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Development of a Test Method to Measure "In-Use" Emissions from Stationary and Portable Diesel Sources

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ABSTRACT

A cost-effective, accurate and an easy-to-use in-field test method was developed that would allow regulatory bodies, such as the California Air Resources Board (CARB) to determine in-use compliance with emission standards for newly manufactured portable and stationary engines. Engine-dynamometer/chassis dynamometer tests have been shown to be unrepresentative of actual in-field operation of the engine; hence, emissions measured during such conditions do not faithfully reflect real-world emissions. Engines may be compliant with certification standards during an engine-dynamometer test, but may still deviate from the standard by two times during an actual "in-use" operation. Hence, a test method that functions like an Inspection and Maintenance (I/M) type test method (serves as a "screening tool") and is capable of measuring in-use emissions from portable and stationary engines was developed. Only concentration measurements of pollutants such as oxides of nitrogen (NO_x) and carbon dioxide (CO_2) are required to determine compliance using this "Compliance Factor, F" approach. Hence, errors introduced due to engine work output measurement and exhaust flow rate measurement are avoided. It should be noted that in-field torque measurement from mechanically controlled engines is not trivial.

A Compliance Factor, F, defined as the ratio of in-use concentrations NO_x and CO_2 to the manufacturer reported brake specific emissions of NO_x and CO_2 was developed, and it forms the basis of the new method. Application of this approach is illustrated in multiple ISO 8178 tests on mechanically controlled and electronically controlled engines.

Raw exhaust gaseous emissions were measured using a Mobile Emission Measurement System (MEMS) developed by West Virginia University. A gravimetric analysis of Particulate Matter (PM) in raw exhaust was accomplished in accordance with the procedures outlined in the California Air Resources Board (CARB) Method 5 document. The raw exhaust measurements were then correlated with the constant volume sampling (CVS) measurements that were performed in accordance with the procedures outlined in ISO 8178 and CFR 40, Part 89 to establish the validity of the raw exhaust measurements. It was also determined that the front-half of the Method 5 PM measurement methodology, as outlined in the EPA Method 5 procedure, is in good agreement with the CVS system based engine certification PM test method. Further, a modified Method 5 sampling train comprising of a multi-hole sampling probe that spans the diameter of the exhaust stack, and a sample transfer tube maintained at ambient temperature could be a likely configuration for measuring PM from stationary and portable diesel engines in the field.

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NOMENCLATURE

AC	Alternating Current
ATCM	Airborne Toxic Control Measure
C	Certification ratio
CARB	California Air Resources Board
CO_2	Carbon Monoxide
CO	Carbon Dioxide
CFR	Code of Federal Regulations
CVS	Constant Volume Sampling
DAS	Data Acquisition System
DC	Direct Current
DDC	Detroit Diesel Corporation
DTC	Digital Throttle Control
ECU	Engine/Electronic Control Unit
EERC	Engine and Emissions Research Center
EPA	Environmental Protection Agency
F	Compliance Factor
Ft lbs	foot pounds
GE	General Electric Company
GPS	Global Positioning System
HC	Hydrocarbon
I	In-field Pollutant ratio
I/M	Inspection and Maintenance
ISO	International Organization for Standardization
Kv	Discharge coefficient
LCD	Liquid Crystal Display
LFE	Laminar Flow Element
MEMS	Mobile Emission Measurement System
MTA	Metro Transit Authority, New York
MY	Model Year
NDIR	Non-Dispersive Infrared Radiation
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
PM	Particulate Matter
ppm	parts per million
Q	Volumetric flow rate
SBC	Single Board Computer
scfm	Standard cubic feet per minute
S-HDDE	Settling-Heavy Duty Diesel Engine
SOF	Soluble Organic Fraction
SwRI	Southwest Research Institute
TEC	Thermo Electric Chiller
THC	Total HydroCarbons
WVU	West Virginia University

1 Introduction

1.1 Introduction

Real-world or "in-use" emissions can be very different from certification cycle emissions (1). As such, certification of engines based on emissions data gathered during a certification test will not serve the regulatory agencies in meeting their emissions attainment goals. In addition, the "Consent Decrees" (2) that were entered into by the United States and the Settling Heavy-duty Engine (S-HDDE) manufacturers has highlighted that mobile engine-powered equipment could be configured to emit lower emissions during a certification test. Hence, the objective of this study was to provide the California Air Resources Board (CARB) with a viable, easy-to-use, cost-effective and accurate "in-use compliance testing tool" that would enable compliance-monitoring during "in-use" operation of the engine. Two heavy-duty diesel engines were exercised on multiple ISO-8178 eight mode steady state test cycles and emissions data was collected using certification quality instruments. As part of the study, a Mobile Emission Measurement System (MEMS) designed and developed by WVU and the "Method 5" principle based Particulate Matter (PM) sampling system was evaluated.

Diesel exhaust is considered to be a likely human carcinogen (3). They are also a source of fine particulate matter – an agent held responsible for thousands of premature deaths (due to lung damage and asthma) every year nationwide, oxides of nitrogen, and several other toxic gases (3). Exposure to diesel exhaust will lead to respiratory ailments, especially in children who breathe more air per pound of their body weight than adults. NO_x emitted from diesel engines reacts with the hydrocarbons from diesel exhaust to form ground level ozone in the presence of sunlight (4).

According to a current EPA report (5), the particulate matter emissions from off-road engines exceed those emitted by the on-highway engines, while emitting as much total emissions as their on-highway counterparts. Since 1996, emissions from these off-road engines are being regulated and EPA aims at achieving over 60% reduction in NO_x emissions and over 40% reduction in PM emissions from 1996 levels by the year 2007. Recent developments in exhaust gas aftertreatment promise 90% emissions reduction from current levels, in conjunction with ultra low sulfur fuel usage (5).

Off-road diesel engines include a diverse set of engines used in farming, construction, earthmoving, mining industry etc. They also include portable engines used in irrigation pumps. Stationary engines are not included under off-road engines and are currently being regulated by state and local governments.

Development of an accurate test method that can be used as a compliance and/or a screening tool across all portable and stationary engines is now imperative for the CARB in light of the urgent need for California to develop State Implementation Plans to meet the stringent emission standards for 2010. The main objective of this exercise, thus, is to develop a surrogate Inspection and Maintenance (I/M) type test method that may be used to determine compliance of various portable and stationary engines with applicable emission standards.

1.2 Objectives

The objective of this study was to develop a test method for CARB to measure emissions from portable and stationary engines. Four engines, two for laboratory testing and two for field testing, were rented. Specifically, a MY 1992, 12.7 liters, 350 hp, electronically controlled and turbocharged, DDC Series 60 engine and a MY 1997, 2.4 liters, 56 hp, mechanically controlled and naturally aspirated, Isuzu C 240 engine was chosen for engine-dynamometer laboratory testing. The engines were exercised on multiple ISO 8178 eight mode steady state test cycles. A MY 1990, 3.8 liters, 56 hp, mechanically controlled and naturally aspirated, Isuzu QD-100 engine and a MY 2002 3.9 liters, 70 hp, mechanically controlled and naturally aspirated, Perkins engine were chosen for field testing. The field test engines were operated on their regular duty cycle. Federal diesel No. 2 fuel was used for all the laboratory and field testing. In each phase of the testing, the raw exhaust data obtained using the MEMS was first compared with the laboratory grade analyzers for accuracy of the data followed by application of the ‘Compliance Factor’ methodology. PM in the raw exhaust was collected using the Method 5 principle and then compared with the CVS based gravimetric method. A “modified (simplified) Method 5” set-up was also tested for suitability to “in-field” testing.

1.3 Methods

The two engines selected for laboratory testing were installed on an engine dynamometer test bed and exercised on multiple ISO 8178 test cycles. A low output engine (Isuzu C 240) was chosen to reveal any limitation in the portable emission measurement systems, such as resolution capability of the analyzers that could prohibit accurate measurement of low concentrations of pollutants during low load - high speed conditions. ISO 8178 eight mode tests provide a universally accepted method of certification of these engines and hence qualified as the laboratory test protocol. The engine exhaust was directed into a full flow primary dilution tunnel equipped with a Constant Volume Sampling (CVS) system and emission measurements were performed consistent with the guidelines placed in CFR 40 Part 89, Subpart E and in ISO 8178. Engine speed and torque were logged to provide brake specific emissions.

Determination of the mass emission rates of NO_x and CO_2 in raw exhaust was achieved using a Mobile Emission Measurement System (MEMS), a portable emission measurement system designed and developed by West Virginia University. The MEMS uses a solid state NDIR detector for CO_2, a zirconium oxide sensor for NO_x and an Annubar^{TM} averaging Pitot tube for measurement of exhaust flow rate. A gravimetric analysis of Particulate Matter (PM) in raw exhaust was accomplished according to the procedures outlined in Method 5 document of the CARB. These raw exhaust measurements were then correlated with dilute exhaust measurements from laboratory grade, certification quality analyzers. In addition, a modified method of sampling PM, using the Method 5 system was tested. This “modified method” attempted to simplify the current Method 5 procedure and make it user-friendly for “in-use” measurement by employing a multi-hole stainless steel sampling nozzle that spanned the entire diameter of the exhaust stack, instead of the regular quartz gooseneck nozzle. This measure, if successful, would not necessitate the traversing of the sampling probe across the exhaust stack. The sampling probe and the filter box were also maintained at ambient temperatures and at the stipulated temperature of 250ºF. This measure would permit the use a non-heated stainless steel transfer tube instead of an expensive heated quartz tube. Additionally, tests were performed to investigate the effect of conditioning on the PM filters. Instead of following the procedures outlined in 40 CFR, Part 89 and ISO 8178, the modified method included conditioning and weighing of filters in a laboratory, placing them in a "non-environmentally controlled" atmosphere before and after the test (to mimic the shipping of filters to the test site and back to the laboratory), followed by re-conditioning and weighing of filters. This exercise could set the pace for the use of conditioned pre-weighed filters that could be shipped to the test site, used in a test, and then shipped back to the laboratory, where they can be re-conditioned and weighed.

In-use emissions tests (field testing) were performed to validate the proposed test method. Two engines – a Multiquip-Whisperwatt diesel powered (MY 1990 Isuzu QD 100) AC generator and a SullAir 185 diesel powered (MY 2002 Perkins) air compressor were selected for the study. Both the engines were tested during their "in-use" duty cycle. Emissions data was collected using the laboratory grade analyzers, the secondary dilution tunnel mounted on a transportable laboratory (6) and the MEMS-the portable emission measurement system built by WVU.

1.4 Results

The MEMS was evaluated for its ability to provide accurate raw exhaust emission measurements. It was shown that the MEMS can provide data within 10 % of those measured using laboratory grade analyzers. A "test method" for in-field testing was developed after evaluation of the MEMS and the Method 5 systems and protocols for field testing were developed. This test method introduces a "Compliance Factor" parameter that utilizes only the concentration values of NO_x and CO_2 to determine compliance during "in-use" operation of such engines; hence, avoids the onerous and unreliable task of measuring work output of the engine and its exhaust flow rate. It is shown that the "Compliance Factor" could be expressed in two forms, either as CO_2-specific or as fuel-specific, and is illustrated for the two engines. The mean CO_2-specific Compliance Factor for the Isuzu C 240 engine varied from 0.64 to 1.25 across different modes of the 8-mode cycle that typically represents different engine applications. Similarly, the CO_2-specific Compliance Factor varied from 0.73 to 1.1 for different engine operating conditions of the DDC Series 60 engine. The corresponding fuel-specific Compliance Factors differed by 3.1717. It is shown that the engines may be tested for compliance with applicable emission standards without measuring the work output and the exhaust flow rate from the engine. However, the test method requires manufacturer reported ISO- averaged brake-specific emission values for NO_x and CO_2.

It was also determined that the front-half of the Method 5 PM measurement methodology is in good agreement with the CVS system-based engine certification test method. The Total Particulate Matter (TPM) determined using the Method 5 procedure, as outlined by EPA, was within 10% of those determined using the CVS-full flow dilution tunnel certification procedure. Further, a "modified" Method 5 sampling train comprising of a multi-hole sampling probe that spans the diameter of the exhaust stack, and a sample transfer tube maintained at ambient temperature could be a likely configuration for measuring PM from stationary and portable diesel engines in the field. This approach does away with the cumbersome method of traversing the exhaust stack to acquire samples at 8 locations along the stack diameter and the use of a delicate quartz sample nozzle. A filter-based gravimetric method using pre-conditioned and pre-weighed filter cassettes, and a micro-dilution tunnel is recommended for PM measurements. A modified Method 5 (with the front-half extraction) sampling train could be used, but the process could be avoided by using a micro-dilution tunnel because both procedures yield similar results (7). The modified Method 5 procedure would still require the extraction of the front half i.e. extraction of PM from the sampling probe and the front half of the filter holder plus the filter catch, after every test. In addition, Method 5 procedure requires the use of glassware and a delicate, expensive quartz sampling probe. Using such a fragile set up for in-field testing for in-use PM measurements would require very competent handling, since such instruments are prone to breakage. Also, it is likely that many future off-road engines, including the portable & stationary engines, will implement the usage of exhaust after-treatment devices that may significantly change the speciation of PM downstream of the device (8). The disproportionate amount of soluble organic fraction (SOF) in relation to total particulate matter (on a mass basis) could result in poorer correlation of Method 5/Modified Method 5 with CVS dilution tunnel based methods. The use of micro dilution tunnel will result in condensation of these hydrocarbons on the filter and would also account for the atmospheric reactions of the particulate matter. This method, since it is mimicking the standard CVS dilution system, could likely provide for better comparison with the standard than the modified Method 5 procedure, which omits the dilution principle.

2 Review of Literature

2.1 Stationary and portable engines versus non-road engines.

Stationary engines are not included under the non-road engines category (see Figure 1 below). According to the EPA (9), stationary engines are internal combustion engines that are either installed at a fixed location as in irrigation pumps and in power plants or packaged in a transportable application in which the engine will stay at a single site for at least one full year. The flow chart, Figure 1, shows the classification of diesel engines (10).

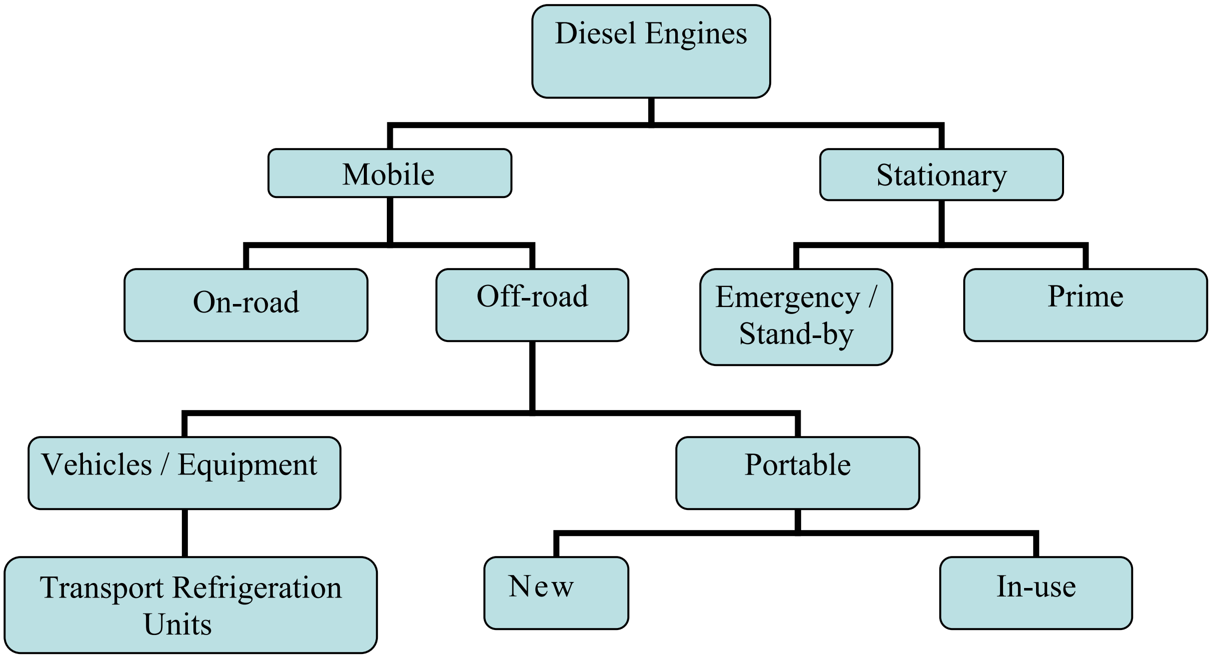

Figure 1 Classification of Diesel Engines

Stationary engines are classified as either emergency (stand-by) engines or as prime engines. Emergency (stand-by) engines represent 70% of the total stationary engines and are used to provide electrical back-up during unscheduled power outages or during maintenance operations. Such engines usually operate for about 50 hours annually. Prime engines are used to supplement power requirements at facilities and in applications such as agricultural irrigation pumps, compressors, cranes and grinders/screening units. Prime engines vary from 50 horsepower to about 2000 horsepower and operate for several thousand hours annually.

Portable engines move from location to location but are not used to propel any mobile equipment or vehicles. Typical applications include agricultural irrigation pumps, cranes, oil well drilling, military tactical support, pile-driving hammers, rock crushing and in wood chippers. Portable engines are included in the non-road engine category (and hence applicable to the emissions standards shown in Table 1) that include engines used in loaders, locomotives, scrapers, dozers as well as those used in marine applications.

Agricultural engines, stationary (prime) or portable, are currently not required to meet any air quality requirements.

2.2 Emission Standards

In response to a congressional directive, EPA has now set emission standards for new non-road diesel engines. However, stationary engines are currently under the supervision of district authorities and are not applicable to the non-road emission standards. However, certain regulations, as outlined in § 2.3, govern the operation of stationary engines in California.

EPA/Federal emission standards for stationary diesel engines are expected before mid-2006. Recently, EPA decided to adopt the National Emission Standards for Hazardous Air Pollutants (NESHAP) standards (11) for stationary engines above 500 hp.

Table 1 outlines the current emission standards for new non-road engines (12).

2.3 Current Regulations, California (13, 14):

According to the Health and Safety Code Division 26, Section 40000, ARB has direct responsibility for controlling emissions from motor vehicles in California and the districts are responsible for controlling emissions from all sources other than motor vehicles.

Table 1 Current Non-road Engine Emission Standards

Rated Power		Year	CO (g/bhp-hr)	HC (g/bhp-hr)	HC+ NOx (g/bhp-hr)	NMHC + NOx (g/bhp-hr)	NOx (g/bhp-hr)	PM (g/bhp-hr)
FEDERAL	50 ≤ hp <100	1998+					6.9(ABT)	
	100 ≤ hp < 175	1997+					6.9(ABT)	
	175 ≤ hp < 750	1996+	8.5	1.0			6.9(ABT)	0.4
	hp = 750+	2000+	8.5	1.0			6.9(ABT)	0.4
FEDERAL	11 < hp[e]	2000	6.0			7.8 (ABT)		0.74 (ABT)
		2005+	6.0			5.6 (ABT)		0.6 (ABT)
	11 ≤ hp < 25[e]	2000	4.9			7.0 (ABT)		0.6 (ABT)
		2005+	4.9			5.6 (ABT)		0.6 (ABT)
	25 ≤ hp < 50[e]	1999	4.1			7.0 (ABT)		0.6 (ABT)
		2004+	4.1			5.6 (ABT)		0.44 (ABT)
	50 ≤ hp < 100	2004	3.7			5.6 (ABT)		0.3 (ABT)
		2008+	3.7			3.5 (ABT)		
	100 ≤ hp < 175	2003	3.7			4.9 (ABT)		0.22 (ABT)
		2007+	3.7			3.0 (ABT)		
	175 ≤ hp < 300	2003	2.6			4.9 (ABT)		0.15 (ABT)
		2006+	2.6			3.0 (ABT)		
	300 ≤ hp < 600	2001	2.6			4.8 (ABT)		0.15 (ABT)
		2006+	2.6			3.0 (ABT)		
	600 ≤ hp < 750	2002	2.6			4.8 (ABT)		0.15 (ABT)
		2006+	2.6			3.0 (ABT)		
	hp = 750+	2006+	2.6			4.8 (ABT)		0.15 (ABT)
CALIFORNIA	25 < hp Class I	1995-98	350		12.0			0.9
		1999+	100		3.2			0.25
	25 < hp Class II	1995-98	350		10.0			0.9
		1999+	100		3.2			0.25
	175 ≤ hp < 750	1996-2000	8.5	1.0			6.9	0.4
		2001+	8.5	1.0			5.8	0.16
	hp = 751+	2000+	8.5	1.0			6.9	0.4

For gaseous emissions, most stationary sources are required to meet the corresponding MY (and horsepower rating) emissions regulations for non-road engines. Some districts in California have adopted source specific regulations to control emissions from existing stationary and portable diesel engines. The regulations set standards for NO_x, CO and HC emissions. No standards are outlined for PM, but the South Coast Air Quality Management District (SCAQMD) expects a large number of existing stationary and portable diesel engines to be taken out of service due to the cost of satisfying the NO_x standard (13). Hence, PM emissions are expected to come down by the end of 2004.

The following regulations for stationary and portable engines require aftertreatment of the diesel exhaust to control PM emission and consequently require the use of ultra low sulfur fuel.

2.3.1 New Source Review Rules

Major new and modified stationary sources have been placed under two distinct pre-construction programs by the New Source Review Ruling (14) within the Federal Clean Air Act. Such sources constructing in non-attainment areas are required to apply the Lowest Achievable Emission Rate (LAER) control technology to minimize emissions and to "offset" the remaining emissions with reductions from other sources. Also, new and modified stationary sources found to be emitting above the specified levels are required to apply the Best Available Control Technology (BACT) by the State Health and Safety Code. Sources constructing in attainment areas are required to apply the Best Available Control Technology (BACT) and meet additional requirements aimed at maintaining the region's air. The regulations are enforced through a permit system issued by the district. These permits usually incorporate the federal and state ambient air quality requirements.

2.3.2 Toxic New Source Review

The Toxic New Source Review was not formulated to control emissions from diesel engines only. The review established guidelines for the installation of the Toxic Best Available Control Technology (T-BACT) and denial of operating permit for any source that emitted above a "risk level." Since even relatively small number of diesel engines operating for relatively short periods are capable of posing cancer risks, there by triggering the installation of T-BACT devices, a Risk Management Guidance for the Permitting of New Stationary Diesel-Fueled Engines was adopted by the ARB in September 2000, for permitting of new stationary diesel-fueled engines (14).

The Risk Management Guidance assists local air pollution control districts in making risk management decisions for allowing diesel-fueled engines greater than 50 hp to operate in the region. The guidance identifies minimum technology requirements and performance standards for reducing particulate matter emissions from new stationary diesel engines. The approach identifies engine categories that may be approved without a site-specific health risk assessment (HRA) provided the minimum technology requirements or performance standards are met and certain diesel-specific adjustments that may be used if a site-specific HRA is required.

Engines used for agricultural purposes are exempted from any regulation. Table 2 highlights the guidelines outlined in the Risk Management Guidance for New Stationary Engines.

The following are the recommendations of the Risk Management Guidance,

- Engines under group 1 do not require a site-specific HRA and will be approved if they meet the minimum technology requirements or performance standard for PM. Congruence with minimum technology requirements will result in application of best available control technology and the lowest achievable risk levels in consideration of the costs, uncertainty in emissions, approved ‘health values’ and exposure estimates.
- Emergency stand-by engines are not required to meet low sulfur fuel requirements until the analysis supporting the Emergency Stand-by Retrofit ATCM is complete.
- Site-specific HRA is required for all engines under group 2, that is, engines with operating hours more than 400 per year. If the HRA estimated a potential cancer risk greater than or equal to 10 chances in a million, the district would have to review additional site-specific information such as location of sensitive receptors, alternative technologies, site-specific design considerations before making a Specific Findings (SF) Report. It is further required that the public be given the opportunity to review and comment on

the proposed permit action. However, no upper level risk level is formulated, since it is believed to be too restrictive on well-controlled new stationary diesel fueled engines performing critical functions like supplying emergency power, for which there is no economic or technically feasible substitute.

- For group 2 engines, risk assessments would have to conducted according to the procedures outlined in Air Toxics "Hot Spots" program, California Air Pollution Control Officers Association (CAPCOA), Revised 1992 Risk Assessment guidelines (Risk Assessment Guidelines), dated October 1993 and in the Risk Assessment Guidance presented by the ARB. Diesel PM to be used as a surrogate for all toxic air contaminants from diesel-fueled engines when determining the potential cancer risk and non cancer chronic hazard index for the inhalation pathway.
- The risk estimation is based on the Scientific Review Panel's (SRP) recommended unit risk factor of 300 excess cancers per million per microgram per cubic meter of diesel PM ($3 \times 10^{-4}(\mu g/m^3)^{-1}$) based on 70 years of exposure.

2.3.3 AB 2588 "Hot Spots" Information and Assessment Act

The main objectives of the act include establishment of a formal air toxics emissions inventory risk quantification program for districts to manage and to collect emissions data indicative of routine releases of toxic substances to the air; to identify facilities having localized impacts and to evaluate health risks from exposure to the emissions.

Table 2 Permitting Requirements for New Stationary Diesel-Fueled Engines

Engine Category	Annual Hours of Operation	Group	Performance Standard	Minimum Technology Requirements			Additional Requirements	
				New Engine PM Emission Levels (g/bhp-hr)	Fuel Technology Requirements	Add-on Control	HRA Required	SF Report
Emergency / Standby > 50 hp	≤ 100 hours	1	0.1	0.1	CARB Diesel or Equivalent	No	No	No
All Other engines > 50 hp	≤ 400 hours	1	0.02	0.1	Very low-sulfur CARB Diesel / Equivalent	Catalyst based DPF or Equivalent	No	No
	> 400 hours	2	0.02	0.1	Very low-sulfur CARB Diesel / Equivalent	Catalyst based DPF or Equivalent	Yes	If HRA shows risk > 10/ million

2.4 Future Regulations (15)

The CARB plans to adopt the "Airborne Toxic Control Measure for Stationary Compression Ignition Engines" (15) which specifically aims at reducing particulate matter and other "criteria pollutant" (gaseous pollutants) emissions from diesel engines. The ATCM becomes effective on January 1, 2005 and supports the current "Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel Fueled Engines and Vehicles" program, adopted by the CARB in September, 2000 (14).

An important feature of the ATCM is that it brings new agricultural engines into its fold for regulation. Agricultural engines were, hitherto, exempted from any regulation.

Table 3 Summary of the Emission Standards and Operating Requirements for New Stationary Emergency Standby Diesel-Fueled CI engines > 50 BHP

DIESEL PM				OTHER POLLUTANTS
DIESEL PM STANDARDS (g/bhphr)	Maximum Allowable Annual Hours of Operation for Engines Meeting Diesel PM Standards			HC, NOx, NMHC+NOx and CO standards (g/bhp-hr)
	Emergency Use	Non-Emergency Use		
		Emission Testing to show compliance	Maintenance and Testing (hours/year)	
≤ 0.15	Not Limited by ATCM	Not Limited by ATCM	50	Off-Road CI Engine Certification Standards for an off-road engine of the same model year and horsepower rating, or Tier 1 standards for an off-road engine of the same maximum horse power rating
≤ 0.01	Not Limited by ATCM	Not Limited by ATCM	51-100 (Upon Approval By District)	

In Table 3, the more stringent of the two PM standard, that is, 0.15 g/bhp-hr and the off-road certification standard for an off-road engine of same model year and maximum horsepower rating is chosen. The option of Tier 1 standard for "other pollutants" is available only if no off-road certification standard is established for an off-road engine of the same model year as new stationary emergency stand-by engine. The districts are allowed to set more stringent standard for each of the above pollutants, including PM.

A "new" stationary engine is defined as a compression ignition (CI) engine installed at a facility after January 1, 2005 and includes engines relocated from an off-site location after January 1, 2005. An 'In-Use' is defined as a CI engine that is not a "new" engine.

In Table 4, "baseline levels" refer to emissions level of a diesel-fueled engine using CARB diesel fuel as configured upon initial installation or by January 1, 2003, whichever is later.

In Table 5, option 3, PM emission rate has to be reduced by at least 30% from the baseline level, by no later than January 1, 2006 and diesel PM emission reduced to the rate of 0.01 g/bhp-hr or less by no later than July 1, 2011. As shown in Table 5, the regulations apply to in-use stationary prime diesel-fueled CI engines only. Standards applicable to new stationary diesel-fueled CI engines used in agricultural operations can be found in (15).

