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Wesley Clark Riddle
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**Design and Evaluation of the Emissions Measurement Components
for a Heavy-Duty Diesel Powered Vehicle
Mobile Emissions Measurement System (MEMS)**

Wesley C. Riddle

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

**Master of Science
in
Mechanical Engineering**

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Department of Mechanical and Aerospace Engineering

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2001**

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Techniques**

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ABSTRACT

The objective of this study was the design, construction, and preliminary qualification of the Mobile Emissions Measurement System (MEMS) for in-use, on-road testing of heavy-duty diesel-powered vehicles. This included selection of emissions analyzers and sampling system components capable of producing emissions results of similar accuracy to those attained with laboratory-grade instruments. A thorough investigation of commercially available systems, and a literature review, identified no suitable designs. Therefore, a complete emissions measurement system, designed specifically for the testing of heavy-duty diesel powered vehicles, was developed using available components.

The candidate analyzers that performed successfully during bottled gas bench tests were then incorporated into a sampling system and tested with diesel engine exhaust. Emissions concentrations reported by the MEMS were compared to concentrations reported by laboratory-grade analyzers. Results indicated that the system is capable of reporting cycle-integrated, brake-specific CO₂ within 3%, and NO_x within 5% of laboratory data over an FTP cycle.

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The MEMS project was successful due to the hard work and cooperation of numerous people. Construction and testing of the MEMS emissions components would not have been possible without the work of friends and colleagues. The work presented in this thesis was performed in conjunction with Dan Carder and Ben Shade, who were great assets to the project. Thanks to Greg Thompson for questioning everything to make sure it was done right, and thanks to Andy Fuller for operating the engine on all those late nights at the lab. I wish to thank Ryan Barnett and Aaron Barnett for their assistance with fabrication and integration of components, and Jared Knight for his contributions to research related to downsizing and improving the current emissions measurement system. Also, I would like to thank Tom Spencer, Richard Atkinson and Andy Pertl for excellent electronics and computer related support. Finally, I would like to thank the engine manufacturers for providing funding, as well as valuable opinions, for the project.

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NOMENCLATURE

CARB	California Air Resources Board
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
EC	Electrochemical
ECM	Engine Control Module
ECU	Engine Control Unit
EERL	Engine and Emissions Research Laboratory
EGS	Electrochemical Gas Sensor
EPA	Environmental Protection Agency
FID	Flame Ionization Detector
HC	Hydrocarbons
HDDE	Heavy-Duty Diesel Engine
HFID	Heated Flame Ionization Detector
MEMS	Mobile Emissions Measurement System
N ₂	Nitrogen
NDIR	Non-Dispersive Infrared
NDUV	Non-Dispersive Ultraviolet
NH ₄	Ammonia
NMHC	Non-Methane Hydrocarbons
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Oxides of Nitrogen
O ₂	Oxygen
O ₃	Ozone
OREMS	On Road Emissions Measurement System
PM	Particulate Matter
ppm	parts per million
ROVER	Real-time On-road Vehicle Emissions Recorder
THC	Total Hydrocarbons
WVU	West Virginia University

Chapter 1 INTRODUCTION

Emissions from heavy-duty trucks make up a large portion of the mobile emissions inventory. Vehicles are classified as heavy-duty if their gross vehicle weight rating is greater than 8,500 lb (14,000 lb after 1995 in the state of California). Traditionally, the testing procedure to measure emissions output from these vehicles has been performed by loading the engine with a dynamometer. Loading may be applied by a dynamometer in a test cell if the engine is removed or by a chassis dynamometer through the drive wheels of the vehicle. These methods do not accurately represent actual driving conditions for most cases. In-use testing is the most realistic method of determining exhaust emissions over a certain driving route.

On-road testing of diesel trucks presents many challenges with currently available instruments. Diesel engine emissions are generally significantly different than those from a gasoline engine. Namely, oxides of nitrogen (NO_x) concentrations are typically much higher for diesels while carbon monoxide (CO) and hydrocarbon (HC) concentrations are much lower when compared to a gasoline engine. Many species of hydrocarbons commonly found in diesel exhaust condense at higher temperatures than those in gasoline engine exhaust.

Diesel engines found in heavy-duty trucks usually have displacements ranging from 7 to 13 liters with horsepower ratings from about 200 to 600. Electronically controlled, turbocharged, direct injection diesel engines are now used in most on-road, heavy-duty trucks in the United States. Electronic controls provide many options to decrease exhaust emissions as well as improve power output and fuel consumption.

Gasoline engines are generally not used in heavy-duty trucks for several reasons. Fuel efficiency is a primary driving factor for the use of diesel engines. Also, longevity is on the order of several times better for diesel engines of comparable size. There are also disadvantages to using diesel engines in heavy-duty trucks. These include higher initial cost, possible cold starting problems, particulate emissions and lower power-to-weight ratio. For heavy truck applications, the advantages of using diesel engines outweigh the disadvantages. Therefore, the diesel engine is likely to be the powerplant of

choice for heavy-duty trucks in the near future. Hybrid diesel/electric powerplants are another option currently under investigation. Hence, efforts are currently underway to develop measurement systems for in-use diesel engine exhaust emissions.

This study addresses the requirements of the Consent Decrees that were entered into by the six Settling Heavy-Duty Diesel engine manufacturers (Caterpillar Inc, Cummins Engine Company, Inc., Detroit Diesel Corporation, Volvo Truck Corp., Mack Trucks Inc., and International Truck and Engine Corporation) and the U.S. Government [14]. The MEMS was designed to report emissions on a brake-specific (g/bhp-hr) basis. This was possible without measuring torque because the ECU of diesel engines that meet SAE J1587 may be connected to an adaptor from the manufacturer, which provides a percent load output. SAE J1939, which is available on engines produced starting in May 2000, provides for an estimated torque broadcast from the ECU. Torque is inferred by the ECU from parameters such as fueling rate, engine speed and intake manifold pressure. Without this estimated torque signal, torque would actually need to be measured with a load cell. This is complicated because much more labor would be involved to test a truck if a device containing a load cell was installed in the drive system. Also, equipment costs would rise because driveshafts, if equipped with load cells, would have to be available for every truck that could be tested. Several methods of measuring torque directly were considered at the onset of the project. One idea was to use a commercially available wireless torque cell in the driveshaft. Another alternative was to use drive wheels equipped with wireless torque meters. Both these methods would have added significantly to the system cost and complexity, if they could at be implemented at all.

Intake or exhaust flow rate must be measured in order to convert emissions measurements from a concentration basis to a mass basis. If intake air flow rate was measured, the air-fuel ratio would also be required for the calculation. This could have been inferred from the CO₂ analyzer reading. However, the use of an exhaust flow measurement device was deemed appropriate primarily due to the fewer errors in detecting brake-specific mass emissions. Brake-specific mass emissions rates were required by the Consent Decrees.

Exhaust emissions concentrations were determined by sampling and analyzing raw exhaust. Avoiding dilution of the exhaust eliminates potential sources of error. Furthermore, a dilution system would have added complexity, weight and cost to the system. Additionally, available emission analyzers, suitable for on-road testing, would be operating at the lower end of their ranges if exhaust were diluted. All of the analyzers tested were designed for sampling raw exhaust from gasoline engines. Therefore, CO and HC concentrations were at the lower end of the analyzer ranges with raw diesel exhaust.

The primary objective of this research was to develop an emissions measurement system for on-road testing using currently available components. The entire Mobile Emissions Measurement System includes the analyzers, sampling system, exhaust flow measurement device, data acquisition system, interface to the engine ECU, and sensors to measure ambient humidity and temperature. A global positioning system was also included as part of the system for confirmation of vehicle speed and distance measurements. The design of the sub-system to measure emissions concentrations of raw diesel exhaust is the main focus of this document. This sub-system will be termed the emissions measurement component of the MEMS. The emissions measurement component includes exhaust gas analyzers and the sampling system, which consists of a heated pump, heated filter, heated lines, moisture removal unit, NO_x converter, and flow and temperature control devices.

The emissions measurement component of the MEMS consists of gaseous emissions analyzers and a sampling system. CO₂ and NO_x were the gases of primary concern. Emissions analyzers were selected to provide high accuracy while meeting the requirements for on-road use such as small size and resistance to vibration. The ability to accurately report exhaust emissions results from transient operation was of paramount importance. Included in this thesis is the selection of analyzers and sampling system components, integration of those components into a system, and verification of the system.

Chapter 2 LITERATURE REVIEW

An extensive literature review was performed at WVU and results were reported in the paper, “Assessment of Mobile Monitoring Technologies for Heavy-Duty Vehicle Emissions,” [19]. A large portion of the following literature review is reprinted directly from that document.

2.1 Prior Portable and Mobile Emissions Measurement Systems

2.1.1 Introduction to Portable and Mobile Systems

Portable and mobile emissions measurement systems have been used in numerous inspection and maintenance (I/M) programs as well as for research studies related to human exposure and emissions inventories. Portable systems may be transported to the emissions source while mobile systems may be installed on a vehicle for in use testing. A literature review was performed covering prior portable and mobile emissions measurement systems of the past 20 years. Several of the mobile systems were designed and/or evaluated in parallel with or after the MEMS designs were established. Some of the information presented was not available until after completion of the MEMS.

2.1.1.1 Southwest Research Institute, 1983

Southwest Research Institute conducted a project from 1978 to 1983 to develop a transportable system for I/M testing of diesel engines in a mining application [6]. The system consisted of laboratory-grade emissions analyzers, a portable dynamometer, laboratory-grade emissions instruments, volumetric fuel flowmeter, and a laminar air flowmeter. The emissions measurement system consisted of a heated flame ionization detector (HFID) for HC, non-dispersive infrared (NDIR) analyzers for CO and CO₂, a heated chemiluminescent analyzer (CLA) for NO_x, and a polarographic analyzer for oxygen (O₂). 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.

2.1.1.2 Michigan Technological University, 1992

Michigan Technological University (MTU) researchers developed an Emissions Measurement Apparatus (EMA) system and reported results from underground mining equipment tests [10]. 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 CO₂ 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.

2.1.1.3 University of Minnesota, 1997

The emissions-assisted maintenance procedure (EAMP) for diesel-powered mining equipment was developed by the University of Minnesota [43]. 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, NO₂, CO, CO₂, and O₂. 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

On board measurements have long been viewed as the most realistic method to determine emissions from a vehicle over a driving cycle. Rapid advancement toward commercially available systems for diesel powered vehicles has been made in the past two years. Until recently, most work in the field of on-board measurements was focused toward internal research projects of engine manufacturers.

2.1.2.1 Caterpillar, 1982

A portable bag collection system was developed by Caterpillar to quantify fuel-specific NO_x emission levels from in-use diesel engines [15]. 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 EPA's database of transient engine emissions [23]. 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, NO_x, O₂, and CO₂ 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 [31]. The exhaust sample was taken at the outlet of the catalytic converter. Water was removed from the exhaust sample with an ice-cooled trap. 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. Data was recorded at 1Hz. The analyzers included a Horiba MEXA 311GE for CO₂ 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. Hydrocarbons measurements made with the NDIR devices were corrected to FID concentrations. Ambient CO measurement was 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 flowmeter 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 [34,35,7,20]. 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 CO₂, 3% for CO, 10% for NO_x, and 7% for HC. The on-road

test showed that the OBE system was within (on average) 10% for CO, 1% for CO₂, 6.6% for NO_x, 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, O₂, and CO₂, 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 the above systems were designed for gasoline-fueled vehicles.

2.1.2.5 U.S. Coast Guard, 1997

The 1990 Clean Air Act Amendments required the assessment of emissions from marine vessels as non-road sources of air pollution. The results of on-board emissions testing of U.S. Coast Guard Cutters are discussed in a 1994 SAE paper and a 1997 report from the U.S. Coast Guard [4,5]. An Enerac 2000E analyzer from Energy Efficiency Systems, Inc. was used to measure concentrations of CO, NO, NO₂, SO₂, O₂, and HC. CO₂ was determined from the O₂ measurement. The monitoring system incorporated air and fuel flow measurements as well as propeller shaft speed and torque. Torque was obtained through the use of radio transmitted signals from strain gages mounted on the propeller shaft. Wireless Data Corporation power metering equipment recorded the radio transmitted torque and speed signals. The emissions sample was taken at the outlet of the turbocharger due to space limitations. Emissions were successfully measured, but the system was large and difficult to maneuver.

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 [45]. A RG240 five-gas analyzer from OTC SPX was used to measure the undiluted gas concentrations of HC,

CO, CO₂, NO_x (actually NO), and O₂. 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.

2.1.2.7 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 CO₂ and CO, an FID to determine HC concentrations, and a chemiluminescent analyzer to measure NO_x. 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 [1]. 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 CO₂ 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 NO_x, a 22 percent difference for HC, and a 9 percent difference for the fuel consumption calculation.

2.1.2.9 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, CO₂, HC, O₂ 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 (ECU)), 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 [8]. PREVIEW is reported to be a fully integrated, portable system that simultaneously measures exhaust mass emissions (CO, CO₂, NO and HC) and up to forty engine parameters (through the engine control module readout) [19]. Results from the PREVIEW were compared to those obtained from analyzers in the dynamometer laboratory over the FTP and HWFET. The results agreed within 1.5% for CO₂, 3.4% for CO and 0.4% for NO_x and 12.3% for hydrocarbons. PREVIEW uses a NDIR analyzer to measure hydrocarbons while the lab data was obtained using a FID analyzer [8].

2.1.2.11 Horiba, Ltd. and NGK, 2001

Horiba, Ltd. and NGK have developed an onboard NO_x emissions measurement system [32]. The system makes use of a solid state zirconium oxide sensor to measure NO_x in the 0-5000 ppm range. Several other parameters are monitored including intake air flow rate with a Karman vortex volumetric flowmeter, vehicle speed, engine speed, ambient pressure, intake air temperature, ambient temperature, intake manifold air pressure, excess-air ratio, intake air relative humidity, and engine coolant temperature. Data was reported by the authors to be within 4% of laboratory regulatory compliance tests for NO_x mass emissions measurements. Differences of 3% for calculated fuel consumption and 1% for distance were reported.

2.1.2.12 Honda R&D and Nicolet Instrument Corp., 2001

Honda R&D Americas, Ltd., Honda R&D Co., Ltd., and Nicolet Instrument Corp. are developing an FTIR-based system for measuring NMHC, NO_x and CO [30]. The system is targeted for measuring in-use emissions from light-duty gasoline vehicles. Problems of vibration and are not yet resolved.

2.1.2.13 U. S. EPA, 2000

The U.S. EPA is currently working on a portable emissions measurement system (PEMS) to record in-use emissions from on-road and non-road vehicles [17]. Following some of the design concepts of the MEMS, the PEMS incorporates a ZrO_2 sensor for NO_x measurement, a pressure drop device for flow measurement, and a data acquisition system that is used to record various information such as vehicle speed, engine speed etc. The system can be installed on vehicles in less than one hour and does not interfere with normal operation according to the EPA. No data has been reported to date.

2.1.2.14 Sensors, Inc., 2001

Sensors Inc. is developing an on-board system, the SEMTECH-D, for measurement of diesel emissions including HC, CO, CO_2 , NO, NO_2 and particulate matter. [40]. A heated sample line is used from the vehicle exhaust to the analyzer enclosure. A unique feature of this system is the hydrocarbon measurement with an infra-red optical bench operating at 200 deg C. Downstream of the heated HC analyzer is a non-heated NDIR analyzer used to measure CO, CO_2 and HC. HC speciation results are optional. NO and NO_2 are measured separately with two NO electrochemical cells in parallel, one of which has an NO_x converter upstream. PM is measured with a laser light scattering principle from a separate diluted sample. GPS is available and data transmission is possible through wireless telemetry. Another option is the use of an NDUV analyzer for NO, NO_2 and SO_2 .

2.1.2.15 Analytical Engineering Inc., 2001

An on-board measurement system, the SPOT was integrated by Analytical Engineering, Inc. for the U.S. EPA [12]. The primary objective of the system is the reporting of instantaneous brake-specific NO_x . This system is essentially similar to the PEMS. Measured parameters include NO_x and O_2 concentration, engine speed, exhaust mass flow rate, exhaust temperature, ambient temperature, barometric pressure, altitude, and vehicle velocity and position. NO_x is calculated on a grams per bhp-hr basis and fuel-specific basis.

2.1.2.16 Clean Air Technologies International, Inc., 2001

Clean Air Technologies International, Inc. (CATI) has attempted to develop an on-board emissions testing system for light and heavy-duty vehicles with gasoline or diesel engines. This five-gas system, the OEM 2100, is currently on the market [33]. CO, CO₂, NO_x, HC and O₂ are reported as concentration, grams per second and grams per mile. Exhaust mass flow rate is calculated from data output by the ECU. Installation reportedly requires only 10 to 15 minutes and a screwdriver is the only tool required. Calibration is required only every one to three months according to the manufacturer. CATI's claim indicates that the system is likely not appropriate for tests where accuracy is the primary concern.

2.2 Classification of Emissions Analyzers

Analyzers used for measuring emissions from internal combustion engines in vehicles may be categorized into garage-grade inspection and maintenance analyzers and laboratory-grade analyzers. Laboratory-grade analyzers are accepted world wide as the standard for measuring emissions from engines used in on-road vehicles. Garage-grade analyzers are typically small, lightweight and low-cost compared to laboratory grade analyzers in which accuracy is the primary concern. Size constraints for a system that is reasonably easy to transport and install eliminate most laboratory grade analyzers as candidates for use in the MEMS. Furthermore, laboratory-grade analyzers were designed for stationary operation in a controlled laboratory environment. I/M-grade analyzers are not necessarily designed for mobile operation, but most utilize solid-state sensors that should be resistant to vibration-induced errors. Most garage-grade analyzers meet specifications set forth by the California Bureau of Automotive Repair for instruments used to perform emissions testing on in-use, spark ignition powered vehicles. Instruments which meet these specifications, known as the BAR-97 Emissions Inspection System Specifications, are typically used for certifying in-use vehicles are in compliance with state regulated emissions standards. These analyzers are also sometimes used to diagnose malfunctioning engines. Most I/M grade analyzers utilize NDIR techniques for measurement of CO, CO₂ and HC, and electrochemical cells for NO and O₂ if so equipped.

2.3 Principles of Gaseous Concentration Detector Operation

Principles of detector operation were reviewed at the onset of this project in order to more thoroughly investigate the feasibility of using the available analyzers for on-road diesel exhaust testing. Also, this knowledge allowed more accurate prediction of possible problems with detectors that were selected for testing. The following methods of gas concentration measurement apply to regulated gaseous emissions in diesel engine exhaust, but not all are suitable for this application.

2.3.1 Non-Dispersive Infrared Analyzers

Non-Dispersive Infrared (NDIR) detection is a principle based on the absorption of energy of unique wavelengths by different gases. An infrared light source provides light energy and a filter allows only a very specific wavelength to pass through to a detector at the opposite end of a sample cell. Non-dispersive indicates that the light energy is not dispersed by prisms or other methods, but is totally absorbed. When the gas being measured, or other gas which absorbs a similar wavelength, is not present all of the light energy passing through the filter reaches the detector. As the concentration of gas being measured increases, the amount of energy absorbed by the gas increases. Therefore, the amount of energy reaching the detector is reduced causing a change in output from the detector.

Some analyzers are designed so that the light waves pass alternately through a sample cell and a reference cell filled with inert gas before reaching the detector. Other analyzers contain only a sample cell before the detector, and the light source is switched off and on. Several types of detectors are used in NDIR analyzers. A solid-state photoconductive detector is often used where vibration may be of concern. This type of detector changes conductance based on the IR energy falling on it. A Luft type detector is generally capable of higher accuracy than a solid-state photoconductive detector and is often used in laboratory-grade analyzers that will not be subjected to vibration. Luft type detectors measure pressure through the use of a diaphragm with a capacitor between the moving diaphragm and a stationary object. A Luft detector may be placed between two chambers of the candidate gas, with one chamber receiving energy through a reference cell, and one receiving energy through a sample cell. Another method of detection using

a Luft detector is a series arrangement consisting of a sample cell followed by two sealed detection cells containing the candidate gas. A chopper wheel or pulsed light source is used to switch the light path from one cell to the other in the parallel arrangement, while the light is simply switched on and off or periodically blocked off by the chopper wheel in the series arrangement.

A series arrangement of the two detector cells allow the first cell, which is shorter, to absorb energy closest to the ideal wavelength while the second cell absorbs energy in the fringe areas of the wavelength range. The second cell must be longer than the first because energy in the fringe wavelengths is absorbed less efficiently. The lengths of the two cells are chosen to result in zero pressure difference when all of the light energy reaches the detection cell. When some of the available energy is absorbed by gas in the sample cell, less energy is absorbed by the first detection cell than by the second detection cell. Therefore, the higher pressure in the second detection cell causes a deflection of the diaphragm. Interference from other gases that absorb light of a similar wavelength is minimized because the pressure in the second cell decreases more than the pressure in the first cell when interfering gases in the fringe wavelengths are present in the sample cell. The same arrangement of sample and detection cells may be used in conjunction with a microflow sensor between the two detection cells. In this case, as the gas is heated or cooled, it flows between the two cells to maintain virtually constant pressure. The output of the capacitor or the microflow sensor is then converted to gas concentration in the sample cell based on calibration with known gas concentrations [29].

A parallel detection scheme, consisting of a reference cell and a sample cell, followed by two detection cells, may also use a photoconductive detector, a Luft detector or a microflow detector. One detection cell absorbs light passing through the sample cell and another detection cell absorbs light energy passing through the reference cell. As with the series arrangement, the detection cells are sealed and contain the gas being measured. When there is no candidate gas present in the sample cell, both detection chambers receive the maximum energy given off by the light source. As the concentration of candidate gas increases in the sample cell more energy is absorbed by that gas, so the energy reaching the detection cell following the sample cell is reduced.

This results in a pressure differential for the Luft detector or flow of gas across a microflow sensor. If a single photoconductive detector is used in a parallel arrangement, mirrors may be used to direct the light beams passing through the sample and reference cells to a single detector.

An AC signal is output from the detector due to the pulsing or blocking of the light source by a chopper. An AC signal is desirable because AC amplifiers are less prone to drift than DC amplifiers. The signal is then rectified to DC after being amplified [13].

Sample cell length is chosen based on the expected concentration of the measured gas in the sample stream. Longer cells are used for lower concentrations and shorter cells for higher concentrations. While a longer cell will provide higher resolution, it will be less linear and will have a slower response to transient events [13].

NDIR analyzers are available for measurement of CO₂, CO, and HC. Commercially available instruments vary widely in size depending on their intended use. Laboratory-grade analyzers are typically too large for use in a MEMS. However, accuracy is generally sacrificed as size is decreased because the most accurate designs such as a sample and reference cell in parallel followed by a series detection cell requires the most room. Single cell analyzers incorporating a solid-state detector may be very compact and lightweight which qualifies them for use on the MEMS.

