 500 kS/sec and multiplexers extending the available input channels to 32 or 64, are available. These boards may also contain other hardware to provide digital I/O ports, digital-to-analog converter (DAC) outputs, and counter/timer capabilities.

ISA bus plug-in cards have typical bus transfer rates of 2 to 3 Mega-Bytes/sec (MB/sec). These cards are available with DOS drivers, and custom driver software can easily be written. These cards are available from numerous vendors and are reasonably priced. There may be up to 20 cards in the same system providing significant data acquisition capabilities. Disadvantages of these cards include inefficient or awkward drivers for 32-bit software applications, and diminishing vendor support. They do not fit in laptops, and on faster systems there may be significant limitations on the cards' bus transfer speeds, thus impacting performance.

PCI bus plug-in cards have typical bus transfer rate of 80 MB/sec. These cards are relatively inexpensive, and are the current standard. Support and drivers are widely available for 32-bit programming. However, there are only 4 PCI card slots available in a standard PC system (although a PCI bridge can be used), and these cards are not available for laptops.

Universal serial bus devices have typical bus transfer rates of 1.5 MB/sec. USB devices have a simple serial interface that does not require the fairly complicated step of setting up bus operating parameters. There is a growing availability of computers with USB ports, and devices usually are fairly inexpensive. USB seems to be an emerging standard and 32-bit programming support and drivers are available for Windows 95/98 and Windows NT. An external ADC device with a USB cable of up to 15 feet in length provides more room and less electrical noise. Up to 127 such devices can be connected to the same USB controller through adapter hubs. The devices are small but can still provide up to 64 ADC channels. Power can be provided to devices through the USB bus itself. The USB device standard allows "hot" swappable devices, which would avoid time-consuming computer reboots for system reconfigurations. Disadvantages to USB include not being as fast as a parallel bus and being relatively new there is a current lack of available hardware devices.

The PC card (or PCMCIA) interface designed for laptop computers is essentially the same as the PCI bus but in a smaller package. PCMCIA devices have a fast interface with widespread availability of inexpensive products. This interface is the current standard for laptop plug-in cards. The cards enjoy 32-bit programming support with drivers widely available. Disadvantages include the lower number of channels, typically up to 16, and fairly fragile connectors, both of which can be attributed to the cards' small size.

Parallel printer port devices have bus transfer rates of 0.5 MB/sec. They have a simple interface that does not require the fairly complicated step of setting up bus operating parameters.

They are inexpensive, small, and are an established standard. There is 32-bit programming support and drivers available and programming the interface is simple. Available products are often of the low-end type with limited number of channels and analog-to-digital conversion rates.

7.4 Computer Hardware Options

There are numerous hardware and software options available for portable use. The data acquisition and system integration for the MEMS will be dependent upon the specific analyzers and equipment used for the project. The system may consist of off-the-shelf systems with custom user interface software. For example, off-the-shelf portable systems consisting of a portable laptop computer operating under the Windows 98 operating system are available. National Instruments LabView could serve as the software interface for the system. Multiple RS-232 interfaces would be incorporated via a port extension PCMCIA card. A portable SCXI signal conditioner and data acquisition system from National Instruments could be incorporated to read a variety of signals from transducers via the parallel port.

The system could alternatively be built from the ground up using the PC/104 modular computer system which provides the mechanism to develop a customized design with individual (albeit off-the-shelf) components. These cards are smaller than ISA-bus cards found in regular PC's, and are stacked, eliminating the need for a motherboard, backplane, and case. With this system, overall size may be reduced, and many fragile components can be eliminated. Numerous vendors provide a variety of PC/104 components. For example, Adtech Engineering supplies CPU modules, monitors, communication modules, and hard disk interface modules similar to the ones found in conventional PCs. Solid-state disk modules, multiple RS-232 port modules, and GPS modules are also available. The solid-state disk functions like a hard drive but has no moving parts and will contribute to the ruggedness of the system, while RS-232 modules can provide effortless integration of instrumentation. It is anticipated that a DOS or Windows-based operating system would serve as the foundation for the system with the data acquisition and control code written in one of the commonly-used programming languages such as Basic or C.