Table 4 Summary of the Emission Standards and Operating Requirements for In-Use Stationary Emergency Standby Diesel-Fueled CI Engines > 50 BHP

DIESEL PM				OTHER POLLUTANTS
DIESEL PM STANDARDS (g/bhphr)	Maximum Allowable Annual Hours of Operation for Engines Meeting Diesel PM Standards			HC, NOx, NMHC+NOx and CO standards (g/bhp-hr)
	Emergency Use	Non-Emergency Use		
		Emission Testing to show compliance	Maintenance and Testing (hours/year)	
Not Limited by ATCM	Not Limited by ATCM	Not Limited by ATCM	20	Not Limited by ATCM
≤ 0.4 and > 0.15	Not Limited by ATCM	Not Limited by ATCM	21-30	For engines with emission control strategies not verified through the verification procedure: Off-Road CI Engine Certification Standards for an off-road engine of the same model year and horsepower rating, or Tier 1 standards for an off-road engine of the same maximum horse power rating. OR Both (i) and (ii) must be met: (i) No increase in HC or NOx above 10% from baseline levels OR No increase in NMHC + NOx emissions above baseline levels (ii) No increase in CO above 10% from baseline levels.
≤ 0.15 and > 0.01	Not Limited by ATCM	Not Limited by ATCM	31-50 (Upon Approval By District)	
≤ 0.01	Not Limited by ATCM	Not Limited by ATCM	51-100 (Upon Approval By District)	

Table 5 Summary of the Emission Standards for In-Use Stationary Prime Diesel-Fueled CI Engines > 50 BHP

DIESEL PM		OTHER POLLUTANTS
DIESEL PM STANDARDS (g/bhp-hr)		HC, NOx, NMHC+NOx and CO standards (g/bhp-hr)
Applicability	Standard	
All in-use prime engines (both off-road certified and not off-road certified)	85% reduction from baseline levels (Option 1) OR 0.01 g/bhp-hr (Option 2)	For engines with emission control strategies not verified through the verification procedure: Off-Road CI Engine Certification Standards for an off-road engine of the same model year and horsepower rating, or Tier 1 standards for an off-road engine of the same maximum horse power rating. OR Both (i) and (ii) must be met: (i) No increase in HC or NOx above 10% from baseline levels OR No increase in NMHC + NOx emissions above baseline levels (ii) No increase in CO above 10% from baseline levels.
Only in-use prime engines NOT certified in accordance with the Off-road Compression Ignition Standards	30% reduction from baseline levels AND 0.01 g/bhp-hr by no later than july 1, 2011 (Option 3)	

2.5 ARB Test Methods

According to ARB (16), test methods are “formally written procedures for measurement of physical parameters related to air pollution including pollutant emissions concentrations and mass flow rate, materials properties such as asbestos contents of solids and volatile organic content of wastes, and various aspects of the performance of vapor recovery systems at service stations, bulk plants and terminals”.

Table 6 gives the tests methods for determining compliance with district nonvehicular (stationary source) emission standards.

Table 6 Test Methods for Determining Compliance with District Nonvehicular (Stationary Source) Emission Standards.

Method Number	Test Method Title	Date of Adoption / Amendment
Method 1	Sample and Velocity Traverses for Stationary Sources.	July 1,1999
Method 2	Determination of Stack gas Velocity and Volumetric Flow Rate (Type S Pitot Tube).	July 1,1999
Method 2A	Direct Measurement of Gas Volume Through Pipes and Small Ducts.	July 1,1999
Method 3	Gas Analysis for Carbon Dioxide, Oxygen, Excess Air and Molecular Weight.	July 1,1999
Method 4	Determination of Moisture Content in Stack Gas.	July 1,1999
Method 5	Determination of Particulate Matter Emissions from Stationary Sources.	July 28,1997
Method 5A	Determination of Particulate Matter Emissions from Asphalt Processing and Asphalt Roofing Industry.	July 1,1999
Method 5E	Determination of Particulate Matter Emissions from Wood Fiberglass Insulation Manufacturing Industry.	July 1,1999
Method 6	Determination of Sulfur Dioxide Emissions from Stationary Sources.	July 1,1999
Method 7	Determination of Nitrogen Oxide Emissions from Stationary Sources.	July 28,1997
Method 8	Determination of Sulfuric Acid Mist and Sulfur Dioxide Emissions from Stationary Sources.	July 1,1999
Method 10	Determination of Carbon Monoxide Emissions from Stationary Sources.	July 1,1999
Method 11	Determination of Hydrogen Sulfide Content of Fuel Gas Streams in Petroleum Refineries.	July 1,1999
Method 15	Determination of Hydrogen Sulfide, Carbonyl Sulfide, and Carbon Disulfide Emissions from Stationary Sources.	July 1,1999
Method 16	Semi-continuous Determination of Sulfur Emissions from Stationary Sources.	July 1,1999
Method 16A	Determination of Total Reduced Sulfur Emissions from Stationary Sources (Impinger Technique).	July 1,1999
Method 17	Determination of Particulate Emissions from Stationary Sources (In-stack Filtration Method).	July 1,1999
Method 20	Determination of Nitrogen Oxides, Sulfur Dioxide and Diluent Emissions from Stationary Gas Turbines.	July 1,1999
Method 21	Determination of Volatile Organic Compound Leaks.	July 1,1999
Method 100	Procedures for Continuous Gaseous Emission Stack Sampling.	July 28,1997
Method 150	Determination of Hydrocarbon Emissions from Fixed-Roof Crude Oil Process Tanks.	March 28,1986
Method 501	Determination of Size Distribution of Particulate Matter Emissions from Stationary Sources.	September 12,1990

2.6 In-use Emissions Testing

In-use emissions testing provides a faithful picture of an engine's emission characteristics. In-use emissions tests avoid the expensive and time consuming process involved in an engine dynamometer emissions testing that employs test cycles and weighting factors that may not represent an engine's intended application.

The only component required for "in-use" emissions testing is a portable emissions measurement system. A well designed system should give accurate measurements of pollutant concentrations (expressed in volume-ppm), exhaust volumetric flow rate (normalized to standard conditions-scfm) and engine work output (expressed in bhp-hr). However, current portable sensors' technology limits accurate measurement of pollutant concentrations, exhaust flow rate and engine work output measurement as compared to the highly reliable, precision quality technology available for test cell certification. The test method developed in this study for in-use compliance testing, outlined in §4.1, requires only concentration measurements for compliance testing. The concentration measurements are the most accurate of all the measurements given by a portable emissions measurement system (17). To date, WVU's MEMS, US EPA's ROVER and Horiba's OBS 2000 are the few portable emissions measurement systems that have undergone extensive independent evaluations.

The U.S EPA regulates three gaseous pollutants, namely, CO, NO_x and HC. The hydrocarbon emissions are classified as total hydrocarbons (THC) and non-methane hydrocarbons (NMHC). Carbon dioxide is measured for fuel consumption measurement purposes. PM is also regulated.

Portable Emissions Measurement Systems

Previous efforts in development of portable systems for 'in use' emissions testing purposes is highlighted by Gautam et al. (18). Most of these systems were developed for on-board vehicle testing and were built for research purposes. Very few systems are commercially available. Past developers include Southwest Research Institute, Michigan Technological University, University of Minnesota, Caterpillar Inc., Ford Motor Company, General Motors Inc., University of Pittsburgh, U.S Coast Guard, Flemish

Institute of Technology, U.S EPA, Horiba LTD and NGK, Analytical engineering and WVU. Brief description about these systems can be obtained in (19).

2.6.1 Requirements of a Portable Emissions Measurement System

The following requirements are specific to portable emission measurement systems.

1. Compact in size. The system should be transportable to the test site.

2. Accurate and Reliable. Accurately report values of pollutant concentrations, engine exhaust flow rate and engine power. The systems should be capable of measuring low concentrations of pollutants like NO_x, especially from engines that are naturally aspirated (typical of stationary and portable engines) and hence, have a low boost in the intake system. Such engines may have a rated output of 50 hp.

3. Capable of measuring engine's work output in bhp-hr. However, many stationary and portable engines are mechanically controlled and hence do not have an ECU to infer power.

4. Emissions to be reported in g/bhp-hr and be correlated with measurements made by certification quality equipments.

5. Emissions would also need to be time aligned with the engine power output to account for the delays due to time response of the sensor (including the time taken by the sample to reach the sensor).

6. Be robust; withstand the harsh conditions (mainly vibrations) of on-road testing.

7. Low drift desired. Stationary and portable engines mainly operate in steady state modes. Although, intuitively, measurement of emissions during transient cycles can be expected to be more challenging due to time alignment constrains, steady state duty cycles require that these sensors have a lower drift. Colloquially, errors in transient cycle testing tend to be smaller due to errors occurring on both sides of the true value

(and hence, get ‘averaged out’ in the end), where as during steady state operation, ‘accuracy-at-a-point’ comes into effect.

2.6.2 Available Portable Emission Measurement Systems

Most portable emissions measurement systems consist of I/M-grade multi-gas analyzers for CO, CO_2, and HC as 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 (20) is a large supplier of electrochemical NO cells for this application. At least one company offers 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 garage grade testing market.

Some of the most recent in-use (on-board) systems combine laboratory-grade and I/M-grade analyzers and sampling systems. For example, the WVU MEMS uses a laboratory-grade heated line and heated filter along with I/M-grade gaseous analyzers. Another example is the heated line and possible use of a HFID on the Horiba OBS-1000 and Sensors SEMTECH-D for diesel exhaust hydrocarbons. Signal Instruments, UK produces a portable HFID that has been extensively evaluated at WVU (21), and is employed by on-board systems manufacturers. Only a few companies market complete on-board emissions measurement systems capable of providing brake-specific mass emissions data. Information on these systems is shown in Table 7 on the following page. Note that the WVU MEMS and the EPA Rover are shown for comparison purposes only and are not commercially available. However, the systems are available for research and testing purposes on an extended term basis. A detailed explanation about the working principle for these analyzers such as, the non-dispersive Infra-Red (NDIR), electrochemical mechanism, electrocatalytic mechanism, heated flame ionization detection, chemiluminescence and the non-dispersive ultraviolet (NDUV) mechanism is presented by Gautam et al. (19).

Table 7 Available Portable Emission Measurement Systems

Parameter	WVU MEMS	EPA ROVER	AEI SPOT	CATI	HORIBA	SENSORS SEMTECH-D	Developed/On-going R&D for MEMS at WVU
Exhaust Gas Flow Rate Measurement							
1. Annubar	☒	☒					
2. AEI-SPOT Flow meter			☒				
3. Tracer Gas with Mass flow controller							☒
and NDIR detector							
4. V-cone Flow meter							☒
5. ECU-Output based calculation				☒			
6. Differential Pressure Device					☒	☒	
7. Hot Wire Anemometer						☒	
PM Measurement							
1. Light Scattering Techniques					☒	☒	
2. Filter-based Gravimetric PM Measurement							☒
3. Quartz Crystal Micro balance							☒
Gaseous Emissions Concentrations							
1. NOx-Zirconium Oxide Sensor	☒	☒	☒		☒		
2. NOX-NDUV						☒	
3.NOx-NDIR							
4. NO with EC Cell		☒		☒			
2. CO_2-Solid State NDIR	☒	☒	☒	☒	☒	☒	
3. CO_2/CO- Micro flow NDIR							☒
4. HC-Portable HFID for Diesel Engines					☒	☒	☒
5. HC- NDIR for SI engines.	☒	☒		☒	☒	☒	
Torque Measurement							
1. ECU Data	☒	☒	☒	☒	☒	☒	
2. CO_2 /engine speed or bsfc-based method							☒
for mechanically injected diesel engines							
Data Acquisition							
1. Portable Laboratory- grade data	☒						☒
acquisition system (10 Hz)							
2. Data acquisition (1 Hz)	☒	☒	☒	☒		☒	☒
3. Data Logger			☒				
Estimated Price	$45,000 (Cost)	Unknown	$80,000 +	$100,000 +	$100,000 +	$100,000 +	
Overall Comments	**1. Horiba did not respond to the survey.**						
	2. CATI did not respond to the survey.						
	3. Sensors did not want to publish the cost numbers.						
	4. AEI did not provide the cost.						

Particulate matter measurement is one of the most difficult aspects of in-field, in-use emissions testing exercise. The difficulties are even greater for real-time measurement of PM. A relatively simple, but challenging method is gravimetric analysis using a partial flow sampling system, such as a miniature dilution tunnel, to dilute the exhaust gas with ambient air before a sample is drawn across a pre-weighed filter. The difference between pre and post-weight is the mass of PM collected, which can be used to determine the average mass emission rate of PM from the engine over a test. Acquiring a proportional sample of the exhaust stream is the challenging aspect of this method. PM is presently regulated on a mass basis by means of filter capture and gravimetric weighing. A broad range of instruments designed to measure PM parameters including opacity (smoke) meters, mass measurement systems, and instruments which characterize particle count and/or size distribution have been reviewed in (22). Each instrument discussed may not be suitable for portable systems for making in-use emissions measurements.

PM mass measurement systems may be classified as integrated or continuous. Particle separation by size can be obtained by use of an appropriate cyclone in the sampling probe. Coarse particles are defined as particles with a diameter of less than 10 μm (PM_{10}), and fine particles are defined as particles with a diameter of less than 2.5 μm ($PM_{2.5}$). The integrated PM measurement systems involve collection of PM on filter media that undergo gravimetric analyses. This method is handicapped not in its ability to yield accurate information, but rather by its need for cumbersome weighing capability and the associated time requirements that are needed to equilibrate the filters in a controlled environment. Continuous PM measurements would be ideal for in-field emissions measurements from stationary and portable engines. In the past, the most common dynamic (continuous) instruments for PM mass monitoring have been the beta attenuation, and the tapered element mass monitors such as the Tapered Element Oscillating Microbalance (TEOM) (18).

A number of particle counters such as the Scanning Mobility Particle Sizer (SMPS), Electric Low Pressure Impactor (ELPI) and Micro Orifice Uniform Deposit Impactor (MOUDI) exist in the marketplace, but these require assumptions of particle shape, density and confidence in the measured particle size distribution or effective mass mean size to permit their use to predict mass rates of emissions. Detailed working principle of such systems is mentioned in (19).

Martin and Lehmann (23) presented results of an experimental study on the comparison of particle measurement instruments. Their study was the Swiss contribution to the GRPE Particle Measurement Program. Table 8 shows the candidate systems that were investigated by Martin and Lehmann (23). A total of 21 particle measurement instruments were investigated with the objective of generating a data set for future legislative purposes. All 21 instruments simultaneously sampled and analyzed PM in the exhaust stream of a heavy-duty diesel engine in an engine dynamometer test cell, and also from the outlet of an aerosol generator. The metrics include number, length, surface area, volume and mass. Martin and Lehmann (2003) reported results on robustness, repeatability, linearity, sensitivity, limit of detection, and response of each instrument. The study was undertaken in cooperation with the instrument manufacturers.

Manufacturers were given the option to decide where to sample the exhaust, from the full flow tunnel (dilute exhaust) or from the engine exhaust transfer tube (raw exhaust). The authors reported that manufacturers applied their own individual strategy for their measurement set-up with the consequence of reduced comparability between the candidate systems.

It should be noted that two instruments that the US EPA is currently focused upon were not included in the Swiss study. The US EPA is actively investigating the Real-time Particulate Mass Monitor, from the Mid-Atlantic Research Institute (18), and also the newer versions of the TEOM, from Rupprecht & Patashnik (18).

Complete measurement systems were investigated in this study, consisting of sampling and a detection unit. Some of the instruments took their sample from the exhaust gas line, others from the primary full-flow CVS tunnel and a third group took it from the secondary dilution tunnel. The use of different sampling systems has to be taken into account while comparing the instruments to each other.

In order to generate emission values (e.g. in units per kWh), the particle concentrations measured from raw gas exhaust line had to be multiplied by the time-synchronized exhaust gas flow that is measured separately. The separate procedure of exhaust flow measurement had not been taken into account for the assessment of the candidate systems as it is a general requirement for all applications of raw gas measurements.

Table 8 Candidate Systems for Mass Measurement Investigated in the EMPA Study

No.	Name	Manufacturer	Principle	Metrics	Status
1	Gravimetric Filter Method		Weighting of filters	Mass	Current
2	LI2SA	ESYTEC	Laser Induced Incandescence	Mass	Prototype
3	MEXA 1370PM	Horiba	Filter Evaporation method Gas analysis	Mass	Current
4	TEOM 1105	Rupprecht & Patashnick	Harmonic oscillator	Mass	Current
5	PASS	TU Munich	Photoacoustic absorption	Mass	Prototype
6	Mass Monitor (DMM 230) "MasMo"	Dekati	Electrical mobility, Impaction, Electrical detection	Mass	Prototype
7	Coulometry		Filter method Electrical-Chemical Titration	Mass	Current
8	PAS	Matter Engg.	Diffusion Charging, electrical detection	Active Surface	Current
9	AVL 439	AVL	Light extinction opacimeter	Mass	Current
10	Dust Monitor	Grimm	Laser scattering	Mass	Current

2.7 Isokinetic Sampling Theory:

Substantial part of this project involved sampling PM from raw exhaust using the Method 5 procedure in addition to sampling PM from a secondary dilution tunnel in accordance with CVS-full flow dilution tunnel procedure. ARB recommends Method 5 as one of the standard test methods for emissions testing of stationary engines. The theory behind isokinetic sampling is explained below. Method 5 procedure is explained in APPENDIX A.

It is well established unless particulate sampling is isokinetic, that is, where the velocity of the gas entering the sample nozzle is the same as the velocity of the gas stream, the sample collected will not be representative of the stream being sampled (24). Further, the extent to which the sample will not be representative is a function of the isokinetic velocity, size of the particles, and physical properties of the particles and carrier gas.

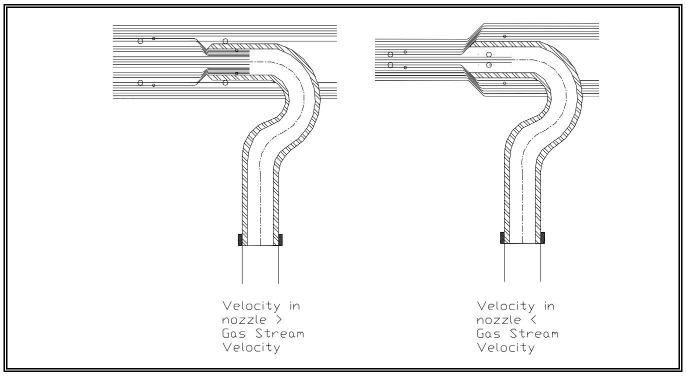

Figure 2 Effects on Sampling for Particulate Matter Due to Anisokinetic Nozzle Velocities.

In Figure 2, if the velocity in the nozzle is less than the gas stream velocity, then the inertia of the larger particles causes a disproportionably large amount of particles to enter into the nozzle. Conversely, if the velocity in the nozzle is greater than the gas stream velocity, then the inertia of the larger particles causes a disproportionably small number of particles to enter into the sampling nozzle. Errors due to departures from isokinetic sampling are dicussed elsewhere (24). The errors increase with increases in size of the particles. Isokinetic sampling is flow proportional sampling where the proportionality constant is the ratio of the sampling nozzle cross-sectional area to the stack cross sectional area.

Table 9 shows the velocities of the sample stream in the nozzle that were obtained for one of the tests in this study. The velocities shown are at each of the eight locations that were traversed by the nozzle. The actual flow rate and hence, the velocity, at the entrance of the nozzle cannot be determined, but can be inferred from the 'percent isokinetic' parameter that was determined at the end of every test. The 'percent isokinetic (%I)' parameter (or 'isokinetic sampling rate') is determined using the temperature and pressure in the stack, velocity of the exhaust gas, volume of dry gas sampled at standard conditions, sampling duration, mole fraction of the exhaust gas, area of the nozzle and the standard absolute pressure and temperature. For a test to be valid, the '%I' is to be within ±10% from the true isokinetic sampling rate. The equation for '%I' is shown in APPENDIX A.

Table 9 Velocities in the Nozzle and in the Gas Stream (as obtained during a test)

Stack Gas Velocity	Percent Isokinetic	Nozzle Velocity
ft/sec	%	ft/sec
234.4	112.1	262.9
235.9	106.0	250.1
236.5	110.9	262.3
236.8	108.6	257.3
236.6	101.6	240.5
235.9	103.2	243.4
232.5	102.1	237.4
229.4	89.5	205.4

3 Experimental Equipment and Procedures (18)

3.1 Introduction

This chapter describes the equipment and the procedures that were used in this study. The chapter provides descriptions of the Mobile Emission Measurement System (MEMS), the Method 5 principle based PM sampling system and the test engines along with a description of the test cycle used in this study. A brief overview of the emissions testing facility and associated procedure is also presented in this section as also presented is the "Compliance Factor" approach used in this study.

The approach utilizes the in-field concentrations of NO_x and CO_2 to obtain a mass based ratio that is in turn expressed as a factor of the ISO 8178-averaged brake-specific NO_x / CO_2 mass ratio, obtained for the test engine either from laboratory evaluation or from the manufacturer. It is up to the regulatory authorities to decide the maximum allowable value for this factor, called "Compliance Factor." This method of "Compliance Factor" based testing is cost-effective and accurate as it avoids engine work output and exhaust flow rate measurements. Measurement of engine work output can be a time-consuming task on mechanically controlled engines. Exhaust flow rate measurement forms the highest source of uncertainty in "in-use" emissions measurement (17). The application of the test method requires only concentration measurements with minimal training and can be easily implemented.

Qualification and validation of the proposed methodology comprised of extensive tests conducted in an engine test cell and in the field. Both battery of tests included collection and analysis of concentration data and exhaust flow rate measurement. Engine speed and load were determined using a dynamometer for the laboratory testing phase of the study. The in-field test engines were typical portable and stationary engines that do not have an ECU. Hence, work output could not be inferred during the in-field tests. The procedure for inference of engine work output using the ECU information is outlined in (25).

3.2 Test Cycle

Table 10 shows the different engine operating conditions required by the ISO 8178, Part 1 test protocol (26). This test method specifies the measurement and evaluation methods for gaseous and particulate exhaust emissions from reciprocating internal combustion engines, particularly non-road (including portable) and stationary engines, operating under steady state conditions on a test bed. Typical examples include engines in earth-moving machines, generator sets, etc.

Table 10 ISO 8178 Part 1, Type C 1 Test Schedule

ISO 8178 Test Mode Number	Engine Speed	Percent Load	Modes Selected For Testing
1	Rated	100	√
2	Rated	75	√
3	Rated	50	√
4	Rated	10	√
5	Intermediate	100	√
6	Intermediate	75	√
7	Intermediate	50	√
8	Idle	0	√

The steady state tests allowed comparative evaluation of the data collected using the Method 5 PM sampling system and the MEMS with the CVS-full flow dilution principle based sampling systems. Since various combinations of speed and load in the ISO 8178 test schedule reflect the different engine applications and operating conditions, numerical estimates of the "Compliance Factor" were developed for each mode. Regulatory bodies, such as, CARB and EPA could utilize this information to develop the criterion for in-use emissions compliance. The proposed test method could be used to better enforce their regulation and achieve their objective of attaining compliance with emission standards.

3.3 Test Engines

This study employed a naturally aspirated, mechanically controlled Isuzu C 240 engine and a turbocharged, electronically controlled DDC Series 60 engine for the laboratory testing phase of the study. Mechanically controlled and naturally aspirated engines such as an Isuzu QD 100 engine and a Perkins engine were selected for "in-use" emission tests (in-the-field tests). The QD 100 engine was used to power a Multiquip-Whisperwatt generator, where as the Perkins engine was used to run an air-compressor. Given below are brief descriptions for each engine.

3.3.1 DDC Series 60 Engine:

Table 11 gives the engine specifications for the MY 1992, 360 hp DDC Series 60 engine. The engine has a peak torque of 1350 ft-lbs at 1200 rpm. Figure 3 shows the DDC Series 60 mounted on the direct current (DC) dynamometer test bed at the Engine and Emissions Research Laboratory (EERL) at WVU.

Table 11 DDC Series 60 Engine Specifications

Engine Manufacturer	Detroit Diesel Corporation
Engine Model	Series 60
Model Year	1992
Displacement	12.7 liters
Power Rating (hp)	360hp @ 1800 rpm
Configuration	Inline-6
Bore (m) x Stroke (m)	0.13 m x 0.16 m
Induction	Turbocharged
Fuel Type	Diesel
Engine Strokes per Cycle	Four
Injection	Electronically Controlled

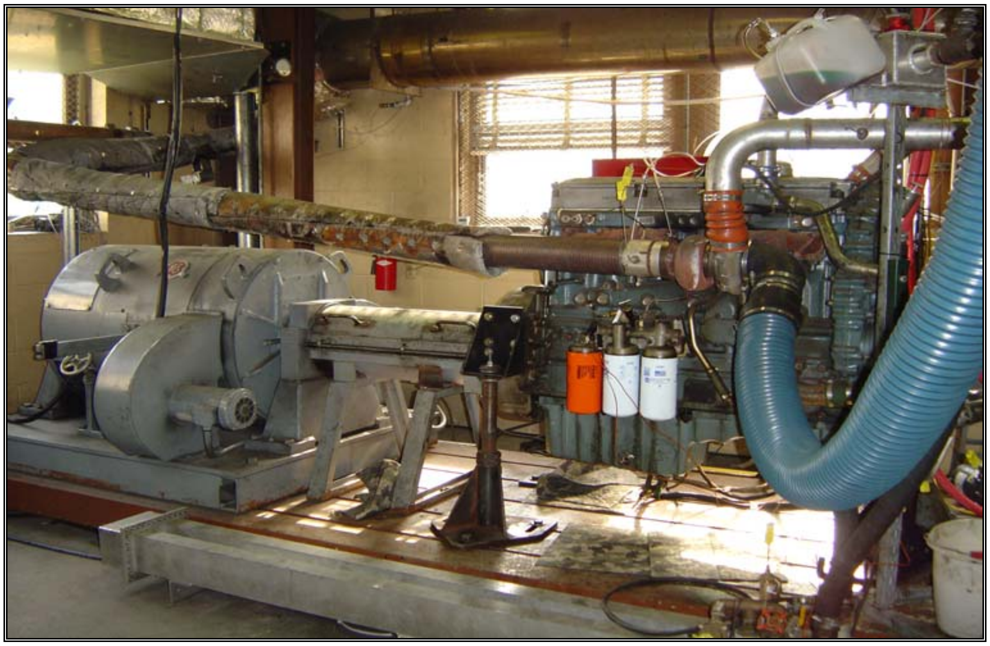

Figure 3 A DDC Series 60 Engine Mounted on the Test Bed

3.3.2 Isuzu C 240 Engine

Table 12 gives the engine specifications for the 50 hp Isuzu C 240 engine. The Isuzu C 240 engine has a peak torque of 91 ft-lbs at 2100 rpm. The Isuzu C 240 is a MY 1997 construction application engine and represents a typical non-road engine. Figure 4 shows the Isuzu C 240 mounted on an eddy current dynamometer skid. The Isuzu C240 is a pre-chamber, in-line four-cylinder, mechanically controlled engine that is used in mining operations. The engine was chosen in order to develop the test method for mechanically controlled engines that typically do not allow direct measurement of engine torque and power.

Table 12 Isuzu C 240 Engine Specifications

Engine Manufacturer	Isuzu
Engine Model	C 240
Model Year	1997
Displacement	2.4 liters
Power Rating (hp)	50hp @ 3000 rpm
Configuration	Inline-4
Bore (m) x Stroke (m)	0.104 m x 0.12 m
Induction	Naturally Aspirated
Fuel Type	Diesel
Engine Strokes per Cycle	Four
Injection	Mechanically Controlled

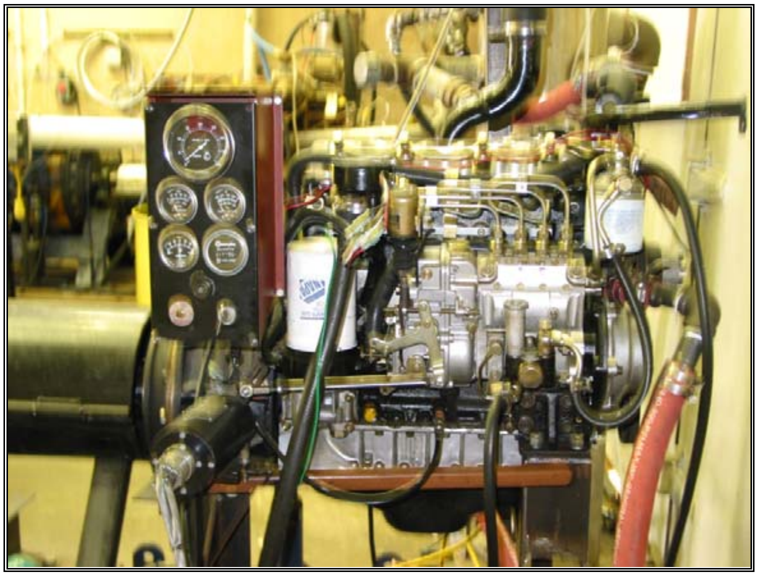

Figure 4 Isuzu C 240 Engine Mounted on the Eddy Current Dynamometer Test Bed

3.3.3 Isuzu QD 100 Engine

In-use emissions tests were performed to validate the proposed test method. Two engines that fall under the “Portable & Stationary Engines” category were selected. A Multiquip-Whisperwatt diesel powered AC generator and a SullAir 185 diesel powered air compressor were rented for the study. The generator was loaded using a thermostatically controlled room heater while a jack hammer was operated using the air compressor. Thus, both the engines were tested during their “in-use” duty cycle. Emissions data was collected using laboratory grade analyzers mounted on a transportable lab and the MEMS. Both gaseous and particulate matter during “in-use” operation were collected. Two runs were performed for each test engine. Table 13 and Table 14 describe the engine specifications for the MY 1990 Isuzu QD 100 engine, that was used to power the generator and the MY 2001 Perkins engine, that was used to run the air compressor respectively.