The sample stream for NDIR analyzers must be filtered and conditioned to an acceptable relative humidity. If water condensed out on the inside of the sample cell the walls will become contaminated with deposits, causing errors in the measurement. Also, water interference is often observed with NDIR analyzers. Effects from water interference are minimized as the relative humidity of the sample stream is decreased.

2.3.2 Electrochemical Sensors

Electrochemical or polarographic analyzers are a relatively simple and inexpensive method of measuring concentrations of emission gases including NO, NO₂, NO_x, SO₂, CO, O₂, and CO₂. An electrochemical cell consists of two or more electrodes

separated by an electrolyte. For a cell with two electrodes, one electrode must be porous so the gas can pass through it after diffusing through a membrane. A resistor is connected between the two electrodes and voltage drop across the resistor is converted to gas concentration. If the rate of diffusion is controlled via a membrane, the current flowing through the resistor and therefore, the voltage drop across the resistor is proportional to the concentration of candidate gas, as stated by Fick's law of diffusion. Fick's law of diffusion is as follows. $i = nFADc/d = kc$, where i is current, n is the number of exchanged electrons per mole of candidate gas, F is the Faraday constant (96,500 coulombs), A is the surface area of the electrode, D is the diffusion coefficient of the gas through the membrane, c is the gas concentration in the electrolyte, d is the thickness of the diffusion layer and k is a constant [29]. The oxidation reaction for an NO at the sensing electrode of an electrochemical cell is shown below [38].

Notice that water is a reactant and therefore must be available in the sample stream to avoid depletion of water from the electrolyte. The potential of the sensing electrode must be within a certain range for the reaction to occur. If the potential of the sensing electrode is outside the design limits the response will be non-linear. Three electrodes may be used to avoid non-linearity due to the counter electrode becoming polarized as a result of high candidate gas concentrations. The third electrode is a reference electrode that is used to maintain a constant potential between itself and the sensing electrode, so the counter electrode potential is not a factor in the measurement. A fourth electrode may be added to react the products of oxidation, which can interfere with the reference electrode potential [38].

Electrochemical cells typically have a T_{90} response time of at least 5 seconds for NO, and approximately 30-40 seconds for CO and NO₂ [19]. Therefore, electrochemical cells were only considered for NO measurement due to highly transient engine operation of in-use vehicles. A NO_x converter would be required to obtain an NO + NO₂ measurement, as required for the MEMS. The sample must be filtered to avoid clogging of the membrane and the sample stream for the NO cells investigated should be between 15 and 90% relative humidity [38].

2.3.3 Electrocatalytic Analyzers

Electrocatalytic analyzers measure oxygen concentrations based on a flow of electrons across a solid zirconium oxide (ZrO_2) catalytic electrolyte. ZrO_2 allows the transfer of O_2^- ions when heated to approximately 700°C . A current is generated if the electrolyte is placed between gases of two different concentrations. O_2 sensors of this type are the standard in the automotive industry for feedback control of air-fuel ratio. This principle may also be used to measure concentrations of NO, CO and HC. NO is measured by first removing O_2 from the sample and then causing the NO to dissociate into N_2 and O_2 . O_2 is removed from the sample through a ZrO_2 electrolyte coated with platinum to catalyze the transfer process. Current must be supplied in this case because the oxygen is being transferred in the opposite direction of the flow that would be induced by the concentration gradient. The sample then flows into a second cavity where the O_2 produced from the dissociation process is measured with a second electrocatalytic device of the same design as the first [26].

Some disadvantages of electrocatalytic sensors include the negative response to components such as CO and HC if they are oxidized at the high operating temperatures with the presence of oxygen. In fact, a similar type of sensor is used to measure CO and HC by oxidizing the component gases with a heated platinum wire. These sensors are known as catalytic oxidation sensors or pellistors. Gas concentrations are determined based on the resistance change of the wire as its temperature increases due to the combustion of candidate gas. A second platinum wire, poisoned so it does not catalyze the reaction, is used as a reference resistance. The resistance values of the two wires are compared using a Wheatstone bridge to determine the gas concentration [19].

2.3.4 Chemiluminescent Analyzers

Chemiluminescent analyzers are commonly used for the measurement of NO concentration. NO concentration is determined from the infrared energy emitted when NO is converted to NO_2 . The sample gas containing NO is reacted with excess ozone (O_3) to produce NO_2 . About 10% of the NO_2 molecules formed are in an electronically-excited state. Photon emissions from the conversion of excited molecules to the non-

excited state are directly proportional to the concentration of NO. A light detection sensor is used to provide an electrical signal based on light intensity. The intensity of the light emitted is proportional to the number of NO molecules, so sample flow rate must be accurately controlled in order to determine a volume concentration of NO. An NO₂ to NO converter upstream of the analyzer is required for measurement of NO_x [29]. Chemiluminescent analyzers may not be suitable for the MEMS due to the size required to contain an ozone generator and NO_x converter.

2.3.5 Heated Flame Ionization Detectors

Hydrocarbon concentrations from diesel engines are typically measured with a heated flame ionization detector (HFID). A flame from the reaction of a mixture of hydrogen and helium with air produces little ionization unless hydrocarbons are added to the mixture, in which case the ionization is much greater and easily measurable. Polarized electrodes attract the electrons, causing a current flow, which is proportional to the number of carbon atoms that make up hydrocarbons in the sample stream. As with chemiluminescent analyzers, sample gas flow rate control is critical to determine concentration because the number of carbon atoms is measured. These analyzers are also very sensitive to the flow rate of the hydrogen and helium mixture and the oxygen. Capillary tubes are commonly used to control the flow rate of all three gases [13].

2.3.6 Non-Dispersive Ultraviolet Photometers

Non-dispersive ultraviolet (NDUV) photometers operate on a similar principle to NDIR detectors. The ultraviolet light is of shorter wavelength but higher energy than infrared light. The higher energy ultraviolet light is easier to measure accurately than the infrared light energy. Two different wavelengths of ultraviolet energy are transmitted through a single sample cell. Two band-pass filters are used, one to provide energy of a wavelength absorbed by the candidate gas, and one to provide energy of a wavelength that is not absorbed by the candidate gas. The transmitted energy of each wavelength range is measured and compared to determine candidate gas concentration. An advantage of NDUV detectors over NDIR detectors is the ability to sample wet exhaust because water absorbs very little energy in the ultraviolet wavelength range used [19].

2.3.7 Fourier Transform Infrared Spectroscopy

Fourier transform infrared spectroscopy (FTIR) analyzers are a relatively new method of measuring emissions gases. FTIR devices may be used to measure several gases at once. The infrared energy absorbed over a wide wavelength range, typically 5 to 25 micrometers is recorded. This data is then converted to concentrations with a Fourier transform [29]. Currently available FTIR analyzers capable of measuring emissions gases from engine exhaust are very expensive relative to other available instruments. These devices are likely too large in size and weight for the MEMS [19].

2.3.8 Miniature Gas Chromatographs

Gas chromatographs are available for measurement of emissions gases found in engine exhaust. Hewlett Packard manufactures a small handheld unit. However, the time response is not adequate for on-road vehicle testing, as the T_{90} response is approximately 180 seconds [19].

2.4 Available Analyzers

The available analyzers capable of measuring emissions gases in the ranges found in raw diesel exhaust were reviewed for possible use with the MEMS. Most I/M grade analyzers consist of multi-gas analyzers for CO, CO₂, and HC because all three can be measured with the same NDIR system. NO is commonly measured with electrochemical cells due to the relatively low cost. City Technology Limited is a large supplier of electrochemical NO cells for this application. At least one company markets a portable NO analyzer using NDIR detection. Also available is a zirconium oxide solid-state NO sensor from Horiba Instruments, Inc. The majority of microbench analyzers are manufactured by Andros, Horiba Instruments, Inc., Sensors, Inc., and Siemens. Several companies incorporate these microbenches into complete emissions measurement systems for the gasoline automotive testing market. All of the microbenches available at the time of this study were intended primarily for measurement of emissions from gasoline engine exhaust and none were specifically designed for diesel exhaust.

2.5 U.S. Emissions Regulation and Enforcement

The U.S. EPA determines federal emissions standards for heavy-duty, diesel engines for on-highway vehicles. Vehicles sold in the U.S. must meet the federal requirements but may also be required to meet more strict requirements in some states at the discretion of that state's government. Diesel engines for heavy-duty vehicles are divided into three classes based on GVWR of the vehicle as follows [14]. Light heavy-duty class ranges from 8500 lb. to 19,500 lb. except after 1995 in California where it is from 14,000 lb. to 19,500 lb. Medium heavy-duty is from 19,500 lb. to 33,000 lb., and heavy heavy-duty is greater than 33,000 lb.

The MEMS would be a practical way of testing in-use engines to assure they meet emissions standards throughout their useful service life. However, if used for certification purposes, the MEMS must never give an inaccurate reading that would cause a compliant engine to fail and be removed from service.

2.5.1 Current Heavy-Duty Emissions Standards

The U.S. EPA regulates emissions of NO_x, HC, CO, and PM for new diesel engines used in heavy-duty on-highway trucks and urban buses. Only the engine is certified for heavy-duty vehicles over 14,000 lb GVWR. Heavy-duty vehicles under 14,000 lb GVWR may be chassis certified at the discretion of the manufacturer. For this reason, heavy-duty emissions standards are in terms of g/bhp-hr, and therefore, the MEMS should be capable of reporting emissions in g/bhp-hr. Current federal emission standards for heavy-duty truck engines operated over the FTP are shown in Table 1 and California State standards are shown in Table 2. Vehicles must meet these standards for a predetermined service life, as detailed in Table 3.

Table 1 EPA Emissions Standards for the FTP in g/bhp-hr for Model Year 1990-2003 Heavy-Duty Diesel Truck Engines.

Model Year	NO _x	HC	CO	PM
1990	6.0	1.3	15.5	0.60
1991-1993	5.0	1.3	15.5	0.25
1994-1997	5.0	1.3	15.5	0.10
1998-2003	4.0	1.3	15.5	0.10

Table 2 California Emissions Standards for the FTP in g/bhp-hr for Model Year 1987-2003 Heavy-Duty Diesel Truck Engines.

Model Year	NO _x	THC	NMHC	CO	PM
1987-1990	6.0	1.3	-	15.5	0.60
1991-1993	5.0	1.3	1.2	15.5	0.25
1994-2003	5.0	1.3	1.2	15.5	0.10

Table 3 EPA Model Year 1987-2003 Useful Service Life for Heavy-Duty Diesel Truck Engines.

Heavy-Duty Sub Class	Useful Service Life
Light	8 years or 110,000 miles, whichever occurs first
Medium	8 years or 185,000 miles, whichever occurs first
Heavy	8 years or 290,000 miles, whichever occurs first

2.5.2 Engine Test Cycles for Certification

The Federal Test Procedure (FTP) for transient operation of heavy-duty vehicles is currently used for engine certification in the U.S. Two new tests were brought into use as a result of the Consent Decrees signed in 1998 [14]. These additional tests are required only for some manufacturers up to 2004 based on the Consent Decrees. Beginning with model year 2007 nationally and 2005 in California, all heavy-duty truck engines will require certification on the three test cycles. These two new requirements are the Not-to-Exceed limits and the Supplemental Emission Test.

The Not-to-Exceed limits cover engine operation within a calculated area under the lug curve of that engine, so the NTE zone is different for different engines. The NTE zone was designed so the engine would be operated through a wide range of load and engine speed points to cover the most common operating conditions. As per the Consent Decrees, regulated emission gases within the NTE may not exceed 1.25 times the FTP limit, except for International Truck and Engine Company where the limit is 1.5 times the FTP limit. Emissions are averaged over a minimum of thirty seconds within the NTE for comparison to the limits [14].

The Supplemental Emission Test is a 13-mode steady-state test. Each mode is weighted and a total result is calculated for comparison to the standards. Engine operating modes range from low idle to 100% load. This test is the same as the European ESC test [14].

2.5.3 Consent Decrees

The Consent Decrees are a set of agreements resulting from an October 1998 court settlement between the U.S. EPA, Department of Justice, California ARB and engine manufacturers (Caterpillar Inc, Cummins Engine Company, Inc., Detroit Diesel Corporation, Volvo Truck Corp., Mack Trucks Inc., and International Truck and Engine Corporation). The Consent Decrees came about because many heavy-duty diesel engines produced since the early 1990's exhibited higher than normal NO_x emissions under certain operating conditions [14]. Engine manufacturers were programming the ECU to change injection parameters to increase power and efficiency under steady-state conditions. These advantages were not possible without an increase in NO_x emissions. On-highway heavy-duty truck engines were not previously certified at steady state, so the engines would pass the normal certification procedure. This practice led to a court decision in which S-HDDE manufacturers were required to provide funding aimed at reducing emissions from heavy-duty diesel engines produced in the near future. A new steady-state test, termed the Supplemental Steady-State Test was implemented, in addition to the FTP, for certification. Engine manufacturers were also required to provide funding for independent research on mobile emissions measurement devices. West Virginia University was awarded the contract for Phase I and Phase II of this project, which resulted in the development and testing of the MEMS at WVU. Another penalty was the requirement to meet emissions standards scheduled for 2004 fifteen months before the originally planned implementation date. Some existing engines must be modified to comply with the standards during the production of those engines.

Chapter 3 Experimental Setup

3.1 Introduction

First, the analyzers believed to be most suitable were selected from those currently on the market. The selected analyzers were then evaluated with a predetermined set of tests using bottled gas of known concentrations. These tests included subjecting the analyzers to conditions such as vibration and inclination that may be encountered during on-road testing. Candidate analyzers were eliminated from the selection process if they did not meet one or more requirements of the evaluation process that was necessary for accurate on-road operation. Analyzers that performed satisfactorily during the gas bottle tests were evaluated with diesel engine exhaust emissions. A sampling cart was constructed for the initial engine exhaust tests where sampling system components were evaluated in tandem with the analyzers. Sampling system components such as pumps, filters and moisture removal systems were selected and sized based on results from those engine tests with the sampling cart. Components that met the gas bottle testing and stationary engine exhaust performance requirements were then incorporated into a 24" by 24" by 12" NEMA 12 enclosure for on-road evaluation. This enclosure was retained for the final system after many revisions to the sampling system and testing with different analyzers.

3.2 Selection of Analyzers for Evaluation

Microbenches were chosen for evaluation based on specifications provided by manufacturers, a study of operating principles, and discussions with experts in the emissions testing field. It was discovered that there are several companies using the same microbench as part of their complete emissions measurement systems. In these cases, the microbench only was tested if possible. Six instruments were evaluated, three of which were from Horiba Instruments, and one from each of the following: Andros, Sensors Inc., and Siemens. These instruments selected for evaluation were believed to be the best products available for use in the MEMS. The primary goal was to select analyzers that would provide the highest level of accuracy under the conditions of on-road testing while maintaining a system of reasonable size.

3.3 Descriptions of Evaluated Analyzers

Concentrations of CO₂, CO and HC were measured with NDIR detection schemes by all of the evaluated analyzers. NO concentration was measured with electrochemical cells, an NDIR microbench and a zirconium oxide electrocatalytic device. Some of the analyzers were also capable of measuring O₂ with an electrochemical cell, but this feature was not required and therefore not thoroughly evaluated. Detailed descriptions of the operating principles and features of each device follow.

3.3.1 Horiba BE-140

The Horiba BE-140 analyzer measures CO, CO₂, and HC concentration. Options include serial interfacing to the Horiba BE-220 NO analyzer and the measurement of O₂ with an electrochemical cell. The BE-140 is NDIR based with solid-state optical sensors, so large scale effects from vibration due to on-road testing are unlikely. A single sample cell is used for all three gases. Light energy is supplied by a broad-band infrared source that is directed through the sample cell onto the sensors at the opposite end of the cell. A chopper wheel rotates to allow the light source to reach only one of four sensors at any time. A stepper motor is used to drive the chopper wheel at a constant speed. A narrow band pass filter in front of each detector allows only energy of the wavelength corresponding to the gas of interest to reach that sensor. One of the four sensors is a reference sensor receiving infrared energy filtered to provide an equal response to the three candidate gases. The output from each of the other three sensors is compared to the output of the reference sensor. Each of the sensors is a dual element unit with only one element exposed to the light source. This provides for nullification of temperature effects. In addition, each of the sensors includes a field effect transistor (FET) to cancel out electrical noise in the signal [24].

The BE-140 was designed for gasoline engine automotive testing and meets BAR97 standards when used with the recommended sampling system. Measurement ranges include typical concentrations of raw exhaust gases from diesel engines. However, CO and HC ranges are much higher than required which could result in poor resolution and/or accuracy at lower concentrations. The Horiba BE-140 is shown in Figure 1 below.

Figure 1 Horiba BE-140.

3.3.2 Andros 6800

The Andros 6800 is a 5-gas analyzer and miniature sampling system capable of measuring CO, CO₂, HC, NO and O₂ concentrations. The sampling system includes a water trap, filter, solenoid valves for calibration, and sample pumps. The analyzer itself is the Andros 6602 Miniature Automotive Gas Analyzer. The solid-state NDIR detection scheme uses non-scanning infrared light frequencies for CO, CO₂ and HC and electrochemical cells for NO and O₂. A single infrared source is divided between separate sample cells for each gas and a reference cell by an optical beam splitter. The reference cell is used to compensate for variations of the infrared source. The infrared source is electronically modulated at 1 Hz. Sample pressure and temperature are monitored with a thermistor and pressure transducer to allow correction by the microprocessor. Optical band pass filters are located downstream of the sample cell,

before the detector, to allow only infrared light of specific wavelength ranges to reach the detectors. The solid-state detectors produce an output proportional to light intensity. The output from the detectors of each candidate gas cell is compared to the output of the reference cell to calculate gas concentrations [3]. The Andros 6800 is shown in Figure 2.

Figure 2 Andros 6800.

3.3.3 Sensors Inc. AMBI

The Sensors Inc. AMBI incorporates NDIR detection schemes for CO, CO₂ and HC, and electrochemical cells for NO and O₂. Measuring ranges for CO₂ and NO are well suited to raw diesel exhaust. CO and HC ranges, as with most microbenches, are higher than desired for diesel exhaust. Three sample cells are used with a solid-state modulated infrared light source for each. Thermocouples detect the amount of energy allowed to pass through the sample cells. As the concentration of candidate gas

increases, the thermocouple detector reading decreases. The cell for measuring HC is followed by two detectors, one for HC and one for reference. The reference detector is used to account for infrared source and temperature variation. Optical band pass filters selectively allow the infrared energy in the wavelength range of the candidate gas to reach the detectors [2]. The Sensors AMBII contains no moving parts and is very compact. See Figure 3 below.

Figure 3 Sensors, Inc. AMBII.

3.3.4 Siemens SIBENCH

The SIBENCH is an NDIR-based microbench for measurement of CO, CO₂ and HC and NO. The NDIR measurement is accomplished with a microflow detection method. CO, CO₂ and HC are measured with divided detection cells placed in series with two sample cells. Energy from the infrared source passes through the first sample cell prior to entering the CO₂ and CO detectors, respectively. The remaining infrared energy

is then transmitted through a second, longer sample cell before reaching the HC detector. The detection cells are divided into two chambers, which are connected via microflow sensors. A chopper wheel mechanically switches the light from the infrared source to provide an AC signal. As infrared energy is absorbed by gas in a detection chamber, the pressure in that chamber increases. Gas flow is initiated across the sensor from the chamber with the higher pressure to the chamber with the lower pressure. The first chamber absorbs energy primarily around the center of the wavelength corresponding to those gases, while the second chamber absorbs mostly fringe wavelengths. A flow from the second to the first chamber when the light was switched on would indicate a candidate gas was present in the sample cell because energy closest to the center of the spectrum for that gas is absorbed most efficiently. NO is measured with a divided detection cell in a dedicated sample tube, using the same principle [27]. The Siemens SIBENCH is shown in Figure 4 below.

Figure 4 Siemens SIBENCH Microbench.

3.3.5 Horiba MEXA 120

The Horiba MEXA 120 is a NO_x analyzer that utilizes a zirconium oxide (ZrO₂) sensor. Measurement range is from 0 to 5000 ppm NO_x. The electronic components and display are remote from the sensor, which is only slightly larger than a common automotive O₂ sensor. See Figure 5. The estimated sensor life is 100,000 miles of vehicle operation, which is much greater than the life of an electrochemical NO cell. Platinum-coated zirconium oxide, when heated to approximately 1292°F (700°C) will allow oxygen to readily pass through the material as O₂⁻ ions. The oxygen will migrate toward the side of the zirconium oxide exposed to the lowest concentration of oxygen, unless it is subjected to an electric current, which can be used to cause a flow of oxygen ions from a higher to lower concentration. The sensor is divided into two small chambers. Oxygen is pumped out of the sample gas in the first chamber by supplying current to a section of the chamber wall that is zirconium oxide. NO is dissociated into N₂ and O₂ in the second cavity. This O₂ is then removed from the cavity by supplying a constant voltage across a second section of zirconium oxide coated with platinum. NO concentration is determined from the current required to pump the O₂ out of the second cavity [26].

Some noteworthy limitations of this analyzer include a response to ammonia and sensitivity to damage by rapid temperature fluctuations. Response to ammonia should not present a problem, as the concentration of ammonia is not significant in diesel exhaust. Water droplets in the sample impacting the sensor may cause rapid cooling. This rapid cooling can cause the ceramic material to crack, as it is normally maintained at approximately 1292°F (700°C). Also, condensation on the surface of the sensor after power is switched off should be avoided, because re-powering the sensor could cause uneven heating due to the water droplets [26]. High CO or HC concentrations can cause a decrease in the reading because some of the oxygen, from the dissociation of NO, may react with those gases due to the high temperature [29].

Figure 5 Horiba MEXA-120 NO_x Analyzer.

3.3.6 Horiba BE-220

A Horiba Instruments prototype BE-220 NO analyzer was received by WVU before the evaluation process began. A later production version of this analyzer, which could be interfaced with a BE-140 analyzer, was purchased by WVU a few months later. This is an NDIR analyzer with a Luft detector. Measuring range is 0-5000 ppm, and the output is an analog signal from 0 to 5 volts [25]. This analyzer measures only NO, which would mandate the use of a NO_x converter because NO_x measurement was a basic requirement of the MEMS. Luft detectors are generally sensitive to vibration and therefore may not be suitable for on-road testing. The detector consists of a diaphragm between two sealed cells containing the candidate gas. The diaphragm deflects according to the pressure difference between the two chambers. This deflection is measured with a capacitor, one side being attached to the moving diaphragm and the other side to a stationary object. The diaphragm is mounted vertically so acceleration of the analyzer in

the vertical direction should not affect the signal. The BE-220 received at the beginning of the evaluation process was a prototype (shown in Figure 6) and was substituted with the production model (shown in Figure 7) when it became available. The production model had a slightly slower response time, but much better signal stability.