8 ADDITIONAL CRITICAL FACTORS AFFECTING MEMS OPERATION

8.1 Time Response Effects With Transient Operation

It is a requirement that the MEMS is able to report emissions levels, in brake specific units of g/bhp-hr, during speed and torque transients. Engine torque and consequently engine output power may change rapidly during transient engine operations. During transients the mass airflow (either at the exhaust or intake), broadcast torque, and analyzer outputs will all change, but they will not change simultaneously nor in the same functional fashion. It is not possible to report instantaneous emissions merely by identifying the "best fit" delay times between the various input signals, because all of the sensors enjoy different frequency responses. For a theoretical step increase in torque, there will be residence time distributions of species in the exhaust and sampling lines, and slow response functions from the analyzers. The time response of pressure and temperature measurement systems must also be considered. Two options are available to counter this problem, namely:

1) The treatment of all signals (through imposition of smearing, or signal distribution in time) to reflect the behavior of the slowest response signal or component, so that the continuous emissions output is fully synchronized, but represents a weighted window average of emissions, rather than a true instantaneous value. The window implied would still be shorter than any sampling period used for enforcement (expected to be 30 seconds), but naturally the actual peak values of emissions spikes would be reduced.

2) The use of back transforms to infer the actual instantaneous property (such as a temperature or a species concentration) from the various continuous signals. Although this approach has the potential to yield values that are fair reflections of instantaneous emissions, it is computationally intensive. Detailed models of component responses to changing time histories are required, and there is a danger of instability in the computed data if too fine a time interval is imposed during numerical back transformation. It is anticipated that developing a procedure for adequately considering transient lag times and gas dispersion will represent one of the most challenging aspects of a satisfactory operating MEMS.

8.2 Air Filter Effects

A partially blocked air filter will have an adverse affect on the performance and emissions of diesel engines. The engine response must be a compromise between de-rating power, or reducing the air/fuel ratio, leading to elevated CO and PM emissions. In FTP certification, the issue of a blocked air filter does not arise because the intake depression is independently specified. Prescription of air filter condition during MEMS testing is a matter of policy, but it is suggested that the air filter must be in a condition that does not trip the visual differential pressure indicator before emissions measurement commences. In fact, in-use testing procedures may recommend that a new air filter be installed prior to an in-use test with MEMS.

8.3 After-treatment Device Effects

Many vehicles have exhaust after-treatment devices such as catalytic converters or particulate traps. It is generally the responsibility of the vehicle owner to maintain these devices. Some vehicle owners may replace or modify these devices over the lifetime of the vehicle and the influence of these devices must be considered in the test procedure.

8.4 Test Fuel Effects

The properties and composition of the fuel used by a diesel engine can greatly influence emissions levels. For the FTP engine certification test, a special test fuel is used to eliminate the influence of varying fuel properties. For in-field testing, the vehicles would normally have fuel selected by the fleet owner. Some fleet owners purchase fuels with specific additives and fuel properties which could influence the levels of some emissions constituents. It is expected that most of in-field MEMS based emissions testing may be conducted with the in-use fuel (in the vehicle's fuel tank).

Similarly, engine oil properties can influence emissions. In order to assure that in-field emissions tests are comparable and repeatable, it will be necessary to account for or control the influence of varying engine oil properties. However, it is expected that the in-field MEMS based testing may be conducted with the in-use oil present in the vehicle.

8.5 Exhaust Stacks

The procedure currently followed at West Virginia University for in-use testing of vehicles with dual stacks involves connecting the two stacks into a single outlet. A MEMS must be adaptable to a wide variety of exhaust stack configurations.

8.6 Ambient Temperature, Humidity, and Barometric Pressure Measurements

Ambient conditions have a profound effect on in-use exhaust emissions. A MEMS should measure and archive ambient temperature, humidity, and barometric pressure.

8.7 Definitions and Terminology

The success of any measurement system is largely dependent upon the consistency of definitions and terminology when reporting data. A common set of definitions and terms must be employed when reporting the results. For instance, the definitions found in the American Society for Testing and Materials specifications E177-90a and E456-96 should be used when reporting the data from a MEMS.