The Isuzu QD 100 engine, being a MY 1990 make, was not designed to meet any emissions standard. The Perkins engine, built in 2001 was certified to the pertinent emission standards.

Figure 5 Side View of the Multiquip-Whisperwatt Generator

Table 13 Isuzu QD 100 Engine Specifications

Multiquip-Whisperwatt Diesel Powered AC Generator	
Model	DCA-44SPXI
Generator Model	DB-0667I
Rated output	35 kW
Rated voltage	120 V 240 V
Rated current	182 A 182 A
Engine Model	1990 Isuzu QD-100 (4BD1)
Type	4 cylinders, 4 stroke
Rated Output	56 hp @ 1800 rpm
Displacement	3853 cc

3.3.4 2001 Perkins Engine

Table 14 2002 Perkins Engine Specifications

SullAir 185 Diesel Powered Air Compressor	
Model	2002 SullAir 185
Rated capacity and Pressure	185 CFM @ 100 PSIG (87L/s @ 7 Bar)
Maximum Pressure	125 PSIG @ 8.5 Bar
Rated Output	51.9 kW @ 2200 rpm
Engine Model	2001 Perkins
Type	4 Stroke 4 cylinders
Displacement	3.9L
Idle	800 RPM

Figure 5 shows the lateral view of the diesel powered generator. Figure 6 shows the SullAir 185 being tested for in-use emissions. As shown in the above tables, both the in-field test engines are 4 stroke, 4 cylinders and have approximately the same displacement. Emissions from these "in-use" engines were expressed in mass emission rate values (g/s).

Figure 6 SullAir 185 Diesel Powered Air Compressor

3.4 Test Fuel

Federal on-road D2 fuel, with low sulfur content was used for the study. The fuel was purchased from Guttmann Oil. Since a standard commercially available fuel was used for the entire study, a fuel analysis is not presented.

Table 15 Test Matrix for the Study

Lab testing (8- Mode Test Cycle)	Engines	Pollutant	Lab-grade Equip-ment	Method 5 Two modes of ISO 8178	MEMS Modes 1-8 of ISO 8178
1.	Isuzu C-240. 4 cylinder, 2.4 liters, mechanically controlled, naturally aspirated and has a rating of 57 hp @3000 rpm.	CO	√		
		CO_2	√		√
		THC	√		
		NOx	√		√
		TPM	√	√	
2.	DDC Series 60. 6 cylinder, 12.7 liters, in-line, turbocharged, electronically controlled on highway engine and has a rating of 360 hp @1800 rpm.	CO	√		
		CO_2	√		√
		THC	√		
		NOx	√		√
		TPM	√	√	
Field Testing	Engines	Pollutant	Lab-grade Equipment	MEMS	
1.	2001 Perkins, 3.9 liters, Naturally aspirated, Mechanically controlled, 70 hp engine.	CO	√		
		CO_2	√	√	
		THC	√		
		NOx	√	√	
		TPM	√		
2.	1990 Isuzu QD 100, 3.8 liters, Naturally aspirated, Mechanically controlled, 56 hp engine.	CO	√		
		CO_2	√	√	
		THC	√		
		NOx	√	√	
		TPM	√		

3.5 Test Matrix

Table 15 gives the test matrix for the study. As mentioned before, the laboratory phase of the testing involved exercising the selected engines on multiple ISO 8178 steady state cycles on an engine-dynamometer test bed. Data was collected from MEMS, Method 5 and from certification quality analyzers. Field testing comprised of regular duty cycles for the respective engines. MEMS and laboratory grade analyzers mounted on a transportable laboratory (6) were used to collect data.

3.6 West Virginia University Engine And Emissions Research Laboratory.

The following section describes the emissions testing facility at WVU, Morgantown, WV. The engine and emissions testing facility is in compliance with the requirements placed in 40 CFR Part 89 (27), 40 CFR Part 86 (28) and in ISO 8178, Part 1 (26). A schematic of the laboratory testing set-up is shown in Figure 7.

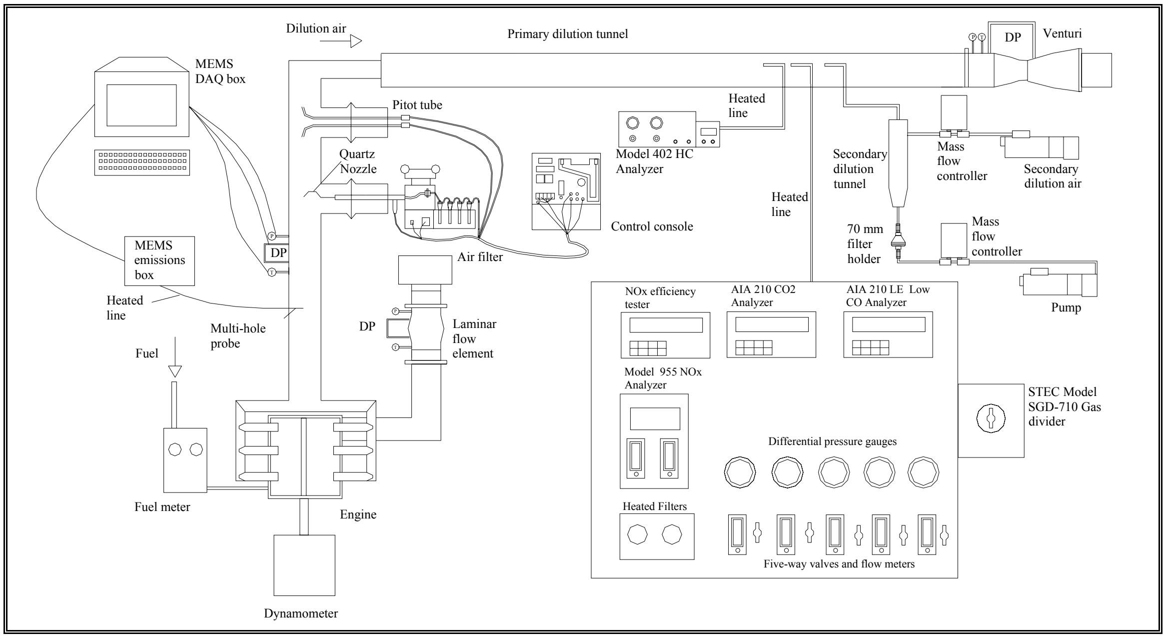

Figure 7 West Virginia University's Engine and Emissions Research Laboratory Emissions Measurement System

3.6.1 Dynamometer/Dynamometer Control

The engines were coupled to a dynamometer to load the engine in order to simulate the real world engine operating conditions. In this study, a DC dynamometer, Model DYC-243, from General Electric Inc. was used to control engine speed and apply load on the DDC Series 60 engine. Torque on the engine was measured using a load cell located on the dynamometer frame. Engine speed was measured using an internal digital speed encoder.

A 100 hp eddy current dynamometer, from Mustang Dynamometer, was used to control the speed and load the Isuzu C 240 engine. The eddy current dynamometer controls speed using a Dyn-Loc IV™ system in combination with a digital throttle controller DTC-1™ system. Both Dyn-Loc IV™ and DTC-1™ systems are manufactured by Dyne systems Co., LLC. A load cell was used to provide torque measurement on the drive shaft. Engine speed was determined using a speed encoder - also coupled to the drive shaft. The choice of the dynamometer is based on the rating of the engine and on the test cycles (presence of motoring phases in the cycles).

3.6.2 Dilute Exhaust Gas Sampling And Analytical System Description

3.6.2.1 Dilution Tunnel

Regulatory requirements necessitate dilution of the engine exhaust. A dilution tunnel used for this purpose serves to simulate the reactions that diesel exhaust undergoes in the atmosphere. The dilution tunnel also prevents water vapor condensation by lowering the dew point temperature of the raw exhaust. Water condensation causes loss of water soluble NO_2. Dilution tunnel design requires a mixing orifice, 8 inches in diameter, to be placed 3 feet downstream of the air and raw exhaust inlets, a minimum tunnel diameter of 18 inches, at least 10 diameters in length to allow complete mixing and the formation of fully developed flow and the use of Critical Flow Venturi-Constant Volume Sampling (CFV-CVS) flow sampling system. The EERL dilution tunnel contains four critical flow venturis of which, three are rated for 1000 scfm flow capacity each and the fourth is rated for 400 scfm. Hence, a minimum dilute exhaust flow rate of 400 scfm and a maximum of 3400 scfm can be obtained. The lab uses a 75 hp electric centrifugal blower, installed downstream of the venturis, to pull the dilute exhaust. The venturis operate on the principle of choked flow, that is, during sonic condition the mass flow rate through the venturi remains constant and is a function of only the upstream conditions of the venturi. The following relation provides the mass flow rate through the venturi,

$$Q = \frac{K_v P}{\sqrt{T}}$$ **Equation 3- 1**

Where, Q = Mass flow rate.

T = Upstream temperature.

P = Upstream Pressure.

K_v = Calibration co-efficient for the venturi.

A Viatran absolute pressure transducer, Model No 1042 AC3AAA20 was used to monitor Pressure (P) and a 3-wire Resistive Temperature Device (RTD) by Tayco Model No. 68-3839 was used to monitor temperature (T).

The dilution air was filtered. All emission measurements were corrected for background concentration levels in the dilution tunnel.

For particulate measurements, a representative, proportional sample was drawn into a secondary dilution tunnel. The sample may be further diluted in the secondary tunnel to satisfy the regulatory requirement of maintaining a 'filter face' temperature less than 125°F.

3.6.2.2 Particulate Matter Sampling and Handling

A gravimetric analysis of PM, in accordance with regulations outlined in CFR 40, Part 89 (27) was performed in this study. PM was collected on a pair of filters-primary and secondary, Pall T60A20 type, 70 mm (2.76 inches) fluorocarbon based (membrane) filters.

A sample of particulate matter (PM) was withdrawn proportionally from the primary dilution tunnel into a secondary dilution tunnel through a 0.5 inch transfer tube. The inlet probe facing upstream, is approximately 7 inches in length and is located so that the dilute exhaust temperature is lower than 375°F, but above the temperature at which water vapor in the exhaust could condense. The diluted sample could be further diluted, if necessary, in the secondary dilution tunnel which is 3.0 inches in diameter and 30 inches long. According to CFR 40, Part 89 the double-diluted exhaust sample must have a temperature lower than 125°F when passing through the two PM collection filters. The total flow and the secondary dilution air flow through the secondary tunnel is controlled using two Sierra Instruments 740-L-1 series mass flow controllers and two Gast series 1023-101Q-583X rotary vane pumps. The total flow can vary from 0 scfm to 6 scfm while the secondary dilution air flow varies between 0 scfm to 3 scfm. The controllers provide real time control over the flow rate, that is, flow through the secondary dilution tunnel varies continuously in proportion to the flow through the primary dilution tunnel. However, for steady state testing, a constant flow rate of 4 scfm (without secondary dilution) was used for all the modes. The mass flow controllers were calibrated using a Meriam Instruments laminar flow element (LFE) Model No. 50MW20, rated at 0 scfm to 23 scfm.

A stainless steel filter holder containing the primary and secondary filters was connected at the end of the secondary dilution tunnel. The filter holder is constructed of stainless steel to prevent reactions with the corrosive exhaust sample and is designed to allow easy access to the filters.

The PM samples were collected on separate filters during each mode of engine testing. The PM consists primarily of elemental carbon as well as sulfates, soluble organic fraction (SOF), engine wear metal and bound water. The sulfuric acid in the diesel exhaust contains bound water. PM filters were placed in unsealed but covered glass Petri dishes. Glass dishes are preferred over plastic to avoid loss of PM due to static electric charges in plastic Petri dishes. The Petri dishes were unsealed to allow humidity exchange. The filters were conditioned for a period of at least one hour in an environmentally controlled room maintained at 50% relative humidity (RH) and 70°F temperature. The filters were conditioned before and after the tests. The humidity control in the environmental chamber ensures accurate gravimetric analysis of PM.

The filters were placed on a radioactive-neutralizer that would remove any static charges on the filter before weighing on a Cahn C-32 microbalance, certified for CFR 40, Part 86 application.

Quality control of the humidity control on the measured PM mass was established using two reference filters, in accordance with the specifications outlined for their use in CFR 40, Part 86, Subpart N. PM mass was corrected for background PM in the primary dilution tunnel.

3.6.2.3 Gas Analysis System

Three gaseous pollutants NO_x, HC and CO were measured in this study. CO_2 was measured to provide redundant fuel consumption information and for the calculation of the dilution ratio. All pollutants were measured using laboratory grade (certification quality) analyzers. Stainless steel probes connected ten diameters downstream of the orifice in the dilution tunnel were used to transfer the gaseous pollutants to the respective analyzers. All probes faced upstream and were approximately six inches into the tunnel. Heated lines were used to transfer the gaseous pollutants from the probes to the respective analyzers. The hydrocarbon line and probe were maintained at a wall temperature of 375°F ±10°F to prevent condensation of higher molecular weight hydrocarbons and all other probes and lines were kept at 235°F±10°F to prevent water condensation. Water in sample lines can cause the analyzers to perform incorrectly. gives the required specifications for the analyzers.

3.6.2.3.1 Hydrocarbon Analyzer

A Rosemount Analytical Model 402 heated flame ionization detector (HFID) is used to measure the total hydrocarbon (THC) content in diesel exhaust. The analyzer's working principle includes a burner as a sensor. Flame is produced by regulated flows of air and pre-mixed hydrogen/helium fuel gas. Ions are produced when a regulated flow of sample gas flows through the flame and are collected on the polarized electrodes causing current to flow through the associated electronic measuring circuitry. The current flow is proportional to the rate at which carbon atoms enter the burner. Hydrocarbons are measured wet, that is, water vapor is not taken out from the sample going into the HC analyzer.

3.6.2.3.2 CO/CO_2 Analyzer

The NDIR uses the exhaust gas species being measured to detect itself by the principle of selective absorption, which means that the infrared energy of a particular wavelength, specific to a certain gas, will be absorbed by that gas. All other Infrared energy (other wavelengths) will be transmitted by that gas. CO and CO_2 are measured dry, that is, water vapor in the sample going into the analyzers is condensed out. Water vapor can cause interference, due to its wavelength being close to that of CO and CO_2.

3.6.2.3.3 NO_x Analyzer

The NO/NO_x analyzer is a Rosemount Model 955 Chemiluminescent Analyzer. The analyzer can determine the concentration of either NO or NO + NO_2 which together is referred to as NO_x. For the determination of NO, the sample NO is quantitatively converted into NO_2 by gas-phase oxidation with molecular ozone which is generated inside the analyzer by an ozone generator, that is supplied with an external bottled air supply. When this reaction takes place, approximately 10% of the NO_2 molecules are elevated to an electronically excited state followed by immediate reversion to the non-excited state accompanied by a photon emission. The emitted photons are detected and the instrument response is calibrated to the total NO in the converted sample. The operation for NO_x is identical to that of NO except that the gas sample stream is first passed through a converter, which converts the NO_2 into NO. In this case, the instrument response is proportional to the NO present in the original sample plus the NO produced by the dissociation of $NO_{2.}$ NO_x is measured wet.

Table 16 Analyzer Specifications (29, 30, 31, 32, 33, 34, 35, 36):

Analyzer	Measured Gas	Detection Principle	Accuracy	Repeat ability	Zero drift	Span Drift
Rosemount 955	NO_x	Chemi-luminescence	± 2% Full-scale	Within ± 0.5 % Full scale	± 1 % full scale / 24 hrs	± 1 % full scale / 24 hrs
Rosemount 402	HC	Heated Flame Ionization	± 2% Full-scale	Within ± 1% Full scale	N/A	N/A
Horiba AIA 210	CO_2	Non-Dispersive Infra-red Radiation	± 2% Full-scale	Within ± 1% Full scale	Within ± 1 % full scale/ 8 hrs	Within ± 1 % full scale/ 8 hrs
Horiba AIA 210 LE	CO	Non-Dispersive Infra-red Radiation	± 2% Full-scale	Within ± 1% max value	Within ± 1 % max value/ 8 hrs	Within ± 1 % max value / 8 hrs
Horiba Mexa 120 (MEMS NO_x Sensor)	NO_x	Zirconium Oxide Detector	±30 ppm (<1000 ppm NO_x), ± 3 % Full-scale (> 1000 ppm)	N/A	N/A	N/A
Horiba BE-140 (MEMS CO_2 Sensor)	CO_2	Solid state NDIR	± 0.3 % vol (<8% vol), ± 0.4 % vol (8-15% vol)	Within ± 0.13 % vol	Within ± 0.4% / 4 hrs	Within ± 0.4% / 4 hrs
Sensors AMB II	NO_x	Electro-chemical cell, Fick's law of diffusion	± 25 ppm (absolute or 4% rdg)	2 % rdg	± 5 ppm / 24 hrs	± 2 % rdg / 8 hrs

3.6.2.3.4 Bag Sampling

Continuous samples of dilution (background concentration) air were collected in a 80-liter tedlar bag during the each mode of the test. After the test, the 'bag samples' were routed to the analyzers for background measurements. The background measurements of the regulated emissions in the tunnel were used to correct the continuous sample readings. No dilute gas bag sample was collected, since only steady state tests were conducted for this study. However, the dilute gas bag sample can be used as quality control check over the continuous measurements; the bags provide the average emissions for the test.

The design of the transportable laboratory is described in (6).

3.7 Method 5 Analysis:

3.7.1 Principle and Operation (37, 38):

The objectives of this exercise are two fold – first, to evaluate the Method 5 test method against the Constant Volume Sampling (CVS)-full flow dilution tunnel procedure (outlined in ISO 8178 part 1 (26) protocol) and second, to simply, if possible, the Method 5 PM sampling procedure for "in-the-field" emission measurement purposes. The simplified Method 5 system/procedure, developed to fulfill the second objective, will be referred to as "Modified Method 5 System" in this study.

A gravimetric analysis of particulate matter (PM) emissions from stationary sources was performed using the Method 5. In this method (37), PM from the engine is sampled isokinetically and collected on a filter maintained at 250°F. The water vapor in the exhaust gas along with any condensed organics is removed downstream of the filter - in impingers immersed in an ice bath. The sample gas leaving the impingers is then drawn through a felt filter, to remove any foreign matter, before entering the sample pump. The outlet of the pump is connected to the control console that comprises a dry gas meter to measure sample volume and a calibrated orifice. The sample gas exits the control console through the calibrated orifice. A U-tube manometer is connected across the calibrated orifice to provide a reference to control sample flow rate. Isokinetic sampling is achieved by comparing the Pitot tube differential pressure (ΔP), provided by a type S Pitot tube inserted eight diameters downstream of the sampling nozzle, with the dry gas meter orifice differential pressure reading (ΔH) and then adjusting the orifice differential pressure (ΔH) to the desired value. Details of the Method 5 sampling train, as well as associated theories and data analysis is included in APPENDIX A.

The CARB Method 5 document defines PM as "any material that condenses at or above the filtration temperature, determined gravimetrically after removal of uncombined water." According to the ARB Method 5, matter that is liquid at standard temperature must be included in the determination of TPM. This matter is assumed to pass as gas through the filter and is condensed in the impingers. Hence, "impinger catch" and "impinger catch extract," together referred to as 'back half,' are included in the determination of TPM.

It should be noted that other regulatory bodies, such as, the US EPA, do not consider the back half for determination of TPM. Only the front half, that is, "probe catch" and "filter catch" are required to determine TPM. It should also be noted that there is a separate method (39), outlined as Method 202 – "Determination of Condensable Particulate Emissions from Stationary Sources," that governs the extraction of the back half contents.

Proportional sampling was conducted to collect total particulate matter from the CVS. Tests were conducted on Isuzu C 240 engine for the 'R100' (Rated speed and 100% load) and the 'I100' (Intermediate speed and 100% load) steady state modes, and also on the DDC Series 60 engine for the 'I50' (Intermediate speed and 50% load) and 'I75' (Intermediate speed and 75% load) steady state modes of engine operation. PM analysis is reported with and without the back-half in Table 39 under § 4.4.

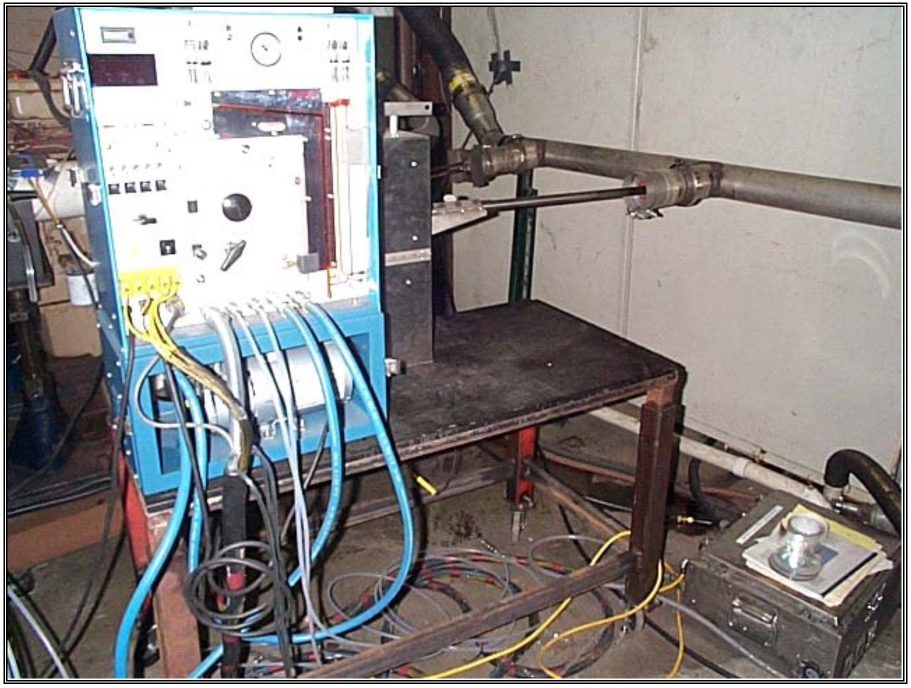

Figure 8 Front view of the Method 5 Sampling System

Figure 9 Lateral view of the Method 5 Sampling System.

3.7.2 Modified Method 5 Test:

Based upon results from our Method 5 tests, and subsequent discussions with CARB, this program attempted to determine whether a modification to the Method 5 would yield valid results that could improve the ease of use of Method 5 sampling train in the field. The goal of this exercise was to determine if the existing Method 5 sampling trains could be employed to determine PM emissions in a convenient, yet accurate manner, which would yield results similar to the regulatory PM method used in an engine certification test.

WVU determined that the total PM measured with the CVS, in accordance with the requirements of ISO-8178, and 40 CFR, Part 89, was in very good agreement with the front-half of the Method 5 test protocols. The findings are supported by the study conducted by researchers at CE-CERT, University of California, Riverside (40). The system was adapted for "in-use" emissions measurement purposes by employing a multi-hole stainless steel sampling nozzle that spanned the entire diameter of the exhaust stack, instead of the regular quartz "gooseneck" nozzle that had to be traversed across the stack diameter. This measure, if proved successful would not necessitate the traversing of the sampling probe. The sampling probe and the filter box were maintained at ambient temperatures, and, then at the stipulated temperature of 250ºF. The objective of this exercise was to ascertain if a non-heated stainless steel transfer tube could be used during "in-use" emissions testing instead of an expensive heated quartz tube. Additionally, tests were performed to investigate the effect of conditioning on the PM filters. The filters, placed in unsealed glass petri dishes, were first conditioned according to the regulatory requirements (CFR 40, Part 86, subpart N) in an environmental chamber for 8 hours and weighed. They were then taken outside the environmental chamber and conditioned to the local conditions in the unsealed petri dishes that permitted humidity exchanges. This was done to mimic the equilibration of in-field test filters in uncontrolled environments (during pre- and post-test). These filters were then used for testing. After the tests were completed, the filters were then allowed to condition under local conditions for two days (to mimic the time required to ship the filters back) and then taken to environmental chamber to undergo conditioning according to regulatory requirements. The filters were then weighed after they had been conditioned to the set humidity and temperature. Thus, the entire sub-test would approximate remote filter usage of filters that were pre- and post-weighed at a laboratory location.

A test matrix for the “modified Method 5 study” is shown in Table 17. A DDC Series 60 engine was selected for the above tests and run at 50% and 75% loads, at intermediate speed.

The aim of the first set of experiments (Test#1 and #2 for the ‘I 50’ engine operating condition, and Test#7 and #8 for the ‘I 75’ engine operating condition) was to determine if a multi-hole sampling nozzle could be used for sampling PM. Instead of the regular gooseneck type sampling nozzle, a three-hole sampling nozzle made of stainless steel was used for the purpose. The holes spanned the diameter of the exhaust pipe and were in line with the engine exhaust. The design is outlined in CFR 40, Part 89, under § 89.412-96. The temperature of the probe and the filter box were the same as in regular Method 5 tests (250°F). The filters were pre-conditioned as required in the Method 5 procedure, that is, the PM filters were placed in glass petri dishes in an environmental control room maintained at 50% RH and 75°F temperature for a period of at least 8 hours before use. The engine was operated at ‘I 50’ (50% load at intermediate speed) and at ‘I 75’ steady-state modes of the ISO 8178 test protocol. Neither the probe catch of the front-half, nor the back-half were extracted. Only the PM mass collected on the filter was compared with the corresponding mass from the dilute CVS system and with the original Method 5 sampling system, for the corresponding engine operating modes. However, it should be noted that the results obtained using the “Modified Method 5 set up” do not include the probe catch of the front half as opposed to the results obtained using the original Method 5 system that did include the probe catch. Based on the values for the probe catch obtained using the original Method 5 system, its contribution can be estimated to be as much as 20 % of the TPM.

In the second set of the experiments (Test#3 and #4 for the ‘I 50’ engine operating condition, and Test#9 and #10 for the ‘I 75’ engine operating condition), the temperature controller for the probe liner and the filter box was shut-off. Other parameters were the same as those in the first set of experiments. The objective was to determine if a simple non-heated stainless steel probe could be used for “in-use” testing. The results obtained in this experiment (multi-hole nozzle + no temperature control) could be compared with those obtained in the first set where the use of a multi-hole nozzle was the only distinguishing feature.

The aim of Test #5 and #6 for the ‘I 50’ engine operating condition, and Test #11 and #12 for the ‘I 75’ engine operating condition was to investigate the possibility of shipping pre-weighed conditioned filters to the test site. The objective of modifying the filter conditioning procedure was to mimic the time involved in shipping the filters (in filter cassettes or filter holders) when the filters are exposed to ambient temperature and humidity. The data from this set of experiments, test # 5, #6, #11, #12 (multi hole nozzle + no temperature control over the probe, filter box + “no pre-conditioning”) can be compared with Test # 3, #4, #9 and #10 (multi hole nozzle + no temperature control over the probe, filter box) respectively.

Table 17 Test Matrix for the “Modified” Method 5 Tests

Mode	Test #	Probe Temperature	Filter box Temperature	Sampling nozzle	Method 5 Filter conditions
I 50	1 Base-line	250°F	250°F	Multihole averaging nozzle.	Pre-conditioned at 50% Relative Humidity and 75°F temperature
	2	Repeat Test # 1			
	3	Ambient temperature	Ambient temperature	Multihole averaging nozzle.	Pre-conditioned at 50% Relative Humidity and 75°F temperature
	4	Repeat Test # 3			
	5	Ambient temperature	Ambient temperature	Multihole averaging nozzle.	“local” (uncontrolled) conditioning for filters
	6	Repeat Test # 5			
I 75	7 Base-line	250°F	250°F	Multihole averaging nozzle.	Pre-conditioned at 50% Relative Humidity and 75°F temperature
	8	Repeat Test # 7			
	9	Ambient temperature	Ambient temperature	Multihole averaging nozzle.	Pre-conditioned at 50% Relative Humidity and 75°F temperature
	10	Repeat Test # 9			
	11	Ambient temperature	Ambient temperature	Multihole averaging nozzle.	“local” (uncontrolled) conditioning for filters
	12	Repeat Test # 11			

3.8 Mobile Emission Measurement System (18)

A Mobile Emission Measurement System (MEMS), designed and developed by WVU, was used for the study. The system was developed for on-board testing of on-highway vehicles. However, the requirements of an emissions measurement system for portable and stationary engines do not differ significantly from those of on-board systems. Basic requirements for a portable emission measurement system to measure emissions from stationary and portable engines are listed in §2.6.1.