Figure 6 Horiba BE-220 Prototype Microbench.

Figure 7 Horiba BE-220 Production Model Microbench.

3.3.7 Sensors Inc. Electrochemical NO Cell

The electrochemical NO cell and accompanying manifold supplied with the Sensors Inc. AMBII was tested separately. These sensors have a response to NO only, so a NO_x converter would be required to measure NO_x. Measurement range is 0-5000 ppm NO [2]. This electrochemical cell is very small and relatively low cost compared to other NO or NO_x analyzers tested. The ZrO₂ sensor of the Horiba MEXA-120 is slightly smaller, but requires an accompanying signal processing and display unit. Before testing began, there were concerns of unnoticed inaccuracy due to depletion of the electrolyte and slow response time. Electrochemical cells were tested as stand-alone units by creating a calibration curve using bottled gases. The recommended operating range of relative humidity is between 15% and 90%. The sample stream to the NO cell should be at least 15% relative humidity to prevent water from the electrolyte from diffusing out into the sample stream. If the electrolyte volume decreases by 40% or more, the output

signal will be affected. Operating the sensor above 90% relative humidity will cause water to be absorbed by the electrolyte and cause possible leakage. Temperature changes will affect both the zero and span output of the sensor [38]. This could be software corrected as a post-processing operation, with temperature response curves supplied by the manufacturer. However, the operating temperature of the MEMS enclosure was stable enough that temperature correction was not required. The electrochemical cell is shown installed in the manifold in Figure 8.

Figure 8 Sensors Inc. Electrochemical NO Cell and Manifold.

3.4 Calibrations

Calibration requirements vary depending on the analyzer and accuracy desired. Some analyzers allow the user to select a multiple-point calibration and in some cases specify the number of points desired. Where possible, calibrations were performed prior to each set of tests conducted for evaluation of the analyzers. A Horiba SGD-710C gas divider with an advertised accuracy of $\pm 0.5\%$ was used for multiple-point calibrations. Nitrogen or zero air was used to set the zero or reference value. A flowmeter was used to maintain flow rate during calibrations at a constant value within the recommended range. The flow rate used during calibration was maintained throughout subsequent tests except tests performed specifically to investigate flow-rate effects.

3.5 Evaluation of Analyzers

The analyzers were evaluated by performing accuracy and repeatability tests and by subjecting them to conditions likely to be encountered during on-road testing. Comparisons were made to laboratory-grade analyzers and known gas bottle concentrations for accuracy evaluations. The microbenches were mounted in 12"x12"x6" steel electrical enclosures to reduce electrical noise in the signal and prevent exposure to varying ambient air currents.

3.5.1 Evaluation of Analyzers with Bottled Gases

The first step in evaluation of the analyzers was to supply gases of known concentration and record the responses. Single component and blended gases were supplied to each candidate analyzer from bottles of known concentration. The accuracy of concentration on most gases used was approximately $\pm 1\%$ of that concentration. Error due to inaccuracies in the gas concentrations can be nullified for the purposes of analyzer evaluation if the analyzer is spanned with the same gas with which tests are performed. A computer activated solenoid valve was used to switch between two gases for response time testing. Various other tests representative of predicted operating conditions were performed with bottle gases. These tests consisted of examining the analyzer output for response from water interference, vibration, inclination, gas interference from gases found in diesel exhaust, and flow rate variation.

3.5.1.1 Steady State Testing

The candidate analyzers were first evaluated by subjecting them to steady-state tests with gases from bottles of known concentrations. A Horiba SGD-710C gas divider was used to supply gases concentrations in fractions of the bottle concentration. Nitrogen was used as the diluent for these tests. The responses of each analyzer were examined for differences to the expected responses that were based on gas bottle concentration and gas divider setting. Linearity and repeatability were compared to the manufacturer specifications to verify performance.

3.5.1.2 Response Time Testing

Response time of the analyzers is critical to the success of an in-use emissions testing system, as highly transient operation is common under real-world conditions. Time response of the analyzers was tested by alternately passing a component gas and nitrogen through the analyzers at predetermined time intervals. A computer program controlling an RTI815 board, and an electric solenoid valve were used to rapidly and accurately switch between the component gas and nitrogen. The computer program was used to open and close the solenoid valve 5 times at each of 10, 8, 5, 4, 3, 2, and 1 second intervals with 20 seconds between each series. A long period of 100% component gas flow at the end of the test allowed T_{90} response time to be approximated. A flowmeter was placed in the sample line before each analyzer to ensure constant flow throughout a test. Also, a tee was installed, with one leg open to the atmosphere, upstream of the flowmeter if the analyzer being tested contained an internal pump. This step was taken to prevent possible over-pressurizing of the sampling system of the analyzer. Figure 9 below shows the set up used to supply a step input, between a zero gas and a candidate gas, to the analyzers.

Figure 9 Setup for Response Time Testing of Analyzers (from source [18]).

3.5.1.3 Inclination Testing

Each analyzer was tilted to 15 and 45 degrees from horizontal about each axis. This test was performed to determine if there would be negative effects from the truck traveling up and down grades or on off-camber surfaces.

3.5.1.4 Vibration Testing

The MEMS will be subjected to vibration over a wide range of frequency and amplitude. Therefore, vibration must have minimal effect on the components. The analyzers are of primary concern. Some types of analyzers such as those containing a Luft type detector may not be suitable for use where this level of vibration is experienced. Analyzers containing solid-state detection methods are least prone to problems due to vibration. The Horiba BE-140 and Sensors AMBII both utilize solid-state NDIR detectors. The Mexa-120 and the electrochemical NO cell are also solid-state devices.

Vibration testing was first performed by a crude in-lab method of shaking the analyzers by hand while recording the output. Shaking the analyzers by hand provided high amplitude but low frequency oscillations. Later testing was performed by subjecting

the analyzers to an actual on-road cycle in a Mack class 8 tractor. The analyzers were first zeroed using N₂ then the output was recorded with the analyzers sampling ambient air from inside the cab over the entire cycle. The data was examined for the presence of vibration-induced errors on the Horiba BE-140, Horiba BE-220, Horiba MEXA-120 and Sensors Inc. NO electrochemical cell.

3.5.1.5 Effects of Flow and Pressure Variation

The analyzers for a MEMS should exhibit minimal or no change in response when the pressure and/or flow of the sample stream is varied within the designed operating range of the respective analyzers. The Horiba MEXA 120 NO analyzer should not be sensitive to changes in flow rate, as it is a non-sampling sensor, however the flow should be constant to provide a constant time lag for the sampling system. Other sampling analyzers are likely to show a change in output when flow rate and therefore pressure is changed. The candidate analyzers were evaluated for changes in response to the same gas when the flow rate was varied.

3.5.2 Engine Exhaust Testing of Analyzers

Engine exhaust tests were conducted on each candidate microbench that performed satisfactorily during the gas bottle testing procedures. During the initial testing of the analyzers on raw exhaust, a sampling system was housed in a movable cart shown in Figure 10. The sampling system was designed to provide adequate flow for all of the analyzers under investigation. A mass flow controller was used to supply a constant flow rate to the microbenches during the evaluations with diesel engine exhaust. An ADI standard heated head pump, a Unique Products heated filter housing with a 2.5”x 1 in. element, a Horiba Com 11HRB NO_x converter, and a Universal Analyzers 1080 gas cooler were initially installed on the sampling cart. A Perma-Pure Nafion tube dryer was tested in place of the electric gas cooler. A heated, flexible sample line was connected between the engine exhaust and the inlet to the cart sampling system. Temperatures of the heated components were controlled via Omega model CN4431(TR)-R1 temperature control modules. This sampling cart was also used to condition raw exhaust for the

laboratory analyzers at the EERL in order to make raw exhaust comparisons with the candidate microbenches.

Figure 10 Sampling Cart used for Initial Verification of Analyzers with Engine Exhaust Gases.

3.5.3 Power Consumption

Originally, a design goal for the MEMS was the ability to utilize only the truck's charging system for power. An inverter to convert the power from 12VDC to 120 VAC was tested. This proved to be impractical because the power requirements were greater than the average charging system capacity. Therefore, a generator set was used to power the system. Another option considered was the use of a battery pack consisting of rechargeable lead-acid automotive batteries in conjunction with the inverter. This idea was abandoned because a generator set would be lighter and eliminate the voltage drop due to battery discharging. An un-interruptible power supply is used to prevent power interruptions when switching from house power to generator power. A switching box

with solid-state relays automatically switches to house power when plugged in. This allows the generator to be turned off for refueling, calibration etc. if desired.

Total maximum current draw on the first emissions system was approximately 15 amps at 120VAC. The latest design eliminates much of the power required for heated lines along with reduced pump size. Actual power consumption was determined for the complete emissions component with a clamp-on ammeter at startup and at stabilized conditions.

3.5.4 Operating Temperature

The analyzers tested, with the exception of the Horiba MEXA-120, have operating temperature limits of around 122°F (50°C). Therefore, none of the analyzers capable of measuring HC could be operated at the recommended temperature of 375°F (191°C) to prevent condensation of certain species of HC found in diesel exhaust. Representatives from Horiba Instruments indicated that the BE-140 and the BE-220 may be operated at up to 131°F (55°C) despite the 122°F (50°C) recommendation in the instruction manual. This allowed these two analyzers to be operated without drying the exhaust sample stream because the exhaust dew point was approximately 122°F (50°C) without drying at high engine load.

The enclosure was maintained at a constant temperature with three 4 inch fans controlled with an Omega CN4431(TR)-R1 temperature control module. Tests were performed with the enclosure temperature at several settings including 120°F (49°C), 100°F (38°C) and 95°F (35°C). The 120°F (49°C) setting was adequate to prevent condensation of water from exhaust gas when a drying method was not employed. With a dried sample, the temperature setting could be lowered significantly, but the temperature control system was left in operation primarily to provide a stable operating environment for the analyzers.

3.5.5 Size/Weight

The size and weight of the analyzers was an important consideration for the design of the MEMS. Several analyzers were eliminated as possible candidates due to their large size and/or weight. All of the analyzers tested were relatively small and

lightweight compared to commonly used laboratory analyzers. See the manufacturer specifications in Appendix A for size and weight specifications of each analyzer that was evaluated.

3.5.6 Cost and Availability

The analyzers tested vary widely in cost, in part because some of them are primarily used for inspection and maintenance in the automotive repair industry while others are used primarily for research. Most I/M microbenches are available for less than \$2000. Retail cost of a Horiba MEXA-120 is approximately \$15,000 and production is very limited at this time.

3.6 Sampling System

Design of the sampling system is critical to provide the analyzers with a sample stream that closely represents the engine exhaust emissions concentrations. Flow rate and temperature must be maintained within the analyzer manufacturer's specifications. Design of the sampling system was broken down into three categories: selection of component types, sizing of components, and integration with other components in an enclosure. The first version of the MEMS emissions box was a 24 in.x24 in.x12 in. steel NEMA 12 electrical enclosure. This large enclosure was selected because the components were still undergoing evaluation, so easy replacement and reconfiguration was desired. A smaller aluminum enclosure is being constructed for the next version for weight reduction. The enclosure should be metallic to act as a shield against electrical noise for the analyzers. Individual components tested for use in the sampling system are described in detail in the following subsections.

3.6.1 Sample Pump

The main sample pump for the MEMS should be small, lightweight, and robust. Also the pump should be sized to provide the necessary flow under the most extreme conditions such as heavy filter loading combined with a long sample line to the exhaust. The sample pump was selected so HC could be measured according to the Code of Federal Regulations (CFR) 40 if an analyzer was found to be suitable or became available at a later time. Therefore, the pump should contain a heated head capable of maintaining

375°F (191°C) for extended periods. Additionally, the pump should be a diaphragm type constructed with material that would not contaminate the sample stream, as the pump will be upstream of the analyzers. A KNF Neuberger UN026 ST.111 pump was tested first. This pump did not provide the necessary flow at the backpressure encountered with the initial setup. Next, an ADI standard heated head pump was tested. This pump was larger and heavier, but easily met the flow requirements with 27 liters per minute (LPM) free flow. Therefore, this pump was used for most of the testing and verification of the system. Finally, a miniature ADI pump was tested in its place. This pump was much smaller and lighter, yet met the flow requirements, which were reduced substantially from the initial set up. Specifications for these three pumps are detailed in Table 4.

Table 4 Specifications for Sample Pumps Tested.

Manufacturer	ADI	KNF Nueberger	ADI
Model	Standard Dia-Vac heated head	UN026 ST.111	Micro Dia-Vac heated head
Pump Type	Teflon diaphragm	Teflon diaphragm	Teflon diaphragm
Free Flow	27 LPM	16 LPM	7.2 LPM
Heated Head	Yes	Yes	Yes
Max. Head Temperature	400°F	400°F	400°F
Size (length x height x width)	9.3 in. x 10.7 in. x 7.0 in.	8.9 in. x 8.0 in. x 5.5 in.	6.5 in. x 6.1 in. x 2.4 in.
Power Requirements	120 VAC, 2.0-5.4 amps	120 VAC	120 VAC

Figure 11 ADI Standard Heated Head Dia-Vac Pump (from source [21]).

Figure 12 Performance Curve for the ADI Standard Heated Head Dia-Vac Pump (from source [21]).

Figure 13 ADI Heated Head Micro Dia-Vac Pump (from source [21]).

Figure 14 Performance Curve for the ADI Heated Head Micro Dia-Vac Pump (from source [21]).

A pump without a heated head was considered for use in the MEMS. However, if the pump head were not heated, the pump would need to be within an enclosure maintained at 120°F (49°C) or above or downstream of the moisture removal system to prevent condensation within the pump. Additionally, if HC is to be measured, the pump head must be maintained at 375°F (191°C) or the pump must be downstream of the HC analyzer. Some manufacturers do not recommend placing the pump downstream of the analyzer. Moreover, ambient air would be drawn through the analyzer(s) in the event of a leak anywhere upstream of the analyzer(s) or within the analyzer. Placing a non-heated pump downstream of the NO_x converter and moisture removal device is currently being investigated.

3.6.2 Temperature Control

Controlling ambient air temperature inside the enclosure provides more stable readings from the analyzers and keeps them within their recommended operating temperature range. Temperatures of the filter, NO_x converter, pump head, and heated sample lines also must be controlled. Omega model CN4431(TR)-R1 temperature controllers were used to maintain the temperature of these components at a preset value.

CFR 40 standards require that the heated sample line for raw diesel exhaust be maintained at 375°F (191°C) if hydrocarbons are to be measured [11]. This prevents condensation of heavy hydrocarbons in the sample line. Any other components before an HC analyzer must also be maintained at or above 375°F (191°C) for accurate HC measurements. The analyzers tested were not capable of operating at this temperature and therefore accurate HC measurements were not possible. Line temperatures must still be maintained to a temperature above the highest dew point of raw exhaust to prevent condensation. Condensation can cause loss of some components of exhaust gas such as NO. Some components such as the pump, pressure regulator and analyzers may be damaged by water condensation.

A flexible 0.25 in. heated line is used to transport the sample stream from the exhaust stack to the inlet of the enclosure. Where heated sample lines were required inside the emissions enclosure, stainless steel tubing was heated with rope heaters from Omega and covered with insulation. Internal temperature of the enclosure was maintained by controlling three cooling fans with a temperature controller. Sufficient heat was generated by the components to maintain the enclosure at up to 120°F (49°C), and the fans could maintain 80°F (27°C) at 70°F (21°C) ambient if desired. Enclosure temperature was set to different values in this range depending on the configuration of analyzers, moisture removal, flow control etc.

Plans for a future version have the enclosure divided into hot and cold sections. These may be combined in one enclosure or the heated section may be remotely mounted on the exhaust stack. The analyzers, temperature controllers, power supply, switches and wiring will be contained in the cold region. A heated head sample pump, if required, along with the heated filter and NO_x converter will be housed in the hot compartment.

The hot side will be maintained above the dew point of raw exhaust so the small sections of stainless steel tubing between components do not need additional heating. This would reduce power consumption because sufficient heat would be given off by the pump, filter and converter to maintain this temperature.

3.6.3 Flow Control

Control of the sample flow rate is necessary for several reasons. All of the analyzers tested, except the Horiba MEXA-120, require a stable and constant sample flow for accurate measurements. Filter loading will cause a variation in inlet pressure to the pump and therefore a change in flow rate without some type of active control. If the change in flow rate due to filter loading is minimal, the analyzer readings will not change significantly as determined in the flow rate testing of candidate analyzers. Flowmeters with needle valves were the first method of flow control tested. A flowmeter was placed upstream of each analyzer, so two flowmeters were required for testing configurations using two separate analyzers in parallel. The flowmeters were later replaced with a differential pressure regulator in conjunction with a needle valve. A pressure regulator was selected with the lowest available regulated pressure of 3 psi. and with downstream pressure control. That is, the flow rate is controlled via pressure feedback from a port located downstream of the regulator and the needle valve. This configuration was selected so as to minimize the pressure at which the pump must operate while allowing the regulator to be positioned away from the analyzers. A minimum differential pressure of 3 psi is required for proper operation of the regulator. Therefore, the regulator was installed so the pressure feedback port was at the lowest possible pressure in the sample stream just before the analyzers. Testing with the pressure regulator was performed only with the BE-140, MEXA 120 and NO cell in combination as these were selected before a need was apparent to actively control flow rate. Downstream of the first needle valve, the sample flow was split to provide 0.5 LPM, controlled by a second needle valve, to the NO cell and 3.0 LPM to the BE-140. The differential pressure regulator is shown below.

Figure 15 Moore Products Differential Pressure Relay.

The total flow rate requirements through the pump, filter and NO_x converter should be minimized in order to minimize the size requirements of the said components. Low flow rates tend to degrade transient response due to smearing. Smearing is the mixing of exhaust emission gases of different concentrations within the sample system. This leads to lower peak and higher minimum concentrations at the analyzers compared to concentrations actually released from the exhaust system of the vehicle. Increased sample flow reduces the effects of smearing because more volume of the sampling system is filled with exhaust gas produced over a set time interval. Even though mixing is likely greater at higher flow rates, a longer length of line is filled with gas from each second of engine operation, which provides more gas that is less mixed with gases of different concentration. As mentioned previously, there are several disadvantages as flow rate is increased. For example, most analyzers are designed to operate within a specified flow range. Furthermore, flow greatly affects performance of devices used to condition the sample, such as NO_x converters, filters, coolers, heated lines etc. Some of the sample may be bled off of upstream of first flow sensitive component to provide

proper flow rates through them along with a higher flow rate up to that point in the sampling system. Tests were performed with various flow rates to observe the difference in analyzer responses.

3.6.4 Humidity Control

Water vapor in the exhaust gas occupies considerable volume at higher engine loads. If the exhaust sample is measured with the water vapor present, the concentrations of emissions will be lower than if the sample is dried, simply because the volume of gas is reduced and virtually none of the other gases are removed. Some hydrocarbons present in diesel exhaust will condense out along with the water. However, the total volume of the sample is not noticeably affected because the volume contribution of HC to the total gas mixture is very small (usually less than 50 ppm by volume). A water removal system should be placed downstream of the NO_x converter, as NO₂ is water-soluble so a portion would be lost with the condensate.

Water vapor in the sample stream must not condense out on components of the sampling system. Therefore, the entire sampling system must be above the dew point of the sample gas or moisture must be removed from the sample stream. The dew point of diesel exhaust was found to be approximately 120°F (49°C) under high load conditions. See equation below for the ideal combustion of diesel fuel with a hydrogen to carbon ratio of 1.8.

Equation 1

The mass distribution is as follows: $1.8 \cdot n/2 \cdot 18$ H₂O, $n \cdot 44$ CO₂, $(n + 1.8 \cdot n/4) \cdot 3.76 \cdot 28$ N₂. As the number of moles of fuel (n) is cancelled, this results in a mass fraction of H₂O of $(1.8/2 \cdot 18)/(1.8/2 \cdot 18 + 44 + (1.45) \cdot 3.76 \cdot 28)$. Specific volume of the mixture is determined from the Ideal Gas Law. Specific gas constants are calculated from the molecular weights of H₂O and the mixture. The gas constants specific to the mixture and to the water vapor, along with temperature and pressure are used to calculate specific volume of each. Volume fraction is then calculated with those specific volumes and the mass fraction. See Figure 16 for a graph of water and CO₂ volume fraction in raw,

unconditioned exhaust. The spreadsheet used for these humidity calculations is provided in Appendix C.

Figure 16 Water Vapor and CO₂ versus A/F Ratio for a Diesel Engine.

These equations predict a maximum water concentration of 7.6% of the total exhaust mass for stoichiometric conditions. This is equivalent to 11.4% H₂O by volume. A dew point of 41°F (5°C) corresponds to only 0.86% water by volume whereas a the dew point of raw exhaust is up to 131°F (55°C) which corresponds to 15.5% water by volume [44]. Most modern diesel engines rarely reach stoichiometric air-fuel ratio due to PM emission limitations, but the MEMS should be capable of operation at these conditions. Volumetric water concentration can be calculated from the measured CO₂ concentration and used to convert dry emissions measurements to wet measurements if desired. Dry measurements eliminate the chance of water interference with the analyzer response and the volume of sample occupied by water vapor remains nearly constant. The volume concentration of H₂O produced from the combustion process is 90% of the

volume concentration of CO₂ produced if the hydrogen to carbon ratio of the fuel is 1.8. The correction factor to convert analyzer readings from a dry to wet basis is as follows.

$$\text{Wet Conc.} = \text{Dry Conc.} / (1 + ((\text{H:C})/2 * (\% \text{CO}_2 \text{ in dry sample}/100)))$$

Equation 2

Several methods of moisture removal were tested. These included Nafion tube dryers, desiccant dryers, water traps that were at ambient temperature and water traps in ice water. Tests were also performed on engine exhaust with no method of water removal from the sample stream. In this case, the internal temperature of the enclosure was maintained at 120°F (49°C) to prevent condensation. Effectiveness of each of the components was gauged with either a sampling type chilled-mirror hygrometer or a calibrated hand-held humidity probe placed in the sample stream at the exit of the device.

3.6.4.1 Perma-Pure Nafion Tube Dryer

Nafion tube dryers operate on the principle of water absorption by the tubing, which has a very high water-of-hydration. Nafion can absorb up to 22% of its weight in water due to its exposed sulfonic acid groups that will absorb up to thirteen water molecules each. The humidity gradient across the Nafion tubing drives the transport of water vapor through the tubing walls. The water remains as vapor phase throughout the reaction, so loss of components in the sample gas to condensed water is not a concern. The purge air is passed over the Nafion tubes in a counter-flow pattern [37].