9 CONCLUSIONS

This study has reviewed the currently available methods for measuring engine speed, vehicle speed, engine torque, exhaust flow rate, along with available options for system integration, and has highlighted potential candidate instruments and technologies for a Mobile Emissions Measurement Systems (MEMS). An evaluation of currently available technologies for measurement of the levels of constituents of heavy-duty exhaust emissions has identified components that could potentially be incorporated into a MEMS. A review of prior in-field emissions measurement systems has shown that the currently available measurement technologies will require extensive evaluations to determine their accuracy, precision and repeatability. It is anticipated that significant engineering studies will be required in order to select and demonstrate the measurement technologies and instruments which are most appropriate for an on-board mobile measurement system for measuring the emissions from heavy-duty engines.

10 NOMENCLATURE AND ABBREVIATIONS

10.1 Nomenclature

A	Area at the Restriction
β	Diameter Ratio
C	Discharge Coefficient
ΔP	Difference in Pressure ($P_{1\ upstream} - P_{2\ restriction}$)
g_c	Gravitational Constant
k	Specific Heat Ratio c_p/c_v
ρ_f	Density of Flowing Fluid
ρ_0	Density of Fluid
q_m	Mass Flow Rate
r	Ratio of P_2 to P_1
V_0	Fluid Velocity
Y	Expansion Factor

10.2 Abbreviations

A/F	Air-to-Fuel Ratio
ADC	Analog-to-Digital Converter
AIGER	American Industry/Government Emissions Research
BAR	Bureau of Automotive Repair
bhp	Brake Horsepower
CFR	Code of Federal Regulations
CLA	Chemiluminescent Analyzer
CLD	Chemiluminescent Detector
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAC	Digital-to-Analog Converter
EAMP	Emissions-Assisted Maintenance Procedure
EC	Electrochemical Cell
ECat	Electrocatalytic Cell
ECM	Electronic Control Module
EMI	Electro-Magnetic Interference
EGS	Electrochemical Gas Sensor
EMA	Emissions Measurement Apparatus
EPA	United States Environmental Protection Agency
FID	Flame Ionization Detector
FTIR	Fourier Transform Infrared
FTP	Federal Test Procedures
g	Grams
g/bhp-hr	Unit of brake specific emissions.

GC	Gas Chromatograph
GFC	Gas Filter Correlation
GPS	Global Positioning System
HC	Hydrocarbon
HFID	Heated Flame Ionization Detector
HEUI	Hydraulically Actuated, Electronically Controlled Unit Injector
hr	Hour
I/M	Inspection and Maintenance
I/O	Input/Output
lpm	Liters per Minute
kB	KiloByte
kW	KiloWatt
MEMS	Mobile Emissions Measurement System
MTU	Michigan Technological University
NDIR	Non-Dispersive Infrared
NDUV	Non-Dispersive Ultraviolet
NESCAUM	Northeast States for Coordinated Air Use Management
NIST	National Institute of Standards Technology
NMHC	Non-Methane Hydrocarbons
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
O_2	Oxygen
O_3	Ozone
OBD	On-Board Diagnostic
OBE	On-Board Emissions System
OS	Operating System
PC	Personal Computer
PM	Particulate Matter
ppm	Parts Per Million
PREVIEW	Portable Real-Time Emission Vehicular Integrated Engineering Workstation
RF	Radio Frequency
ROVER	Real Time On Road Vehicle Emissions Recorder
S-HDDE	Settling Heavy-Duty Diesel Engine
SO_2	Sulfur Dioxide
THC	Total Hydrocarbons
T_{90}	Time required for response to exceed 90% of final value given a step change input.
T_{95}	Time required for response to exceed 95% of final value given a step change input.
USB	Universal Serial Bus
VOEM	Vito's On-the-Road Emission and Energy Measurement System
VITO	The Flemish Institute for Technological Research
WCLA	Wet Chemiluminescent Analyzer