The system was evaluated for its ability to provide accurate emissions measurements. Emissions testing on the naturally aspirated, mechanically controlled 50 hp engines such as the Isuzu C 240 impose additional challenges for NO_x measurement because a lack of boost pressure in the intake manifold results in lower concentrations of NO_x in the raw and dilute exhaust. Also, stationary and portable engines usually have lower exhaust flow rates than on-highway engines; hence, flow measurements instruments had to be designed to accurately measure such flow rates.

Some of these evaluations were performed using engines configured for uses other than portable and stationary vocation, such as the electronically controlled DDC Series 60 engine; however, for system evaluation purposes this would not affect conclusions drawn concerning test methodology.

Overview of MEMS

The MEMS, as configured for on-highway vehicles, includes an exhaust flow rate measurement system, an emissions sampling and analysis box, a data acquisition box, and an ambient humidity and barometric pressure measurements box. MEMS measures engine work output through the ECU broadcast and can log vehicle speed and distance through the GPS. The operation of each of these components is discussed in this section. Figure 10 shows the data acquisition and the sample conditioning and analysis systems of MEMS.

Figure 10 Data Acquisition (left) and Sample Conditioning and Analysis Systems (right) of MEMS.

3.8.1 Flow Rate Measurement System

MEMS uses a Dietrich Standard Annubar^{TM} shown in Figure 11 to measure exhaust flow rates. The Annubar^{TM} is a multi-point (holes spanning the diameter of the stack) averaging Pitot tube that works on the principle of Bernoulli's theorem and uses the differential and absolute pressures at a point in the exhaust stream along with exhaust temperature to calculate the flow rate at standard conditions. Figure 11 shows the various probes that were fitted on the exhaust stack to get the emissions data from the MEMS.

The Annubars were calibrated using the Laminar Flow Elements (LFE). The LFE's were calibrated against NIST traceable subsonic venturis by Meriam Instrument Inc (41).

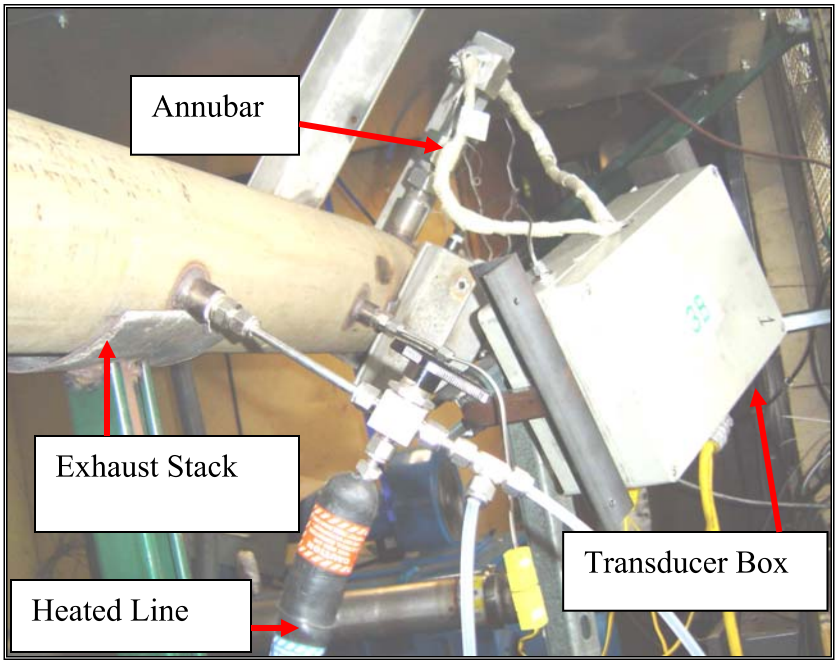

Figure 11 Representation of the Exhaust flow Measurement System Fitted to the Test Engine

3.8.2 Gaseous Sample Conditioning System

The sampling probe that was placed in the exhaust stream complies with the design regulations set in the 40 CFR, Part 89.412.96 (27). The probe is made of stainless steel and has nine holes along the periphery. The probe spans the diameter of the exhaust stack and a sample was drawn from the exhaust stream. Major components of the exhaust sampling system include a heated teflon line, heated filter and a sample pump. A heated teflon sample line was used to transfer the sample from the sample probe to the heated filter that removed particulate matter in the sample. The heated line was maintained at 250°F to prevent condensation of water vapor in the heated line. A MEXA 120 zirconium oxide NO_x sensor from Horiba Inc., was housed in a manifold along with a custom designed NO_x converter and was placed downstream of the heated filter and upstream of the Air Dimensions Inc. Micro Dia-Vaç sample pump.

The purpose of the NO_x converter is to convert NO_2 to NO. NO_2 emissions usually constitute 3%-8% of total engine out NO_x. Catalyzed traps, designed to filter PM in the exhaust, convert NO to NO_2. It has been noted in (17), that the commercially available

NO_x converters are either not very effective in this conversion or consume a large amount of space.

A custom-designed compact Peltier effect based gas chiller was provided downstream of the sample pump to remove moisture from the sample stream, and provided an outlet dew point of approximately 40°F. A differential pressure regulator, in conjunction with needle valves, controlled flow rate to the CO_2 analyzer and the electrochemical NO sensor to 3.0 LPM and 0.5 LPM respectively. A schematic of the sampling system is shown in Figure 12.

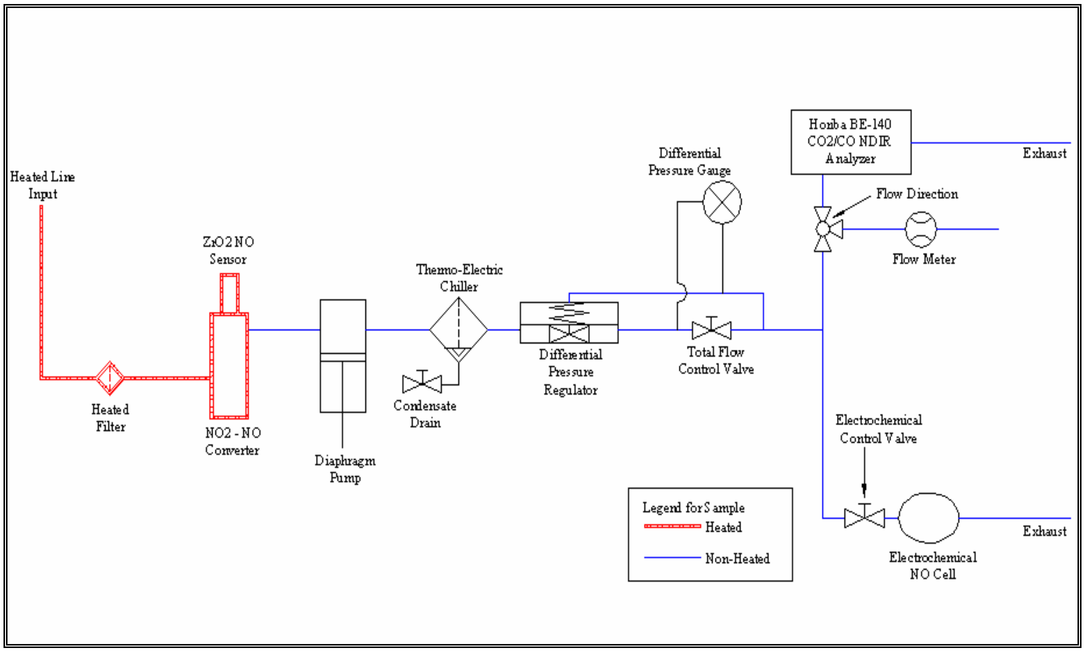

Figure 12 Schematic of the MEMS Sampling System. (17)

Peltier Coolers

Humidity in the exhaust sample was removed by chilling the sample and condensing the moisture. The gas chiller consisted of a thermo-electric chiller (TEC), which is solid-state heat pump that employs the Peltier effect. During operation, DC current flows through the TEC causing heat to be transferred from one side of the TEC to the other, creating a cold and hot side. The thermal energy is transferred from the hot side to a heat sink, which dissipates the heat to the environment. This dissipation of thermal energy present in the sample helps in lowering the dew point temperature and aids in the condensation.

3.8.3 Engine Speed and Torque Measurement

The MEMS uses ECU broadcast to record engine and vehicle speed. The distance traveled was determined with a GPS. The ECU broadcasts engine load on a percent load basis. According to SAE J1587 protocol, the engine speed is to be broadcast at 10 Hz with a resolution of 0.25-rpm and the engine percent load at 10 Hz with a 0.5% resolution (25).

3.8.4 Data Acquisition, Reduction and Archival Subsystem

The Data Acquisition System (DAS) used by MEMS was designed to withstand the vibrations encountered during on-road testing. The DAS was so configured that it can adapt to a wide array of test vehicles and variety of signals.

The DAS was controlled by an Advantech PCM-9570/S single board computer (SBC) running at 850 MHz and supported by a 256 MB RAM. The SBS was configured with PC104 capabilities, which allowed the system to be more modular, and reduced the overall size of the system. The signal conditioning of analog signals were done using a SC-2345 National Instruments signal conditioning system. A National Instruments PCMCIA E-Series DAQ Card-6062 read the conditioned signals. The DAQ card can have up to 16 analog input channels and 12 bits of resolution. The ECU broadcast uses a Dearborn Group Protocol Adapter, DPA III to communicate with the SBC. The DAS also houses the control panel for the Horiba MEXA 120, as well as the keyboard, mouse, and the front panel LCD monitor.

3.8.5 Global Positioning Sensor

The GPS is not required for stationary and portable engine applications. However, it was incorporated into the MEMS to provide a redundant method for measuring vehicle speed along with the broadcasted ECU speed for on-highway applications. A Garmin GPS35 was mounted on each vehicle as part of the MEMS equipments.

3.8.6 Power Supply

The vehicle-mounted generator set fulfilled the power requirements of the current MEMS design. Surge protectors are used for the DAS.

3.8.7 Transducers

Various transducers were used as part of flow measurement system of MEMS. It includes transducers for the measurement of absolute pressure, differential pressure, exhaust gas temperature and ambient relative humidity.

3.8.7.1 Absolute Pressure Transducer

The Omega PX-213 transducer was used to provide absolute pressure measurement for the Annubar flow measurement. The specifications of this transducer are listed in Table 18.

Table 18 Absolute Pressure Transducer Specifications.

General specifications	
Ranges	0-15 psi, 0-30 psi
Accuracy	+/-0.25% FS, includes non-linearity, hysteresis and non-repeatability
Response Time	1 msec
Proof Pressure	150% Full Scale
Pressure Ports	1/4”-18 NPT
Environmental Specifications	
Operating Temperature	-4 to 185 °F
Temperature Error	+/-0.017% FS / °F

3.8.7.2 Differential Pressure Transducer

The Validyne Model P55D differential pressure transducer was selected for the purpose of Annubar flow measurement. The specifications of the P55D transducer are given in Table 19.

Table 19 Differential Pressure Transducer Specifications

General specifications	
Ranges	0-8”, 0-10”, 0-22” H2O
Accuracy	+/-0.25% FS, includes non-linearity, hysteresis and non-repeatability
Overpressure	200% FS up to 4000 psi maximum with less than 0.5% FS output shift
Line Pressure	3200 psig maximum, with zero shift less than 1%/Kpsi
Pressure Ports	1/8” female NPT with 8-32 Bleed Screw & Gasket, STD
Environmental Specifications	
Operating Temperature	-65 to +250 °F
Compensated Temperature	0 to +160 °F (STD) -65 to +250 °F (Extended)
Temperature Error	+/-0.5% FS – STD Range +/-0.75% FS – Extended Range

3.8.7.3 Relative Humidity Transducer

The Omega model HX92-A was used for the purpose of monitoring continuous ambient relative humidity and pressure. A thin-film polymer capacitor senses relative humidity. The transmitter output is linearized and temperature compensated. A stainless steel mesh-wire filter that is easily removable for cleaning protects the sensor. The specifications of this transducer are provided in Table 20.

Table 20 Relative Humidity Transducer Specifications

Input Voltage Range	24 Vdc
Measuring Range	3 to 95%
Temperature	-4 to 167 °F
Accuracy	+/- 2.5% RH from 20 to 80% RH
	+/- 3.1% RH below 20 and above 80% RH
Output Voltage	0 to 1Vdc for 0 to 100% RH
RH Temperature Compensation	-4 to 167 °F
RH Time Constant (90% response at 25° C, in moving air at 1m/s)	>10 seconds, 10 to 90% RH
	>15 seconds, 90 to 10% RH
Repeatability	+/-1% RH, 0.5 °F

3.8.8 Exhaust Gas Analyzers

Oxides of nitrogen (NO_x) and carbon dioxide were identified as the key gaseous pollutants to be measured. Table 21 gives the list of analyzers used, their operation type, the detection device used and their source.

Table 21 Analyzers in MEMS

Source	Horiba Instruments, Inc.	Horiba Instruments, Inc.	Sensors Inc.
Model	BE-140 AD	MEXA-120	AMB-II
Operation Type	NDIR	Zirconium oxide (ZrO_2)	Electrochemical
Detection Device	Solid State Optical	Non-Sampling ZrO_2	Solid State optical
Gases Measured	CO_2	NO_x	NO

3.8.8.1 Carbon Dioxide Analyzer

The BE-140 AD five gas analyzer was used for the measurement of carbon dioxide. The features and the operating principle of the analyzer are mentioned in the following sections.

General Features of BE-140 AD

Based on the principle of non-dispersive infrared analysis, BE-140 AD includes:

- Broad-band infrared light source
- Chopper motor
- Four detectors -- one reference and one each for CO, CO_2, and HC.

Operating Principle of BE-140 AD

Figure 13 provides a schematic of the operating principle of the BE-140 AD analyzer. Light emission from the broad-band infrared light source is passed through the sample cell containing the gases to be analyzed. The gases absorb some of the intensity of the light beam passing through the sample. The attenuated beam modulated by the chopper motor sequentially passes into each of the four detectors. Each detector has a narrow band-pass filter, which isolates a spectral region specific to the corresponding gas (CO, CO_2, or HC). The reference detector is insensitive to all three gases. When a non-absorbing gas (like nitrogen) flows through the sample cell, the same amount of light emission reaches the reference and sample detectors. When absorbing gases (CO, HC, CO_2) flow through the sample cell, less intensity reaches the sample detectors than the reference detector. An electrical signal is produced in proportion to the changes in energy absorption. The difference between sample and reference signals represents concentration of the respective components, and an output is generated.

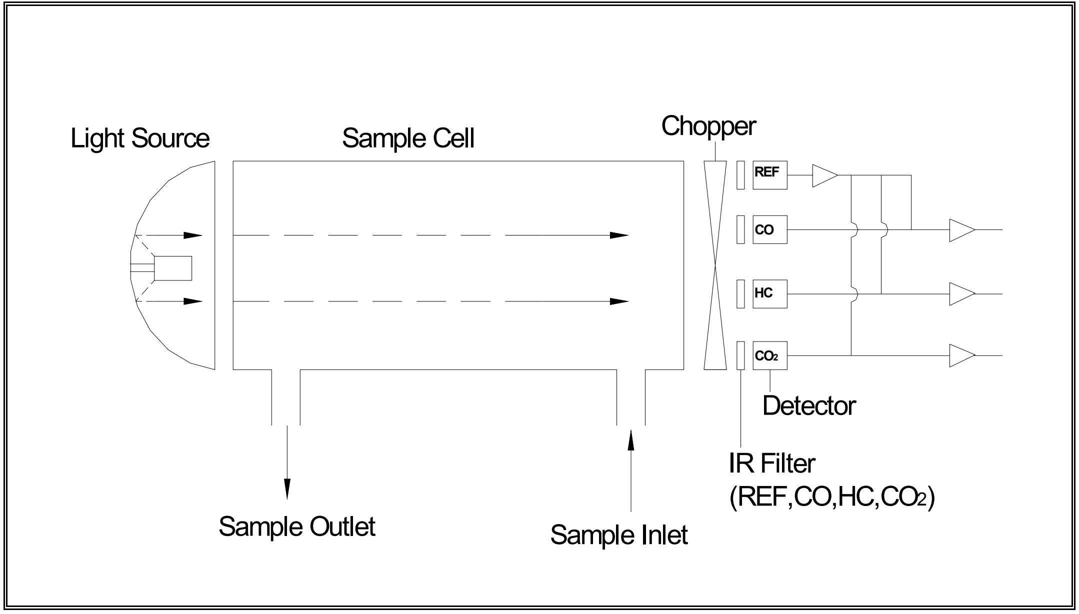

Figure 13 Schematic of the Operating Principle of the BE-140AD Analyzer (18).

3.8.8.2 Oxides of Nitrogen Analyzer

Two analyzers were used for the purpose of measurement of the oxides of nitrogen. One was the MEXA-120 NO_x analyzer from Horiba Inc., and another one was the electro-chemical (EC) NO_x from Sensors Inc. The general features and the operating principle are clearly described below.

General Features of MEXA 120 NO_x

The model MEXA-120 NO_x is a portable analyzer for measuring the NO_x concentrations in exhaust gas streams with its unique sensor made of zirconium oxide ceramic. The main features include:

- Light weight, compact size

- In-situ detection (non-sampling analyzer)
- Fast time response ($T_{90} < 1$ sec)
- Flexible power configuration (12 to 24 V DC, 100 to 240 V AC available)

Table 22 Specifications of MEXA 120 NO_x Analyzer

Ranges	0-5000 ppm
Response Time	T_{90} within 1 s
Accuracy	± 30 ppm or ± 3% of reading, whichever is larger
Warm-up Time	3 minutes
Acceptable Vibration	For sensor: 0-294 m/s^2 0-30 G
Calibration Gas	Calibration gas: NO 50-5000 ppm with H_2O
Sample Gas Conditions	Measurement gas temperature: -7 to 800°C
Ambient Conditions	For main unit: 5 to 45°C; less than 80% R.H.
Dimensions and Weight	W x H x D: 5.9 x 6.0 x 11.3 in , 6.6 lbs
Power	85 to 264 V AC, 12 to 24 V DC, 70 VA
Outputs	Analog: 0-1 V DC or 0-5 V DC, Digital: RS-232C
Accessories	Unit includes: Cable for sensor (10 m)

Operating Principle of MEXA 120 NO_x

Measured gas flows into the first internal cavity through the first diffusion path. Oxygen concentration inside the first internal cavity is kept low, by pumping out oxygen from the cavity. Then, the measured gas diffuses into the second internal cavity. In the second internal cavity, oxygen concentration is kept at a lower value and NO is split into nitrogen and oxygen. Oxygen generated by this reaction is pumped out and NO concentration is calculated by measuring the pumping current.

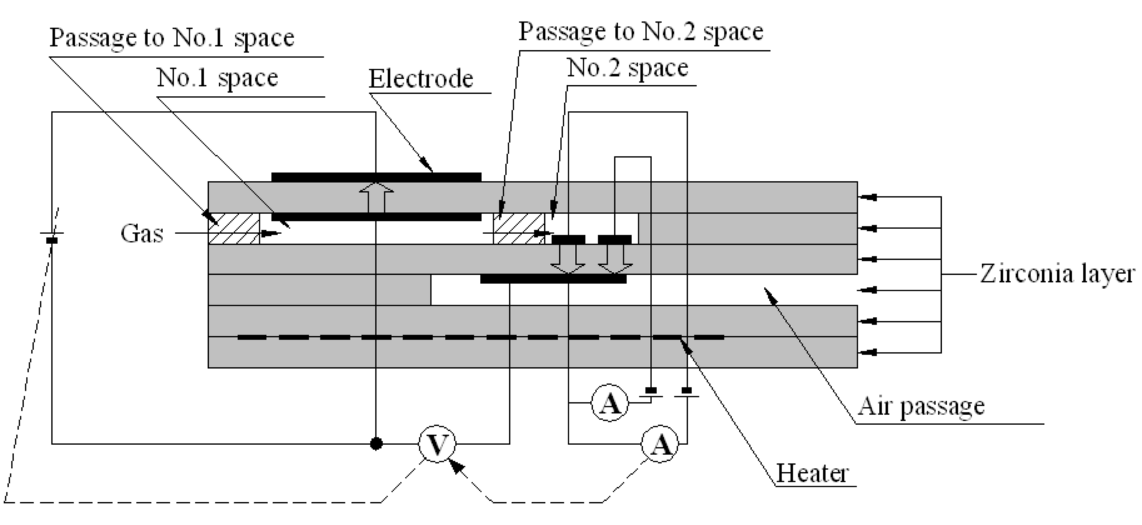

Figure 14 Schematic of the Operating Principle of NO$_x$ Sensor (18).

General Features of Electrochemical NO$_x$

An Electrochemical NO$_x$ sensor was used for collecting redundant NO$_x$ measurements. The electro chemical sensor used in the MEMS meets the BAR 97 specifications.

The system comprises a transducer and a manifold. In addition to the electrochemical sensor, the transducer contains a small lithium battery and a biasing circuit to assure that the sensor is ready to work upon installation. The manifold is designed to protect the transducer from the effects of vibration and shock. The manifold also contains pre-amp electronics that amplify and temperature compensates the transducer signal.

Table 23 Specifications of Electrochemical NO_x Analyzer

Ranges	0-5K ppm (measured as NO)
Response Time	T90 within 12 s
Accuracy	± 25 ppm (absolute or 4% of reading)
Ambient Conditions	35 °F to 115 °F
Zero Drift	± 5 ppm in 24 hours
Span Drift	± 2 % of reading over 8 hours
Repeatability	± 2 % of reading
Noise	Less than 16 ppm (below 1000 ppm)

Operating Principle of Electrochemical NO_x

An electrochemical cell consists of two or more electrodes separated by an electrolyte. For a cell with two electrodes, one of the electrodes needs to be porous so that the gas can pass through it after diffusing through the membrane. A resistor is connected between the two electrodes and voltage drop across the resistor is converted to gas concentration. This is in accordance to Fick's law of diffusion, where 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.

The analyzers were calibrated with a Horiba SGD-710C gas divider using calibration gases that were ± 1% accurate. The concentrations of gases used were dependent on the maximum concentration in the exhaust of the engine being tested.

A Heise™ PTE-1 pressure calibrator and a hand pump were used to calibrate the absolute and differential pressure transducer on the Annubar.

4 Results & Discussion:

This study resulted in the development of an in-the-field test method for stationary and portable engines that will enable determination of compliance with emissions standards for newly manufactured off-road engines as promulgated by either the California Air Resources Board (CARB) or the U.S. Environmental Protection Agency (EPA). The test method and protocols developed in this study will also allow determination of compliance with emission limits established by the Statewide Portable Equipment Registration Program in California. The method is accurate, cost-effective, and reliable and will allow for quantification of emissions from diesel-fueled portable and stationary engines under real-world conditions. Measurement tools discussed in this report, and some of the commercially available tools could be employed for determination of brake-specific emissions.

Recognizing the fact that most stationary and portable engines are mechanically controlled, that is, they do not have any means of broadcasting engine speed and load, the commercially available portable emissions measuring instruments are not equipped to measure brake-specific emissions data from such engines. Also, determination of mass emissions would involve measurement of exhaust flow rate, which is one of the biggest sources of uncertainty in emissions measurements (17). Unfortunately, most stationary and portable engines in the field will not allow ready access to the engine stack for measurement of exhaust flow rates.

Discussed below are data that were generated in the process of evaluating various tools for measuring regulated emissions, conclusions that were drawn from these results, and the development and validation of the “Compliance Factor” approach that was recommended to the CARB as a means of determining compliance of engines in the field.

Both, the Isuzu C 240 and the DDC Series 60 engines were operated over the ISO 8178 8-mode test cycle and brake specific emissions data was collected by the MEMS and the engine laboratory equipment. All engine laboratory data were acquired from diluted exhaust using laboratory grade analyzers, speed sensors and load cell on the dynamometer, and the critical flow venturi related sensors. The MEMS measured raw exhaust mass emissions and combined these with engine speed and load data, retrieved from the engine dynamometer data, to arrive at brake-specific mass emissions data.

This section will present data from one test run of the Isuzu and the DDC engines. Data from additional runs are presented in APPENDIX B.

Table 24 and Table 25 show the weighted-averaged brake-specific emissions of NO_x and CO_2 for the two engines, as measured by the MEMS and the laboratory grade analyzers. NO_x and CO_2 emissions measured by the two systems were within 10% of each other. These small differences between the laboratory data and the MEMS data were observed over repeated runs on both engines. Similar differences were obtained for the mass of either pollutant, on a mode-by-mode basis, that is, in g/mode.

The 8-mode data presented here serves two purposes. First, it validates the use of the MEMS for measuring in-use emissions from stationary and portable engines operating in the field. Second, the brake-specific emissions data presented in this study will serve to support the major recommendation of this study, namely, use of a concentration based compliance factor to determine whether or not an engine is in compliance with the emissions standards.

Testing on the naturally aspirated, mechanically controlled 50 hp engines imposed additional challenges for NO_x measurement because of lack of boost pressure in the intake that resulted in very low concentrations of NO_x in the raw and dilute exhaust. A custom-made flow measurement device, utilizing an averaging Pitot tube, was used to measure exhaust flow rate from the engine. The flow measurement device was designed according to the principles outlined in the Annubar flow handbook (42). The device was calibrated with a 400 cfm laminar flow element from Meriam Instruments (41).

Given all the constraints that challenge the measurement of brake-specific emissions from stationary and portable sources, a compliance monitoring test method that involves the measurement of concentration of the pollutants only is shown below. The equipment necessary to conduct such measurements would also be very inexpensive.

Table 24 ISO 8178 Test Results on Isuzu C240 (Run #1)

Isuzu C 240	Laboratory data						MEMS data		Percent	
	HC	CO	CO_2	NO_x	PM	Work	NO_x	CO_2	NO_x	CO_2
Mode	g/mode					bhp-hr	g/mode		%	
R100	1.2	19.2	2470.0	13.8	-	4.0	13.5	2733.8	2.2	-10.7
R75	6.1	15.8	1901.7	12.1	-	3.0	11.4	2064.4	6.1	-8.6
R50	0.8	8.4	1468.5	8.6	-	2.0	7.9	1583.2	8.4	-7.8
R10	0.7	20.5	911.3	3.6	-	0.2	2.7	839.7	23.9	7.9
I100	0.3	7.2	1812.5	7.0	-	3.1	6.7	2048.9	3.2	-13.0
I75	0.4	8.7	1420.0	8.5	-	2.4	8.7	1613.5	-2.7	-13.6
I50	3.1	22.5	915.8	6.1	-	1.6	8.0	1133.0	-30.1	-23.7
IDLE	59.0	0.4	55.0	0.4	-	0.0	0.4	50.6	5.0	8.0
Weighted Emissions g/bhp-hr	5.1	6.0	669.4	3.7	-		3.7	735.8	2.2	-9.9

Table 25 ISO 8178 Test Results on DDC Series 60 (Run #1)

DDC Series 60	Laboratory data						MEMS data		Percent	
	HC	CO	CO_2	NO_x	PM	Work	NO_x	CO_2	NO_x	CO_2
Mode	g/mode					bhp-hr	g/mode		%	
R100	2.4	24.2	25157.2	414.7	2.6	53.5	404.2	24559.2	2.5	2.4
R75	2.2	13.1	18860.9	353.9	1.9	40.1	349.1	18425.6	1.3	2.3
R50	2.2	13.1	12978.9	287.1	1.5	26.7	273.9	12500.9	4.6	3.7
R10	2.4	7.3	4201.4	75.3	1.8	5.4	71.3	4174.5	5.4	0.6
I100	5.1	37.4	21262.0	313.2	3.9	44.8	311.6	21598.7	0.5	-1.6
I75	1.8	148.9	15852.7	273.6	2.1	33.7	267.7	16320.4	2.2	-3.0
I50	1.0	65.9	10547.3	234.2	0.7	22.5	220.9	10808.4	5.7	-2.5
IDLE	0.3	7.5	334.6	5.6	0.1	0.0	5.9	341.5	-6.0	-2.1
Weighted Emissions g/bhp-hr	0.1	1.2	480.4	8.7	0.1		8.4	476.2	2.7	0.9

4.1 Compliance Factor

Previous uncertainty analysis performed on the MEMS system (17) indicated the major uncertainties involved in the flow measurements. Results (17) have shown that the uncertainty due to flow measurement may be as high as 5% (possibly higher) in certain portions of its map. Hence, alternative methods to quantify exhaust emissions that preferably avoid measurement of exhaust flow rate such as, the Compliance Factor approach (43,44) described in this section are necessary.