A Perma Pure Inc., Model PD-1000-12-KA Nafion tube dryer, in the twelve-inch long version was selected for evaluation as a drying method for the exhaust sample. Maximum recommended inlet temperature of this model was 302°F (150°C), and a dew point of 32°F (0°C) should be attainable, with a flow rate up to 16 LPM, and with the dryer at 77°F (25°C). In the first set of tests, ambient air was pumped through a desiccant dryer with a Barnant model 400-1901 diaphragm pump then used to purge the moisture from the Nafion tube dryer. The flow of purge air was more than twice the flow of sample gas, as recommended by Perma Pure Inc. Later, a Perma Pure HD Series heatless, continuously regenerated, desiccant dryer was used to supply the purge air. The Nafion tube dryer was operated at several temperatures from ambient up to 302°F

(150°C). The inlet temperature of the sample gas was kept as high as possible to reduce condensation of heavy-end hydrocarbons within the dryer.

Figure 17 Perma Pure Nafion Tube Dryer.

Figure 18 Barnant Diaphragm Pump used for Purge Air to Nafion Tube Dryer.

3.6.4.2 Water Traps

Water traps operate on the principle of a condensation due to the water-laden gas being exposed to a surface colder than its dew point. Therefore, temperature of the trap surfaces, as well as surface area and residence time contribute to the drying efficiency of a water trap. Smaller traps result in less lag time but are less efficient at water removal. If the trap is a fixed size the surface temperature must be decreased to increase efficiency. This led to the testing of a water trap submerged in ice-water to improve the water removal efficiency and maintain the trap at a constant temperature. The water trap used for testing is shown in Figure 19.

Figure 19 Water Trap.

3.6.4.3 Universal Analyzers Model 1080 Electric Gas Cooler

The first electric gas cooler tested was a Universal Analyzers model 1080. This electric gas cooler, also known as a thermoelectric cooler, operates on the Peltier principle. An electric current passed through a loop containing two junctions between dissimilar metals or semiconductors will release heat at one junction and absorb heat at the other. The effect occurs when the electron distribution of the materials is different and a voltage difference exists at the junctions. Heat is released where the voltage difference opposes that of the voltage source, and heat is absorbed at the other junction where the voltage difference assists the voltage source [29]. The Universal Analyzers model 1080 is a dual-stream cooler with a total flow rate capacity of 10 LPM. According to the manufacturer, this cooler is capable drying the sample gas to a dew point of 41°F (5°C) at a flow rate of up to 5 LPM per side. This cooler was tested primarily because it was on hand at the WVU EERL and determined to be of adequate size. The cooler is

heavy, at 38 lbs., for use on the MEMS and consumed 740 watts of power at 120 VAC. External dimensions were 15 in. high by 12 in. wide by 12 in. deep. The wetted parts of this cooler were stainless steel. Peristaltic pumps were used with this cooler to remove the collected water. [44]

3.6.4.4 M & C ECP 1000 Electric Gas Cooler

A second thermoelectric cooler, an M&C Products Model ECP 1000, was selected based on required flow and dew point of the sample gas. This Peltier-effect cooler was much smaller than the Universal Analyzers model 1080. The M&C cooler measured 10.8 in. long, 8.7 in. tall, and 5.4 in. deep and weighed approximately 12 lbs. The sample dew point was set at 41°F (5°C) but was adjustable if desired. Testing was performed at the default dew point setting of 41°F (5°C), which is equivalent to 0.86 % water by volume.

Figure 20 M & C Thermoelectric Chiller Mounted to the Emissions Enclosure.

3.6.5 Sample Filtering

The exhaust gas sample must be filtered upstream of the analyzers, NO_x converter, pump and electric gas cooler, if so equipped. A heated filter housing is required to prevent water condensation on the filter media. Most of the analyzers tested required 100% removal of particles greater than 1 µm, so filter media was chosen that provided 95% removal of particles larger than 0.3 µm. A stainless steel filter housing was used to avoid contamination of the sample stream and to prevent possible corrosion. See Figure 21 for the first filter housing that was tested. A rope resistance wire heater was wrapped around the outside of the housing and then covered with exhaust wrap insulation. There were two problems with this filter housing. First, the housing developed leaks after the O-rings underwent several thermal cycles between room temperature and 375°F (191°C). Also, the outlet gas temperature would overshoot the target value as the heater cycled on and off. This was due to the large wall thickness of the stainless steel between the heater and the inside of the housing. A commercially available Unique Products model FLT 1584-B-B-4-A-AJ/K-000 heated filter assembly was tested next. See Figure 22. A 2.5 in. by 1 in. element was used in this housing as opposed to the 7 in. by 1 in. element in the first housing.

Figure 21 Stainless Steel Filter Housing for 7 in. x 1 in. Element.

Figure 22 Unique Products Heated Filter Housing for 2.5 in. x 1 in. Element.

3.6.6 Sample Lines

A flexible 0.25 in. heated line is used from the exhaust pipe to the inlet of the emissions box. Most of the sample line within the emissions box was a 0.25 in. OD x 0.035 in. wall stainless steel tubing. Stainless steel was selected to eliminate possible corrosion and or contamination problems. Where necessary for flexibility, 0.25 in. OD x 0.065 in. wall Teflon tubing was used. Teflon tubing can withstand temperatures up to 375°F (191°C) and does not react with any of the measured gases in the sample stream.

3.6.7 Sample Probe

The exhaust gas sample probe was designed in accordance with CFR 40 Part 89.412.96 [11]. A 0.25 inch diameter stainless steel tube with nine sampling holes serves as the exhaust probe. Three holes are located at the center of the exhaust pipe, with three more at each location one-fourth the exhaust pipe diameter away from the walls. The holes are 120 degrees apart around the sampling probe circumference at each of the aforementioned locations within the exhaust pipe. The holes are 5/64 in. diameter which provides greater area than the cross section of the inside diameter of the tube. This type of sample probe was chosen to provide the best representation of the average composition of the exhaust gas mixture.

Figure 23 Exhaust Gas Sample Probe.

3.6.8 NO_x conversion

The electro-chemical NO cells only detect NO. Therefore, NO₂ must be converted to NO if NO_x is to be measured by this device. A similar problem exists with the Horiba MEXA-120 analyzer. It has a response to NO₂, but the response is not 100%; it varies depending on NO₂ concentration as shown in the results section. The NO_x converter was chosen based on size and conversion efficiency. The converter was placed upstream of any moisture removal systems utilized to prevent loss of water-soluble NO₂. Conversion efficiency tests were performed with NO₂ concentrations typically observed in diesel exhaust. NO concentrations were measured with either the analyzer(s) in the MEMS or with the Rosemount model 955 NO_x analyzer at the WVU EERL. A Rosemount model 958 NO_x efficiency tester was also used for some of the converter efficiency tests.

The first NO_x converter tested was a Horiba COM-11HRB. Power consumption of this converter is approximately 1 amp at 115 VAC. The length was approximately 21 in. and the diameter was 3.5 in., as shown in Figure 24. The length of this converter was shortened about 2 in. after confirming the alteration with Horiba Instruments. This was done so the converter could be installed directly after the pump head exit to minimize line length and the consequential additional heating requirements.

Figure 24 Horiba COM-11HRB NO_x Converter.

The Horiba COM-11H-1A NO_x converter was considered for use in the planned downsized system. It is significantly shorter at around 12 in., but the diameter is about the same as the Horiba COM 11HRB at 3.5 in.. The COM-11H-1A is shown in Figure 25. A more compact NO_x converter is currently being developed and tested by researchers in West Virginia. This unit would significantly reduce power and space requirements.

Figure 25 Horiba COM-11H-1A NO_x Converter.

3.6.9 Calibration Provisions

Originally, calibrations were performed by removing the sample line from the inlet to the emissions box and replacing it with a Teflon line from the gas divider. Next, calibrations were performed by removing the sample line from the exhaust and connecting it with a Teflon line from the gas divider. The current version of the MEMS is calibrated by flowing calibration gases into the heated sample line at the junction with the exhaust stack. A three-way valve is placed at the entrance of the heated line. This valve is switched between the exhaust stack during sampling, and to the Teflon line from the gas divider during calibration.

A Horiba SGD-710C gas divider is used for calibration of the analyzers. Various methods of calibration were evaluated, depending on the analyzers in use, to examine the benefits of multi-point calibrations with varying numbers of points. The current

procedure includes a zero and span calibration of the Horiba BE-140 and a three-point calibration of the Horiba MEXA 120 and the electrochemical NO cell.

3.6.10 Maintenance

Changing the filter is the most obvious maintenance procedure. The filter is usually checked after approximately one hour of operation, and changed if necessary based on the filter loading observed. The filter elements usually lasted for several hours before loading was heavy enough to affect the flow rate. Also, the NO_x converter must be maintained by replacing the catalyst if the efficiency drops below 90%. For maintenance purposes, NO_x converter efficiency is tested with NO₂ from a bottle of known concentration and the NO analyzers in the MEMS.

3.7 Verification of Complete Systems by testing on engine exhaust

Each version of the complete system was evaluated by sampling exhaust from an engine operated through predetermined cycles in the test cell at the West Virginia University Engine and Emissions Research Laboratory (WVU EERL). Later versions were also tested in the WVU Transportable Emissions Testing Laboratory.

3.7.1 WVU EERL

The WVU EERL is capable of testing heavy-duty diesel engines of up to 550 hp on a GE DC dynamometer. A complete emissions sampling system for gaseous emissions and diesel particulate matter is available.

The EERL was inspected and verified by EPA prior to certification tests on the Mack E7-400 engine. In a recent report to the S-HDDE, EPA reported that the WVU FTP test cell had no problems. The FTP and steady-state testing results from the WVU and Mack Trucks Inc. laboratories were in excellent agreement.

3.7.1.1 Gaseous Emissions Sampling System

Verification of engine exhaust measurement by the analyzers in conjunction with the sampling systems was conducted at the WVU EERL. Raw exhaust comparisons were made using laboratory grade analyzers.

The laboratory contains an 18 in. diameter full flow stainless steel dilution tunnel. A full flow tunnel dilutes the entire exhaust stream whereas a mini-dilution tunnel dilutes only a sample pulled from the engine exhaust stream. Flow through the tunnel is controlled via four critical flow venturis (CVS) upstream of a 75 hp blower. One 400 scfm and three 1000 scfm allow tunnel flow rates from 400 to 2400 scfm. The upper flow is limited to 2400 rather than 3400 due to blower size [9].

Heated sample lines transport exhaust sample gas from the tunnel to HC, CO, CO₂, and NO analyzers. For raw exhaust sampling, the heated lines were connected to the previously described sampling cart, which contained a sample pump, NO_x converter, and heated filter. The HC line temperature is maintained at 375°F (191°C) to prevent condensation of heavy end hydrocarbons onto the wall surface. The sample line to the NO_x analyzer is maintained at 235°F (113°C) ±10°F (±5.6°C) to prevent condensation of water. A third sample line controlled to 250°F (121°C) ±10°F (±5.6°C) is used for CO and CO₂. Particulate matter is filtered out of the HC sample onto a 70mm filter within the analyzer. Particulate matter is removed from the other two lines with 2.5 in.x1 in. quartz filter elements in heated filter housings maintained at 250°F (121°C) for the CO/CO₂ line and 235°F (113°C) for the NO_x line. HC measurements are made with a Rosemount Model 402 HFID hydrocarbon analyzer. A Rosemount 868 NDIR analyzer is used for CO, and a Rosemount 880 NDIR analyzer is used for CO₂ measurement. A Beckman Model 958 NO_x efficiency test unit is used to verify that NO_x converter efficiency is at least 90%. This efficiency tester was also used to verify the efficiency of the NO_x converter used in the MEMS. A Rosemount Model 955 heated chemiluminescent analyzer was used to measure NO_x concentrations.

Figure 26 Emissions Analyzer Bench at the WVU EERL.

3.7.1.1.1 Calibration of Analyzers

Each of the analyzers is calibrated with a ten-point curve. A Horiba SGD-710C gas divider is used to provide gases from 0 to 100% of the span gas concentration in increments of 10% for the calibration process. The gas divider accuracy is $\pm 0.5\%$ of full scale. All of the data points must be within 2% of the fitted curve value at that point for the analyzer calibration to be considered valid. Standard Reference Materials (SRM) certified gas concentrations are used to verify non-SRM gas bottles routinely used for calibration purposes. The zero and span readings of the analyzers are typically checked before each test.

3.7.1.1.2 HC Analyzer

A Rosemount Model 402 HFID analyzer is used to measure hydrocarbon concentrations. This analyzer incorporates a sampling pump and heated filter. The sample is maintained at 375°F (191°C) from the exhaust stack to the analyzer to prevent loss of heavy hydrocarbons due to condensation. The measurement range is up to 250,000 ppm.

3.7.1.1.3 NO_x Analyzer

NO_x is measured at the EERL with a Rosemount model 955 chemiluminescent analyzer. This analyzer has a built-in NO_x converter and may be operated in an NO only or NO_x mode by switching a solenoid that directs sample flow either around or through the converter. NO_x efficiency tests are routinely performed to insure at least 90% NO₂ to NO conversion efficiency. The NO_x sample is filtered externally but is not dried.

3.7.1.1.4 CO₂ Analyzer

A Rosemount model 880 NDIR based analyzer is used to measure CO₂. A Luft type detector is used to measure pressure variations between two detection chambers. The sample is dried and filtered externally. Water interference is common with NDIR CO₂ analyzers because the infrared absorption wavelength is close to that of water. A refrigerated dryer is used to dry the sample. The measurement ranges are 0-5% and 0-20%. The higher range allows raw exhaust gas sampling.

3.7.1.1.5 CO Analyzer

Rosemount model 868 analyzers are used to measure CO. Two analyzers are available to cover a wide range of concentrations. These are NDIR based analyzers that will measure from 0-1000 ppm and 0-5000 ppm on the low range unit, and 0-2% and 0-10% on the high range unit. A dried and filtered sample is drawn from the same line as the CO₂ sample.

3.7.1.2 Test Engines

Three different engines were used for raw exhaust comparisons to laboratory-grade analyzers. These engines are a good representation of engines commonly found in medium and heavy-duty on road vehicles. The Cummins ISM 370 ESP and Mack E7-400 engines are usually found in heavy-duty on-road trucks while the Navistar T444E is commonly used in medium-duty trucks and school buses. All three engines were tested using a GE 550 horsepower capacity DC dynamometer. Specifications of the engines are given in Table 5 below.

Table 5 Test Engine Specifications.

Manufacturer	Cummins	Mack	Navistar
Model	ISM 370 ESP	E7-400	T444E
Model Year	1999	1995	1999
Displacement	10.8 l (661 in ³)	12.0 l (728 in ³)	7.3 l (444 in ³)
Rated Power	370hp @ 2100 rpm	400hp @ 1800 rpm	210hp @ 2300 rpm
Rated Torque	1350 ft-lb @ 1200 rpm	1460 ft-lb @ 1200 rpm	520 ft-lb @ 1500 rpm
Cylinder Configuration	Inline 6	Inline 6	90° V-8
Injection Type	Direct, Electronically Controlled	Direct, Electronically Controlled	Direct, Electronically Controlled
Induction Type	Turbocharged, Intercooled	Turbocharged, Intercooled	Turbocharged, Intercooled
Compression Ratio	16.3:1	16.1:1	17.5:1
Typical Use	Heavy-Duty Trucks	Heavy-Duty Trucks	Medium-Duty Trucks and Buses

3.7.2 WVU Transportable Emissions Testing Laboratory

The WVU Transportable laboratory makes use of the same type of emissions sampling system as the WVU EERL. However, the Transportable laboratory consists of a heavy-duty chassis dynamometer capable of inertia loading and loading with eddy-current dynamometers. Power is transferred from the vehicle drive axles through driveshafts from the driven wheels, rather than through the tires to rollers as with most chassis dynamometers. This configuration eliminates tire slippage on the rollers as a

factor in the power transferred through the load cell to the dynamometers. Hence, a source of error is eliminated.

3.7.2.1 Test Vehicle

A 1995 Mack class 8 road tractor with an E7-400 Mack engine and 10 speed transmission was used for chassis dynamometer and on-road testing of the MEMS. See the dynamometer trailer with the Mack class 8 tractor ready for testing in Figure 27 below. This vehicle has a similar E7-400 engine as the one used for part of the dynamometer cell testing at the EERL.

Figure 27 1995 Mack Class 8 Tractor on the WVU Transportable Heavy-Duty Dynamometer.

3.8 Evaluated Versions of Complete System

Each time a major change was made to the emissions components, a new version was designated to the system. The following table summarizes these changes and the chronological order in which they were made.

Table 6 Changes to Each Version of the Emissions Box.

Version	Analyzers	Sample Flow Rate	Sample Flow Control	Sample Filter	Sample Drying	NO _x Converter	Enclosure Temperature
1.0	BE-140 BE-220 prototype	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	Perma- Pure with amb. Purge air	Horiba Com 11HRB	Not controlled
1.1	BE-140 BE-220 prototype	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	Heated Perma- Pure with amb. Purge air	Horiba Com 11HRB	Not controlled
1.2	BE-140 BE-220 prototype	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	Perma- Pure with dried Purge air	Horiba Com 11HRB	Not controlled
1.3	BE-140 BE-220 prototype	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	None	Horiba Com 11HRB	120°F
1.4	BE-140 BE-220 prototype	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	Water Trap in ice water	Horiba Com 11HRB	120°F
1.5	BE-140 BE-220 prototype	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	Water Trap in amb. air	Horiba Com 11HRB	120°F
1.6	BE-140 BE-220 production version	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	Water Trap in amb. air	Horiba Com 11HRB	120°F
1.7	BE-140 BE-220 production version E/C NO	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	Water Trap in amb. air	Horiba Com 11HRB	120°F

1.8	BE-140 MEXA-120 E/C NO	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	Water Trap in amb. air	Horiba Com 11HRB	120°F
1.9	BE-140 MEXA-120 E/C NO	3 LPM each in parallel	Flow meters	7 in. x 1 in. with rope heater	Universal Analyzer's Gas Cooler	Horiba Com 11HRB	120°F
1.10	BE-140 MEXA-120 E/C NO	3 LPM each in parallel	Diff. Pressure Regulator	2.5 in. x 1 in. heated housing	M&C Gas Cooler	Horiba Com 11HRB	95°F

Note: Red text indicates changes made.

Figure 28 MEMS Emissions Box, Version 1.6.

Figure 29 MEMS Emissions Box, Version 1.10 (Internal View).

Figure 30 MEMS Emissions Box, Version 1.10 (Front View).

Figure 31 MEMS Emissions Box, Version 1.10 (Right Side View).

3.9 Additional Requirements for On-Road Measurements

Multiple inputs other than emissions concentrations are required to the MEMS to facilitate calculation of emissions on a brake-specific (g/bhp-hr) basis. Exhaust flow rate, engine speed, estimated percent load or torque broadcast by the ECU, and ambient temperature, pressure and humidity, are used to convert emissions from volume concentrations to brake-specific units. Vehicle speed and distance are also recorded. Selection and evaluation of exhaust flow rate measurement and pressure measurement devices were discussed in detail in source [36] and source [16], respectively.

3.9.1 Exhaust Flow Rate Measurement

Exhaust flow rate measurement is necessary to convert the emission gas concentrations to a mass measurement per time, which can then be converted to a mass measurement per distance or per bhp-hr. The device was selected based on research presented in source [36]. An Annubar multiple inlet pitot tube device was chosen over a

venturi, vortex shedder, Accutube, and reverse pitot tube device. Tests were first performed on each device using the available high volume, low-pressure air supply at the WVU EERL. The devices were also tested on engine exhaust and compared to the flow indicated with a laminar flow element (LFE) placed in the intake air system between the air filter and turbocharger inlet. Flow rate inferred from the pressure drop across the LFE was corrected to exhaust flow rate by adding the additional volume from combustion of fuel.

3.9.2 Engine Speed Measurement

Engine speed is logged from the output of the ECU. This is necessary to calculate horsepower from torque. Engine speed may also be useful for correlations to certain emission gases and/or route development.

3.9.3 Engine Torque Estimate

All heavy-duty diesel engines covered under the Consent Decrees are controlled by an ECU that broadcasts engine percent load. Starting with model year 2000 an estimated torque signal is also broadcast. The MEMS must have an engine percent load or torque signal in order to calculate exhaust emissions in units of g/bhp-hr. The MEMS was required to be capable of testing only vehicles with a percent load or torque output signal from the ECU. Actual measurement of torque with a strain gage based device was thoroughly investigated because percent load and torque signals from the ECU are known to be as much as 20% in error, especially at low loads. Measurement of torque with a load cell was determined to be impractical due to cost and difficulty of implementation for testing a large number of vehicles. Variations between the drivetrains of vehicles would have dictated the availability of a measurement device for every possible vehicle that would be tested. Also, installation of a torque cell in the driveline would be time consuming and likely objectionable by fleet owners.

3.9.4 Vehicle Speed and Distance

Vehicle speed and distance measurements are not necessary to meet the requirements of the Consent Decree. However, vehicle speed and distance were used for route development for on-road testing during evaluation of the MEMS. Vehicle speed

and distance may also be useful for future studies or development of routes for other purposes. Details of on-road testing with the MEMS are provided in source [41]. Vehicle speed is an available output from the engine ECU, and a Global Positioning System (GPS) is used to assure data quality of the vehicle speed signal.

3.9.5 Ambient Temperature, Pressure and Humidity

Ambient temperature, pressure and humidity are recorded with a thermocouple, a pressure transducer, and relative humidity sensor, respectively. Temperature, pressure and humidity are all used to convert the results of a test to results taken at standard conditions per the CFR 40. Ambient pressure and humidity are required if corrected NO_x according to the CFR 40 is desired. The production of NO_x tends to decrease with increasing humidity due to lower cylinder temperatures caused by the diluting effect and possibly the reduction of flame travel speed. Ambient pressure may also be used to calculate changes in altitude over a test route if high accuracy is not required.