11 REFERENCES

1. McKain, D. L., Clark, N. N., McDaniel, T. I., and Hopie, J. A., "Chassis Test Cycle Development for Heavy-Duty Engine Emissions Test Compliance," SAE Technical Paper No. 980407, 1998.
2. Branstetter, R., Burrahm, R., and Dietzmann, H., "Relationship of Underground Diesel Engine Maintenance to Emissions," Final Report for 1978 to 1983 to the U.S. Bureau of Mines, Department of the Interior Contract H0292009, 1983.
3. Chan, L., Carlson, D. H., and Johnson, J. H., "Evaluation and Application of a Portable Tailpipe Emissions Measurement Apparatus for Field Use," SAE Technical Paper No. 921647, 1992.
4. Spears, M. W., "An Emissions-Assisted Maintenance Procedure for Diesel-Powered Equipment," University of Minnesota, Center for Diesel Research, Minneapolis, MN, 1997.
5. Englund, M. S., "Field Compatible NOx Emission Measurement Technique," SAE Technical Paper No. 820647, 1982.
6. Human, D. M. and Ullman, T. L., "Development of an I/M Short Emissions Test for Buses," SAE Technical Paper No. 920727, 1992.
7. Kelly, N. A. and Groblicki, P. J., "Real-world emissions from a modern production vehicle driven in Los Angeles," *Journal of the Air & Waste Management Association*, Vol. 43, No. 10, 1993.
8. Mackay, G. I., Nadler, S. D., Karecki, D. R., Schiff, H. I., Butler, J. W., Gierczak, C. A., and Jesion, G., "Dynamometer Intercomparison of Automobile Exhaust Gas CO/CO_2 Ratios and Temperature Between On-Board Measurements and a Remote Sensing Near Infrared Diode Laser System," Phase 1b Report to the Coordinating Research Council and National Renewable Energy Laboratory, 1994.
9. Mackay, G. I., Nadler, S. D., Karecki, D. R., Schiff, H. I., Butler, J. W., Gierczak, C. A., and Jesion, G., "Test Track Intercomparison of Automobile Exhaust Gas CO/CO_2 Ratios and Temperature Between On-Board Measurements and a Remote Sensing Near Infrared Diode Laser System," Phase 1c Report to the Coordinating Research Council and National Renewable Energy Laboratory, 1994.
10. Butler, J. W., Gierczak, C. A., Jesion, G., Stedman, D. H., and Lesko, J. M., "On-Road NOx Emissions Intercomparison of On-Board Measurements and Remote Sensing," Final Report, Coordinating Research Council, Inc., Atlanta, GA, CRC Report No. VE-11-6, 1994.
11. Gierczak, C. A., Jesion, G, Piatak, J. W., and Butler, J. W., "On-Board Vehicle Emissions Measurement Program," Final Report, Coordinating Research Council, Inc., Atlanta, GA, CRC Report No. VE-11-1, 1994.
12. Bentz, A. P. and Weaver, E., "Marine Diesel Exhaust Emissions Measured by Portable Instruments," SAE Technical Paper No. 941784, 1994.
13. Bentz, A. P., "Final Summary Report on Project 3310, Marine Diesel Exhaust Emissions (Alternative Fuels)," United States Department of Transportation United States Coast Guard Systems, Report No. CG-D-08-98, 1997.
14. Vojtisek-Lom, M. and Cobb, Jr., J. T., "On-Road Light-Duty Vehicle Mass Emission Measurements Using a Novel Inexpensive On-Board Portable System," Proceedings of the Eighth CRC On-Road Vehicle Workshop, San Diego, CA, April 20-22, 1998.

15. "Construction Equipment Retrofit Project," Northeast States for Coordinated Air Use Management, Boston, MA, 1998.
16. Butler, J. W., Kornisk, T. J., Reading, A. R., and Kotenko, T. L., "Dynamometer Quality Data On-board Vehicles for Real-World Emission Measurements," Proceedings of the Ninth CRC On-Road Vehicle Workshop, April 19-21, San Diego, CA, 1999.
17. Jahnke, J. A., *Continuous Emission Monitoring*, Van Nostrand Reinhold, New York, 1993.
18. Heinein, N. A. and Patterson, D. J., *Emissions and Combustion Engines,* Ann Arbor Science Publishers, Inc., 1972.
19. Reschke, G. D., "Optimization of a Flame Ionization Detector for Determination of Hydrocarbon in Diluted Automotive Exhausts," SAE Technical Paper No. 770141, 1977.
20. Stephens, R. D., Mulawa, P. A., Giles, M. T., Kennedy, K. G., Groblicki, P. J., Cadle, S. H., and Knapp, K. T., "An Experimental Evaluation of Remote Sensing-Based Hydrocarbon Measurements: A Comparison to FID Measurements," *Journal of Air & Waste Management*, Vol. 46., No. 2, 1996.
21. Jones, L, Personal Communications, Environmental Protection Agency, Ann Arbor, MI, 1999.