The section illustrates the application of this methodology to obtain estimates for Compliance Factor, F using the data gathered from a DDC Series 60 engine that was exercised on multiple ISO 8178 test cycles. The test method thus developed, was then applied to two "in-the-field" engines operated on their regular duty cycle (in-use operation) to obtain the values for the Compliance Factor, F during in-use operation of such engines. This information may be used to simplify the current compliance monitoring procedure for newly manufactured portable and stationary engines.

Let r_1 be the ratio of the mass of NO_x over mass of CO_2. Let r_2 be the ratio of mass of NO_x over mass of fuel consumed. Hence, r_1 is the CO_2-specific ratio and r_2 the fuel specific ratio.

$$r_1 = \frac{NO_X \ mass}{CO_2 \ mass}$$

Equation 4- 1

Using the definition of mass,

Mass = Density x Volume

$$r_1 = \frac{\tilde{C}_{NO_x} \times (MW_{NO_x} / c.f) \times Volume}{\tilde{C}_{CO_2} \times (MW_{CO_2} / c.f) \times Volume}$$

Where $\tilde{C}_{NO_x}$ is the concentration of NO_x in ppm and $\tilde{C}_{CO_2}$ is the concentration of CO_2 in ppm. c.f is the conversion factor that relates molecular weight to density. MW_{NO_x} is the molecular weight of NO_x and MW_{CO_2} is the molecular weight of CO_2. Volume occupied by the gas is measured in scf (standard cubic feet).

Canceling common terms in the numerator and in the denominator, yields,

$$r_1 = \frac{\tilde{C}_{NO_x} \times MW_{NO_x}}{\tilde{C}_{CO_2} \times MW_{CO_2}}$$

Equation 4- 2

$$r_2 = \frac{NO_x \text{ mass}}{\text{fuel mass}}$$

Equation 4- 3

$$r_2 = \frac{NO_x \text{ mass}}{\text{Mass of C} + \text{Mass of H}}$$

Equation 4- 4

The following relation is utilized to calculate the mass of carbon, G_s.

$$G_s = R_2 \times \text{HC mass} + (\frac{12.011}{28.011}) \times \text{CO mass} + (\frac{12.011}{44.011}) \times CO_2 \text{ mass}$$

Equation 4- 5

Where,

G_s = Grams of carbon measured during the test cycle.

HC mass = Grams of hydrocarbon emissions measured during the test cycle.

CO mass = Grams of carbon monoxide emissions measured during the test cycle.

R_2 = Grams of carbon in the fuel per gram of fuel.

Neglecting the contributions of HC and CO results in:

$$G_s = \text{Mass of C} = (\frac{12.011}{44.011}) \times CO_2 \text{ mass}$$

Equation 4- 6

Continuing, to calculate mass of H, the following relationship is used:

Mass = (Molecular weight × Number of moles)

Mass of H = 1.008 × (Number of moles of H).

The H/C ratio (α) of the fuel (expressed in moles of H per mole of C) is known and if the total number of moles of C is also known, then the total number of moles of H can be determined. Therefore,

$$\text{Mass of H} = 1.008 \times (\alpha \text{ moles H / mole C}) \times \text{Moles C}$$

Where, 'α' is the H/C ratio of the fuel, expressed in moles H/mole C. However,

$$\text{Moles C} = \frac{\text{Mass of C}}{MW_C}$$

Equation 4- 7

$$\frac{\text{Mass C}}{MW_C} = \frac{\frac{12.011}{44.011} \times (\tilde{C}_{CO_2} \times \frac{44.011}{\text{c.f}}) \times \text{Volume}}{12.011}$$

Canceling common terms,

$$\text{Moles C} = \frac{\text{Mass C}}{\text{MW}_\text{C}} = \frac{\tilde{C}_{CO_2}}{\text{c.f}} \times \text{Volume}$$ **Equation 4- 8**

$$\therefore \text{Mass of H} = 1.008 \times \alpha \times \frac{\tilde{C}_{CO_2}}{\text{c.f}} \times \text{Volume}$$ **Equation 4- 9**

Substituting the values for mass of NO_x, mass of C and mass of H in the equation for r_2,

$$r_2 = \frac{\tilde{C}_{NO_x} \times (\text{MW}_{NO_x} / \text{c.f}) \times \text{Volume}}{(\frac{12.011}{44.011}) \times CO_2 \text{ mass} + 1.008 \times \alpha \times (\frac{\tilde{C}_{CO_2}}{\text{c.f}}) \times \text{Volume}}$$

Again CO_2 mass can now be in turn expressed as,

$$CO_2 \text{ mass} = \tilde{C}_{CO_2} \times \frac{\text{MW}_{CO_2}}{\text{c.f}} \times \text{Volume}$$ **Equation 4- 10**

Hence, r_2 may be rewritten as

$$r_2 = \frac{\tilde{C}_{NO_x} \times (\text{MW}_{NO_x} / \text{c.f}) \times \text{Volume}}{(\frac{12.011}{44.011}) \times \tilde{C}_{CO_2} \times \frac{\text{MW}_{CO_2}}{\text{c.f}} \times \text{Volume} + 1.008 \times \alpha \times (\frac{\tilde{C}_{CO_2}}{\text{c.f}}) \times \text{Volume}}$$

Canceling common terms, yields

$$r_2 = \frac{\tilde{C}_{NO_x} \times \text{MW}_{NO_x}}{12.011 \times \tilde{C}_{CO_2} + 1.008 \times \alpha \times \tilde{C}_{CO_2}}$$

that is,

$$r_2 = \frac{\tilde{C}_{NO_x} \times \text{MW}_{NO_x}}{(12.011 + 1.008 \times \alpha) \times \tilde{C}_{CO_2}}$$ **Equation 4- 11**

Considering the ratio $\frac{r_2}{r_1}$,

$$\frac{r_2}{r_1} = \frac{\dfrac{\tilde{C}_{NO_x} \times MW_{NO_x}}{(12.011 + 1.008 \times \alpha) \times \tilde{C}_{CO_2}}}{\dfrac{\tilde{C}_{NO_x} \times MW_{NO_x}}{\tilde{C}_{CO_2} \times MW_{CO_2}}}$$

$$\frac{r_2}{r_1} = \frac{MW_{CO_2}}{12.011 + 1.008 \times \alpha}$$ **Equation 4- 12**

Assuming an α of 1.85 and MW_{CO_2} as 44.011,

$$\frac{r_2}{r_1} = \frac{44.011}{12.011 + 1.008 \times 1.85} = 3.1717$$ **Equation 4- 13**

The CO_2-specific ratio, r_1, may be used to represent a ratio of brake specific mass emissions of the pollutants (since a ratio of two brake-specific terms essentially reduces to a ratio of pollutant concentrations). The fuel specific ratio, r_2, represents ratio of the mass of NO_x emitted per mass of fuel consumed and can also be calculated using only pollutant concentrations. The value 3.1717, can be applied to obtain these ratios interchangeably, that is, if the ratio r_1 is given, then the ratio r_2 can be estimated and vice versa.

The following tables provide an illustration of the methodology of the test method. A Compliance Factor, F was introduced as the ratio of the In-field pollutant ratio (I) and the Certification ratio (C). The In-field pollutant ratio is defined as the ratio of mass emissions of NO_x to the mass emissions of CO_2, for each in-field operation (or each steady state operation mode, as in the case of an ISO 8178 test cycle) and is determined using either the r_1 relation or the r_2 relation. The Certification ratio (C) is defined as the ratio of brake specific NO_x (weighted) mass emissions to brake specific CO_2 (weighted) mass emissions, each measured over an entire 8-mode cycle. Hence, C is obtained either from the laboratory evaluation of the engine on the ISO 8178 test cycle or from the emissions data gathered from the manufacturer.

Hence,

$$F = \frac{I}{C}$$ **Equation 4- 14**

$$I = \frac{(\mathrm{NO_x\ mass\ \ emissions})_{\text{In-field Operation}}}{(\mathrm{CO_2\ mass\ \ emissions})_{\text{In-field Operation}}}$$ **Equation 4- 15**

$$C = \frac{(\mathrm{NO_x\ mass\ emissions})_{\text{ISO 8178 test cycle}}}{(\mathrm{CO_2 mass\ emissions})_{\text{ISO 8178 test cycle}}}$$

As shown in Equation 4-11, the fuel specific ratio (r_2) of the pollutant concentrations finally reduces to

$$r_2 = \frac{\tilde{C}_{NO_x} \times MW_{NO_x}}{(12.011 + 1.008 \times \alpha) \times \tilde{C}_{CO_2}}$$

The multiplier for $\tilde{C}_{CO_2}$ $([12.011+1.008\times 1.85])$ is now termed as Carbon Molar Weight (CMW) multiplier and is defined as molecular weight of the fuel normalized by the number of moles of carbon. This is done to distinguish this multiplier from the multiplier used in the denominator of the ratio r_1 (molecular weight of CO_2). Hence,

$$r_2 = I = \frac{\tilde{C}_{NO_x} \times MW_{NO_x}}{\tilde{C}_{CO_2} \times CMW}$$ **Equation 4- 16**

The reason for expressing the Certification ratio, C, as a ratio of brake specific emissions is the difficulty associated in obtaining concentration specific data from the manufacturer. However, the In-field pollutant ratio, I, obtained using either the r_1 (CO_2-specific ratio) relation or the r_2 (fuel specific ratio) relation, is calculated using "in-field" concentration data of NO_x and CO_2. In this study, "in-field" concentration data was obtained from MEMS. Concentration data is more reliable than the brake specific data due to errors associated in exhaust flow rate and work output measurements

Reiterating, the In-field pollutant ratio (I) required for the calculation of the Compliance Factor, F was obtained from the MEMS. The certification ratio (C) was obtained from the lab. Hence, the Compliance Factor, F is the ratio of I (obtained from MEMS) over C (obtained from lab). The ratio r_1 requires the concentration of CO_2 to be multiplied by its molecular weight. The ratio r_2 requires the concentration of CO_2 to be multiplied by a constant, CMW. Accordingly, the Infield pollutant ratio, I and hence, Compliance Factor F, is derived separately using the ratios r_1 and r_2, and is shown in Table 26 through Table 31.

4.2 Application of Compliance Factors for ISO 8178 Tests on an Isuzu C 240 and a DDC Series 60 Engines

Table 26 through Table 31 show test method related data from the 8-mode tests that were conducted on the C 240 and Series 60 engines. Data presented in each table demonstrates the validity and the viability of this method that could be implemented to measure in-field engine emissions.

Table 26 illustrates the application of this test method on the DDC Series 60 engine and includes concentrations of CO_2 and NO_x in undiluted exhaust for each of the 8 modes. These concentrations were reported by MEMS. For illustration of the test method, CO_2 concentrations have not been corrected for moisture in the sample. Similarly, NO_x concentrations have not been corrected for humidity in the engine intake air. In-field ratios (I) were calculated for each steady-state mode of a test, where as, the Certification ratios (ISO 8178 averaged brake-specific NO_x/CO_2 ratio) were calculated for the entire test. For example, in Table 26, for the 'R100' engine operating condition of the DDC Series 60 engine, a fuel-specific In-field ratio was obtained by dividing the product-concentration of NO_x * Molecular Weight of NO_x with the product-concentration of CO_2 * 'Carbon Molar Weight' of CO_2. Hence, the number 50772 was divided by the number 1109264 to yield an Infield ratio of 0.046. Likewise, a CO_2-specific In-field ratio, I, was obtained by dividing the product-concentration of NO_x * Molecular Weight of NO_x with the product-concentration of CO_2 * Molecular Weight of CO_2. Hence, the number 50772.0 was divided by the number 3520880.0 to yield 0.014 as the In-field ratio for the 'R100' condition. The Certification ratio, C, of 0.018 for the first run of the ISO 8178 test cycle, was obtained by dividing the number 8.67 (weighted NO_x in g/bhp-hr in Table 25) by the number 480.44 (weighted CO_2 in g/bhp-hr in Table 25). However, for an actual in-field test, a manufacturer-supplied (for the particular engine model year) Certification ratio may be used. A ratio of 'I' over 'C' yields the Compliance Factor, F for the 'R100' engine operating condition. Compliance Factors for other engine operating conditions and for the subsequent runs are shown in Table 26 through Table 31 for both engines. Figure 15 and Figure 16 illustrate the mean CO_2-specific Compliance Factors for each operating mode and the mean fuel-specific Compliance Factors for each operating mode of the DDC Series 60 engine. The error represents two standard deviations or 95% confidence level. As shown in Table 28, CO_2-specific ‘F’ values for the Isuzu C 240 engine operated over the ISO 8178 cycle were found to range from 0.64 (at Intermediate speed and 100% load) to 1.25 (idle condition). Corresponding F values, obtained using fuel-specific I values, are presented in Table 29. Each table shows multiple F values; one for each mode. The 8-mode test was helpful in that each mode could be considered as an independent in-field operation of the engine. Generally speaking, it could be assumed that one or more of the 8 modes of this steady-state cycle could represent an in-field engine operation, due to the largely steady-state vocations performed by portable and stationary engines. This provided an opportunity to evaluate several F-values for the same engine test run. It should be noted that the fuel-specific and CO_2-specific Compliance Factors differ by 3.1717.

Table 51 through Table 59 in APPENDIX B show multiple repeats and analyses of the 8-mode results for the Isuzu C 240 and DDC Series 60 engines.

Table 26 Illustration of the Test Method on a DDC Series 60 Engine Operated on an ISO 8178 Test Cycle

DDC Series 60 8 mode Run 1- MEMS Data						Fuel Specific Compliance	
ISO 8178 mode	CO_2	NO_x	CO_2 * CMW	NO_x * MW	I	Certification Ratio C	Compliance Factor F
	ppm	ppm					
R100	80000.0	1103.5	1109264.0	50772.0	0.046	0.018	2.54
R75	73600.0	1160.0	1020522.9	53371.6	0.052		2.90
R50	63200.0	1160.0	876318.6	53371.6	0.061		3.37
R10	26548.0	415.0	368109.3	19094.2	0.052		2.87
I100	103000.0	1170.0	1428177.4	53831.7	0.038		2.09
I75	94800.0	1250.0	1314477.8	57512.5	0.044		2.42
I50	80447.0	1346.9	1115462.0	61968.9	0.056		3.08
Idle	13016.0	198.5	180477.3	9134.9	0.051		2.80

Table 27 Illustration of the Test Method on a DDC Series 60 Engine Operated on an ISO 8178 Test Cycle (Contd..)

DDC Series 60 8 mode Run 1- MEMS Data						CO_2 Specific Compliance		
ISO 8178 mode	CO_2	NO_x	CO_2 * MW	NO_x * MW	I	Certification Ratio C	Compliance Factor F
	ppm	ppm					
R100	80000.0	1103.5	3520880.0	50772.0	0.014	0.018	0.80
R75	73600.0	1160.0	3239209.6	53371.6	0.016		0.91
R50	63200.0	1160.0	2781495.2	53371.6	0.019		1.06
R10	26548.0	415.0	1168404.0	19094.2	0.016		0.91
I100	103000.0	1170.0	4533133.0	53831.7	0.012		0.66
I75	94800.0	1250.0	4172242.8	57512.5	0.014		0.76
I50	80447.0	1346.9	3540552.9	61968.9	0.018		0.97
Idle	13016.0	198.5	572847.2	9134.9	0.016		0.88

Table 28 “Modal” CO_2- Specific Compliance Factors for the Isuzu C 240 Engine

CO_2-Specific Compliance Factors for the Isuzu C 240 Engine on the ISO-8178 Test Cycle								
Mode	Run1	Run2	Run3	Run4	Mean	Std dev	CoV (%)	Range
R 100	0.79	0.72	1.04	1.05	0.90	0.17	18.6	0.33
R 75	0.90	0.83	1.31	1.30	1.08	0.25	23.5	0.48
R 50	0.84	0.81	1.34	1.29	1.07	0.29	26.7	0.53
R 10	0.58	0.48	0.85	0.83	0.69	0.19	27.0	0.37
I 100	0.53	0.51	0.75	0.77	0.64	0.14	21.5	0.26
I 75	0.89	0.85	1.17	1.14	1.01	0.16	16.2	0.32
I 50	1.24	1.08	1.22	1.35	1.22	0.11	9.1	0.27
IDLE	1.29	1.15	1.33	1.24	1.25	0.08	6.3	0.18

Table 29 “Modal” Fuel-Specific Compliance Factors for the Isuzu C 240 Engine

Fuel-Specific Compliance Factors for the Isuzu C 240 Engine on the ISO-8178 Test Cycle								
Mode	Run1	Run2	Run3	Run4	Mean	Std dev	CoV (%)	Range
R 100	2.51	2.29	3.29	3.33	2.85	0.53	18.62	1.04
R 75	2.87	2.63	4.15	4.13	3.44	0.81	23.48	1.52
R 50	2.67	2.57	4.26	4.11	3.40	0.91	26.71	1.70
R 10	1.85	1.52	2.70	2.65	2.18	0.59	26.99	1.18
I 100	1.69	1.61	2.38	2.43	2.03	0.44	21.50	0.82
I 75	2.83	2.71	3.72	3.60	3.22	0.52	16.18	1.01
I 50	3.94	3.42	3.88	4.28	3.88	0.35	9.11	0.86
IDLE	4.10	3.65	4.23	3.93	3.98	0.25	6.34	0.58

Table 30 “Modal” CO_2-Specific Compliance Factors for the DDC Series 60 Engine

CO_2-Specific Compliance Factors for the DDC Series 60 Engine on the ISO-8178 Test Cycle							
Mode	Run1	Run2	Run3	Mean	Std dev	CoV	Range
R 100	0.80	0.90	0.97	0.89	0.09	9.72	0.17
R 75	0.91	1.00	0.99	0.97	0.05	4.97	0.09
R 50	1.06	1.20	1.01	1.09	0.10	8.79	0.19
R 10	0.91	0.99	1.11	1.00	0.10	10.42	0.21
I 100	0.66	0.72	0.80	0.73	0.07	9.83	0.14
I 75	0.76	0.83	0.88	0.83	0.06	7.20	0.12
I 50	0.97	1.04	1.11	1.04	0.07	6.58	0.14
IDLE	0.88	1.20	1.20	1.10	0.19	16.87	0.32

Table 31 “Modal” Fuel-Specific Compliance Factors for the DDC Series 60 Engine

Fuel-Specific Compliance Factors for the DDC Series 60 Engine on the ISO-8178 Test Cycle							
Mode	Run1	Run2	Run3	Mean	Std dev	CoV	Range
R 100	2.54	2.86	3.08	2.83	0.27	9.72	0.55
R 75	2.90	3.17	3.15	3.07	0.15	4.97	0.28
R 50	3.37	3.80	3.21	3.46	0.30	8.79	0.59
R 10	2.87	3.13	3.53	3.18	0.33	10.42	0.66
I 100	2.09	2.30	2.54	2.31	0.23	9.83	0.45
I 75	2.42	2.64	2.80	2.62	0.19	7.20	0.38
I 50	3.08	3.31	3.51	3.30	0.22	6.58	0.43
IDLE	2.80	3.82	3.82	3.48	0.59	16.87	1.02

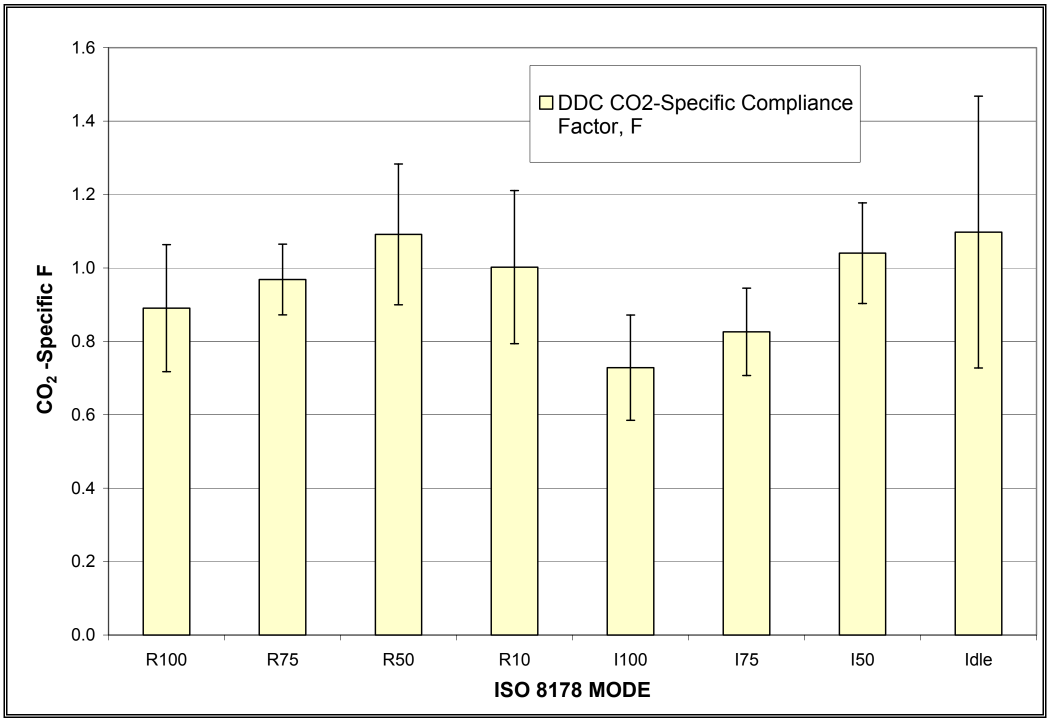

Figure 15 “Modal” CO_2-Specific Compliance Factors for the DDC Series 60 Engine

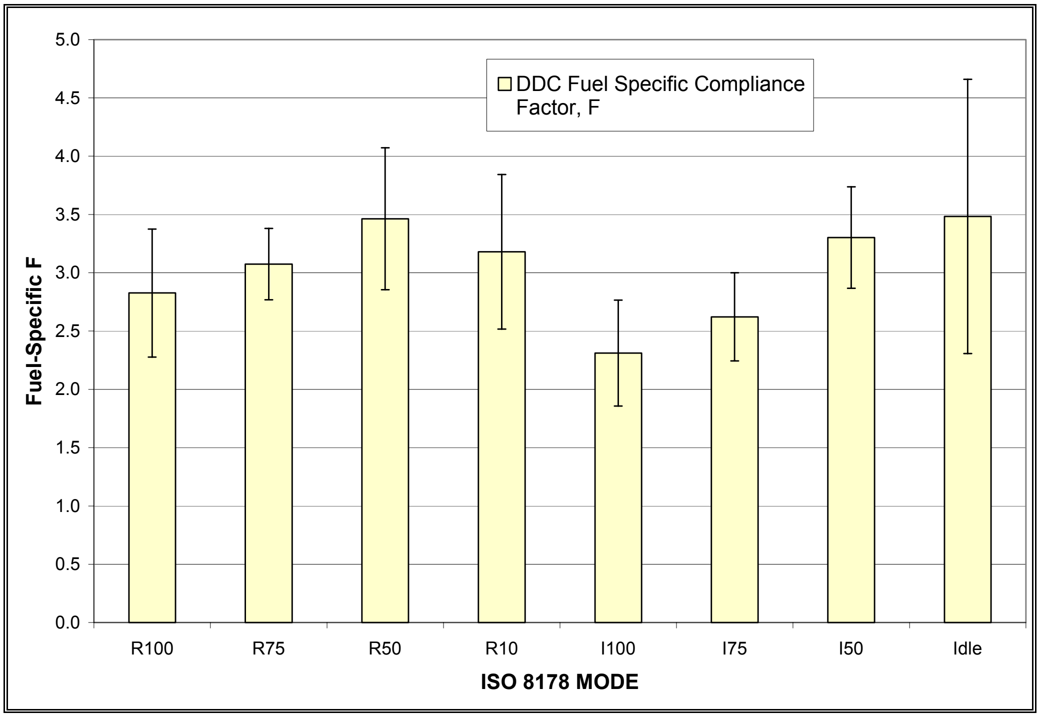

Figure 16 “Modal” Fuel-Specific Compliance Factors for the DDC Series 60 Engine

Compliance Factor - Field Tests

The data shown below was recorded from two in-field test engines (MY 1990 Isuzu QD 100 and MY 2001 Perkins engines) during their in-use duty cycle. The application of the test method is shown in Table 34 through Table 37. The In-field pollutant ratio (I) was obtained using MEMS. Since certification data for the two in-field test engines was not available from the manufacturer, a Certification ratio that may be expected to be close to the certification ratio of the test engines was utilized, for demonstration of the application of the test method. The Certification ratio (C) was obtained from the laboratory evaluation of the Isuzu C 240 engine. The Isuzu C 240 that was tested has the same horsepower rating as the Isuzu QD 100 (56 hp) and is comparable with the Perkins (70 hp) engine. Actual in-use evaluation of such engines will require the manufacturer to report the brake specific based Certification ratio (C).

Table 32 In-use Test Results for the Perkins Engine.

IN-USE TEST RESULTS ON 2001 Perkins										
Engine	Run #	Laboratory Data					MEMS Data		Percent diff	
		CO_2	NO_x	HC	CO	PM	CO_2	NO_x	CO_2	NO_X
		g/s	g/s	g/s	g/s	g/s	g/s	g/s		
MY 2001 Perkins	Run1	5.278	0.071	0.003	0.009	N/A	5.304	0.067	0.48	-5.42
	Run2	5.396	0.071	0.003	0.009	N/A	5.420	0.065	0.45	-8.34
	Run3	5.683	0.067	0.004	0.010	0.004	5.396	0.064	-5.06	-4.27
	Run4	5.740	0.063	0.004	0.010	0.003	5.692	0.061	-0.82	-3.72

Table 33 In-use Test Results for Isuzu QD 100 Engine.

IN-USE TEST RESULTS ON ISUZU QD 100										
Engine	Run #	Laboratory Data					MEMS Data		Percent diff	
		CO_2	NO_x	HC	CO	PM	CO_2	NO_x	CO_2	NO_X
		g/s	g/s	g/s	g/s	g/s	g/s	g/s		
MY 1990 Isuzu QD100	Run1	4.808	0.080	0.009	0.012	N/A	4.723	0.077	-1.77	-4.15
	Run2	4.701	0.081	0.008	0.013	N/A	4.706	0.072	0.12	-10.85
	Run3	5.072	0.081	0.008	0.011	0.008	4.917	0.072	-3.06	-11.19
	Run4	4.982	0.079	0.008	0.011	0.004	4.814	0.073	-3.38	-8.33

Table 34 Application of the Test Method on the Perkins Engine, Using Fuel-Specific In-field Pollutant Ratio, I.

Engine	Run #	Fuel-specific compliance - MEMS data						
		CO_2	NO_x	CO_2 * CMW	NO_x * MW	In-field pollutant Ratio I	Certification ratio C	Compliance Factor F
		ppm	ppm					
MY 2001 Perkins	Run1	64100.1	791.6	888799.0	36423.0	0.041	0.006	6.83
	Run2	64727.0	755.3	897492.3	34750.5	0.039		6.45
	Run3	66332.5	743.8	919752.7	34220.9	0.037		6.20
	Run4	67974.0	736.0	942513.8	33863.7	0.036		5.99

In Table 32 and in Table 33, the in-use PM was collected for two runs and was measured gravimetrically. The mass emission rate of all the pollutants was expressed in g/s (grams/second) due to the lack of means in measuring power from mechanically controlled engines. Hence, mass emissions data in g/bhp-hr are not presented. Also, the mass emission rate (g/s) of PM, in particular, was derived using the ratio of g/cycle to the total test length. As the in-use operation was a transient cycle (with several steady state modes in between), the unit g/s, represents average mass emission rate of the pollutant over the entire cycle instead of the average instantaneous mass emission rate (as in the case of a steady state test when emissions are expressed on a modal basis).

Table 35 Application of the Test Method on the Isuzu QD 100 Engine, Using Fuel-Specific In-field Pollutant Ratio, I.

Engine	Run #	Fuel-specific compliance - MEMS data						
		CO_2	NO_x	CO_2 * CMW	NO_x * MW	In-field Pollutant ratio I	Certification ratio C	Compliance factor F
		ppm	ppm					
MY 1990 Isuzu QD100	Run1	54101.1	869.4	750154.5	40000.6	0.053	0.006	8.89
	Run2	54500.0	812.6	755686.1	37387.3	0.049		8.25
	Run3	57678.9	861.7	799763.7	39648.4	0.050		8.26
	Run4	57500.0	897.0	797283.5	41270.1	0.052		8.63

Table 34 and Table 35 demonstrate the application of the test method on the two ‘in-field’ engines. Compliance Factor, F, was obtained using the fuel-specific relation for the In-field pollutant ratio, I. Table 36 and Table 37 also demonstrate the application of the test method where in the Compliance Factor, F, was calculated using the CO_2-specific In-field pollutant ratio. Again, the difference in corresponding compliance factors is approximately 3.1717.