3.10 Error Analysis

Uncertainty was calculated on an absolute and root-sum square basis. Absolute error is simply the sum of the absolute values of error contributed by each variable. The root-sum square formula is a combination of random and bias error. Bias error is due to an actual offset of the value, while random error is due to fluctuation or repeatability of the value. Random error is typically accounted for using a normal distribution and specifying a probability. For example, a 95% probability indicates that 95% of the data points should be within the calculated error based on this theory. A variable, z , is calculated from the mean value, value at the point of interest, and the standard deviation. The probability is a function of z and is determined from the cumulative density function ($\Phi(z)$) [42]. The corresponding z value is 1.96 for 95% confidence [39]. The resulting root-sum square formula is expressed in equation 3 below.

$$\text{Total Error} = [\text{Bias}_1^2 + \text{Bias}_2^2 + \text{Bias}_n^2]^{1/2} + 1.96[\text{Random}_1^2 + \text{Random}_2^2 + \text{Random}_n^2]^{1/2}$$

Equation 3

Table 7 shows the accuracy and repeatability of the instruments and supplies used for the initial evaluation of microbenches with bottled gases. The total root-sum square error for 95% confidence with 12% CO₂ was calculated in equation 4. This error does not include the error of the analyzer, rather it demonstrates the error possible in the gaseous concentration being measured.

$$\Delta\text{CO}_2 = [(0.005*12)^2 + (0.01*12)^2]^{1/2} + 1.96[(0.002*12)^2]^{1/2} = 0.18\% \text{ CO}_2$$

Equation 4

Table 7 Manufacturer Specified Errors for Components Used to Evaluate the Microbenches on bottled gases.

Component	Accuracy (Random)	Repeatability (Bias)
Gas Divider	±0.5% Gas Bottle Conc.	±0.2% Gas Bottle Conc.
Gas Bottle Concentrations	±1.0% of Concentration	-
Sum of Errors	±1.5% from Gas Bottle	±0.2% Gas Bottle Conc.

Chapter 4 Results

4.1 Component Testing Results

The results of testing individual components are detailed in this section. These results were used to compare and select components to be integrated into the complete emissions sampling system.

4.1.1 Analyzer Selection and Testing Results

The Horiba BE-140 analyzer performed satisfactorily for measurement of CO₂ and was selected for use in the MEMS following a thorough review of the results. Vibration and inclination, and water interference tests showed little or no effect on the response of the analyzer. Sample flow rate did show a change in output that would not be acceptable if flow was allowed to vary ± 1 LPM during a test. However, a differential pressure regulator was selected to control flow rate and the maximum variation observed from the set value was approximately ± 0.1 LPM of the total flow of 3.5 LPM. Accuracy of HC and CO measurements with the BE-140 were significantly in error compared to laboratory-grade analyzers. This same problem existed with all the microbenches tested due to the low concentrations of the components in diesel exhaust compared to the designed operating ranges of the instruments. Therefore, the analyzers were selected based on CO₂ and NO_x measurement performance.

The Andros 6800 microbench suffered an electrical component failure on the circuit board only a few seconds after the first time it was supplied power. The exact cause of failure was not determined. All electrical connections to the power supply were verified to be correct after the failure. A replacement unit was not received until after the completion of the selection process.

Evaluation of the Siemens SIBENCH was also discontinued before completion of the planned tests. This was due to the extreme orientation bias and un-resolvable software problems.

The Sensors Inc. AMBII analyzer performed satisfactorily on most tests but was eliminated as a candidate primarily due to software related issues. The serial data was

not output at a constant time interval, which would bias transient data. Problems with the electrochemical NO cell were encountered if there was a slight backpressure at the exhaust of the cell or if flow rate varied slightly at high concentrations. The electrochemical NO cell from the AMBII performed reasonably well as a stand-alone unit but was not considered reliable enough for use as the primary NO measurement device.

The Horiba BE-220 NO analyzer performed well on the time response and gas divider tests, but was not acceptable due to poor performance during the on-road vibration test. A Horiba MEXA-120 analyzer was tested as a replacement candidate for NO_x measurement. The response of the MEXA-120 was less than 100% to NO₂, so it could not be qualified as a NO_x measurement device as it is by the manufacturer. A NO_x converter was planned for the system before the elimination of the BE-220 and electrochemical cells, so this did not pose a problem. The MEXA-120 performed adequately on all tests and was chosen as the primary method of NO_x measurement. A Sensors Inc, electrochemical NO cell performed sufficiently well on all tests to be used as a QC/QA device. The tests performed on each analyzer are indicated in Table 8.

Table 8 Summary of Gas Bottle Tests Performed for Evaluation of Analyzers.

Test	Andros 6800	Horiba BE-140	Sensors AMBII	Siemens SIBENCH	Horiba BE-220	Horiba MEXA-120
CO ₂ Gas Divider		◆	◆			
NO Gas Divider			◆		◆	◆
CO Gas Divider		◆	◆			
HC Gas Divider		◆	◆			
CO ₂ Time Response		◆	◆			
NO Time Response			◆		◆	◆
CO Time Response		◆	◆			
HC Time Response		◆	◆			
Water Interference		◆	◆			◆
Gas Interference		◆	◆	◆	◆	◆
Inclination		◆	◆	◆	◆	
Vibration		◆	◆		◆	◆
Flow Rate Variation		◆			◆	

◆ indicates that test was performed.

4.1.1.1 Single Component Gas Divider Tests

Tables 9 through 17 summarize the results of tests performed by supplying the analyzers with divided concentrations of single component gases. The analyzers were zeroed and calibrated with one or two non-zero points prior to the tests. A reading was first recorded with the gas divider set to 100%, and subsequent readings were taken at 10% increments after a stabilization period. The process was repeated starting with the gas divider set to 0% and ending at 100%. The average of the two values at each concentration was used for comparison purposes. The average was used to effectively cancel any time response effects. An average was computed of the absolute values of the percent differences between the average analyzer reading and the expected concentration from the gas divider. This value, along with the absolute value of the maximum percent difference error, allows a quick comparison of analyzer performance on these tests.

Table 9 Horiba BE-140 CO₂ Gas Divider Test.

Analyzer:	Horiba BE-140	Flow (SLPM):	3		
Component Gas:	CO ₂	Analyzer Temperature:	44.8°C		
Bottle Conc. (%):	20.00	Analyzer Pressure:	99.2 kPa		
Diluent Gas:	N ₂	Time at Point:	30 sec.		
Cal. Pts. (excluding 0)	1	Analyzer Reading			% Diff.
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
100	20.0	20.00	20.00	20.00	0.00
90	18.0	17.94	17.90	17.92	-0.44
80	16.0	15.91	15.90	15.91	-0.59
70	14.0	13.88	13.84	13.86	-1.00
60	12.0	11.80	11.77	11.79	-1.79
50	10.0	9.81	9.80	9.81	-1.95
40	8.0	7.87	7.85	7.86	-1.75
30	6.0	5.92	5.93	5.93	-1.25
20	4.0	3.98	3.96	3.97	-0.75
10	2.0	2.02	2.02	2.02	1.00
0	0.0	0.00	0.00	0.00	0.00
Average of Absolute % Diff. for the Averaged Analyzer Readings:					1.05
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					1.95

Table 10 Horiba BE-140 HC Gas Divider Test

Analyzer:	Horiba BE-140	Flow (SLPM):			3
Component Gas:	C ₃ H ₈	Analyzer Temperature:			44.8°C
Bottle Conc. (ppm):	300	Analyzer Pressure:			99.2 kPa
Diluent Gas:	N ₂	Time at Point:			30 sec.
Cal. Pts. (excluding 0)	1 at 1500 ppm	Analyzer Reading			% Diff.
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
100	300	300	298	299.0	-0.33
90	270	273	269	270.6	0.22
80	240	237	233	235.3	-1.96
70	210	204	210	206.9	-1.49
60	180	180	175	177.5	-1.42
50	150	145	149	147.1	-1.96
40	120	122	120	120.6	0.49
30	90	86	88	87.3	-3.05
20	60	57	57	56.9	-5.23
10	30	27	25	26.5	-11.76
0	0	0	0	0.0	0.00
Average of Absolute % Diff. for the Averaged Analyzer Readings:					2.79
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					11.76

Table 11 Horiba BE-140 CO Gas Divider Test

Analyzer:	Horiba BE-140	Flow (SLPM):			3
Component Gas:	CO	Analyzer Temperature:			44.5°C
Bottle Conc. (%):	2.00	Analyzer Pressure:			99.2 kPa
Diluent Gas:	N ₂	Time at Point:			30 sec.
Cal. Pts. (excluding 0)	1	Analyzer Reading			% Diff.
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
60*	1.20	1.20	1.19	1.20	-0.42
50	1.00	1.00	0.99	1.00	-0.50
40	0.80	0.80	0.79	0.80	-0.63
30	0.60	0.59	0.59	0.59	-1.67
20	0.40	0.38	0.38	0.38	-5.00
10	0.20	0.17	0.17	0.17	-15.00
0	0.00	0.00	0.00	0.00	0.00
Average of Absolute % Diff. for the Averaged Analyzer Readings:					3.32
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					15.00

*Analyzer was spanned at 60% on gas divider because maximum span value of analyzer is 1.20%.

Table 12 Sensors AMBII CO₂ Gas Divider Test with 1-Point Calibration.

Analyzer:	Sensors AMBII	Flow (SLPM):	3		
Component Gas:	CO ₂	Analyzer Temperature:	-		
Bottle Conc. (%):	19.90	Analyzer Pressure:	-		
Diluent Gas:	N ₂	Time at Point:	30 sec.		
Cal. Pts. (excluding 0)	1	Analyzer Reading	% Diff.		
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
100	19.9	19.9	19.9	19.90	0.00
90	17.91	18.1	18.0	18.05	0.78
80	15.92	16.2	16.1	16.15	1.44
70	13.93	14.2	14.1	14.15	1.58
60	11.94	12.2	12.1	12.15	1.76
50	9.95	10.3	10.2	10.25	3.02
40	7.96	8.3	8.2	8.25	3.64
30	5.97	6.2	6.1	6.15	3.02
20	3.98	4.1	4.1	4.10	3.02
10	1.99	2.0	2.0	2.00	0.50
0	0	0.0	0.0	0.00	0.00
Average of Absolute % Diff. for the Averaged Analyzer Readings:					1.88
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					3.64

Table 13 Sensors AMBII CO₂ Gas Divider Test with 2-Point Calibration.

Analyzer:	Sensors AMBII	Flow (SLPM):	3		
Component Gas:	CO ₂	Analyzer Temperature:	-		
Bottle Conc. (%):	19.90	Analyzer Pressure:	-		
Diluent Gas:	N ₂	Time at Point:	30 sec.		
Cal. Pts. (excluding 0)	2	Analyzer Reading	% Diff.		
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
100	19.9	19.9	19.9	19.90	0.00
90	17.91	18.1	18.0	18.05	0.78
80	15.92	16.1	16.0	16.05	0.82
70	13.93	14.1	14.0	14.05	0.86
60	11.94	12.1	12.0	12.05	0.92
50	9.95	10.1	10.0	10.05	1.01
40	7.96	8.0	8.0	8.00	0.50
30	5.97	6.0	5.9	5.95	-0.34
20	3.98	3.9	3.9	3.90	-2.01
10	1.99	1.9	1.9	1.90	-4.52
0	0	0.0	0.0	0.00	0.00
Average of Absolute % Diff. for the Averaged Analyzer Readings:					1.18
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					4.52

Table 14 Sensors AMBII HC Gas Divider Test with 1-Point Calibration.

Analyzer:	Sensors AMBII	Flow (SLPM):	3		
Component Gas:	C ₃ H ₈	Analyzer Temperature:	-		
Bottle Conc. (ppm):	300.00	Analyzer Pressure:	-		
Diluent Gas:	N ₂	Time at Point:	30 sec.		
Cal. Pts. (excluding 0)	1	Analyzer Reading			% Diff.
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
100	300	300	297	298.5	-0.50
90	270	274	269	271.5	0.56
80	240	246	240	243.0	1.25
70	210	216	210	213.0	1.43
60	180	187	183	185.0	2.78
50	150	159	153	156.0	4.00
40	120	127	123	125.0	4.17
30	90	98	93	95.5	6.11
20	60	64	60	62.0	3.33
10	30	33	28	30.5	1.67
0	0	0	0	0.0	0.00
Average of Absolute % Diff. for the Averaged Analyzer Readings:					2.58
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					6.11

Table 15 Sensors AMBII HC Gas Divider Test with 2-Point Calibration.

Analyzer:	Sensors AMBII	Flow (SLPM):	3		
Component Gas:	C ₃ H ₈	Analyzer Temperature:	-		
Bottle Conc. (ppm):	300.00	Analyzer Pressure:	-		
Diluent Gas:	N ₂	Time at Point:	30 sec.		
Cal. Pts. (excluding 0)	2 (300ppm/60 ppm)	Analyzer Reading			% Diff.
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
100	300	300	299	299.5	-0.17
90	270	271	267	269.0	-0.37
80	240	244	238	241.0	0.42
70	210	213	209	211.0	0.48
60	180	185	179	182.0	1.11
50	150	154	148	151.0	0.67
40	120	125	120	122.5	2.08
30	90	93	89	91.0	1.11
20	60	62	57	59.5	-0.83
10	30	31	26	28.5	-5.00
0	0	0	0	0.0	0.00
Average of Absolute % Diff. for the Averaged Analyzer Readings:					1.22
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					5.00

Table 16 Sensors AMBII NO Gas Divider Test with 1-Point Calibration.

Analyzer:	Sensors AMBII	Flow (SLPM):			0.3
Component Gas:	NO	Analyzer Temperature:			-
Bottle Conc. (ppm):	5000	Analyzer Pressure:			-
Diluent Gas:	N ₂	Time at Point:			30 sec.
Cal. Pts. (excluding 0)	1	Analyzer Reading			% Diff.
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
80	4000	4015	4015	4015.0	0.38
70	3500	3522	3518	3520.0	0.57
60	3000	3012	3007	3009.5	0.32
50	2500	2500	2491	2495.5	-0.18
40	2000	1996	1977	1986.5	-0.68
30	1500	1496	1479	1487.5	-0.83
20	1000	995	981	988.0	-1.20
10	500	503	488	495.5	-0.90
0	0	8	8	8.0	-
Average of Absolute % Diff. for the Averaged Analyzer Readings:					0.63
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					1.20

Table 17 Horiba BE-220 NO Gas Divider Test (High Concentration).

Analyzer:	Horiba BE-220 prod.	Flow (SLPM):			2
Component Gas:	NO	Analyzer Temperature:			-
Bottle Conc. (ppm):	2463	Analyzer Pressure:			-
Diluent Gas:	N ₂	Time at Point:			1 min.
Cal. Pts. (excluding 0)	1	Analyzer Reading			% Diff.
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
100	2463	2458	2462	2460.0	-0.12
90	2216.7	2213	2211	2211.7	-0.22
80	1970.4	1955	1951	1953.4	-0.86
70	1724.1	1693	1689	1691.2	-1.91
60	1477.8	1461	1458	1459.4	-1.25
50	1231.5	1223	1220	1221.0	-0.85
40	985.2	973	976	974.7	-1.06
30	738.9	727	731	728.9	-1.35
20	492.6	488	489	488.1	-0.91
10	246.3	247	247	247.3	0.40
0	0	3	2	2.5	-
Average of Absolute % Diff. for the Averaged Analyzer Readings:					0.99
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					1.91

Table 18 Horiba BE-220 NO Gas Divider Test (Low Concentration).

Analyzer:	Horiba BE-220 prod.	Flow (SLPM):	3		
Component Gas:	NO	Analyzer Temperature:	-		
Bottle Conc. (ppm):	500	Analyzer Pressure:	-		
Diluent Gas:	N ₂	Time at Point:	1 min.		
Cal. Pts. (excluding 0)	1	Analyzer Reading			% Diff.
Gas Divider Setting (% Component Gas)	Ideal Concentration from Gas Divider (%)	Test 1	Test 2	Average	Average
100	500	500	500	500.0	-0.01
80	400	406	399	402.2	0.54
60	300	312	290	300.7	0.24
40	200	210	196	202.9	1.44
20	100	116	109	112.3	12.31
0	0	0	0	0.0	0.00
Average of Absolute % Diff. for the Averaged Analyzer Readings:					2.42
Maximum Absolute % Diff. for the Averaged Analyzer Readings:					12.31

4.1.1.2 Gas Interference Tests

Interference tests were performed with gases that are constituents of diesel engine exhaust. Results from these tests were compared to manufacturer specified interference limits where available. The analyzers were first zeroed with N₂ then spanned with single component gases of the concentration used for testing. Values were recorded with the zero gas input just after the analyzers were zeroed. A single component gas was then supplied and response on all gases was recorded. Next, zero gas was supplied, followed by the single component gas again. Values of all the gas concentrations were recorded at each step of the test. NO was the only gas that caused a significant interference with other gas responses throughout these tests. See Table 19, Table 20, and Table 21 for details. Each of the analyzers was calibrated using the gas indicated in the charts before the start of the test. The Scotty Blend gas is a mixture with target concentrations of 12% CO₂, 4%CO, 2000 ppm NO, and 1200 ppm HC balanced with N₂. Single point calibrations (zero and span) were used for the gas interference tests.

Table 19 Gas Interference Results on the Sensors Inc. AMBII.

Analyzer:		Sensors Inc., AMBII				Calibration:	1pt. on Scotty Blend	
test	zero	Gas	Conc.	HC (ppm)	CO (%)	CO ₂ (%)	O ₂ (%)	NO _x (ppm)
	◆	zero air	-	-	-	-	-	-
◆		CO ₂	15%	-	-	14.4	-	-
◆		zero air		4	0.00	0.0	20.54	0
◆		CO ₂	15%	0	0.00	14.6	-0.18	0
	◆	zero air		0	0.00	0.0	20.68	0
◆		CO	4%	0	4.00	0.0	-0.16	0
◆		zero air		0	0.00	0.0	20.68	0
◆		CO	4%	-1	4.02	0.0	-0.19	0
	◆	zero air		0	0.00	0.0	20.60	0
◆		propane	1000ppm	1026	0.00	0.0	20.67	0
◆		zero air		2	0.00	0.0	20.65	0
◆		propane	1000ppm	1023	0.00	0.0	20.69	0
	◆	zero air		-	-	-	-	-
◆		NO _x	2000ppm	146	-3.00	4.0	-139.09	-1165
◆		zero air		0	0.00	0.0	22.40	0
◆		NO _x	2000ppm	148	-3.84	4.0	-139.05	-1165

Note: ◆ in the zero column indicates that the analyzer was zeroed at that point. ◆ in the test column indicates values were recorded only (analyzer was not adjusted).

Table 20 Gas Interference Results on the Horiba BE-140.

Analyzer:		Horiba BE-140				Calibration:	1pt. on Scotty Blend	
test	zero	Gas	Conc.	HC (ppm)	CO (%)	CO ₂ (%)	O ₂ (%)	NO _x (ppm)
	◆	zero air	-	0	0	0	N/A	N/A
◆		CO ₂	15%	1	0	15.20	N/A	N/A
◆		zero air		12	0	0	N/A	N/A
◆		CO ₂	15%	10	0	14.98	N/A	N/A
	◆	zero air		2	0	0	N/A	N/A
◆		CO	4%	2	4	0.01	N/A	N/A
◆		zero air		1	0	0	N/A	N/A
◆		CO	4%	3	3.99	0.01	N/A	N/A
	◆	zero air		0	0	0	N/A	N/A

Note: ◆ in the zero column indicates that the analyzer was zeroed at that point. ◆ in the test column indicates values were recorded only (analyzer was not adjusted).

Table 21 Gas Interference Results on the Siemens SIBENCH.

Analyzer:		Siemens SIBENCH				Calibration:	1pt. on Scotty Blend	
test	zero	Gas	Conc.	HC (ppm)	CO (%)	CO ₂ (%)	O ₂ (%)	NO _x (ppm)
	◆	zero air	-	-9	-0.004	0	N/A	6
◆		CO ₂	15%	-15	-0.001	15.37	N/A	1
◆		zero air		-14	-0.002	0.03	N/A	-1
◆		CO ₂	15%	-16	0.001	15.35	N/A	-1
	◆	zero air		C	C	C	N/A	C
◆		CO	4%	-1	3.969	0	N/A	-3
◆		zero air		-2	0	0	N/A	3
◆		CO	4%	-3	3.963	0	N/A	-5
	◆	zero air		-1	0.002	0	N/A	2
◆		propane	1000ppm	527	-0.001	0.01	N/A	4
◆		zero air		1	0.003	0	N/A	5
◆		propane	1000ppm	533	0	0	N/A	0
	◆	zero air		3	0.003	0	N/A	2
◆		NO _x	2000ppm	2	0.004	0	N/A	31570
◆		zero air		3	0.005	0.01	N/A	2
◆		NO _x	2000ppm	2	0.003	0	N/A	31589
	◆	zero air		1	0.001	0	N/A	7

Note: ◆ in the zero column indicates that the analyzer was zeroed at that point. ◆ in the test column indicates values were recorded only (analyzer was not adjusted).

4.1.1.3 Time Response Tests

Time response of the analyzers for the MEMS is critical to achieve results representative of the exhaust exiting the stack. Tests were conducted with single gases and blended gases containing the four regulated emissions gases: CO, CO₂, NO_x, and HC. Each test consisted of switching the solenoid valve five times between a zero gas and a component gas in the following time increments: 10, 8, 5, 4, 3, 2 and 1 seconds. At the end of this series, the solenoid was switched to flow 100% of the component gas to observe the time required to obtain a stable reading. The solenoid valve was placed as close as possible to the inlet of the benches; less than six in., to minimize the effects of residence time in the line. This effect should be negligible with six in. of line because at 3 LPM, the residence time in the line is less than 0.05 seconds, which is small in comparison to the observed T₉₀ times. Table 22 below is a comparison between experimental and advertised T₉₀ response times for each of the analyzers tested. Experimental T₉₀ times were determined by switching from a zero gas, after the reading

was stabilized, to a span gas and observing the time difference between the switching of the solenoid valve and the point where the analyzer response crossed 90% of the span value.

Table 22 Comparison of Advertised and Experimental T_{90} Response Times for Gaseous Analyzers.

Analyzer		Advertised T_{90}	Experimental T_{90}
Horiba BE-140	CO ₂	3.5 sec. at 2 LPM	4.5 sec. at 3 LPM
	CO		5 sec. at 3 LPM
	HC		5 sec. at 3 LPM
Horiba BE-220		5 sec. at 3 LPM	3.5 sec. at 3 LPM
Horiba MEXA-120		< 1 sec.	5 sec. at 3 LPM
Sensors AMBII	CO ₂	3.5 sec.	1 sec. at 3 LPM
	CO	3.5 sec.	2 sec. at 3 LPM
	NO	3.5 sec.	5 sec. at 0.5 LPM

The Horiba BE-220 NO analyzer exhibited significant overshoot and a T_{90} time of approximately 3.5 seconds, as shown in Figure 32. Figure 33 and Figure 34 show the T_{90} response of the Horiba BE-140 was about 4.5 seconds for CO₂ and 5 seconds for CO. NO time response test results for the Sensors Inc. AMBII microbench are shown in Figure 35. The T_{90} time for NO is approximately 5 seconds, while the T_{100} time of about 12 seconds is greater than the T_{100} time of the other NO and NO_x analyzers evaluated. CO₂ and CO time response results for this microbench are illustrated in Figure 36 and Figure 37. These time responses are excellent compared to the other analyzers evaluated, although the signal is output at only about 1Hz, which is obvious in the graphs. The spikes in the signal were likely the result of electrical noise interference. The Sensors Inc. AMBII HC measurement responds similarly to the CO and CO₂ except it tends to overshoot the span value as shown in Figure 38. Figure 39 shows the time response test results for the Horiba MEXA-120 NO_x analyzer. The T_{90} time was estimated at 5 seconds. The noisy signal during this test was probably the result of a lack of electrical shielding. More detailed results of the time response tests are illustrated in Appendix A.

Figure 32 Time Response Test of the Horiba BE-220 NO Analyzer.

Figure 33 CO₂ Time Response Test of the Horiba BE-140 Analyzer.

Figure 34 CO Time Response Test of the Horiba BE-140 Analyzer.

Figure 35 NO Time Response Test of the Sensors AMBII Analyzer.

Figure 38 HC Time Response Test of the Sensors AMBII Analyzer.

Figure 39 NO Time Response Test of the Horiba MEXA-120 NO_x Analyzer.

4.1.1.4 Inclination Tests

Only one of the microbenches tested exhibited significant error induced by inclination. This was the Siemens SIBENCH, which was eliminated from the testing due to software problems that were not resolved. The worst results observed from the SIBENCH were as follows with 1000 ppm propane flowing at 3 LPM. 6401 ppm HC, 12.40% CO₂, 17.70% CO, and 6162 ppm NO were reported. Results with 1000 ppm propane at the normal orientation are within the manufacturer specified accuracy limits. Zero air at the inclined angle resulted in responses of 5887 ppm HC, 12.40% CO₂, 17.70% CO, and 6170 ppm NO. Each microbench was oriented at 15 degrees and 45 degrees from horizontal on each side. The readings were observed at each position and compared to the readings at the normal orientation, which is where the analyzers were calibrated. The BE-140, BE-220, Sensors AMBII and MEXA-120 passed the test based on the fact that any fluctuation in output was very minor and within the error limits of the instrument.

4.1.1.5 Vibration Tests

Vibration is a major concern with on-road testing. Laboratory vibration tests performed by shaking the analyzers by hand showed no vibration effects on the Horiba BE-140 or the Sensors AMBII microbenches. The same test on the Horiba BE-220 produced some error. This error was not measured as the shaking of analyzers by hand was used only to predict if there could be a response to vibration. Some of the analyzers evaluated exhibited unacceptable errors from vibration when subjected to on-road testing in a Mack class 8 tractor. The on-road tests to determine vibration effects were performed by sampling ambient air over a test route.

Vibrations encountered during on-road testing had a detrimental effect on the accuracy of the Horiba BE-220 NO analyzer. See Figure 40. The spikes from vibration of the Luft detector are about 1500 ppm, around the maximum value measured during engine testing. This analyzer was immediately disqualified for use in the MEMS after review of on-road vibration data. However, the electrochemical NO cell was considered

unreliable for use as the primary NO_x measurement device due to time response and longevity issues. This led to the testing and validation of the Horiba MEXA-120.

The same vibration test was performed on the Horiba BE-140 analyzer. Results for CO₂ are shown in Figure 41. A laboratory-grade Rosemount model 880 CO₂ analyzer was tested for comparison and to verify that this type of analyzer was not suitable for on-road testing. The variation in concentration over the test of the BE-140 is much less than that of the model 880 analyzer. Some of the small variation in these tests could be due to the actual gas concentrations changing inside the truck during the route. The BE-140 CO₂ reading varied within 0.15% absolute concentration over the test. The vibration test results for the Rosemount 880 CO₂ analyzer are shown in Figure 3. The Rosemount 880 varied within 0.90% absolute concentration throughout the test.

The 880 and BE-220 are Luft-type 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 causes the diaphragm to deflect. The BE-140 employs a solid-state NDIR detector and as expected showed no response that could be positively attributed to vibration. The Horiba MEXA-120 and the electrochemical NO cell are also solid-state devices, so vibration errors should be negligible in amplitude. Figure 43 shows the results of the MEXA-120 over the same test route used for vibration analysis of the other two microbenches.

Figure 40 On-Road Vibration Test of the Horiba BE-220 NO Analyzer (from source [18]).

Figure 41 On-Road Vibration Test of the CO₂ Response on the Horiba BE-140 Analyzer (from source [18]).

Figure 42 On-Road Vibration Test of the Rosemount Model 880 CO₂ Analyzer (from source [18]).

Figure 43 On-Road Vibration Test of the Horiba MEXA-120 NO Analyzer [18].

4.1.1.6 Sample Flow Variation Tests

Flow rate was varied through the Horiba BE-140 and the Sensors electrochemical NO cell. Single component gases were used for calibration and the tests for each gas component were performed individually with the same single component gases used for calibration. Nitrogen was used to zero the analyzers. Gases of the following concentrations were used for the calibration and testing: 150 ppm HC, 1.01% CO and 19.90 % CO₂. Flow was maintained at 3 LPM during calibration on the BE-140. See Table 23 for results of the flow tests on the Horiba BE-140 and Table 24 for results on the Sensors electrochemical NO cell. Results of the flow variation tests emphasize the importance of maintaining a constant flow rate.

Table 23 Horiba BE-140 Flow Variation Test.

Flow (SLPM)	HC		CO		CO₂	
	Reading	% Diff.	Reading	% Diff.	Reading	% Diff.
2.0	148 ppm	-3.3	0.97%	-4.1	19.45%	-2.8
3.0	153 ppm	0.0	1.01%	0.0	20.00%	0.0
4.0	160 ppm	4.6	1.06%	5.0	20.90%	4.5

Table 24 Stand-Alone Sensors Inc. Electrochemical NO Cell Flow Variation Test.

Flow (SLPM)	1491 ppm NO	
	Reading	% Diff.
0.1	1457	-2.3
0.3	1491	-
0.5	1512	1.4

4.1.1.7 Water Interference Tests

Water interference tests were performed by passing a component gas through room temperature water as bubbles for a distance of approximately three inches. This provided nearly 100% relative humidity. Specific humidity was calculated based on 100% relative humidity using equation 5 relating specific humidity to relative humidity.

$$\omega = R_{\text{gas}}/R_v * \phi * P_g / (P - P_g);$$

Equation 5

where ω is specific humidity based on mass, ϕ is relative humidity (1 in this case), R_{gas} is the ideal gas constant for the gas, R_v is the ideal gas constant for the water vapor, P_g is the partial pressure of the gaseous portion of the water which is equal to P_{sat} at T , and P is the total pressure.

The percent volume of water in the sample was calculated from the specific humidity and the specific volumes at 70°F (21°C). The percent volume of water in the sample was used to calculate the new percent volume concentration of the component gases because the component gases were originally 0% water. The wet concentrations were multiplied by $1/(1 - v_{\text{vapor}}/v_{\text{total}})$ to obtain concentrations corrected for the volume occupied by water vapor. The analyzer was calibrated with a four-gas blend of CO₂, CO, HC and NO at a flow rate of 3 LPM. Tests were performed with single component 28.93% CO₂ at 3 LPM. The results of the tests are summarized in Table 25 below for the Horiba BE-140. The water vapor caused a slight increase in the response of the CO₂ output after correction for water volume in the sample. This is expected with an NDIR CO₂ analyzer, as water absorbs energy of a similar wavelength as CO₂. The error from water interference was well within the manufacturer specified accuracy of $\pm 5\%$ at this high concentration of CO₂.

Table 25 Horiba BE-140 Water Interference Test.

Test #	Gas Condition	Analyzer Readings			CO ₂ corrected to dry	Corrected CO ₂ % Diff. from average of dry gas tests	% vol. Water
		HC	CO	CO ₂			
1	Dry from Bottle	3 ppm	0.00%	29.25%	-	-	0
2	Dry from Bottle	1 ppm	0.00%	29.30%	-	-	0
Average	Dry from Bottle	2 ppm	0.00%	29.275%	-	-	0
3	Bubbled through H ₂ O at 70 °F	8 ppm	0.00%	28.85%	29.57%	1.0%	2.4%
4	Bubbled through H ₂ O at 70 °F	5 ppm	0.00%	28.90%	29.62%	1.2%	2.4%
Average	Bubbled through H ₂ O at 70 °F	6.5 ppm	0.00%	28.875%	29.58%	1.0%	2.4%

4.1.1.8 Engine Exhaust Tests

The Horiba BE-140, Horiba BE-220, Horiba MEXA-120 and the Sensors Inc. electrochemical NO cell underwent extensive engine exhaust testing. Limited engine testing was performed with the Sensors Inc. AMBII because an analog signal was not available and the serial signal was not output at constant time increments. The Horiba MEXA-120 was received after the MEMS sampling system was functional, so it was integrated in the sampling system for evaluation with engine exhaust.

Engine exhaust tests were performed during the analyzer selection process primarily to identify problems with the analyzers such as CO ranges that were too low for accurate measurements. Accuracy of CO measurements with the Horiba BE-140 and the Sensors AMBII were not adequate due to the very low concentration in diesel exhaust relative to the minimum span values of the analyzers. Also, some sampling system issues became evident that would need addressed to obtain accurate measurement of raw

exhaust gas concentrations. Hydrocarbon hang up became evident during the engine exhaust tests and in one case exceeded 1100 ppm on the Horiba BE-140 while sampling ambient air after an engine test. The test setup in this case included the Perma-Pure dryer just downstream of the filter, which was at first maintained at 200°F (93°C) in an attempt to cause heavy-end hydrocarbons to condense on the filter media. This procedure was not successful, as the HC reading approached 450 ppm after an FTP cycle on the Navistar engine. The filter element was then changed and the filter housing was heated to 385°F (. This resulted in an HC reading of approximately 1100 ppm at the end of the next FTP. A primary contributing factor to the HC hang up problem was the Perma-Pure Nafion tube dryer. However, other drying methods caused a loss of hydrocarbons, so accurate measurements were not possible with any of the analyzers due to their low operating temperatures.

The Horiba BE-140 performed well for CO₂ measurements on raw exhaust gases. Tests with the BE-140 analyzer sampling raw exhaust from the Navistar engine are shown in Table 26. These tests were performed to show repeatability and determine raw exhaust gas concentrations from this engine for future selection of calibration gases. The values reported are averages over the steady-state tests. Concentrations reported by the laboratory analyzers for diluted exhaust, so a direct comparison cannot be made to the BE-140 results. This test was performed with the sampling cart with the following setup. A heated line from the exhaust sample probe to the cart was set at 265°F (129°C) and a heated filter was set at 160°F (71°C) to prevent condensation of water. The gas was allowed to cool to approximately 75°F (24°C) before entering a mass flow controller set to 3 SLPM. Notice the hydrocarbon values reported by the BE-140 on raw exhaust are similar to those reported by the laboratory analyzer on dilute exhaust, which indicates very large errors. This was expected on this set of tests because the sampling components were maintained at a temperature below the condensation temperature of some HC species in diesel exhaust. Similar tests performed with the Sensors AMBII microbench are shown in Table 26. As with the BE-140, CO and HC measurements are not accurate due to resolution limitations and condensing problems, respectively.

Table 26 Steady-State Raw Diesel Exhaust Tests on the Horiba BE-140 Analyzer.

Engine Load	Test #	Analyzer(s)	CO ₂	CO	HC
122 ft-lb @ 2000 rpm	1	BE-140	4.01%	0.01%	3ppm
		Dilute Lab.	5395ppm	2.7ppm	4.1ppm
122 ft-lb @ 2000 rpm	2	BE-140	3.99%	0.00%	5ppm
		Dilute Lab.	5443ppm	2.8ppm	8.3ppm
122 ft-lb @ 2000 rpm	3	BE-140	4.04%	0.00%	4ppm
		Dilute Lab.	5536ppm	2.8ppm	11.4ppm
406 ft-lb @ 2200 rpm	4	BE-140	7.13%	0.00%	2ppm
		Dilute Lab.	17850ppm	3.6ppm	5.1ppm
406 ft-lb @ 2200 rpm	5	BE-140	7.22%	0.00%	0ppm
		Dilute Lab.	18300ppm	3.9ppm	4.4ppm
406 ft-lb @ 2200 rpm	6	BE-140	7.22%	0.00%	4ppm
		Dilute Lab.	18500ppm	4.0ppm	4.6ppm

Table 27 Steady-State Raw Diesel Exhaust Tests on the Sensors AMBII Analyzer.

Engine Load	Test #	CO ₂	CO	HC	NO
122 ft-lb @ 1250 rpm	1	4.1%	0.00%	10ppm	324ppm
122 ft-lb @ 2000 rpm	2	4.0%	0.01%	4ppm	-
406 ft-lb @ 2200 rpm	3	7.4%	0.01%	0ppm	-
122 ft-lb @ 1250 rpm	4	3.8%	0.01%	-1ppm	-
122 ft-lb @ 2000 rpm	5	3.8%	0.01%	-1ppm	-
406 ft-lb @ 2200 rpm	6	7.6%	0.01%	0ppm	-

4.1.2 Sampling System

Numerous revisions were made to the emissions sampling system before arriving at the current configuration – version 1.10. The sampling system is capable of providing at least 10 LPM with the ADI standard Dia-Vac Teflon Diaphragm pump operating with the current components and a loaded filter. This pump is obviously oversized for the required total flow of 3.5 LPM. However, the required flow was not known during the initial selection of components and this pump could be replaced with an ADI Micro Dia-Vac pump, which is a smaller heated head pump of the same design. Flow rate control, temperature control and filtering of the sample stream are accomplished with laboratory-grade components that function well for this purpose. The NO_x conversion efficiency is less than desired at higher concentrations of NO₂, but should provide >90% efficiency over most engine operating conditions. Details of the performance and selection of each component and/or subsystem are provided.

4.1.2.1 Flow Control

A differential pressure regulator, controlling pressure across a needle valve, maintains a constant flow rate through the sampling system. These components were selected because they provided a more stable flow rate compared to flow meters. Flowmeters were first tested to control the flow rate of the sample stream. Several problems were encountered with the use of flowmeters. The flow and pressure would vary when the floats of the flowmeters moved due to vibration. Another problem, at one point in the design process, was the accumulation of water within the flowmeters. This was not a problem when the sample stream was adequately dried. However, pressure and flow fluctuations cause variations in the output of the infra-red and electrochemical devices. The flowmeters were eliminated from the sample train that is used during testing. A single flowmeter is used to set the flow through the analyzers but is bypassed during analyzer calibration and engine testing.

As discussed in the experimental setup, flow rate has a great effect on transient testing results. A laboratory-grade Rosemount 880 CO₂ analyzer was used to test response to a transient test at different flow rates. See Figure 44 below for an illustration

of flow rate effects on the analyzer response over a portion of an FTP cycle performed at the EERL.

Figure 44 Flow Rate Effects on CO₂ Laboratory Analyzer Reading (from source [18]).

The flow rate for the MEMS was chosen based on required flow rates for the analyzers, NO_x converter and electric gas cooler. Performance of the NO_x converter and gas cooler are degraded as flow rate is increased. Conversely, response to transient events is improved as flow rate is increased. Sampling system components such as the filter and pump must be sized according to flow rate, so issues of size and power consumption contributed to the choice of flow rate. The final design maintains recommended flow rates of 3 LPM for BE-140 and 0.5 LPM for the electrochemical NO cell. The total flow of 3.5 LPM was first passed through a manifold for the zirconium oxide NO_x sensor to minimize its response time. A schematic of the sampling system is illustrated in Figure 45.

Figure 45 Schematic of the MEMS Sampling System.

4.1.2.2 Humidity Control

The water content of the sample stream must be known or approximated to determine the actual concentration of measured emissions. Humidity of the sample stream varies rapidly with time and most humidity measurement devices do not respond fast enough for accurate results. Therefore, humidity is estimated based on the CO₂ reading. This allows the concentration of emissions to be reported on a wet or dry basis.

Moisture should not condense out on certain components of the sampling system or the analyzers. Therefore, the entire sampling system must be above the dewpoint of the sample gas or moisture must be removed from the sample stream. The dewpoint of diesel exhaust was found to be approximately 120°F (49°C) under high load conditions. Tests were performed on engine exhaust with the internal temperature of the enclosure maintained at 120°F (49°C) and no method of water removal from the sample stream. First, water condensed out inside the flowmeters and resulted in erratic flow control. The

flowmeters were mounted external of the enclosure so the flow rate could be observed while in operation, so they were slightly cooler than the internal enclosure temperature. A second problem was the liquid water was sometimes carried in large drops by the sample stream from the flowmeters to the analyzers before re-evaporation was complete. Any water entering the infrared analyzers in liquid form will cause deposits to form on the walls of the sample cell, which results in inaccurate readings. The flowmeters were later eliminated from the sample stream, due to erratic flow control from vibration encountered during on-road testing. However, the microbenches were operating at or above the maximum recommended temperatures and hydrocarbons were condensing within them. The problems encountered led to the decision to use a water removal system that would provide a constant sample stream humidity so the emissions measurements could be converted to the original, wet concentrations based on the CO₂ measurement.

An electro-thermal cooler was eventually chosen to remove moisture from the sample stream. Several methods of moisture removal were first tested. These include Nafion tube dryers, desiccant dryers, water traps that were at ambient temperature and water traps in ice water. Two thermoelectric chillers were tested, a Universal Analyzers Model 1080 and an M&C Products ECP 1000. The Universal Analyzers chiller was tested first and then replaced with the M&C chiller that much smaller and met the flow requirements.

The Nafion tube dryer was eliminated due to complexity, packaging, and operation problems. To reach the desired efficiency level, the dryer required the use of externally supplied and dried purge air. This meant a compressor and continuously renewed desiccant dryer were required. These additional parts were deemed too large and heavy for the MEMS. Additionally, the Nafion tubes are prone to clogging with condensed out hydrocarbons. The maximum allowable inlet temperature of the unit tested was 150°C, limited by the epoxy resin used to bind the tube bundle together. Nafion tubing itself will withstand 160°C operating temperature, but this is below the temperature at which certain hydrocarbons present in diesel exhaust will condense out of the sample stream.

Table 28 shows the results of testing the Perma-Pure Nafion tube dryer with ambient external purge air pumped through a desiccant dryer at approximately 10 LPM. Sample flow rate was 3 LPM and room air was 81°F (27°C) and 63% RH.

Table 28 Perma-Pure Dryer Test Results.

Sample Gas	Dewpoint (°C)
Ambient air	16.5
Ambient air through water	22.8
Ambient air through Perma-Pure	8.7
Ambient air through water and Perma-Pure	9.5

A water trap was tested in place of the Nafion tube dryer due to the previously discovered problems. First, the water trap was placed in ice water to maintain a constant wall temperature and therefore a constant dew point for the exiting sample stream. The water trap submerged in ice water removed enough water to avoid condensation within components inside the enclosure, however there was no way to remove the collected water from the trap during testing and this water would sometimes travel in large drops out of the water trap and through the sample lines. Assuring the ice did not melt before completion of a test was another complication.

The next revision was the elimination of the ice water and the water trap was placed in ambient air outside the box. This eliminated problems due to ice melting and water spilling, but the wall temperature of the trap varied more and was much higher, so the dew point of the sample stream was also higher and varied too much over a test for accurate conversion to wet concentrations using CO₂ values. Water removal during testing still posed a problem as with the trap in ice water, therefore thermoelectric chillers were evaluated for drying the sample stream.

A thermoelectric chiller proved to be the most reliable and repeatable method of drying the sample stream. A comparison of the effectiveness of the three water removal methods is shown in Figure 46. Relative humidity of the gas was approximately 100% at

70°F before entering the water removal devices. Testing was also performed with the to determine the stability of relative humidity over an engine test cycle in the dynamometer cell at the EERL. See Figure 47 for the results without water removal, Figure 48 for the results with the water trap in ice-water, and Figure 49 for the results with a thermoelectric chiller set to a dew point of 5°C.

Figure 50 shows the difference in NO_x concentration between a wet and dry raw sample as measured with the Rosemount 955 NO_x analyzer at the EERL. As expected, the integrated results over the transient test cycle were 8.5% higher when the sample was dried to a dewpoint of 5°C compared to wet sample.

Figure 46 Comparison of Water Removal Methods Based on Relative Humidity of 5% CO₂ with N₂ balance.

Figure 47 Engine Exhaust Relative Humidity and CO₂ Concentration Reported by the MEMS without Moisture Removal.

Figure 48 Engine Exhaust Relative Humidity and CO₂ Concentration Reported by the BE-140 with a Water Trap in Ambient Air.

Figure 49 Engine Exhaust Relative Humidity and CO₂ Concentration Reported by the BE-140 with a Thermoelectric Chiller.

Figure 50 Comparison of Concentrations Reported by the 955 NO_x Analyzer with Wet and Dry Exhaust Samples from the Mack E7-400 Engine at the EERL.

4.1.2.3 NO_x Conversion

The NO_x converter efficiency was tested via two methods. First a Beckman Model 958 NO_x efficiency tester was used. NO concentration after the converter was measured with both the electrochemical NO cell and the Horiba MEXA-120 NO_x sensor as shown in Table 29. Only NO should be measured to calculate converter efficiency based on the equations from the Rosemount manual. The calculations were repeated with the NO_x values from the ZrO₂ sensor to verify that those converter efficiency results were lower. Those results were lower because the ZrO₂ sensor reports approximately 75% of NO₂ while the electrochemical cell has very little response to NO. Later, a bottle of 620 ppm NO₂ was acquired for NO_x converter efficiency testing. Results of the gas bottle tests are shown in Table 30. The Horiba Com 11HRB satisfied the requirements of 90% conversion efficiency at the sample stream flow rate of 3.5 LPM with up to approximately 100 ppm NO₂. NO₂ concentrations in modern heavy-duty diesel engine exhaust are typically less than 40% of the total NO_x concentration. Table 33 shows the results of measurements made with the Horiba MEXA-120 on dilute diesel exhaust compared to the Rosemount 955 analyzer in NO_x mode.

Table 29 Horiba Com 11HRB NO_x Converter Efficiency Test with Rosemount Converter Efficiency Tester.

Test #	Converter Efficiency Measured with E/C NO	Converter Efficiency Measured with ZrO₂ NO_x
1	98.6%	96.5%
2	99.0%	93.8%
3	101.6%	96.0%
Average	99.7%	95.6%

Table 30 Horiba Com 11HRB NO_x Converter Efficiency Test with NO₂.