Table 36 Application of the Test Method on the Perkins Engine, Using CO_2-Specific In-field Pollutant Ratio, I.

Engine	Run #	CO_2-specific-compliance - MEMS data						
		CO_2	NO_x	CO_2 * MW	NO_x * MW	In-field pollutant Ratio I	Certification ratio C	Compliance Factor F
		ppm	ppm					
MY 2001 Perkins	Run1	64100.1	791.6	2821109.0	36423.0	0.013	0.006	2.15
	Run2	64727.0	755.3	2848702.1	34750.5	0.012		2.03
	Run3	66332.5	743.8	2919358.3	34220.9	0.012		1.95
	Run4	67974.0	736.0	2991603.3	33863.7	0.011		1.89

Table 37 Application of the Test Method on the Isuzu QD 100 Engine, Using CO_2-Specific In-field Pollutant Ratio, I.

Engine	Run #	CO_2-specific compliance - MEMS data						
		CO_2	NO_x	CO_2 * MW	NO_x * MW	In-field Pollutant ratio I	Certification ratio C	Compliance factor F
		ppm	ppm					
MY 1990 Isuzu QD100	Run1	54101.1	869.4	2381041.9	40000.6	0.017	0.006	2.80
	Run2	54500.0	812.6	2398599.5	37387.3	0.016		2.60
	Run3	57678.9	861.7	2538504.9	39648.4	0.016		2.60
	Run4	57500.0	897.0	2530632.5	41270.1	0.016		2.72

4.3 Summary of In-Use Compliance Factor Approach

Table 26 through Table 31 show Compliance Factor, F, for the two laboratory phase test engines. Table 34 through Table 37, show the Compliance Factor, F, for the two “in-field” phase test engines. Two different ranges of Compliance Factor were obtained based on the choice of expression for the In-field pollutant ratio, I, that is, ‘F’ was obtained using the CO_2-specific as well as the fuel-specific relations for the In-field pollutant ratio, I. The Certification ratio, C, is brake specific emissions based and was obtained from the laboratory evaluation of the respective engines on the ISO 8178 cycle.

It is rather intuitive that either r_1 (CO_2-specific emissions based ratio) or r_2 (fuel-specific emissions based ratio) relations could be used interchangeably without sacrificing consistency of the proposed methodology, but merely resulting in a different absolute value for I and hence, F. Needless to say, each of the corresponding Compliance Factors in Table 28 through Table 31, differ by approximately 3.1717, as supported by Equation 4-13. The Compliance Factors for the in-field test engines also yielded similar results.

The resulting Compliance Factor (F), would then necessarily need to be compared with some established compliance criteria promulgated by a regulatory agency. Obviously, the establishment of such a value would involve increased future research efforts, which are outlined in § 5.1.4. The development and implementation of this compliance criteria would need to account for various stochastic tolerances of all components involved, namely, testing methodology, test equipment, engine deterioration, and certification laboratory variability. The sensitivity of the compliance criteria would need to be studied to prevent false test positives. Only after a thorough investigation of total compliance variability could this compliance criteria value be established to which the Compliance Factor could be compared with to identify non-compliant performance of an in-use engine. This value could be tailor-matched to different engine applications, based on size, vocation, etc.

4.4 METHOD 5: Determination of Total Particulate Matter (TPM):

Re-iterating the discussion that was presented in the Experimental Equipment and Procedures Chapter, the ARB Method 5 document defines PM as "any material that condenses at or above the filtration temperature, determined gravimetrically after removal of uncombined water." According to the ARB Method 5, matter that is liquid at standard temperature must be included in the determination of TPM. This matter is assumed to pass as gas through the filter and condenses in the impingers. Hence, "impinger catch" and "impinger catch extract," together termed as the "back half," is included in the determination of TPM.

It should be noted that other regulatory bodies, such as the US EPA, do not consider the back half for determination of TPM. Only the front half, that is, the "probe catch" and the "filter catch" are required to define TPM.

The Method 5 test results are shown below. Of the eight steady state modes that are part of an ISO 8178 test, two modes were chosen for collecting PM using the Method 5 equipment. The choice of the two modes was based on the total mass of PM desired, and the limitations imposed by the range of the pressure transducer in the Method 5 system. Additionally, attempts were also made to operate the engine in a "wet mode" (high soluble organic fraction) and a "dry mode" (PM emissions would be dominated by elemental carbon). The results show good correlation with the laboratory procedure of measuring TPM when the back half extraction (BHE) is excluded from PM determination. Although the Method 5 analysis could be employed for measuring PM from stationary and portable engines operating in the field, its use for inspection and maintenance type compliance testing appears to be highly impractical.

The following tables gives a comparison of the Method 5 data with the laboratory data with and without the back half extraction (BHE) for the Isuzu C 240 and DDC Series 60 engines. Table 38 and Table 39 show that the PM emissions captured with the Method 5 sampling train were in good agreement with the regulatory method utilizing the CVS, when the BHE is not included in PM mass analysis for the Method 5 procedure, as specified by the EPA. PM emissions for the two methods were within 8 percent at the R100 operating condition, without the back-half. The 'R100' mode is expected to generate relatively smaller amounts of SOF. However, with the back-half extraction included in the Method 5 PM mass calculations, the differences in the two methods deviate by as much as 73% for 'R100' condition. Similar results were observed at the 'I100' condition. Without the back-half, the PM emissions measured by the Method 5 sampling train and the CVS system differed by less than 10%. The differences exceeded 90%, in one of the replicates, when the back-half was included for the 'I100' engine operating condition.

PM results from the DDC Series 60 engine show that with the exception of one of the three runs at 'I50', the brake-specific PM measured by the two methods differed by less than 5%, provided the back-half was not included. The differences were less than 8% for the 'I75' mode, as well. Again, inclusion of the back-half resulted in differences in excess of 30% between the brake-specific PM emissions measured by the Method 5 sampling train and the CVS method for the 'I75' operating condition.

Results obtained in this study are in good agreement with those obtained by CE-CERT, University of California, Riverside under a CARB funded program (40). Recognizing the fact that all diesel engines are certified for PM emissions using a diluted exhaust, the following is being suggested for in-field PM emissions measurement:

- A diluted exhaust sample may be used to collect samples on a filter for gravimetric analysis. A partial flow dilution tunnel may be used for the purpose (7).
- The Method 5 may be used, if necessary, but only the front half needs to be included to satisfy "equivalency" with the CVS based certification data.

Based upon the results obtained above, the following modifications were carried out to simplify the use of Method 5 sampling system in the field:

- Replaced the gooseneck nozzle with a multi-hole nozzle that spanned the diameter of the exhaust stack.
- Reduced the probe temperature from 250°F to ambient conditions
- Investigated the effect of "uncontrolled/ local" conditioning on the PM filters, that is, conditioning the filters per regulatory requirements, weighing the filters, placing the filters in petri dishes and exposing them to ambient conditions before and after the test (to simulate the process of shipping the filters to and from the test site) followed by re-conditioning per regulatory requirements prior to the post-test weighing exercise. This exercise will be referred to as " local conditioning of filters" in the remainder of the text.

The "Modified Method 5" procedure and the test results are discussed below.

Table 38 Method 5 Results on Isuzu C 240 Engine

Isuzu C 240	METHOD 5 DATA							CVS Data	Percent Error	
	Probe catch (mg)	Filter catch (mg)	Impinger catch (mg)	Impinger catch extract (mg)	Raw exhaust flow rate (scfm)	TPM (g/bhp-hr) W/O BHE	TPM (g/bhp-hr) With BHE	TPM (g/bhp-hr)	w/o BHE	With BHE
R 100										
Run 1	7.6	17.8	16.1	2.3	102.01	0.119	0.205	0.129	-7.8	58.9
Run 2	7.9	20	17.1	4.6	101	0.13	0.232	0.134	-3.0	73.1
Run 3	7	22.4	18.6	4.2	103.4	0.132	0.225	0.136	-2.9	65.4
I 100										
Run 1	6.4	25.5	18.1	0.4	82.5	0.149	0.235	0.155	-3.9	51.6
Run 2	8.4	27.3	14.1	1.5	79.3	0.158	0.228	0.151	4.6	51.0
Run 3	8	20.8	17.3	3.9	88.4	0.154	0.268	0.14	10.0	91.4

Table 39 Method 5 Results on the DDC Series 60 Engine

DDC Series 60	METHOD 5 DATA							CVS DATA	Percent Error	
	Probe catch (mg)	Filter catch (mg)	Impinger catch (mg)	Impinger catch extract (mg)	Raw exhaust flow rate (scfm)	TPM (g/bhp-hr) W/O BHE	TPM (g/bhp-hr) With BHE	TPM (g/bhp-hr)	w/o BHE	With BHE
I 50										
Run 1	2.4	9.1	6.1	7.1	325.5	0.040	0.086	0.038	4.4	124.2
Run 2	3.9	7.2	5.1	6.8	335.5	0.040	0.084	0.040	0.1	107.5
Run 3	2.9	5.3	3.4	2.5	320.2	0.029	0.047	0.036	-19.9	31.9
I 75										
Run 1	2.4	14.5	3.8	1.9	430.7	0.056	0.075	0.054	3.3	38.2
Run 2	3.1	15	3.1	1.2	431.7	0.058	0.072	0.063	-7.1	15.0
Run 3	2.4	14.7	4.1	1.4	446.4	0.056	0.075	0.062	-8.3	21.3

4.4.1 Modified Method 5 Test:

As shown above, the total PM measured with the CVS, in accordance with the requirements of ISO-8178 and 40 CFR, Part 89, was in very good agreement with the front-half of the Method 5 test protocol. These findings are supported by the study conducted by researchers at CE-CERT, University of California, Riverside (40). However, application of the Method 5 PM sampling procedure for in-field / in-use emissions testing of stationary sources can still be challenging. Some of the potential issues that will cause problems during in-field testing are the probe traversal, length of the exhaust pipe (since eight diameters are required upstream of the PM sampling probe and the Pitot tube measurement in accordance with Method 1A (45)), elaborate use of glassware (non-robustness) in Method 5, unavailability of “conditioned” filters in the field, extraction constrains, etc. Hence, the study attempted to simplify the current Method 5 procedure and make it user-friendly for “in-use” emission measurement purposes by employing a multi-hole stainless steel sampling nozzle that spanned the entire diameter of the exhaust stack, instead of a quartz gooseneck nozzle. This measure, if proved successful would not necessitate the traverse of the sampling probe. The sampling probe and the filter box were also maintained at ambient temperatures and at the stipulated temperature of 250ºF. This measure, if successful, would allow the use a non-heated stainless steel transfer tube instead of an expensive heated quartz tube.

Table 17 gives the test matrix for the “modified” Method 5 analysis. The DDC Series 60 engine that was used for the development of the test method was chosen for this study. A few simple tests using this “modified” Method 5 sampling system were also performed to investigate the effect of “uncontrolled” or “local” conditioning on the PM filters. Instead of following the procedures outlined in 40 CFR, Part 89 and in ISO 8178, the modified method included conditioning and weighing of filters in a laboratory, shipping them out to a test site, shipping them back to the laboratory after the test, followed by re-conditioning and weighing of the filters. The following text refers to this method as “uncontrolled/ local conditioning of filters”.

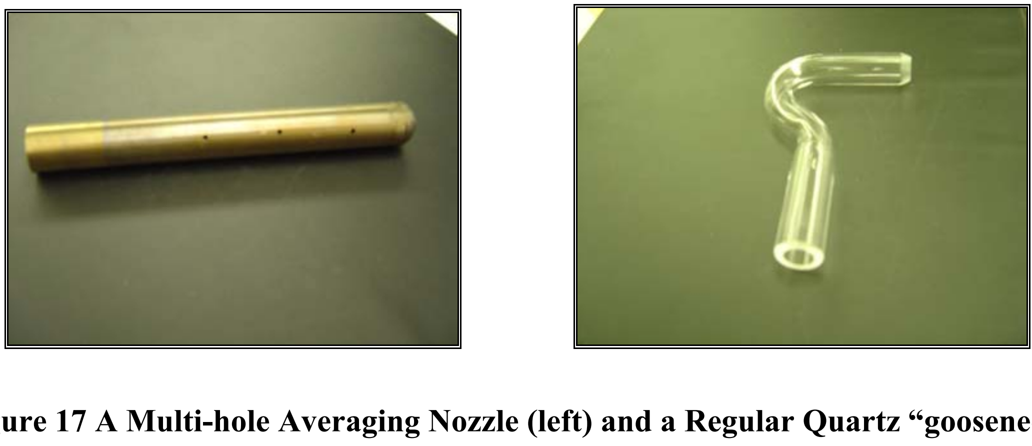

Figure 17 A Multi-hole Averaging Nozzle (left) and a Regular Quartz “gooseneck” Nozzle (right)

Figure 17 shows the stainless steel multi-hole averaging nozzle and the regular quartz nozzle that were used for the Method 5 tests on the DDC Series 60 engine.

The aim of the first set of experiments (Table 40, Test#1 and #2 and Table 41, Test#7 and #8) was to determine if a multi-hole sampling nozzle could be used for sampling PM in a Method 5 system. Instead of the regular gooseneck type sampling nozzle, a three-hole sampling nozzle made of stainless steel was used for the purpose. The holes spanned the diameter of the exhaust pipe and were in line with the engine exhaust. The design is outlined in 40 CFR, Part 89, under § 89.412-96. The temperature of the probe and the filter box were the same as in regular Method 5 tests. The filters were pre-conditioned as required in the Method 5 procedure, that is, the PM filters were placed in glass petri dishes in an environmental control room maintained at 50% RH and 75°F temperature for a period of at least 8 hours before use. The engine was operated at 'I50' (50% load at intermediate speed) and at 'I75' (75% load at intermediate speed) steady-state ISO 8178 modes. Neither the "probe catch" of the front-half, nor the back-half were extracted. Only the "filter catch", that is, the PM mass collected on the filter was compared with the corresponding mass from the dilute CVS system.

Table 40 Comparison of TPM Collected with the Modified Method 5 at I50 Condition of the DDC Series 60 Engine.

DDC Series 60, "I50" operating condition	Filter catch (mg)	Sample flow rate (scfm)	Sample Volume (ft^3)	Sampling Time (min)	Exhaust Gas Flow (scfm)	Engine Speed (rpm)	Engine Torque (ft-lbs)	Modifed M5 TPM	Lab data g/bhp-hr
								g/bhp-hr	
Multi-hole nozzle-Test #1	7.9	1.028	24.5	31.08	320.2	1211	700	0.029	0.036
Multi-hole nozzle-Test #2	8.3	1.005	25.3	32.24	320.2	1211	700	0.030	0.035
No temperature control-Test#3	9.9	1.063	24.9	32	320.2	1211	700	0.034	0.036
No temperature control-Test#4	8.1	1.0725	25.2	32	320.2	1211	700	0.028	0.036
"Local" conditioned filters-Test#5	8	1.098	26.1	32	320.2	1211	700	0.027	0.038
"Local" conditioned filters-Test#6	5.4	1.382	13	15.4	320.2	1211	700	0.030	0.038

Note: Test#1 to #6: Multi-hole sampling nozzle, instead of a gooseneck

Test#3, #4, #5, #6: Probe and Filter box were maintained at ambient conditions

Test#5 and #6:"local conditioning of filters" (Refer to the text for explanation)

The brake specific emissions obtained in this experiment can be compared with the results that were obtained with the original Method 5 sampling system. However, it should be noted that the results obtained using the "modified" Method 5 set up do not include the "probe catch" of the front half as opposed to the results obtained using the original Method 5 system that include the probe catch. Based on the values for the "probe catch" obtained using the original Method 5 system, its contribution can be estimated to be as much as 20 % of the TPM.

In the second set of the experiments (Table 40, Test#3 and #4 and Table 41, Test#9 and #10), the temperature controller for the probe liner and the filter box were shut-off. Other parameters were the same as that in the first set of experiments, that is, a multi-hole sampling nozzle was used along with conditioned filters. The objective was to determine if a non-heated stainless steel transfer tube could be used instead of an expensive heated quartz tube. The results obtained in this experiment (multi-hole nozzle + no temperature control) were comparable with those obtained in the first set where the use of a multi-hole nozzle was the only distinguishing feature.

Tests (Table 40, Test #5, #6 and Table 41 Test #11, #12) were performed to investigate the effect of "local" or "uncontrolled" conditioning on the PM filters. The objective of modifying the filter conditioning procedure was to mimic the time involved in shipping the filters (in filter cassettes or filter holders) when the filters are exposed to ambient temperature and humidity. This exercise could set the pace for shipping out filter cassettes to the in-field site for PM sampling using a mini or a micro-dilution tunnel, and then shipping the filter cassettes back to the laboratory for gravimetric analysis. To further clarify the "uncontrolled/local" conditioning term, all filters actually were conditioned, but not in complete conformance with the requirements of any of the regulatory procedures. The PM filters were first conditioned for 8 hours in an environmental chamber in accordance with requirements of the Method 5 procedure and weighed. PM filters were then placed in glass petri dishes and moved to a location outside the environmental chamber and exposed to ambient temperature and humidity for two days (this would mimic the time required to ship the filters from a laboratory to a test site). Filters were then used in the Method 5 PM sampling routine on the DDC Series 60 engine. After the test, the filters (in the filter holders) were placed outside the environmental chamber for two days. This would mimic the time required to ship the filters back to the laboratory. The loaded filters were then conditioned for a standard period of 8 hours, and weighed. Hence, even though the filters were conditioned, the term “uncontrolled/local” has been adopted to distinguish these filters from those that were conditioned per regulatory requirements. Conditioned filters were used in Test #9 and Test #10 while “uncontrolled/local” conditioned filters were used in Test #11 and Test #12. The data from this set of experiment, Tests # 5, #6, #11, #12 (multi hole nozzle + no temperature control over the probe, filter box + “local-conditioning) can be compared with Tests # 3, #4, #9 and #10 (multi hole nozzle + no temperature control over the probe, filter box) respectively. Results from the I75 (75 % load at intermediate speed) mode show that the last two replicates, Test#11 and #12, where filters were ‘locally conditioned’, the PM results were similar to other tests that used filters that were conditioned per regulatory requirements.

The repeatable data from Tests #9 through test #12 suggest that filters may be conditioned and weighed in a laboratory prior to a test at a remote site; the filters can be packed in filter cassettes that are made of a conducting plastic (or in a regular stainless steel filter holder); shipped out the test site; “shot” in a PM test; shipped back to the chemical laboratory, where the filters are re-conditioned to the original environmental conditions, and then weighed again.

Table 41 Comparison of TPM Collected with the Modified Method 5 at I75 Condition of the DDC Series 60 Engine.

DDC Series 60, "I75" operating condition	Filter catch (mg)	Sample flow rate (scfm)	Sample Volume (ft^3)	Sampling Time (min)	Exhaust Gas Flow (scfm)	Engine Speed (rpm)	Engine Torque (ft-lbs)	Modifed M5 TPM	Lab data g/bhp-hr
								g/bhp-hr	
Multi-hole nozzle-Test #7	10.7	1.127	19.5	24.5	446.4	1211	1050	0.042	0.066
Multi-hole nozzle-Test #8	8.5	1.162	18.8	23.41	446.4	1211	1050	0.034	0.066
No temperature control-Test #9	11.6	1.116	19.9	25.08	446.4	1211	1050	0.045	0.066
No temperature control-Test #10	10.9	1.151	18.4	23.1	446.4	1211	1050	0.045	0.065
"Local" conditioned filters-Test #11	10.7	1.101	19.6	25.17	446.4	1211	1050	0.042	0.064
"Local" conditioned filters-Test #12	11.1	1.116	19	24.34	446.4	1211	1050	0.045	0.069

Note: Test#7 to #12: Multi-hole sampling nozzle

Test#9, #10, #11, #12: Probe and Filter box maintained at ambient conditions

Test#11and #12: “local conditioning of filters”, plus (Refer to the text for explanation)

4.4.2 Summary

All results presented above include brake-specific PM emissions only from the filter catch of the front half. The purpose of modifying the Method 5 procedure was to make the Method 5 system more “user-friendly” for in-use emissions test purposes. Extraction of PM from the sampling probe (“probe catch”) and from the back half were not performed keeping in mind the difficulties associated with such extractions during in-field testing. Results presented in § 4.4 on Method 5 and CVS-based PM results, highlight the fact that only if the front-half extraction (probe-catch) is included, Method 5 will agree with the CVS-based gravimetric analysis of PM. In addition, results presented in Table 38 and in Table 39, and in Section 4.4 present evidence that any total particulate matter measurement with the Method 5 sampling trains should include the entire front half including the probe catch. Using the information from the regular Method 5 tests, it may be estimated that the front half contribution to TPM is approximately 20%. Hence, it may be concluded that once “probe catch” were to be included in the analysis, then a multi-hole nozzle along with the probe maintained at ambient temperature could be used for collecting total particulate matter data from stationary and portable engines operating in the field. In fact, if the "modified" Method 5 results (including the "probe catch") are similar to the CVS based and/or mini-tunnel based PM, then the PM measurement may be significantly simplified by using a mini-tunnel in the field. As mentioned before, the "modified" Method 5 procedure still requires the use of glass ware, and a delicate, expensive quartz sampling probe. Using such a fragile set up for in-field testing for in-use PM measurements would require very competent handling, since such instruments are prone to breakage. Also, it is likely that many future off-road engines, including the portable and stationary engines, will implement the usage of exhaust after-treatment devices that may significantly change the chemical profile of PM downstream of the device. The disproportionate amount of soluble organic fraction (SOF) in relation to total particulate matter (on a mass basis) could result in poorer correlation of Method 5/Modified Method 5 with CVS dilution tunnel based methods. The use of a mini-dilution tunnel will result in condensation of these hydrocarbons on the filter and would also account for the atmospheric reactions of the particulate matter. This method, since it is mimicking the standard CVS dilution system, could likely provide for better comparison with the standard than the modified Method 5 procedure, which omits the dilution principle.

4.5 In-field Testing

In-use emissions testing were performed to validate the proposed test method. Two engines that fall under the "Portable and Stationary Engines" category were selected. A Multiquip-Whisperwatt diesel powered AC generator and a SullAir 185 diesel powered air compressor were rented for the study. The generator was loaded using a thermostatically controlled room heater while a jack hammer was used to load the air compressor. Thus, both the engines were tested during their "in-use" duty cycle. Emissions data was collected using laboratory grade analyzers mounted on a transportable laboratory and the MEMS-the portable emission measurement system built by WVU. Both gaseous and particulate matter during "In-use" operation was collected. Two runs were performed for each test engine.

Emissions from the two engines have been expressed as grams per unit of time. As mentioned before, measurement of work output from such mechanically controlled engines was not possible. Hence, emissions have expressed in mass emission rate units. Table 32 and Table 33 give the average emissions recorded for each engine run on their respective duty cycles while Figure 18 through Figure 21 provide a continuous comparison of mass emission rates measured by MEMS versus the laboratory. CO_2 was measured within 5 % for all the runs and NO_x was measured within 8% of the laboratory for most of the tests. Figure 22 provides an expanded view of the comparison for a section of the test cycle.

Table 34 through Table 37 show application of the compliance factor concept on the in-field test engines. The Isuzu QD 100 - built in 1990, was not designed to conform to any emissions standards for off-road engines while the Perkins - built post emissions standards promulgation, was expected to comply with pertinent emissions regulations. However, “In-use” operation can be markedly different from certification cycles and engines certified on certification cycle can emit 2-3 times more during “In-use” condition.

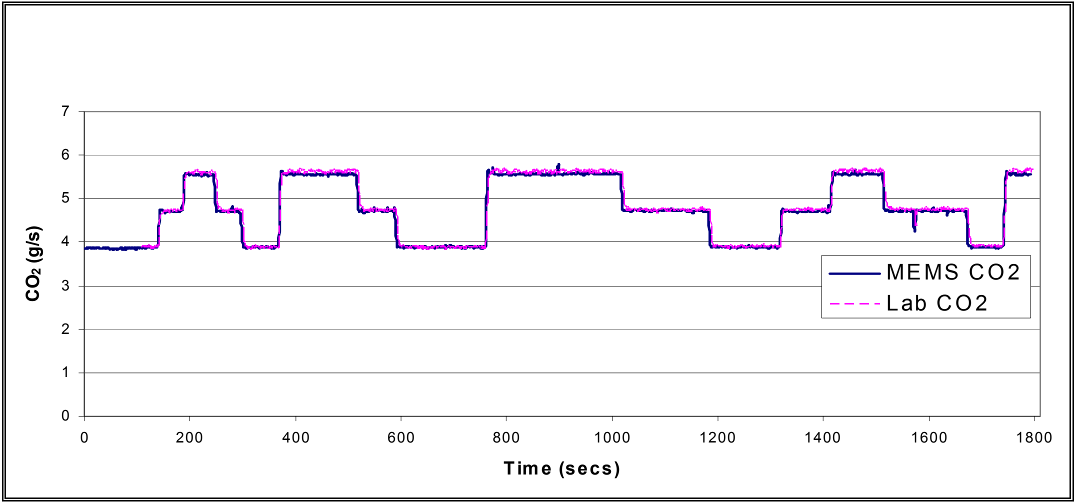

Figure 18 Comparison of CO_2 Mass Emission Rates from MEMS & Lab during In-Use Operation of the Generator. Run 1

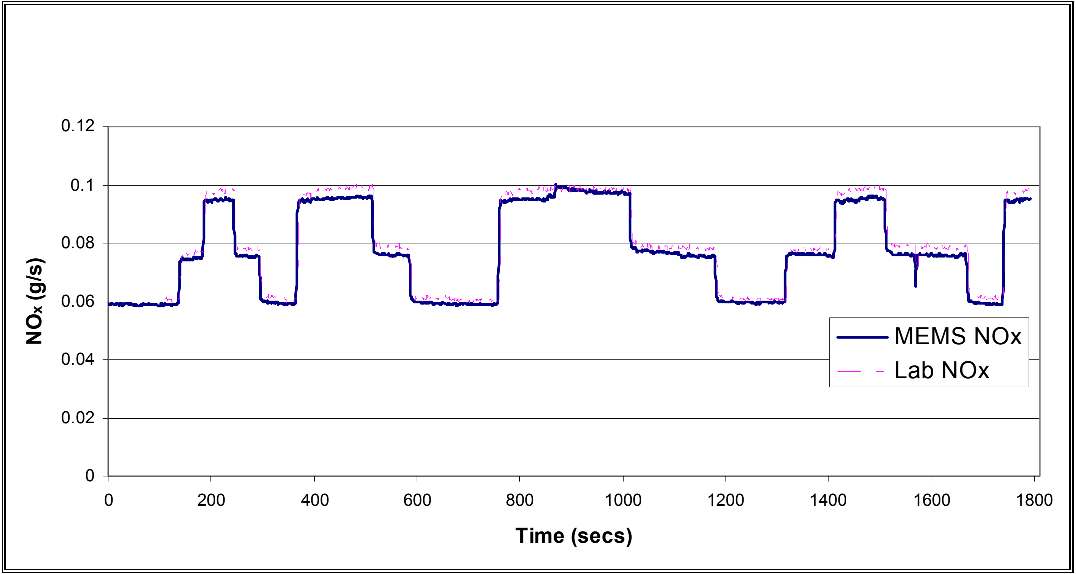

Figure 19 Comparison of NO_x Mass Emission Rates from MEMS & Lab during In-Use Operation of the Generator. Run 1

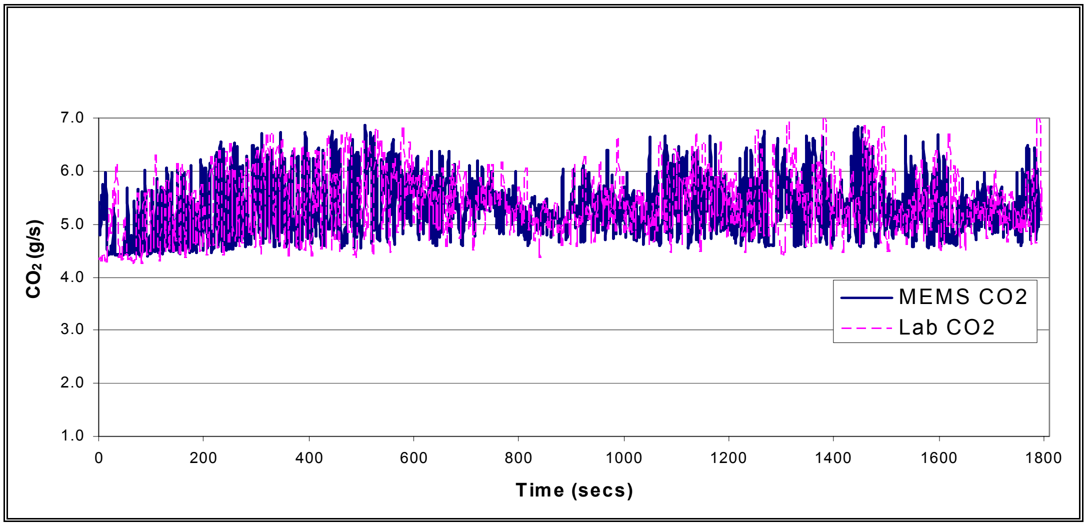

Figure 20 Comparison of CO_2 Mass Emission Rates from MEMS & Lab during In-Use Operation of the Air Compressor. Run 1

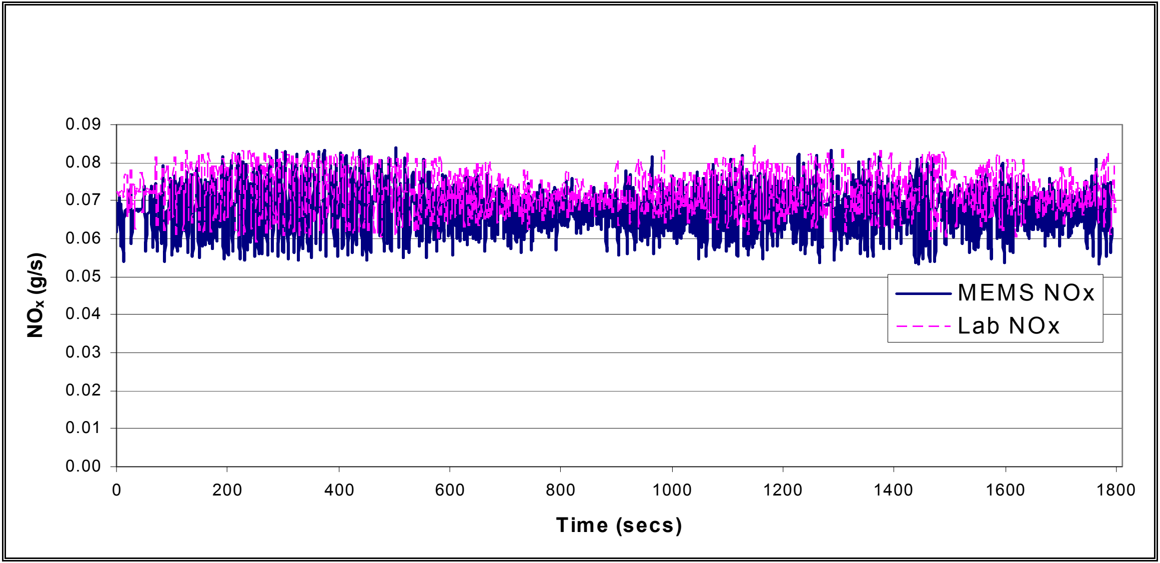

Figure 21 Comparison of NO_x Mass Emission Rates from MEMS & Lab during In-Use Operation of the Air Compressor. Run 1

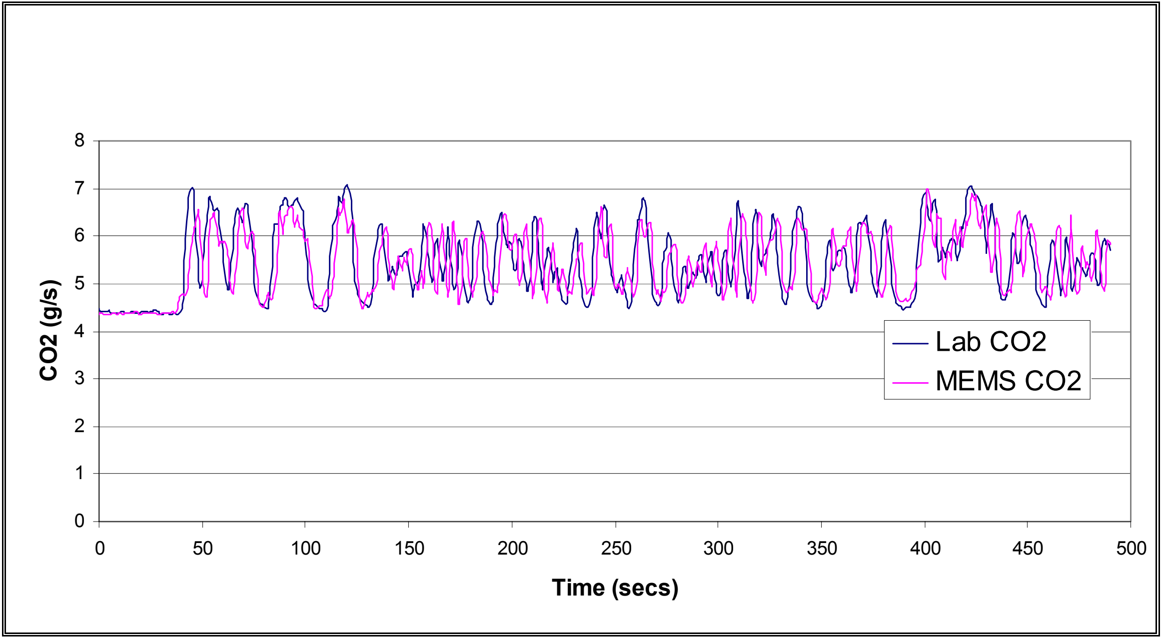

Figure 22 Comparison of CO_2 Mass Emission Rates from MEMS & Lab for a Section of the In-Use Test on the Air Compressor. Run 2

The Certification ratio for these two engines was obtained from the brake specific NO_x and CO_2 emissions obtained during laboratory evaluation of the Isuzu C 240 engine on an ISO 8178 test cycle. Since the Isuzu C 240 was of similar size and type as the Isuzu QD 100 and the Perkins engines, the Certification ratios for these two engines were chosen to be identical to that of the Isuzu C 240 engine. The Certification ratio values were chosen only to illustrate the application of the Compliance Factor concept. Actual in-use emissions test would require the manufacturer to report the brake specific emissions values for NO_x and CO_2 over the entire test.

4.6 Uncertainty Analysis:

An uncertainty analysis was performed in order to evaluate the experimental results. An estimate of the uncertainty in the NO_x concentrations measured by zirconium oxide sensor, CO_2 concentrations measured by the BE-140 system, and PM concentrations measured by the CVS and the Method 5 systems is presented.

According to Horiba Inc., the zirconium oxide sensor for NO_x measurement has a bias error of ± 30 ppm for concentrations less than 1000 ppm. The bias error is ± 3 % of the reading, for concentration values above 1000 ppm. The total uncertainty in zirconium oxide NO_x sensor concentration (including both bias and random errors) is reported to be 30.4 (<1000 ppm) and ± 3.36 % of the reading, for values above 1000 ppm [17]. The Horiba BE-140 sensor has a bias error of ± 2% of full scale. The total uncertainty for CO_2 concentrations measured by the BE-140 sensor has been estimated to be 2.3 % full scale [17]. PM concentrations measured by the CVS method are estimated to have a total uncertainty of 1.95% [46, 47]. Table 42 through Table 48 present brake-specific PM emissions on a modal basis. The brake-specific PM emissions data is provided on a modal basis only to calculate the total uncertainty for each mode. The manufacturer reported bias for Method 5 PM sampling system is 6%. The total uncertainty in PM mass measurement from Method 5 system was estimated using the student's t distribution,

$$Random\,error = \frac{t_{\alpha/2,n-1} \times STDEV}{\sqrt{n}} \qquad \textbf{Equation 4- 17}$$

where $t_{\alpha/2,\ n-1}$ represents the student t value for 95% confidence, with (n-1) degrees of freedom. STDEV is the standard deviation of a set of repetitive values from the mean, and n is the number of repeats or runs. Since there were three runs for every Method 5 test mode, n is equal to 3, resulting in a t value of $t_{0.025,\,2} = 4.303$

The total uncertainty was calculated using the relation,

$$U_{95} = \sqrt{(Bias)^2 + (random\,error)^2} \qquad \textbf{Equation 4- 18}$$

Total uncertainty associated with “modified” Method 5 could not be performed due to the absence of information on bias errors. The limited number of runs using the “modified” Method 5 system made it difficult to do a statistical analysis of random error.

Table 42 Uncertainty Analysis for NO_x, CO_2 and PM Measurements on DDC Series 60. Run1

DDC Series 60	NO_x (MEMS)			CO_2 (MEMS)			PM (lab)		
RUN1	ppm	Bias	Total Uncertainty	ppm	Bias (ppm of full scale)	Total Uncertainty	g/bhp-hr	Bias	Total Uncertainty g/bhp-hr
R100	1103.5	33.1	37.1	80000.0	2400.0	2760.0	0.048	N/A	0.001
R75	1160.0	34.8	39.0	73600.0	2400.0	2760.0	0.047	N/A	0.001
R50	1160.0	34.8	39.0	63200.0	2400.0	2760.0	0.057	N/A	0.001
R10	415.0	30.0	30.4	26548.0	2400.0	2760.0	0.337	N/A	0.007
I100	1170.0	35.1	39.3	103000.0	2400.0	2760.0	0.089	N/A	0.002
I75	1250.0	37.5	42.0	94800.0	2400.0	2760.0	0.062	N/A	0.001
I50	1346.9	40.4	45.3	80447.0	2400.0	2760.0	0.029	N/A	0.001
IDLE	198.5	30.0	30.4	13016.0	2400.0	2760.0	1.889	N/A	0.037

Table 43 Uncertainty Analysis for NO_x , CO_2 and PM Measurements on DDC Series 60. Run2

DDC Series 60	NO_x (MEMS)			CO_2 (MEMS)			PM (lab)		
RUN2	ppm	Bias	Total Uncertainty	ppm	Bias (ppm of full scale)	Total Uncertainty	g/bhp-hr	Bias	Total Uncertainty g/bhp-hr
R100	1237.4	37.1	41.6	77197.0	2400.0	2760.0	0.049	N/A	0.001
R75	1278.1	38.3	42.9	71870.0	2400.0	2760.0	0.040	N/A	0.001
R50	1278.2	38.3	42.9	59980.0	2400.0	2760.0	0.049	N/A	0.001
R10	472.0	30.0	30.4	26870.0	2400.0	2760.0	0.353	N/A	0.007
I100	1260.0	37.8	42.3	97700.0	2400.0	2760.0	0.084	N/A	0.002
I75	1340.0	40.2	45.0	90540.0	2400.0	2760.0	0.062	N/A	0.001
I50	1450.0	43.5	48.7	78050.0	2400.0	2760.0	0.029	N/A	0.001
IDLE	154.4	30.0	30.4	7203.4	2400.0	2760.0	1.884	N/A	0.037

Table 44 Uncertainty Analysis for NO_x , CO_2 and PM Measurements on DDC Series 60. Run3

DDC Series 60	NO_x (MEMS)			CO_2 (MEMS)			PM (lab)		
RUN3	ppm	Bias	Total Uncertainty	ppm	Bias (ppm of full scale)	Total Uncertainty	g/bhp-hr	Bias	Total Uncertainty g/bhp-hr
R100	1320.0	39.6	44.4	79300.0	2400.0	2760.0	0.048	N/A	0.001
R75	1220.0	36.6	41.0	71710.0	2400.0	2760.0	0.040	N/A	0.001
R50	1076.1	32.3	36.2	62005.5	2400.0	2760.0	0.049	N/A	0.001
R10	536.0	30.0	30.4	28100.0	2400.0	2760.0	0.405	N/A	0.008
I100	1335.3	40.1	44.9	97240.8	2400.0	2760.0	0.089	N/A	0.002
I75	1403.2	42.1	47.1	92784.2	2400.0	2760.0	0.065	N/A	0.001
I50	1489.0	44.7	50.0	78494.2	2400.0	2760.0	0.031	N/A	0.001
IDLE	160.3	30.0	30.4	7770.0	2400.0	2760.0	1.881	N/A	0.037

Table 45 Uncertainty Analysis for NO_x , CO_2 and PM Measurements on Isuzu C 240. Run 1

ISUZU C 240	NO_x (MEMS)			CO_2 (MEMS)			PM (lab)		
RUN 1	ppm	Bias	Total Uncertainty	ppm	Bias	Total Uncertainty	g/bhp-hr	Bias	Total Uncertainty in g/bhp-hr
R100	437.6	30.0	30.4	103634.0	2400.0	2760.0	N/A	N/A	N/A
R75	368.9	30.0	30.4	76552.8	2400.0	2760.0	N/A	N/A	N/A
R50	257.4	30.0	30.4	57377.8	2400.0	2760.0	N/A	N/A	N/A
R10	95.9	30.0	30.4	30877.2	2400.0	2760.0	N/A	N/A	N/A
I100	303.3	30.0	30.4	106837.2	2400.0	2760.0	N/A	N/A	N/A
I75	383.4	30.0	30.4	80523.1	2400.0	2760.0	N/A	N/A	N/A
I50	383.3	30.0	30.4	57806.9	2400.0	2760.0	N/A	N/A	N/A
IDLE	16.5	30.0	30.4	2389.0	2400.0	2760.0	N/A	N/A	N/A

Table 46 Uncertainty Analysis for NO_x , CO_2 and PM Measurements on Isuzu C 240. Run 2

ISUZU C 240	NO_x (MEMS)			CO_2 (MEMS)			PM (lab)		
RUN 2	ppm	Bias	Total Uncertainty	ppm	Bias	Total Uncertainty	g/bhp-hr	Bias	Total Uncertainty in g/bhp-hr
R100	499.8	30.0	30.4	102184.1	2400.0	2760.0	0.1	N/A	0.003
R75	432.3	30.0	30.4	77001.2	2400.0	2760.0	0.2	N/A	0.003
R50	306.2	30.0	30.4	55827.7	2400.0	2760.0	0.1	N/A	0.003
R10	99.1	30.0	30.4	30537.8	2400.0	2760.0	0.9	N/A	0.018
I100	367.0	30.0	30.4	106425.9	2400.0	2760.0	0.1	N/A	0.003
I75	461.0	30.0	30.4	79765.3	2400.0	2760.0	0.1	N/A	0.002
I50	434.5	30.0	30.4	59515.0	2400.0	2760.0	0.1	N/A	0.002
IDLE	15.7	30.0	30.4	2011.8	2400.0	2760.0	0.2	N/A	0.005

Table 47 Uncertainty Analysis for NO_x , CO_2 and PM Measurements on Isuzu C 240. Run 3

ISUZU C 240	NO_x (MEMS)			CO_2 (MEMS)			PM (lab)		
RUN 3	ppm	Bias	Total Uncertainty	ppm	Bias	Total Uncertainty	g/bhp-hr	Bias	Total Uncertainty in g/bhp-hr
R100	651.5	30.0	30.4	102709.8	2400.0	2760.0	0.2	N/A	0.003
R75	605.4	30.0	30.4	75684.2	2400.0	2760.0	0.4	N/A	0.008
R50	457.4	30.0	30.4	55605.8	2400.0	2760.0	0.2	N/A	0.004
R10	159.5	30.0	30.4	30611.5	2400.0	2760.0	1.7	N/A	0.032
I100	510.4	30.0	30.4	111309.5	2400.0	2760.0	0.2	N/A	0.004
I75	575.4	30.0	30.4	80182.1	2400.0	2760.0	0.1	N/A	0.002
I50	437.2	30.0	30.4	58468.2	2400.0	2760.0	0.2	N/A	0.003
IDLE	16.7	30.0	30.4	2050.6	2400.0	2760.0	0.3	N/A	0.006

Table 48 Uncertainty Analysis for NO_x , CO_2 and PM Measurements on Isuzu C 240. Run 4

ISUZU C 240	NO_x (MEMS)			CO_2 (MEMS)			PM (lab)		
RUN 4	ppm	Bias	Total Uncertainty	ppm	Bias	Total Uncertainty	g/bhp-hr	Bias	Total Uncertainty in g/bhp-hr
R100	647.4	30.0	30.4	101521.1	2400.0	2760.0	0.2	N/A	0.003
R75	591.4	30.0	30.4	74753.8	2400.0	2760.0	0.4	N/A	0.007
R50	439.8	30.0	30.4	55837.8	2400.0	2760.0	0.2	N/A	0.005
R10	157.6	30.0	30.4	31057.9	2400.0	2760.0	1.7	N/A	0.033
I100	518.6	30.0	30.4	111316.1	2400.0	2760.0	0.2	N/A	0.004
I75	554.6	30.0	30.4	80290.5	2400.0	2760.0	0.1	N/A	0.002
I50	478.3	30.0	30.4	58345.6	2400.0	2760.0	0.2	N/A	0.003
IDLE	16.3	30.0	30.4	2162.3	2400.0	2760.0	0.3	N/A	0.006

Table 49 Uncertainty Analysis for PM Measurements using Method 5 System on Isuzu C 240

Engine Operating Mode	TPM w/o BHE g/bhp-hr	Mean g/bhp-hr	Bias g/bhp-hr	Total Uncertainity g/bhp-hr	TPM with BHE g/bhp-hr	Mean g/bhp-hr	Bias g/bhp-hr	Total Uncertainity g/bhp-hr
R100-1	0.119	0.127	0.008	0.019	0.205	0.221	0.013	0.037
R100-2	0.130				0.232			
R100-3	0.132				0.225			
I100-1	0.149	0.154	0.009	0.015	0.235	0.244	0.015	0.055
I100-2	0.158				0.228			
I100-3	0.154				0.268			

Table 50 Uncertainty Analysis for PM Measurements using Method 5 System on DDC Series 60

Engine Operating Mode	TPM w/o BHE g/bhp-hr	Mean g/bhp-hr	Bias g/bhp-hr	Total Uncertainity g/bhp-hr	TPM with BHE g/bhp-hr	Mean g/bhp-hr	Bias g/bhp-hr	Total Uncertainity g/bhp-hr
I75-1	0.056	0.057	0.003	0.004	0.075	0.074	0.004	0.006
I75-2	0.058				0.072			
I75-3	0.056				0.075			
I50-1	0.040	0.036	0.002	0.016	0.086	0.072	0.004	0.055
I50-2	0.040				0.084			
I50-3	0.029				0.047			

5 Conclusions and Recommendations (18)

Conclusions of this study may be presented in the form of recommendations regarding the test method developed in this study that could be used for determining in-use compliance of stationary and portable engines. These recommendations are listed below:

- In-use Emissions Compliance
- In-use Emissions Measurement Tools (Portable and Stationary Engines)
- In-field Emissions Measurement Standard Operating Procedure

5.1.1 In-use Emissions Compliance Recommendations

The compliance factor concept should be employed to determine compliance of stationary and portable engines. This method uses the in-field ratio of NO_x and CO_2 concentrations (to obtain mass emissions of NO_x and CO_2) from engines operating in the field, and the certification ratio of NO_x and CO_2 (brake-specific emissions) values from engine certification tests. A ratio of the in-field ratio and the certification ratio gives the compliance factor, F.

In summary,

- If BSFC data for an engine were to be available (it is likely, that it will not be), its validity may be in question because of engine deterioration. Hence, brake-specific emissions data will be un-reliable.

- Therefore, fuel-specific/CO_2-specific measurements should be used as a compliance tool. This will require only concentration measurements. Uncertainties arising from flow rate measurement and torque/percent load will be avoided. In-field fuel-specific measurements (NO_x/CO_2) should be compared with the laboratory-generated 8-mode cycle brake-specific emissions data. The in-field measurements should not exceed the product of F and the weighted brake-specific emissions from the ISO 8178 certification test.

- For electronically controlled engines, in-use brake-specific emissions should not exceed the product of F and the weighted brake-specific emissions from the ISO 8178 test applicable to the engine being tested. Engine power should be inferred from the ECU broadcasts.

5.1.2 In-use Emissions Measurement Tools

The recommended compliance factor method would require measurement of concentrations. Hence, an accurate, reliable and portable gas concentration measurement analyzer would serve well. A filter-based gravimetric method using pre-conditioned and pre-weighed filter cassettes, and a micro-dilution tunnel is recommended for PM measurements. A "modified" Method 5 (with the front-half extraction) sampling train could be used, but the tediousness of the process could be avoided by using a micro-dilution tunnel since both procedures yield similar results

Equipment recommendations to conduct the proposed in-field test are as follows:

- PM Measurement
  - Filter-based gravimetric PM measurement (using a portable mini-dilution tunnel, or a micro-dilution tunnel)
  - "Modified" Method 5 may be used, if essential. Modifications to the original Method 5 include, (i) multi-hole averaging sampling probe, (ii) ambient temperature probe, (iii) pre-conditioned and pre-weighed filters, and (iv) front-half extraction should be included in the PM analysis.
- Gaseous Emissions Concentrations
  - NO_x – Zirconium Oxide sensor with NO_2-NO converter to measure NO_x
  - (NO_x – Micro flow NDIR from Horiba; Non-dispersive ultra-violet analyzer from ABB)
  - CO_2/CO – Solid State NDIR
  - (CO_2/CO – Ultra portable NDIR from Horiba)
  - HC – Portable HFID for diesel engines, possibly NDIR for spark ignited engines (21).
  - Short heated sample line(s), heated head pump maintained at temperatures required by CFR 40, Part 89, if non-sampling type sensors are not used.

Measurement of engine work output and the exhaust flow rate to determine the brake-specific emissions is not necessary for compliance monitoring purposes. However, if necessary, the following recommendations are being suggested for torque and flow rate measurements.

- Exhaust Flowrate Measurements
    - Annubar averaging Pitot tube flow meter
- Torque Measurement
    - Inference from ECU data if available (25).
    - From BSFC data, if available, for the engine. But, this data is always suspect because of engine and fueling system wear and tear, mal-maintenance, and possible engine re-builds since the original engine certification.

5.1.3 In-field Emissions Measurement Standard Operating Procedure

A Standard Operating Procedure (SOP) for a complete mass emissions measurement procedure is presented below. If the recommendations made in this study were to be followed, then flowrate measurement, the engine load and speed data are not required:

- Identify the test engine, and collect engine description (make, model, serial number, etc.) prior to site visit to “check-out” the engine. Collect engine certification and performance data from the manufacturer.
- Ensure that the engine is in good working condition. This includes inspection of the engine air filter and exhaust system. If there is reason to suspect a problem, the default protocol is to install a new air filter prior to an emissions test. A leak in the exhaust system will result in erroneously low reported mass emissions data.
- Transport portable gaseous and PM emissions measurement equipment, sample handling and conditioning systems, data acquisition, data archival and data analysis systems to the field. (Exhaust flow rate measurement systems also need to be transported, if mass emission rates are to be measured).
- Prepare the engine for testing. That is, get access to the exhaust stack. Implement personnel safety protocols around the engine. (Install flow meter on the engine exhaust stack, if necessary)
- Install sampling probes and connect to the sample conditioning system/analyzers using heated lines.
- Connect data acquisition and control system (DAC) to the measurement systems.
- Power-up, warm-up and stabilize the concentration measurement analyzers, PM mass measurement systems, heated lines, DAC, etc.

- Leak-check the systems.
- Zero and span the analyzers
- Calibrate the analyzers.
- Warm-up by idling for 10 minutes approximately. Engine could be loaded slowly, if possible, so that oil and coolant temperatures stabilize. If it is not possible to increase the load slowly, then engine should be allowed to operate at high idle for 20 minutes.
- Operate the engine over the "in-use" duty cycle and collect emissions data (gaseous concentration, PM data, and engine speed and flow rate, if needed). The actual engine operation will be dependent upon its intended application.
- Emissions data, especially PM, should be collected for at least 20 minutes.
- Multiple tests should be staged such that similar engine pre-test conditioning is afforded.
- Stationary and portable engines in the future will most likely be equipped with exhaust after-treatment devices such as catalytic converters or particulate traps. It should be noted that the effect of previous operating conditions (prior to the beginning of the compliance test) may be observed during an emissions test. For example, a long period of idling the engine prior to a test may result in increased emissions during the test.
- Collect a fuel sample (one gallon) for standard fuel analysis. The properties and composition of the fuel can greatly influence emissions levels (29). Previous research (29) using different commercially available on-road diesel #2 from local fueling stations noted that NO_x emissions varied up to 10% from fuel to fuel over the same test performed in an engine test cell. Fuel analysis should be performed on each new batch of fuel.
- Note: Local fuel quality can be very problematic. It has been shown that there is a 10% variation in the NO_x from one pump to the next (29). However, a fuel analysis should explain the variation.
- Archive the data for off-site analysis.
- Dissemble emissions measurement equipment.
- Conduct final engine/equipment inspection to ensure that the engine is returned to pre-test condition.

5.1.4 Recommendation of Future Research Activities

In order to further develop test methods for stationary and portable engine emissions, some specific objectives have been identified as a result of the research findings reported under the present study.

A larger data base needs to be established in order to validate the proposed Compliance Factor methodology. Not only does such additional testing and analysis verify the methodology, but this would also assist in identifying a critical value for the Compliance Factor that could ultimately be used to establish non-compliant in-use engines. More specifically, the Compliance Factor, as presented herein, merely involves a ratio of the in-field NO_x/CO_2 concentrations to brake-specific values of NO_x/CO_2 that are averaged over the ISO certification test cycle. This value must then be compared to some established compliance value, which would account for various stochastic tolerances of all components involved. For instance, variability in certification data exists, and this could be caused by engine-to-engine emissions production variability as well as laboratory-to-laboratory emission measurement variability. An increased number of tests, as well as analysis of currently available emissions data, could serve to identify the level of accuracy and precision for emissions certification data as well as actual engine emissions production variability. Similarly, the accuracy and precision of the compliance methodology and hardware proposed by this study should also be identified. Only after a thorough investigation of total compliance variability could a value be established to which the compliance factor could be compared with to identify non-compliant performance of an in-use engine.

Specifically, an inter-laboratory comparison, involving agencies such as MTA/CARB, SWRI, WVU, and Environment Canada could be performed in order to quantify the accuracy and precision of current “certification quality” emissions measurement facilities. Such “round-robin” testing would be critical to establishing a compliant standard. In addition, analysis of available manufacturer’s data on new production engines could assist in quantifying variability of new engine emissions data. A survey of emissions from a number of current in-use engines (using the in-field emissions testing methodology prescribed by this study) of various sizes and from a variety of manufacturers could help to establish the variability of in-use engine emissions, owing to various components – wear, maintenance, etc. Finally, a rigorous test of compliance level emissions measurement devices (such as the system used for this project as well as other currently available, comparable systems) must be performed to identify variability of the in-field test equipment. Only after such thorough investigation and integration of the quantitative results, could a value be established with which the Compliance Factor, prescribed herein, be compared to ultimately identify non-compliant engines in a pass/fail manner.

Extension of the test methodology reported herein to include PM measurements would also need further investigation. The study proposes a PM methodology based upon a mini-dilution technique. This dilution system would provide for gravimetric-based PM concentrations that could be integrated with engine exhaust flow rate to arrive at a PM mass emissions data. The exhaust flow rate could be measured either directly, or by more simply measuring or estimating engine intake air mass flow rates. The methodology would have to be devised with the sampling system as the governing parameter, since in-field compliance tests would inherently necessitate simple and robust measurement systems. With this in mind, the proposed approach would also require an in-depth analysis to identify variability of the methodology before the inevitable development of a compliance criterion could be established. Not only would system limitations need to be identified, but variability associated with limitations of human and equipment performance would need to be quantified.

Presented below is an approach that may be adopted in future for measurement of PM (18,43). PM mass, M, depends on a string of partial derivatives of the relevant variables and on the changes in those variables themselves. For example,

$$dM = (dM/dP1)dP1 + (dM/dP2)dP2 + \ldots\ldots + (dM/dT1)dT1 + \ldots\ldots(dM/dF1)dF1 + \ldots\ldots$$

$$+ (dM/dx1)dx1 + \ldots$$

where M is the PM measured mass, where the variables P_i ,T_i and F_i denote pressures, temperatures and flow rates at carefully selected points in the sampling system, and where the x_i denote geometric variables. The skill is in selecting reasonable and independent variables. The geometric variables must be chosen carefully to represent all major variations in the size, length and arrangement of the engine exhaust transfer pipe, primary tunnel, secondary tunnel and filter holder. The geometric variables must also be sufficient to identify reasonably the true effects of sampling system geometry, but must be constrained to be easily quantifiable and acceptable in number. Additional variables may be required to describe heat transfer, or perhaps the problem can be treated as two separate cases, such as "uninsulated" and "insulated," in a section of the sampling system. Other factors also need to be considered as cases, such as the type of filter medium used. Variables such as dilution ratio or face velocity will prove to be dependent on the set of independent temperatures, pressures, flow rates and geometry parameters that are used. Each partial differential in the equation can be determined using dedicated sub-models and careful experimentation, and in this way the variability in mass can be attributed directly to the variability in the independent variables. These variabilities may be intentional differences in setpoints and sampling system construction between different laboratories, or they may represent the limits of precision in the control of the variables in a laboratory.