NO₂ Concentration (ppm)	Measured NO Value (ppm)	Converter Efficiency (%)
62	62	99.9
124	104	84.3
186	149	79.9
248	186	75.2
310	216	69.6
372	241	64.8
434	262	60.3
496	272	54.8
558	285	51.2
620	292	47.2

Table 31 Percent of NO₂ Measured with Horiba MEXA-120 and Horiba Com 11HRB NO_x Converter.

NO₂ Concentration (ppm)	Measured NO_x Value with MEXA-120 (ppm)	% of NO₂ Reported
62	63	101.4
124	118	95.1
186	178	95.7
248	237	95.6
310	289	93.1
372	338	90.8
434	383	88.2
496	417	84.0
558	454	81.4
620	482	77.8

Table 32 Percent of NO₂ Reported by the Horiba MEXA-120 Analyzer.

NO₂ Concentration (ppm) before NO_x Converter	Measured NO Concentration (ppm) with the Electrochemical Cell after NO_x Converter	NO₂ Concentration (ppm) after NO_x Converter	Measured NO_x Concentration (ppm) with MEXA-120 after NO_x Converter	NO₂ Concentration (ppm) Measured by MEXA-120	% of NO₂ Reported by MEXA-120
62	62	0	63	1	-
124	104	20	118	14	70
186	149	37	178	29	78
248	186	62	237	51	82
310	216	94	289	73	78
372	241	131	338	97	74
434	262	172	383	121	70
496	272	224	417	145	65
558	285	273	454	169	62
620	292	328	482	190	58

Table 33 Engine Testing Results of the Horiba MEXA-120 without a NO_x Converter.

Analyzer:	Horiba MEXA-120	Flow (SLPM):	2
Component Gas:	NO	Analyzer Temperature:	-
Bottle Conc. (ppm):	244	Analyzer Pressure:	-
Diluent Gas:	N ₂	Time at Point:	-
Cal. Pts. (exluding 0)	2		
OICA 28 Test Mode	Rosemount 955 Laboratory Analyzer Reading (ppm) (NO_x mode)	MEXA-120 Reading (ppm) (NO_x converter bypassed)	
1	5.7	5	-12.28
2	175	164	-6.29
3	75	66	-12.00
4	105	94	-10.48
5	68	61	-10.29
6	116	107	-7.76
7	36.5	34	-8.22
8	184	171	-7.07
9	42	36	-14.29
10	163	147	-9.82
11	41	35	-14.63
12	99	85	-14.14
13	74	66	-10.81
Average of Absolute % Diff. for the Averaged Analyzer Readings:			10.62
Maximum Absolute % Diff. for the Averaged Analyzer Readings:			14.63

4.1.2.4 Temperature Control

Output from the analyzers was found to be more stable if the sample and ambient temperatures were constant. The number and length of heated lines in the emissions box were minimized in order to reduce power consumption. After it was concluded that HC concentrations could not be accurately measured using this system, the internal temperatures were reduced significantly which led to a decrease in power consumption. With the installation of an electric gas cooler, the sample lines downstream no longer required heating to prevent condensation of water. The filter, sample line from the exhaust to the box, NO_x converter, sample pump head, enclosure temperature and line between the filter and pump and NO_x converter are currently temperature controlled. Filter temperature is maintained slightly lower than component temperatures between the filter and the chiller in an effort to avoid hydrocarbon condensation within those components. Hydrocarbons condensed out onto the filter media will be removed when the filter is changed and those condensed out in the chiller will be removed when the condensate is drained. The temperature settings in use at this time are as shown in Table 34 below. Omega CN4431(TR)-R1 controllers were found to be more than adequate for these tasks and likely could be substituted with less complex and lower cost controllers. Relays are used on the controllers operating a load greater than 2 amps.

Table 34 Controlled Temperature Settings.

Component	Temperature (°F)
Sample line from exhaust	300
Sample filter	275
Heated pump head	300
NO _x converter	402
Line between filter and pump	300
Line between pump and NO _x converter	300
Air Inside Enclosure	95

4.1.2.5 Filtering

A standard heated filter housing with a 2.5 in.x1 in. filter element of 95% efficiency at 0.3 microns was found to be sufficient for testing on-road diesel powered vehicles for at least an hour of typical operation. The differential pressure relay was capable of maintaining a constant flow rate under these conditions. The 7 in.x1 in. filter element which was first tested, provided about twice as much sampling time before it became necessary to change the filter to maintain flow rate. The larger filter elements were designed for diesel particulate matter with a course pre-filter on the inside. The smaller filter elements were also available with this pre-filter on the inside. However the pre-filter was not found to significantly prolong filter life except when tested on mechanically injected diesel engines used in off-highway equipment, as the average particle size is much larger than those from electronically controlled on-road engines. The smaller filter was installed so the sample would flow from the outside to the inside of the element to provide more surface area for collection of particles and therefore less restriction of flow with the same amount of loading. The smaller filter was chosen to minimize space requirements provide more stable temperatures because a commercially available heated filter housing would fit within the desired enclosure size. Also, the heated filter housing selected is well insulated which provides protection for surrounding equipment.

4.1.2.6 Sample Lines

A heated sample line from the exhaust to the emissions box was initially maintained at 375°F (191°C) to prevent condensation of heavy-end hydrocarbons present in diesel exhaust. After it was realized that HC concentrations could not be accurately measured with the available analyzers, the line temperature was reduced to 300 F. Sample lines of 0.25 in. OD provided a good compromise between delay time and pressure drop. The residence time at 3 LPM through 0.25 in. OD Teflon tubing with 0.065 in. wall is approximately 0.008 seconds per inch. Stainless steel tubing was used inside the emissions box where heating was required, such as between the filter and pump, and between the pump and NO_x converter. The stainless used is 0.25 in. OD by 0.035 wall, so the residence time is slightly greater than in the 0.25 in. OD Teflon tubing

used in other places, however the thinner wall allows better temperature control by decreasing the time for conduction through the walls. Gas temperature within the sample lines inside the enclosure is measured with K-type thermocouples at the center of the gas stream. This provided more accurate control compared to surface temperature measurements at the tubing wall. Line length within the emissions box was minimized to reduce residence time and minimize power requirements where heating was required.

4.2 System Testing Results

The complete emissions component of the MEMS was tested with gas from bottles of known concentrations as well as with exhaust from three diesel engines in a test cell and one in a Mack class 8 tractor. Testing of the Mack tractor was performed on-road and on a chassis dynamometer.

4.2.1 Gas Bottle Tests

Gas from bottles of known concentration, including SRM certified bottles, was passed through the system to verify responses of the analyzers integrated with the sampling system. These tests are performed periodically on the MEMS to assure data quality. Table 35 below shows a test on version 1.6, where the analyzers (BE-140 and BE-220 in this case) were calibrated with a blended gas normally used for automotive I/M testing and then their response was tested on a blended gas representative of raw diesel exhaust gas concentrations. A second blend gas of higher concentrations was then supplied to the system. The accuracy of the response to the lower concentrations of CO is not adequate at up to 30% error. CO₂, HC and NO responses are acceptable on the higher concentration blend, but all gases except CO₂ are in error by more than 6% with the lower concentration blended gas. The analyzers were in a parallel arrangement with a flow rate of 3 LPM each. Note that the blended gas bottle accuracy is $\pm 1\%$ of the concentration. This could explain the difference of 1.9% of the CO₂ reading on the high concentration blended gas that is almost identical in CO₂ concentration to the calibration gas.

Table 35 Complete System Response to Blended Gases with BE-140 and BE-220.

Gas Component	CO₂	CO	Propane	NO
Calibration Concentration	12.01%	4.01%	1200ppm	2000ppm
Test #1 Bottle Concentration	3.01%	1000ppm	40.5ppm	473ppm
Test #1 Measured Concentration	2.98%	0.07%	38ppm	504ppm
Percent Difference	-1.0%	-30%	-6.2%	6.6%
Test #2 Bottle Concentration	12.0%	5130ppm	151ppm	2540ppm
Test #2 Measured Concentration	11.77%	0.49%	152ppm	2560ppm
Percent Difference	-1.9%	4.7%	0.7%	0.8%

4.2.2 Engine Exhaust Tests

Testing the system on engine exhaust emissions revealed design flaws not previously discovered during gas bottle testing. One of the first obvious problems was maintaining the relative humidity of the sample stream within specifications provided by the analyzer manufacturers. This resulted in testing several methods of controlling the humidity as discussed in section 4.1.2.2.

Measurements of CO₂ and NO_x concentrations in diesel engine exhaust by the MEMS were compared to measurements by laboratory-grade analyzers. HC and CO concentrations were substantially in error compared to the laboratory-grade analyzers. CO, HC and CO₂ data was recorded with the Horiba BE-140 while the Mack E7-400 engine was operated over a set of steady-state conditions within the NTE zone. As shown in Figure 51, the CO₂ results are relatively stable with high resolution and the concentration returns to approximately zero between modes. The poor resolution of CO concentration, measured with the BE-140, is evident as only four distinct values are reported throughout the test shown in Figure 52. Hydrocarbon measurement increased

throughout the test and did not return to zero at any time. See Figure 53. This indicates a hydrocarbon hang up problem within the sampling system and/or analyzer. A portion of the data in this section was previously reported in source [41]. This data is included because several changes were required to the system based on results of engine exhaust tests. Furthermore, the data verifies the accuracy of the complete emissions measurement component of the MEMS.

Figure 51 CO₂ Concentration measured with the Horiba BE-140 over a Set of Steady-State Tests within the NTE Zone on the Mack E7-400 Engine.

Figure 52 CO Concentration measured with the Horiba BE-140 over a Set of Steady-State Tests within the NTE Zone on the Mack E7-400 Engine.

Figure 53 HC Concentration measured with the Horiba BE-140 over a Set of Steady-State Tests within the NTE Zone on the Mack E7-400 Engine.

4.2.2.1 Comparison to Laboratory-Grade Analyzers at the WVU EERL

Most of the testing to verify the emissions sampling components of the MEMS was carried out at the WVU EERL. Raw emissions concentrations were recorded with both the MEMS emissions box and the laboratory instruments. Comparison to laboratory analyzers over transient tests was based primarily on the difference between the integrated results of each instrument. CO₂ concentrations reported by the MEMS were accurate and repeatable based on comparison to laboratory analyzers over various test cycles. NO_x concentrations over an NTE test on the Cummins engine reported by the BE-220 with a NO_x converter and the Rosemount 955 laboratory analyzers are shown in Figure 54. Concentration integrated over the test cycle was 0.9% low for the Horiba BE-220 compared to the laboratory analyzer. Transient response of the BE-220 was very similar to the laboratory analyzer and accuracy was acceptable over the test cycle.

Figure 55 shows an FTP cycle performed on the Mack E7-400 that was previously reported in source [41]. The integrated results over the cycle reported by the MEMS were 1.34% higher than reported by the laboratory analyzer.

Figure 54 Comparison of results reported by the Horiba BE-220 NO analyzer and EERL over a cycle within the NTE zone on the Cummins ISM 370 Engine.

Figure 55 Comparison of CO₂ Reported by the MEMS and the EERL over an FTP Cycle with the Mack E7-400 Engine (from source [41]).

4.2.2.2 Comparison to Laboratory-Grade Analyzers at the WVU Transportable Laboratory

A Mack class 8 tractor with an E7-400 engine was exercised through several test cycles on the dynamometer trailer. Most of the test cycles did not include load to correspond to road grade on the routes in which they were modeled after. Rather, only speed, wind drag and weight were used to determine loading throughout the test cycles performed on the dynamometer trailer. Elevation change was inferred from absolute pressure recorded throughout the on-road test cycles to allow a dynamometer test cycle to include additional load for road grade. Data from chassis dynamometer tests was reported in a previous thesis [41].

4.2.2.3 On-road Testing

Several testing routes were developed around the Morgantown, WV vicinity for testing the MEMS. These tests were performed with the 1995 Mack class 8 tractor. On-road testing results with the MEMS are detailed in a thesis [41]. Some results from the on-road testing were used for the verification and selection of replacement components where required. For example, the Horiba BE-220 NO analyzer was replaced with the Horiba MEXA-120 NO_x analyzer after reviewing data obtained from the on-road vibration tests. Additionally, the flowmeters were eliminated as a means of controlling flow rate through the analyzers. Flowmeters caused fluctuations in the flow rate when the floats moved from acceleration caused by irregular road surfaces.

4.3 Overview of Current MEMS Operating Procedures

4.3.1 Setting Sample Flow Rate

Sample flow rate is set by adjusting two needle valves, one for the total flow and one for the flow through the electrochemical NO cell. A ball float flowmeter is used to set the flow rates. This flowmeter is only used during the flow adjusting procedure and is bypassed during sampling and calibration of the analyzers. First, the flow is directed from the outlet of the ZrO₂ sensor manifold through the flowmeter with a three-way valve. This total flow is set to 3.5 LPM with the needle valve across which pressure is controlled by the differential pressure regulator. Total flow is set with the needle valve to the EC NO cell closed completely. Next, flow to the NO cell is adjusted by opening that needle valve until the flowmeter reads 3.0 LPM. This results in flow rates of 3.5 LPM through the ZrO₂ sensor manifold, 3.0 LPM through the Horiba BE-140 and 0.5 LPM through the NO cell.

4.3.2 Calibration of Analyzers

The analyzers are calibrated with a Horiba SGD-710C gas divider using bottled gases of known concentrations. Gas concentrations are selected based on peak concentrations in the exhaust of the engine being tested. The Horiba BE-140 is adjusted at the zero and span concentrations only while a three-point curve is used for calibration of the EC NO cell and the Horiba MEXA-120 NO_x analyzer. An insulated three-way

valve, placed at the entrance of the heated sample line, allows the calibration line from the gas divider to be connected without removal of the heated line from the sample probe.

Chapter 5 Conclusions

5.1 Measurement of Emission Gas Concentrations

CO₂ and NO_x were the exhaust constituents of primary concern throughout this project. Microbenches were available that were suitable for measuring the CO₂ and NO concentrations common in diesel exhaust. A NO_x converter was required to convert NO₂ to NO to obtain NO_x concentration. All of the microbenches capable of measuring CO and HC were for much higher ranges than emitted by modern heavy-duty diesel engines. Additionally, hydrocarbon hang-up problems could not be eliminated due to temperature limitations of the microbenches. Discussion of issues specific to each of these emissions gases follows.

5.1.1 CO₂

The MEMS developed at WVU is capable of measuring CO₂ with accuracy approaching that of most laboratory grade analyzers. The Horiba BE-140 NDIR analyzer was determined to be the best suitable analyzer for measuring CO₂ in a MEMS application. This analyzer exhibited acceptable response times and accuracy for CO₂ measurement and is capable of providing 5Hz serial port data. The Horiba BE-140 was the only analyzer evaluated for CO₂ that met the above requirements. Furthermore, vibration and inclination encountered during on-road testing did not affect the response of this solid-state detector NDIR analyzer. CO₂ measurements with the MEMS were within 3% of laboratory analyzer results integrated over the FTP at the WVU EERL.

The Sensors Inc., AMBII performed adequately for CO₂ measurement except the frequency of output data varied based on computer speed and usage. Data was output from the AMBII approximately every 1.2 seconds. Attempts to obtain an accurate analog signal were not successful which left the BE-140 as the only microbench that met all of the aforementioned requirements for measuring CO₂.

5.1.2 CO

NDIR techniques are commonly used in laboratory grade analyzers to measure CO emissions from diesel engines. The microbenches tested also measure CO with an

NDIR detector. The primary problem encountered with CO measurement was the poor resolution at engine exhaust concentrations. The micro analyzers were designed to measure CO emissions from gasoline engines including poorly tuned and worn engines. CO emissions from a diesel engine are typically much lower than from a gasoline engine. The maximum value normally observed during steady-state operation of a properly maintained, electronically controlled HDD engine is approximately 1000 ppm. The Horiba BE-140 analyzer is designed for a minimum span gas value of 1.20%. Accuracy of the CO measurement is $\pm 0.02\%$ CO, which is 200 ppm, one fifth of the maximum value likely to be measured. Therefore, CO measurement with this instrument was abandoned. However, this microbench could be used to identify engines emitting much greater than normal concentrations of CO and hence in need of repair.

Recommendations for improving accuracy of CO measurement with the microbenches evaluated include spanning with a lower concentration than recommended by the manufacturer. This may require entering the minimum span value if this is higher than the span gas concentration. If a higher value than the actual span gas concentration must be entered due to software limitations, a post processing correction of the reported data would be required. This option has not yet been thoroughly investigated. The low concentration resolution of the Sensors AMBII bench cannot be improved by this method because an out of range error results. A NDIR microbench with a longer sample cell for low concentration would be ideal for the MEMS, however no such devices were available. A longer cell would result in more of the light energy being absorbed by the gas before it reached the detector and a corresponding higher resolution.

5.1.3 NO_x

The accurate determination of NO_x concentration was one of the primary goals of the MEMS. Brake-specific mass emissions of NO_x were reported by the MEMS within 5% of laboratory results integrated over an FTP cycle. A zirconium oxide sensor along with a NO_x converter was selected for the measurement of NO_x, with an electrochemical NO cell as a QC/QA device. The Horiba MEXA-120 provided T₉₀ response times of 5 seconds or less, accurate measurement and no detectable effects from vibration or orientation bias. However, the Horiba MEXA-120 analyzer did not provide a 100%

response to NO_2 . Consequently, a NO_x converter was required to convert NO_2 to NO in order to obtain a NO_x measurement. The NO_x converter was placed upstream of the thermoelectric chiller to prevent loss of the water-soluble NO_2 before being converted to NO . NO_x concentrations may be measured more accurately by improving the conversion efficiency of the NO_x converter. The NO_x converter efficiency decreases as NO_2 concentration increases, thus the percentage of NO_2 measured depends on engine operating conditions.

5.1.4 HC

A large percentage of the hydrocarbons in diesel engine exhaust condense out at higher temperatures than the microbenches can tolerate. This results in buildup of hydrocarbons within the analyzers especially if the analyzer is the first point in the sample flow that is below the condensation temperature of the hydrocarbons. The condensing of HC causes incorrect and unpredictable measurement because the temperature at some points in the sample system is around the dew-point temperature of one or more HC species. Therefore, some condensed out species will vaporize again as the temperature of the lines, pump analyzers, etc. vary slightly. The current system incorporates a thermoelectric cooler to remove most of the moisture from the sample stream. This also greatly reduces buildup of HC in the analyzers because the cooler is upstream of the analyzers and at a lower temperature. Most of the hydrocarbons that condense out are eventually carried away with the condensed water as it exits the cooler. The cooler is maintained at a constant temperature, so only the HC species with a condensation point very close to the cooler temperature could re-vaporize. This method virtually eliminates HC buildup downstream of the cooler. Any hydrocarbons which condense out upstream of the cooler should not effect the analyzer readings because they would otherwise condense out in the cooler at a lower temperature. A previous system cooled the sample with a water trap at ambient temperature to prevent water and hydrocarbon condensation within the analyzers. This system collected hydrocarbons that condensed at the temperature of the water trap. However, the temperature was significantly higher than the thermoelectric cooler.

NDIR analyzers were the only instruments evaluated for hydrocarbon measurement for the MEMS. The sample required cooling much below the dewpoint of some present hydrocarbon species to meet temperature requirements of the analyzer. This is far from an ideal way of measuring hydrocarbons because a large percentage of the actual raw engine concentration is not detected. However, this method was found to be the best compromise using the available analyzers. Results of hydrocarbon measurement are recorded but are not accurate due to removal of a large percentage of total hydrocarbons by the thermoelectric chiller.

5.2 Sampling System

This study has shown that it is possible to have a laboratory quality sampling system within a compact enclosure that is suitable for use on the MEMS. Most of the sampling system components in the latest version are of the same type typically found in stationary emissions testing facilities. The sampling system is capable of providing a dried exhaust sample (as per CFR 40, Part 86), filtered to 95% efficiency at 0.3 μm , at a stable flow of 3.5 LPM total. At least 90% of the NO_2 concentration is measured at up to 372 ppm NO_2 , which is within the range produced by most modern diesel engines. The size of the pump and enclosure could be reduced significantly with the current configuration. These components were originally oversized to allow for ease of modification to the system during the evaluation process.

5.3 Complete MEMS Performance

The complete MEMS includes the emissions analyzer box, the exhaust flow measurement device, the data acquisition system, and various sensors such as vehicle speed, engine speed, and ambient temperature and pressure. The performance of the complete system was evaluated by comparison with the WVU EERL and the WVU Transportable Laboratory. The current version of the MEMS is capable of reporting cycle integrated, brake-specific CO_2 within 3%, and NO_x within 5% of laboratory data collected at the EERL over an FTP cycle.

5.4 Recommendations for Future Versions

Significant reductions in the size, weight, power consumption and cost of the MEMS emissions box are planned for future versions. It is believed that these improvements are possible without degradation in the data quality available with the current system.

One possibility under investigation is positioning the filter, NO_x converter and a water trap at the exhaust pipe where the sample is obtained. A thermoelectric chiller was found to be the best method of drying the sample in previous testing. However, the sample could still be dried with a chiller at the analyzer box, as with the current configuration, and the water trap would prevent excessive condensation within the sample line between the NO_x converter and analyzer box. This would eliminate the need for a heated sample line as well as a heated head pump. A compact NO_x converter that would reduce power requirements is under development. Testing of this device has not yet been completed.

5.4.1 Decreased Size and Weight

A reduction in size and weight could allow the MEMS emissions box to be easily installed in a vehicle cab by one person. The 24 in. x 24 in. x 12 in. NEMA 12 enclosure was selected for the development process to allow for easy interchange of components and a large sample pump, as flow requirements had not been determined at that time. The size of this enclosure could be reduced to 18 in. x 18 in. x 9 in. with the current components, except the sample pump, which would be the ADI Micro Dia-Vac. Further reduction in size would be possible if some components were located on the exhaust stack. The CO₂/CO NDIR analyzer would remain in the enclosure downstream of the thermoelectric chiller. The sample pump would remain in the primary enclosure, while the filter and NO_x converter would be housed in a secondary enclosure attached to the exhaust flow measurement tube at the sampling port. NO₂ is water soluble, so conversion to NO would be required before exposure to conditions that would allow water to condense out of the sample stream.

5.4.2 Reduced Power Consumption

A reduction in electrical power consumption of the MEMS could allow the elimination of the generator set for on-road testing. Several components could be downsized or eliminated to reduce power consumption. A smaller, DC pump would reduce power requirements and eliminate conversion losses from an inverter. A non-heated pump could be used if it was placed downstream of the NO_x converter, filter and water removal system. The heated sample line could be eliminated if the filter, NO_x converter NO cell, ZrO₂ NO_x sensor, and water trap were located on exhaust stack.

5.4.3 HC Measurement

Accurate hydrocarbon measurement would greatly increase the value of the MEMS as a possible certification tool. Two methods of improved measurement were considered. An HFID analyzer is the most accurate instrument commonly used for HC measurement in diesel exhaust. Large size and weight along with the requirement for transporting the hydrogen/helium fuel mix were the deterring factors for use in the MEMS. The flame ionization unit may be placed in a smaller heated chamber than is used by the manufacturer of the laboratory-grade instrument. This would be possible, in part, by eliminating the internal heated filter and sampling the gas after it passed through the heated filter already in use on the MEMS. If the sampling filter and NO_x converter were placed at the exhaust stack, the HFID could be contained in the same enclosure barring possible vibration problems.

A heated NDIR analyzer was another option considered for accurately measuring hydrocarbons. Although the NDIR analyzer would be inferior in response to some species compared to an HFID, flammable gas would not be required and the overall size would likely be smaller. See Table 36 for NDIR compared to FID response to hydrocarbon species. The heat sensitive components of an NDIR microbench may be isolated from a heated cell and sample line leading to the cell. A heat resistant lens with good insulating properties could be placed between the cell and the detector. Neither a small HFID analyzer, nor a heated NDIR analyzer has been constructed at WVU to date. However, WVU researchers are currently investigating the feasibility of assembling a miniature HFID analyzer.

Table 36 NDIR vs. FID response to HC species (from source [13]).

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

Data was originally published in source [28].

5.4.4 CO Measurement

CO measurement accuracy is limited by the 0.01% CO resolution of the Horiba BE-140 microbench. This poor resolution does not allow accurate measurement of CO at the concentrations in diesel engine exhaust gas. A possible solution for accurate CO measurement is under investigation by WVU researchers. An relatively small NDIR CO detector with a range of 0-1000 ppm is available as part of a complete laboratory analyzer manufactured by California Analytical Inc. The complete analyzer is a 19 in. rack mount unit, which is much too large for the MEMS. However, the NDIR CO detector is only slightly larger than the Horiba BE-140 microbench. This device measures CO concentration with a microflow sensor, which should not be sensitive to vibration.

5.4.5 NO_x Measurement

NO_x measurement with the MEMS is currently acceptable, but improvements in NO_x converter efficiency would likely bring the results closer to those obtainable with laboratory-grade instruments. The NO_x converter is one of the larger components of the emissions sampling system and so restricts the minimum enclosure size. A smaller NO_x converter is under development. Operating the NO_x converter at a higher temperature may increase the conversion efficiency. Another improvement for NO_x measurement would be to supply the E/C NO cell with a wet sample to minimize electrolyte depletion.

5.4.6 Additional Features

A final recommendation is to investigate the addition of a real-time particulate matter (PM) measurement system to the MEMS. Vibration effects may make this a difficult task, as most continuous PM monitoring systems could inherently have a response to vibration. The U.S. EPA regulates PM emissions, along with NO_x, CO and HC emissions, so an accurate real-time measurement of all these constituents of diesel exhaust would be incorporated in the ideal MEMS.

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APPENDIX A – Manufacturer Specifications of Evaluated Analyzers

Table 37 Manufacturer Specifications for the Andros Model 6800 Microbench.

Manufacturer	Andros									
Model	6800									
Measurement Principle	NDIR									
Measured Gases	CO		CO ₂		HC n-Hexane			HC Propane		
Measurement Range	0-10%	10-15%	0-16%	16-20%	0-2000 ppm	2001-15000 ppm	150001-30000 ppm	0-4000 ppm	4001-30000 ppm	300001-60000 ppm
Accuracy	±0.02% Absolute or ±3% Reading	±5% Reading	±0.3% Absolute or ±3% Reading	±5% Reading	±4 ppm or ±3% Reading	±5% Reading	±8% Reading	±8 ppm or ±3% Reading	±5% Reading	±8% Reading
Repeatability	±0.02% Absolute or ±2% Reading	±3% Reading	±0.1% Absolute or ±2% Reading	±3% Reading	±3 ppm or ±2% Reading	±3% Reading	±4% Reading	±6 ppm or ±2% Reading	±3% Reading	±4% Reading
Resolution	0.001 vol. %		0.01 vol. %		1 ppm			1 ppm		
Response Time	T ₉₀ < 8 s, T ₁₀ < 8 s		T ₉₀ < 8 s, T ₁₀ < 8 s		T ₉₀ < 8 s, T ₁₀ < 8 s			T ₉₀ < 8 s, T ₁₀ < 8 s		
Zero Drift	Not Specified									
Span Drift	Not Specified									
Interference	±0.02% Abs.		±0.20% Abs.		±4ppm					
Sample Flow	6 LPM total flow to microbench									
Sample Humidity	0-95% Relative Humidity (non-condensing)									
Sample Inlet Temperature	0-50°C									
In-Use Vibration	Maximum: 1.0g sinusoidal, 5-1000 Hz									
Sample Inlet Pressure	Maximum: 2 psig									
Ambient Temperature	0-50°C									
Warm Up Time	<1min.									
Analog Output	N/A									
Digital Output	RS232									
Physical Dimensions	10.6 in. x 4.3 in. x 3.9 in.									
Weight	4.8 lb.									
Power Supply	9-16VDC									
Power Consumption	13.5 Watts									

Table 38 Manufacturer Specifications for the Andros Model 6800 Microbench (Continued from previous table.)

Manufacturer	Andros		
Model	6800		
Measurement Principle	Electrochemical		
Measured Gases	O ₂	NO	
Measurement Range	0-25%	0-4000 ppm	4001-5000 ppm
Accuracy	±0.1% Absolute or ±3% Reading	±25 ppm or ±4% Reading	± 5% Reading
Repeatability	±0.1% Absolute or ±3% Reading	±20 ppm or ±3% Reading	± 4% Reading
Resolution	0.01 vol. %	1 ppm	
Response Time	T ₉₀ < 15 seconds, Fall Time < 40 seconds	T ₉₀ < 12 seconds, T10< 12 seconds	
Zero Drift	Not Specified		
Span Drift	Not Specified		
Interference	±20 ppm		
Sample Flow	6 LPM total flow to microbench		
Sample Humidity	0-95% Relative Humidity (non-condensing)	15-90% Relative Humidity	
Sample Inlet Temperature	0-50°C		
In-Use Vibration	Maximum: 1.0g sinusoidal, 5-1000 Hz		
Sample Inlet Pressure	Maximum: 2 psig		
Ambient Temperature	0-50°C		
Warm Up Time	<1min.		
Analog Output	N/A		
Digital Output	RS232		
Physical Dimensions	10.6 in. x 4.3 in. x 3.9 in.		
Weight	4.8 lb.		
Power Supply	9-16VDC		
Power Consumption	13.5 Watts		

* Under the presence of the following non-interest gases: 16% CO₂, 1600 ppm Hexane, 10% CO, 3000 ppm NO, 75 ppm HS, 75 ppm SO₂, 9% CO with 18% CO₂, and water-saturated hot air.

Table 39 Manufacturer Specifications for the Horiba BE-140 Microbench.

Manufacturer	Horiba						
Model	BE-140						
Measurement Principle	NDIR with single sample cell with solid-state detector and mechanical chopper wheel						
Measured Gases	CO		CO ₂		HC		
Measurement Range	0-10%	10.01-14%	0-16%	16.1-18%	0-2000 ppmh	2001-5000 ppmh	5001-9999 ppmh
Accuracy	±3% of Reading or 0.02% Absolute	±5% of Reading	±3% of Reading or 0.3% Absolute	±5%	±3% of Reading or 4ppmh Absolute	±5% of Reading	±10% of Reading
Repeatability	0-7.00%	7.01-10.00%	0-10%	10-16%	0-1400 ppmh		1400-2000 ppmh
	±2% of Reading or 0.02% Absolute	±3% of Reading	±2% of Reading or 0.1% Absolute	±3% of Reading	±2% of Reading or 3 ppmh		±3% of Reading
Resolution	0.01%		0.01%		1 ppm		
Response Time	T ₉₀ < 3.5 s at 2 LPM sample flow						
Zero Drift	Drift over the first 1 hour will be within the accuracy tolerance.						
Span Drift	Drift over the first 1 hour will be within the accuracy tolerance.						
Interference	±0.02% *		±0.20% *		±4 ppm *		
Sample Flow	2 – 3 LPM						
Sample Humidity	Non-condensing and no liquid carry-over						
Sample Inlet Temperature	10-50°C						
Sample Filtering Requirement	1 micron or less						
Sample Inlet Pressure	Maximum:						
Ambient Temperature	10-50°C						
Warm Up Time	10 minutes						
Analog Output	Not provided by manufacturer, but possible by soldering wires to circuit board. Signals are in mV ranges.						
Digital Output	RS-232C Serial Interface						
Physical Dimensions	8.9 in. x 5.5 in. x 4.1 in.						
Weight	Approximately 2.2 lb						
Power Supply	+5VDC, +15VDC, and –15VDC or +5VDC,+12VDC and –12VDC						
Power Consumption	23 watts maximum						

* Under the presence of the following non-interest gases: 16% CO₂, 1600 ppm Hexane, 10% CO, 3000 ppm NO, 75 ppm HS, 75 ppm SO₂, 9% CO with 18% CO₂, and water-saturated hot air.

Table 40 Manufacturer Specifications for the Horiba MEXA-120 NO Analyzer.

Manufacturer	Horiba		
Model	MEXA-120		
Measured Gases	NO _x		
Measurement Principle	ZrO ₂ Electrochemical Sensor		
Measurement Range	0-1000 ppm	1001-3000 ppm	3001-5000 ppm
Accuracy	±30 ppm	±3% of reading	±5% of reading
Repeatability	See Accuracy-Accuracy is repeatability added to linearity.		
Resolution	1 ppm from 0 to 2000 ppm, 10 ppm from 2000 to 5000 ppm		
Response Time	T ₉₀ < 1 second		
Zero Drift	Not Specified		
Span Drift	Not Specified		
Interference	Not Specified		
Sample Flow	Flow is not critical, sensor is placed in a gas stream		
Sample Humidity	Non-condensing		
Sample Temperature	-7 to 800°C		
Sample Filtering Requirement	None		
Sample Inlet Pressure	N/A		
Ambient Temperature	Receiver: 5-45°C NO _x Sensor: -7-800°C		
Warm Up Time	3-5 minutes		
Analog Output	0-5VDC		
Digital Output	RS-232C (D-Sub 9-pin)		
Physical Dimensions	11.3 in. x 5.9 in. x 4.9 in.		
Weight	Approximately 7 lb.		
Power Supply	12-24 VDC or 120-240 VAC		
Power Consumption	70W		

Table 41 Manufacturer Specifications for the Horiba BE-220 NO Analyzer.

Manufacturer	Horiba
Model	BE-220
Measured Gases	NO
Measurement Principle	NDIR with Luft detector
Measurement Range	0-2000 ppm
Accuracy	±3%
Repeatability	±2%
Resolution	Not Specified (Analog output device)
Response Time	T ₉₀ = 5 seconds at 3 LPM
Zero Drift	60 ppm over 4 hours
Span Drift	60 ppm over 4 hours
Interference	20 ppm from H ₂ O at 25°C saturated
Sample Flow	3 LPM
Sample Humidity	Non-condensing and no liquid carry-over
Sample Inlet Temperature	10-50°C
Sample Inlet Pressure	Not Specified
Ambient Temperature	5-45°C
Warm Up Time	30 minutes
Analog Output	0-2.5VDC
Digital Output	None
Physical Dimensions	Approximately 8 in. x 5 in. by 5 in.
Weight	Approximately 2 lb.
Power Supply	120 VAC
Power Consumption	60 watts maximum

Table 42 Manufacturer Specifications for the Sensors Inc. AMBII Microbench.

Manufacturer	Sensors				
Model	AMBII				
Measured Gases	CO	CO ₂ ,	HC	NO	O ₂
Measurement Principle	NDIR with 3 cells, solid-state infrared modulation and solid-state detectors for each cell.			Electrochemical Cells	
Measurement Range	0-15%	0-20%	0-20000 ppm Hexane, 0-40000 ppm Propane	0-5000 ppm	0-25%
Accuracy	0.02% CO or 3% of reading	0.3% CO ₂ or 3% of reading	4 ppm or 3% of reading	25 ppm or 4% of reading	0.1% O ₂ or 5% of reading
Repeatability					
Resolution	0.001%	0.01%	0.1 ppm	1 ppm	0.01%
Response Time	T ₉₀ = 3.5 seconds				
Zero Drift	Less than 0.6% of full scale for the first hour and less than 0.4% of full scale per hour thereafter				
Span Drift	Less than 0.6% of full scale for the first hour and less than 0.4% of full scale per hour thereafter				
Interference	Not Specified				
Sample Flow	0.3 LPM for NO cell, up to 6 LPM total				
Sample Humidity	non-condensing				
Sample Inlet Temperature	5-45°C				
Sample Filtering Requirement	100% removal of particles greater than 5 micrometers.				
Sample Inlet Pressure	750-1100 mbar absolute				
Ambient Temperature	5-45°C				
Warm Up Time	< 30 minutes				
Analog Output	None				
Digital Output	RS232				
Physical Dimensions	6.2 in. x 3.8 in. x 2.5 in.				
Weight	1.4lb.				
Power Supply	5VDC ± 0.25V				
Power Consumption	2A typical, 3A max.				

Table 43 Manufacturer Specifications for the Siemens SIBENCH Microbench.

Manufacturer	Siemens			
Model	SIBENCH			
Measured Gases	CO	CO ₂	HC	NO
Measurement Principle	NDIR with micro-flow sensors			
Measurement Range	0-14%	0-18%	0-9999 ppm	0-5000 ppm
Accuracy	± 0.01% CO or 3% of reading	±0.3% CO ₂ or 3% of reading	±4 ppm or 3% of reading	±25 ppm or 3% of reading
Repeatability	± 0.01% CO or 2% of reading	±0.1% CO ₂ or 2% of reading	±3 ppm or 2% of reading	±20 ppm or 2% of reading
Resolution	0.001% CO	0.01% CO ₂	1 ppm	1 ppm
Response Time	Not Specified			
Zero Drift	none due to AUTOCAL			
Span Drift	<2% per year			
Interference	>±0.005% CO	>±0.01% CO ₂	>±4 ppm	<±20 ppm
Sample Flow	0.5-5 LPM			
Sample Humidity	5-95% RH			
Sample Inlet Temperature	0-60°C			
Sample Inlet Pressure	Not Specified			
Ambient Temperature	0-60°C			
Warm Up Time	60 seconds			
Analog Output	None			
Digital Output	RS-232			
Physical Dimensions	Approximately 8 in. x 7 in. x 5 in.			
Weight	Approximately 3 lb.			
Power Supply	9.6-16VDC			
Power Consumption	15 watts			

APPENDIX B - Analyzer Time Response Graphs

Figure 56 10 Second Step Time Response of the Horiba BE-220 NO Analyzer.

Figure 57 8 Second Step Time Response of the Horiba BE-220 NO Analyzer.

Figure 58 5 Second Step Time Response of the Horiba BE-220 NO Analyzer.

Figure 59 4 Second Step Time Response of the Horiba BE-220 NO Analyzer.

Figure 60 3 Second Step Time Response of the Horiba BE-220 NO Analyzer.

Figure 61 2 Second Step Time Response of the Horiba BE-220 NO Analyzer.

Figure 62 1 Second Step Time Response of the Horiba BE-220 NO Analyzer.

Figure 63 Zero to Span Time Response of the Horiba BE-220 NO Analyzer.

Figure 64 10 Second Step Time Response of the Horiba MEXA-120 NO_x Analyzer.

Figure 65 8 Second Step Time Response of the Horiba MEXA-120 NO_x Analyzer.

Figure 66 5 Second Step Time Response of the Horiba MEXA-120 NO_x Analyzer.

Figure 67 4 Second Step Time Response of the Horiba MEXA-120 NO_x Analyzer.

Figure 68 3 Second Step Time Response of the Horiba MEXA-120 NO_x Analyzer.

Figure 69 2 Second Step Time Response of the Horiba MEXA-120 NO_x Analyzer.

Figure 70 1 Second Step Time Response of the Horiba MEXA-120 NO_x Analyzer.

Figure 71 Zero to Span Time Response of the Horiba MEXA-120 NO_x Analyzer.

Figure 72 10 Second Step CO₂ Time Response of the Horiba BE-140 Analyzer.

Figure 73 8 Second Step CO₂ Time Response of the Horiba BE-140 Analyzer.

Figure 74 5 Second Step CO₂ Time Response of the Horiba BE-140 Analyzer.

Figure 75 4 Second Step CO₂ Time Response of the Horiba BE-140 Analyzer.

Figure 76 3 Second Step CO₂ Time Response of the Horiba BE-140 Analyzer.

Figure 77 2 Second Step CO₂ Time Response of the Horiba BE-140 Analyzer.

Figure 78 1 Second Step CO₂ Time Response of the Horiba BE-140 Analyzer.

Figure 79 Zero to Span CO₂ Time Response of the Horiba BE-140 Analyzer.

Figure 80 10 Second Step CO Time Response of the Horiba BE-140 Analyzer.

Figure 81 8 Second Step CO Time Response of the Horiba BE-140 Analyzer.

Figure 82 5 Second Step CO Time Response of the Horiba BE-140 Analyzer.

Figure 83 4 Second Step CO Time Response of the Horiba BE-140 Analyzer.

Figure 84 3 Second Step CO Time Response of the Horiba BE-140 Analyzer.

Figure 85 2 Second Step CO Time Response of the Horiba BE-140 Analyzer.

Figure 86 1 Second Step CO Time Response of the Horiba BE-140 Analyzer.

Figure 87 Zero to Span CO Time Response of the Horiba BE-140 Analyzer.

Figure 88 10 Second Step CO₂ Time Response of the Sensors AMBII Analyzer.

Figure 89 5 Second Step CO₂ Time Response of the Sensors AMBII Analyzer.

Figure 90 1 Second Step CO₂ Time Response of the Sensors AMBII Analyzer.

Figure 91 Zero to Span CO₂ Time Response of the Sensors AMBII Analyzer.

Figure 92 10 Second Step CO Time Response of the Sensors AMBII Analyzer.

Figure 93 5 Second Step CO Time Response of the Sensors AMBII Analyzer.

Figure 94 1 Second Step CO Time Response of the Sensors AMBII Analyzer.

Figure 95 Zero to Span CO Time Response of the Sensors AMBII Analyzer.

Figure 96 10 Second Step HC Time Response of the Sensors AMBII Analyzer.

Figure 97 5 Second Step HC Time Response of the Sensors AMBII Analyzer.

Figure 98 1 Second Step HC Time Response of the Sensors AMBII Analyzer.

Figure 99 Zero to Span HC Time Response of the Sensors AMBII Analyzer.

Figure 100 10 Second Step NO Time Response of the Sensors AMBII Analyzer.

Figure 101 5 Second Step NO Time Response of the Sensors AMBII Analyzer.

Figure 102 1 Second Step NO Time Response of the Sensors AMBII Analyzer.

Figure 103 Zero to Span HC Time Response of the Sensors AMBII Analyzer.

APPENDIX C – Spreadsheet for Humidity Calculations

Table 44 Input Values for Calculation of Percent Volume H₂O and CO₂ in Raw Diesel Exhaust Based on the Ideal Gas Laws.

Component	M
H ₂ O	18
O ₂	32
N ₂	28
CO ₂	44
NO	44
Air	28.84
H to C ratio of fuel	1.8
Temp at analyzer (°F)	120
R H₂O	85.83
R CO₂	35.11
R NO	35.11
specific volume of water vapor at 120°F	39827
(in ³ /lbmass)	
specific volume of NO at 120°F	16293
(in ³ /lbmass)	
specific volume of CO₂ at 120°F	16293
(in ³ /lbmass)	
Pressure (psia)	15

Table 45 Calculation of Percent Volume H₂O and CO₂ in Raw Diesel Exhaust Based on the Ideal Gas Laws.

A/F mass ratio	A/F mole ratio	moles excess air/mole fuel	molecular wt. of mix	R mixture	mass vapor/mass dry	mass vapor/mass total
14.42	1.45	0.00	26.94	57.36	0.0824	0.0761
15	1.51	0.06	27.00	57.22	0.0768	0.0714
20	2.01	0.56	27.42	56.35	0.0487	0.0464
25	2.51	1.06	27.68	55.82	0.0356	0.0344
30	3.02	1.57	27.86	55.45	0.0281	0.0273
35	3.52	2.07	27.99	55.19	0.0232	0.0227
40	4.02	2.57	28.09	54.99	0.0197	0.0194
45	4.52	3.07	28.17	54.84	0.0172	0.0169
50	5.03	3.58	28.24	54.72	0.0152	0.0150
55	5.53	4.08	28.29	54.61	0.0137	0.0135
60	6.03	4.58	28.33	54.53	0.0124	0.0122
65	6.54	5.09	28.37	54.46	0.0113	0.0112
70	7.04	5.59	28.40	54.39	0.0104	0.0103
75	7.54	6.09	28.43	54.34	0.0097	0.0096
80	8.04	6.59	28.46	54.29	0.0090	0.0089
85	8.55	7.10	28.48	54.25	0.0084	0.0084
90	9.05	7.60	28.50	54.21	0.0079	0.0079
95	9.55	8.10	28.52	54.18	0.0075	0.0074
100	10.06	8.61	28.53	54.15	0.0071	0.0070

Table 46 Calculation of Percent Volume H₂O and CO₂ in Raw Diesel Exhaust Based on the Ideal Gas Laws (Continued).

A/F mass ratio	specific volume of mixture	%vol H₂O vapor at analyzer	%mass CO₂	%vol CO₂ at analyzer	% vol CO₂/ % vol H₂O
	(in ³ /lbmass)				
14.42	26613	11.39	20.67	12.66	1.11
15	26550	10.71	19.38	11.89	1.11
20	26147	7.07	12.61	7.86	1.11
25	25899	5.29	9.34	5.88	1.11
30	25731	4.23	7.42	4.70	1.11
35	25609	3.52	6.16	3.92	1.11
40	25517	3.02	5.26	3.36	1.11
45	25446	2.64	4.59	2.94	1.11
50	25388	2.35	4.07	2.61	1.11
55	25340	2.12	3.66	2.35	1.11
60	25301	1.93	3.32	2.14	1.11
65	25267	1.77	3.04	1.96	1.11
70	25238	1.63	2.81	1.81	1.11
75	25213	1.51	2.60	1.68	1.11
80	25191	1.41	2.43	1.57	1.11
85	25172	1.33	2.27	1.47	1.11
90	25154	1.25	2.14	1.39	1.11
95	25139	1.18	2.02	1.31	1.11
100	25125	1.12	1.91	1.24	1.11