Discernable laboratory-to-laboratory and run-to-run variations in PM mass emissions measurements can be attributed to a number of independent variables. These variables include obvious one-dimensional quantities, such as temperatures, pressures and flow rates at critical points in the sampling system, factors that affect the engine operation, and multi-dimensional quantities that describe geometry and materials. With this in mind, the major contributors to variability in PM measurement for any sampling system may be narrowed to three basic components. First, there is deposition of exhaust species on the dilution tunnel walls and throughout the sampling system, coupled with subsequent desorption and shedding of particles from the walls. Second, there are physical, controllable variables such as temperature, humidity, flow rate and pressure that influence particle formation and the filtration process itself. Third, there are unpredictable differences associated both with variability in engine operation and with inaccuracies in the weighing process.

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APPENDIX A Method 5 Theory and Analysis

A-1 Method 5 Sample Train:

The various components of the Method 5 sample train include a quartz nozzle, a heated quartz probe (250°F), a heated filter, four glass impingers connected in series, a rotary vane pump, a dry gas meter to measure sample volume, and a calibrated orifice. Of the four impingers, first, third and fourth are of Greensburg-Smith design with a modified tip while the second is a standard Greensburg-Smith design impinger. A type S Pitot tube, a thermocouple, two U-tube manometers and a dry gas meter are used to determine the exhaust and the sample flow rates.

A-2 Pretest Preparation:

The control console was leak checked before the commencement of the tests according to the procedure described in § 5.6 of the ARB Method 5 document (38,37). The dry gas meter was calibrated in accordance with procedure outlined in § 5.3 of the ARB Method 5. The calibration of the temperature controller was checked before the start of the study.

A-3 Location of the Sampling Port, Pitot Tube, Thermocouple:

Unlike the conventional use of a Method 5 system in a 60” diameter exhaust stack, application of the Method 5 sampling system for engine dynamometer testing presents some major constraints. The size of the exhaust stack is usually limited to less than 5 inches to satisfy requirements placed in CFR 40 Part 89, Subpart N. Location of the sampling nozzle, Pitot tube, and the thermocouple at a single port as envisaged in Method 5, in a 4” exhaust stack would result in increased restriction in the stack, thereby hindering isokinetic sampling. It was decided therefore, after consultations with the CARB, to separate the exhaust flow rate measurement from PM sampling. This method is outlined in US EPA Method 1A (45). Also, eight traverse points across the stack diameter were chosen for sampling. Traversing was performed manually.

A-4 Selection of Nozzle Size, Differential Gauge, Sampling Time, and Sample Flow Rate

The following equation from Appendix A of ARB Method 5 document was used to estimate the ideal nozzle diameter.

$$D_n = \sqrt{\frac{0.0358 * Q_m * P_m}{(T_m + 460) * C_p * (1 - B_{ws})} * \sqrt{\frac{(T_s + 460) * M_s}{P_s * \Delta\overline{P}}}}$$

It was found that this equation yielded the approximate nozzle diameter to be used. For some of the tests, the next bigger size of nozzle was chosen to have improved isokinetic rates. Selection of the right nozzle is critical to maintain isokinetic flow rates. Also, it was observed that using a larger nozzle could lead to suction of the filter by the CVS blower due to decreased restriction provided by a bigger size nozzle.

The Method 5 system purchased from Thermo Anderson® had a differential pressure gauge, manufactured by Dwyer Instruments®, with a range of 10 inches H_2O. It was observed that for five of the eight modes of the ISO 8178 test on the DDC Series 60, the differential pressure gauge would become over-ranged. Only the I50 mode (50 % load @ intermediate speed), I75 mode (75% load at intermediate speed) and the idle mode of the ISO 8178 test were within the range of the gauge. I50 and I75 were chosen for Method 5 analysis. However, in the case of Isuzu C 240 test engine, no such problems with over ranging of pressure gauges were encountered. Hence, R 100 (100 % load @ rated speed) and I 100 (100% load @ intermediate speed) modes of the ISO 8178 test were chosen for Method 5 analysis. These modes typically yield higher concentrations of PM.

As recommended in Method 5 document, a desired sampling flow rate (Q_m) of 0.75 scfm was chosen. Also, sampling duration of 4 minutes at each traverse point was followed. Method 5 document stipulates a minimum of 2 minutes at each traverse point.

A-5 Assembly of the Sampling Train:

A-5.1 Pre-weighing of Impingers.

The first and second impingers were filled with 100 ml of water and weighed. The third impinger was left empty, the fourth impinger was filled with 200 g of silica gel. Weights of the two impingers were recorded. Silica gel was of indicating type with a mesh size of 6-16. A balance from ACCULAB® (model VA series) with a resolution of 0.2 g was used for the purpose.

A-5.2 Pre-weighing of Filters:

PALL® 82 mm glass fiber filters without any organic binder were used to collect PM. Filters were conditioned in an environmentally controlled chamber for a period of

24 hours. The chamber temperature and humidity were maintained at 68°±10°F and 50 percent, respectively. Filters were pre-weighed according to the procedure described in § 4.1.1 of the ARB Method 5 document. A Mettler® AE 240 balance with a resolution of 0.1 mg was used for gravimetric analysis.

A-5.3 Leak Check of the Sample Train:

Before every test, a vacuum leak check of the sampling train was carried out as detailed in § 4.1.4.1 of the ARB Method 5 document. The leak checks were carried out once the sampling train had stabilized at the desired temperatures. Care was taken to release the vacuum slowly to prevent back flush on the filter.

A-6 Pre-test Calculations:

Before start of each test, the manometer was leveled and zeroed. The initial dry gas meter and barometric pressure were noted. In addition, the following parameters were determined using the following equations in Microsoft® Excel™.

A-6.1 Molecular weight of the flue gas, dry pound per pound mole (M_d):

This parameter represents gas density and is required in calculating the exhaust gas velocity.

$$M_d = (\%\,CO_2 * 0.44) + (\%\,O_2 * 0.32) + (\%\,CO + \%N_2 * 0.28)$$

A-6.2 Static pressure in the stack (P_{st}):

This parameter was determined by placing the Pitot tube perpendicular to the exhaust stream. Only one leg of the Pitot tube was connected to the manometer. The other end of the manometer was open to atmosphere.

A-6.3 Absolute Pressure in the Stack. (P_s):

$$P_s = P_{bar} + (\frac{P_{st}}{13.6})$$

where P_{bar} is the barometric pressure.

A-6.4 Determination of the Average VelocityHead ($\overline{\Delta P}$):

The Pitot tube and the temperature probe, both located 8 diameters (32 inches) downstream of the sampling port, were traversed to pre-determined locations across the stack diameter. An average of the differential pressure across the Pitot tube at each point, yielded the average velocity head.

A-6.5 Average Flue Gas Velocity, feet per second (vs):

The following equation was used to estimate the flue gas velocity.

$$\mathrm{vs} = 85.49 * \mathrm{C_p} * \sqrt{\frac{(460 + T_s) * \overline{\Delta P}}{P_s * M_s}}$$

Where C_p is the Pitot tube coefficient. A manufacturer supplied value of 0.84 was used in the calculations.

A-6.6 Absolute Meter Pressure (P_m):

The absolute meter pressure was calculated to correct for any pressure on the gas meter. While using the following formula, an average value of 4 inches of water was assumed for ΔH, the differential pressure across the orifice.

$$\mathrm{P_m} = \mathrm{P_{bar}} + (\frac{\Delta \mathrm{H}}{13.6})$$

A-6.7 Determination of Moisture Content, Molecular Weight of Flue Gas in Wet Pound per Dry Mole (M_s) and Mole Fraction (M_{fd}):

The following formulae may be used to determine the above parameters.

$$\mathrm{M_d} = (\%\,\mathrm{CO_2} * 0.44) + (\%\,\mathrm{O_2} * 0.32) + (\%\,\mathrm{CO} + \%\mathrm{N_2} * 0.28)$$

$$\mathrm{M_{fd}} = 1 - (\frac{\%\mathrm{H_2O}}{100})$$

$$\mathrm{M_s} = (\mathrm{M_d} * \mathrm{M_{fd}}) + (0.18 * \%\,\mathrm{H_2O})$$

These formulae require the knowledge of stack gas composition; hence, require the use of Fyrite or Orsat instruments. Instead, the above parameters were determined from basic thermodynamic principles. The following equations illustrate this method. Only air-fuel ratio and intake air humidity are required for estimating the above parameters.

$$CH_Y + (1+\frac{Y}{4}+Z)*(3.76N_2+O_2)+N_W(H_2O) \rightarrow CO_2+(N_W+\frac{Y}{2})H_20+ZO_2+(1+\frac{Y}{4}+Z)*3.76N_2$$

where,

y = fuel H/C atom ratio
z = moles of excess O_2 in intake air
N_w = moles of water vapor in intake air

Now,

$$AF_d = \text{dry A/F} = \frac{(4.76*(1+\frac{y}{4}+z)*28.97)}{(12.011+1.008y)}$$

Therefore

$$z = \frac{(AF_d*(12.011+1.008*y))}{(4.76*28.97)-(1+\frac{y}{4})}$$

where,

Na,d = number of moles of dry intake air = 4.76 * (1 + y/4 + z)
$N_w = H_a$* Na,d/622
H_a = intake air humidity in grams of water per kg of dry air = (grains/lb)/7.00
N_E = Moles of exhaust per mole of fuel = 1 + (N_w + y/2) + z + 3.76* (1 +y/4 + z)
Exhaust mole % wet CO_2 = (% $CO_{2wet)}$ = 100 / N_E
Exhaust mole % wet H_2O = (% H_2O_{wet}) = 100 * (N_w + y/2) / N_E
Exhaust mole % wet O_2 = (% O_{2wet}) = 100 * z / N_E
Exhaust mole % wet N_2 = 100 * 3.76 * (1+y/4+z) / N_E
r = dry/wet = 1/ (1-% $H_2O_{wet}/_{100}$)
Exhaust mole % dry CO_2 = r * % CO_{2wet}
Exhaust mole % dry O_2 = r * % O_{2wet}
Exhaust mole % dry N_2 = r * % N_{2wet}

These values are then substituted into equations for M_d, $M_{fd,}$ and $M_{s.}$ Given the values of air-to-fuel ratio and the intake air humidity, all the above parameters can be found using an Excel™ spreadsheet.

A-6.8 Determination of K Factor:

The parameter, K-Factor is a number that is used to calculate the desired ΔH setting that would enable isokinetic sampling, that is, the observed ΔP reading at each traverse point is multiplied with this factor to get the desired ΔH value. The following formula is used to calculate the K factor.

$$\text{K factor} = 17{,}365 * \frac{\Delta \mathrm{H}_{@} * (\mathrm{T_m} + 460) * \mathrm{P_s} * \mathrm{D_n}^4 * (1 - \mathrm{B_{ws}})^2}{P_{bar} * (T_s + 460) * [29 - (11 * B_{ws})]}$$

where,

D_n is the ideal nozzle diameter, defined above.

P_s, P_{bar} are the absolute pressure in the stack (defined above) and the barometric pressure respectively.

T_m and T_s are average meter temperature and stack temperature respectively.

B_{ws} = water vapor fraction, $\%H_2O/100$

$\Delta H_{@}$ = Orifice calibration correction factor (= 1.882), derived after calibration.

A-7 Particulate Sampling Train Operation:

After leak checks on the sampling train were completed, the engine was warmed up following a standard warm-up cycle. The PM sampling nozzle was inserted into the exhaust stack only after the engine was warmed up, to minimize the chances of deposition of unrepresentative PM onto the probe walls and on the filter. The nozzle was positioned in its first location in the stack. During the test period, velocity and temperature traverses were performed after the engine had stabilized at the set load and speed conditions. After recording the values at each point, the PM sampling pump was switched on and the flow rate across the orifice was set to the desired ΔH value (derived by multiplying the ΔP reading at each point with the K factor). PM was sampled at each location for four minutes. Towards the end of the sampling period, at each location, the dry gas meter reading was recorded. All the other relevant details, such as, probe temperature, filter temperature, temperature of gas at the exit of the impinger and the meter temperatures were also recorded at each point. The nozzle was then moved to the second location and the above procedure were repeated. The velocity and temperature profiles from a typical test are presented below.

After the test, the sampling pump was switched off and the probe was withdrawn from the stack and sample recovery was conducted.

A-8 Post Test Isokinetic Calculations:

The following calculations were made to validate the test run.

A-8.1 Volume of Dry Gas Sampled at Standard Conditions ($V_{m\,(std)}$):

The following formula corrects the test conditions to standard conditions - 528°R (T_{std}) and 29.92 inches of mercury (P_{std}).

$$V_{m\,(std)} = 17.64 * Y * V_m * \frac{(P_{bar} + (\Delta H / 13.6))}{(T_m + 460)}$$

where,

V_m is the total volume collected during sampling period.

Y is the calibration factor for the dry gas meter.

A-8.2 Volume of Water Vapor at Standard Conditions, Dry standard cubic feet ($V_{w\,(std)}$):

$$(V_{w\,(std)}) = 0.04707 * V_{lc}$$

Where, V_{lc} = Volume of liquid collected, determined after post weighing the impingers.

A-8.3 Moisture Content, Percent by Water (% H_2O):

$$MC = \frac{100 * V_{w\,(std)}}{(Vw_{\,(std)} + V_{m\,(std)})}$$

A-8.4 Mole Fraction of the Flue Gas (Mfd):

$$M_{fd} = 1 - (\frac{\%\,H_2O}{100})$$

A-8.5 Isokinetic Sampling Rate (% I):

$$\%\,I = \frac{P_{std} * 100 * (T_s + 460) * V_{m(std)}}{T_{std} * 60 * P_s * vs * M_{fd} * \Theta * A_n}$$

Where,

Θ is the sampling duration in minutes,

A_n is the nozzle area in square feet.

A-9 Sample Recovery and Extraction:

The particulate sampling train may be divided into two halves. The front half includes the nozzle, the probe, an ‘L’ connector, the top half of the filter holder assembly and the filter itself. The back half consists of the lower half of the filter assembly, a double ‘L’ connector, three impingers, and three ‘U’ connectors. Particulate matter will be deposited in the front half while in the back half particulate matter condenses in the impingers. Hence, two different procedures govern the recovery of the particulate matter from the sampling train.

A-9.1 Recovery of the Front Half Sample:

The filter was removed from the assembly and placed in unsealed petri dishes to permit humidity exchanges. The filter was conditioned for 24 hours in an environmentally controlled room. The filter was weighed using the Mettler® AE 240 balance having a resolution of 0.1 mg. The difference in the pre-test and post-test weights of the filter formed the “filter catch.”

The front half components were washed with acetone at least twice. All the washings were collected in a 500 ml beaker. The contents of the beaker were allowed to evaporate at ambient conditions to about 50 ml under a hood. The sample was then transferred to a tared 25 ml beaker. Care was taken to minimize sample loss. The beaker was then evaporated to dryness and post-weighed. The difference provided the “probe catch.”

A-9.2 Recovery of Back Half Sample:

The liquid present in all three impingers was transferred to a 1000 ml beaker. The impingers were rinsed twice with HPCL grade water. The U-tube connector, the back half of the filter holder assembly and the double L-connector were also rinsed with water. All the washings were transferred to the 1000 ml beaker. All the back half glass wares were then rinsed twice with methylene chloride and the washings were transferred to another beaker. The sample collected in the two beakers was then combined in a 1000 ml separatory funnel. Again, care was taken to minimize sample loss. The funnel was shaken vigorously and the sample was allowed to separate into an organic layer and an aqueous layer. A clear ring was visible after the complete separation. The organic part, being heavier, settled at the bottom, and was drained through the stop cock while the aqueous layer was drained through the top of the funnel to minimize sample contamination. Samples were allowed to evaporate to less than 50 ml and transferred to a tared 25 ml pyrex® beaker. The aqueous portion of the sample was evaporated on a hot plate under a hood to hasten the evaporation process. The beaker containing the organic portion of the sample was evaporated to dryness and post-weighed to give “impinger catch extract” while the beaker containing the aqueous portion of the sample gave the “Impinger catch” after complete evaporation. All samples were weighed to the nearest 0.1 mg.

All the above weights were corrected using field blank residues.

APPENDIX B ISO 8178 8-Mode Test Results for Isuzu C 240 and DDC Series 60 Engines

Table 51 ISO 8178 Test Results on DDC Series 60 Engine. Run 1

DDC Series 60 Run 1	**Laboratory data**						**MEMS data**		**Percent Difference**	
	HC	**CO**	**CO_2**	**NO_x**	**PM**	**Work**	**NO_x**	**CO_2**	**NO_x**	**CO_2**
Mode	**g/mode**					**bhp-hr**	**g/mode**		**%**	
R100	2.38	24.23	25157.2	414.6	2.58	53.53	404.2	24559.2	2.5	2.4
R75	2.24	13.15	18860.9	353.8	1.87	40.08	349.1	18425.6	1.3	2.3
R50	2.24	13.15	12978.9	287.0	1.51	26.70	273.9	12500.9	4.6	3.7
R10	2.40	7.30	4201.4	75.3	1.83	5.44	71.3	4174.5	5.4	0.6
I100	5.06	37.45	21262.0	313.1	3.94	44.84	311.6	21598.7	0.5	-1.6
I75	1.80	148.86	15852.7	273.6	2.09	33.70	267.6	16320.4	2.2	-3.0
I50	1.02	65.93	10547.3	234.2	0.65	22.45	220.8	10808.4	5.7	-2.5
IDLE	0.35	7.47	334.60	5.5	0.08	0.03	5.9	341.5	-6.0	-2.1
Weighted Emissions g/bhp-hr	0.07	1.21	480.4	8.6	0.06		8.4	476.2	2.7	0.9

Table 52 ISO 8178 Test Results on DDC Series 60 Engine. Run 2

DDC Series 60 Run 2	**Laboratory data**						**MEMS data**		**Percent Difference**	
	HC	**CO**	**CO_2**	**NO_x**	**PM**	**Work**	**NO_x**	**CO_2**	**NO_x**	**CO_2**
Mode	**g/mode**					**bhp-hr**	**g/mode**		**%**	
R100	2.53	23.66	24040.7	411.6	2.63	53.22	411.6	24017.0	0.0	0.1
R75	2.06	12.83	18163.6	354.3	1.59	40.10	350.8	18050.7	1.0	0.6
R50	2.27	8.51	12450.8	290.9	1.30	26.73	272.5	12025.8	6.3	3.4
R10	4.69	35.83	4038.7	79.3	1.88	5.31	68.9	3750.9	13.2	7.1
I100	1.66	144.14	20326.0	303.9	3.78	44.79	294.1	20477.0	3.2	-0.7
I75	1.29	62.06	15312.8	261.4	2.08	33.65	251.0	15527.7	4.0	-1.4
I50	0.71	12.14	10308.8	224.4	0.65	22.53	212.9	10515.1	5.1	-2.0
IDLE	0.80	1.78	342.0	6.00	0.08	0.04	6.5	350.3	-9.8	-2.4
Weighted Emissions g/bhp-hr	0.07	1.13	462.5	8.6	0.06		8.3	460.6	3.0	0.4

Table 53 ISO 8178 Test Results on DDC Series 60 Engine. Run 3

DDC Series 60 Run 3	Laboratory data						MEMS data		Percent Difference	
	HC	CO	CO_2	NO_x	PM	Work	NO_x	CO_2	NO_x	CO_2
Mode	**g/mode**					**bhp-hr**	**g/mode**		**%**	
R100	1.23	16.93	14091.5	249.4	1.52	31.48	212.9	13048.9	14.6	7.4
R75	0.88	8.07	11218.8	206.7	0.96	24.10	163.8	10076.1	20.7	10.2
R50	0.85	4.46	7772.3	165.7	0.79	16.12	122.0	7100.5	26.3	8.6
R10	2.19	15.19	2643.1	52.4	1.34	3.31	50.2	2463.5	4.1	6.8
I100	0.63	83.68	11749.6	162.0	2.22	24.93	149.0	11156.4	8.0	5.0
I75	0.58	46.87	9475.1	152.1	1.31	20.23	140.1	9351.9	7.9	1.3
I50	0.30	8.31	6393.5	130.5	0.42	13.48	126.4	6827.4	3.1	-6.8
IDLE	0.67	3.41	287.10	6.2	0.08	0.04	5.5	341.0	11.8	-18.8
Weighted Emissons g/bhp-hr	0.05	1.20	473.65	8.4	0.06		7.2	446.1	15.1	5.8

Table 54 Average Fuel Consumption Data from the Fuel Flow Meter and from the Carbon-Balance of the Emissions Measured by the Laboratory Equipment for the DDC Series 60 Engine.

DDC Series 60 Engine	Run 1			Run 2			Run 3		
	Fuel Flow meter data (kg)	Carbon balance-emissions (kg)	Percent diff	Fuel Flow meter data (kg)	Carbon balance-emissions (kg)	Percent diff	Fuel Flow meter data (kg)	Carbon balance-emissions (kg)	Percent diff
R100	7.64	7.55	1.2	7.70	7.57	1.7	4.64	4.32	7.0
R75	5.72	5.69	0.6	5.73	5.72	0.3	3.48	3.35	3.8
R50	3.91	3.93	-0.6	3.93	3.92	0.4	2.38	2.12	10.7
R10	1.27	1.31	-3.0	1.29	1.29	-0.4	0.80	0.81	-0.9
I100	6.50	6.44	0.9	6.52	6.46	0.9	3.66	3.60	1.7
I75	4.84	4.81	0.6	4.83	4.84	-0.2	2.94	2.95	-0.4
I50	3.14	3.20	-1.7	3.23	3.25	-0.6	1.95	1.99	-2.3
IDLE	0.12	0.09	29.2	0.13	0.08	35.4	0.12	0.09	29.2

Table 55 ISO 8178 Test Results on Isuzu C 240 Engine. Run 1

Isuzu C 240 Run1	Laboratory data						MEMS data		Percent Difference	
	HC	CO	CO_2	NO_x	PM	Work	NO_x	CO_2	NO_x	CO_2
Mode	g/mode					bhp-hr	g/mode		%	
R100	1.25	19.16	2470.0	13.81	-	4.03	13.50	2733.8	2.2	-10.7
R75	6.06	15.85	1901.7	12.11	-	2.96	11.37	2064.4	6.1	-8.6
R50	0.81	8.39	1468.5	8.63	-	1.96	7.90	1583.2	8.4	-7.8
R10	0.72	20.51	911.3	3.56	-	0.22	2.71	839.7	23.9	7.9
I100	0.35	7.19	1812.5	6.97	-	3.09	6.75	2048.9	3.2	-13.0
I75	0.37	8.68	1420.0	8.49	-	2.43	8.72	1613.5	-2.7	-13.6
I50	3.06	22.55	915.8	6.14	-	1.56	7.99	1133.0	-30.1	-23.7
IDLE	59.02	0.38	55.01	0.37	-	0.03	0.35	50.6	5.0	8.0
Weighted Emissions g/bhp-hr	5.07	6.00	669.35	3.73	-		3.65	735.82	2.2	-9.9

Table 56 ISO 8178 Test Results on Isuzu C 240 Engine. Run 2

Isuzu C 240 Run 2	Laboratory data						MEMS data		Percent Difference	
	HC	CO	CO_2	NO_x	PM	Work	NO_x	CO_2	NO_x	CO_2
Mode	g/mode					bhp-hr	g/mode		%	
R100	1.16	4.38	2440.5	17.00	0.59	3.98	17.13	2711.9	-0.7	-11.1
R75	7.15	3.59	1916.0	15.02	0.52	2.98	14.66	2066.1	2.4	-7.8
R50	1.18	1.82	1437.6	11.01	0.29	1.95	10.32	1516.7	6.2	-5.5
R10	0.55	4.29	772.0	3.78	0.20	0.22	3.26	827.3	13.8	-7.2
I100	0.21	1.60	1814.6	8.46	0.46	3.18	9.51	2127.9	-12.4	-17.3
I75	0.15	1.79	1396.3	10.58	0.19	2.43	11.47	1565.8	-8.4	-12.1
I50	0.64	3.14	1065.5	10.02	0.15	1.76	10.34	1137.6	-3.2	-6.8
IDLE	65.94	0.44	66.62	0.45	0.01	0.04	0.34	49.9	24.4	25.1
Weighted Emissions g/bhp-hr	5.46	1.25	659.01	4.67	0.15		4.68	722.6	-0.2	-9.7

Table 57 ISO 8178 Test Results on Isuzu C 240 Engine. Run 3

Isuzu C 240 Run 3	Laboratory data						MEMS data		Percent Difference	
	HC	CO	CO_2	NO_x	PM	Work	NO_x	CO_2	NO_x	CO_2
Mode	g/mode					bhp-hr	g/mode		%	
R100	0.22	2.37	2572.4	15.14	0.68	4.01	16.48	2502.2	-8.8	2.7
R75	8.93	3.80	1953.0	15.32	1.13	2.95	16.17	1920.1	-5.6	1.7
R50	3.05	1.97	1478.5	11.08	0.40	1.95	12.48	1467.0	-12.6	0.8
R10	0.49	6.15	786.8	3.45	0.32	0.20	4.10	806.4	-18.9	-2.5
I100	0.08	1.36	1990.2	8.48	0.63	3.09	11.42	2381.4	-34.6	-19.7
I75	0.03	1.69	1472.8	9.94	0.24	2.42	11.39	1557.8	-14.5	-5.8
I50	1.52	3.15	1106.8	7.62	0.27	1.57	8.15	1090.3	-6.9	1.5
IDLE	70.20	0.47	67.80	0.52	0.01	0.03	0.51	48.3	0.4	28.8
Weighted Emissions g/bhp-hr	6.07	1.22	698.80	4.47	0.23		5.00	712.23	-11.8	-1.9

Table 58 ISO 8178 Test Results on Isuzu C 240 Engine. Run 4

Isuzu C 240 Run 4	Laboratory data						MEMS data		Percent Difference	
	HC	CO	CO_2	NO_x	PM	Work	NO_x	CO_2	NO_x	CO_2
Mode	g/mode					bhp-hr	g/mode		%	
R100	0.14	2.40	2565.1	15.21	0.63	3.98	16.42	2481.9	-8.0	3.2
R75	10.29	4.98	1958.9	15.10	1.06	2.98	15.87	1907.8	-5.1	2.6
R50	2.69	1.98	1481.0	10.67	0.45	1.95	12.03	1475.9	-12.7	0.3
R10	0.51	6.12	796.0	3.43	0.39	0.22	4.05	818.3	-18.2	-2.8
I100	0.11	1.36	1993.0	8.71	0.66	3.18	11.52	2364.8	-32.4	-18.7
I75	0.05	1.72	1473.3	9.20	0.22	2.43	10.94	1554.2	-18.8	-5.5
I50	1.43	3.21	1100.5	8.46	0.27	1.76	8.86	1081.8	-4.7	1.7
IDLE	70.80	0.51	66.60	0.51	0.01	0.04	0.47	49.6	8.4	25.5
Weighted Emissions g/bhp-hr	6.09	1.30	689.05	4.38	0.23		4.88	699.6	-11.4	-1.5

Table 59 Average Fuel Consumption Data from the Fuel Flow Meter and from the Carbon-Balance of the Emissions Measured by the Laboratory Equipment for the Isuzu C 240 Engine.

Isuzu C 240 Engine	Run 1			Run 2			Run 3			Run 4		
	Fuel Flow meter data (kg)	Carbon balance-emissions (kg)	Percent diff %	Fuel Flow meter data (kg)	Carbon balance-emissions (kg)	Percent diff %	Fuel Flow meter data (kg)	Carbon balance-emissions (kg)	Percent diff %	Fuel Flow meter data (kg)	Carbon balance-emissions (kg)	Percent diff %
R100	0.86	0.76	11.5	0.86	0.74	13.3	0.79	0.79	-0.9	0.79	0.79	-0.6
R75	0.65	0.59	9.2	0.66	0.59	10.5	0.61	0.61	-0.2	0.61	0.62	-0.3
R50	0.50	0.45	8.5	0.49	0.44	10.2	0.46	0.46	-0.9	0.46	0.46	-0.7
R10	0.28	0.26	6.1	0.27	0.24	10.5	0.25	0.25	0.0	0.25	0.25	0.0
I100	0.62	0.56	9.4	0.62	0.55	10.9	0.63	0.61	2.2	0.63	0.62	1.6
I75	0.48	0.44	8.6	0.47	0.43	10.0	0.63	0.62	1.6	0.46	0.46	0.2
I50	0.30	0.29	1.7	0.36	0.33	9.4	0.46	0.46	0.2	0.34	0.34	0.3
IDLE	0.09	0.08	10.8	0.09	0.08	10.8	0.09	0.07	23.7	0.09	0.08	18.3