Arnold Schwarzenegger
Governor

AIR QUALITY IMPLICATIONS OF BACKUP GENERATORS IN CALIFORNIA

VOLUME TWO: EMISSION MEASUREMENTS FROM CONTROLLED AND UNCONTROLLED BACKUP GENERATORS

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

What follows is the final report for the project titled, A Study of Peak-Load Energy Production Potential and Air Quality Impacts of Backup Generators (BUGs), contract number 500-00-032, conducted by the University of California, Riverside, Bourns College of Engineering—Center for Environmental Research and Technology (CE-CERT). The report is entitled *Air Quality Implications of Backup Generators in California. Volume Two: Emission Measurements from Controlled and Uncontrolled Backup Generators.* This project contributes to the Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-4628.

Table of Contents

List of Figures

List of Tables

Abstract

The goal of the research presented in this report was to measure criteria and toxic emissions from a number of uncontrolled and controlled diesel backup generators (BUGs) that were representative by age, market share, and size of the more than 4,000 permitted units in California. The final report is in two parts, with Part One focusing on the actual activity of BUGs during the outages and the potential air quality impact. This report, Part Two, focuses on the emission factors from uncontrolled and controlled BUGs. The expectation of the project was to improve the understanding of the environmental effects of producing electricity from diesel BUGs

The final results were from over 700 tests conducted from 16 BUGS with a power output ranging from 300 kilowatts (kW) to 2,000 kW. Eight particular matter (PM) control technologies were demonstrated, including fuel modification, addition of after control technology, and combinations of both. Most of the effort centered on controlling PM, and PM control ranged from about 15% to 99%+. The final product was the creation of the largest database on emissions, to include air toxics, from uncontrolled and controlled modern BUGs. These data were submitted to the U.S. Environmental Protection Agency for inclusion in their AP-42 tables and to peer review journals for publication in the technical literature.

Executive Summary

Introduction

The California Public Interest Energy Research (PIER) Programs are aimed at understanding and/or addressing the environmental effects and costs of energy production. The power outages of 2001 raised an important question. Many companies maintain diesel-fueled backup generators (BUGs) for use in such power blackouts. Thus the question arose as to the harm that would occur to people and the environment if the backup generators were turned on, particularly in areas of California were air quality is already considered dangerous. Accurate data and knowledge on the emissions from BUGs were lacking, along with only a limited understanding of how BUGs were actually used during the power outages.

The point of this research, conducted by the University of California, Riverside Bourns College of Engineering—Center for Environmental Research and Technology (CE-CERT), is to measure criteria and toxic emissions from a number of uncontrolled BUGs that were representative of those in use in California. Later, the project expanded to incorporate a demonstration program of emission control technology. An important element in the approach was the involvement of an advisory group who represented the key stakeholders associated with BUGs. Their input helped to shape the course of research. The final report is in two parts, with Part One focusing on the actual activity of BUGs during the outages and the potential air quality impact. This report, Part Two, focuses on the emission factors from uncontrolled and controlled BUGs. The expectation of the project was to improve the understanding of the environmental effects of producing electricity from diesel BUGs.

Objectives

There were eleven objectives in the total project—two that were the main objectives for this portion of the project:

Task 9: Assess applicable environmental control technologies

Task 10: Conduct field tests of BUGs units and control alternatives

Outcomes

1. Over 700 tests were conducted, including emission measurements and calibration runs. The end result was the measurement of criteria emissions from 16 diesel BUGs that were selected to represent California units, based on market share, size, age, and contribution to the emissions. The power output of the BUGs varied from 300 kilowatts (kW) to 2,000 kW.

2. The measured emissions for particulate matter (PM) compared well with manufacture values but were up to 80% lower than the values listed in the U. S. Environmental Protection Agency's (EPA's) *AP 42.* CE-CERT believes that the manufacturer-reported values differ from the EPA-suggested emission factors

because the manufacturers use analytical methods specified in 40 CFR 89 and the EPA used field methods that included a condensable fraction of PM. Measured oxides of nitrogen (NO_x) values were about 20% lower than the EPA factors.

3. The number of measurements made on emissions of toxics from BUGs comprises the largest database presently available and provides new insight on the toxic emissions. Only carbonyls data are reported, and the values for formaldehyde vary over a wide range, depending on the unit.

4. Eight PM control technologies were demonstrated, including fuel modification, addition of after control technology and combinations of both. Most of the effort centered on controlling PM, and PM control ranged from about 15% to 99%+. A number of emission control options were identified during the project, as indicated below.

    - *Fuel emulsions* reduced PM ~70% and NO_x by 13% for newer engines; and PM by 25% and NO_x by 4% for older engines.

    - *Diesel oxidation catalysts* (DOC) removed 5%–20% of the PM for a 4-stroke, model year (MY) 2000 engine with "dry soot"; and up to 45% for a 2-stroke, MY 1985 engine with "wet soot."

    - *Passive diesel particulate filters* (DPF) removed over 91% of the PM but increased NO_2 levels.

    - *Active traps* removed up to 98% PM without generation of nitrogen dioxide (NO_2).

    - A *fuel-borne catalyst* plus DOC removed 44% of the PM with a 2-stroke engine and 99.7% of the PM from a new engine with a lightly loaded DPF.

5. A report following EPA's AP 42 format was drafted for EPA review and adoption, as well as two publications for peer-reviewed journals.

Conclusions

The in-field test results showed that the criteria pollutants or their precursors were lower than the values in EPA's AP 42. Measurements of emissions from BUGs introduced after 1996 (when EPA regulated emissions from non-road diesel engines) were lower than from earlier units and within the limits specified in the non-road regulation. In addition, new information was provided on the emissions of the carbonyls. Thus the values from this study will provide greater insight into the emissions of BUGs if they are activated in populated and/or non-attainment areas.

Testing with commercial control technologies showed that the PM emissions could be lowered from 15% to 99%, depending on the control technology used. A number of PM control technologies and approaches were demonstrated, including fuel modification and the addition of exhaust after control or both. These controls were found to be effective in reducing the PM levels and other emissions from older and newer BUGs.

The data from this PIER effort will allow the BUG owner and the local regulatory agencies to understand the implications of activating BUGs.

Recommendations

The information gained from this PIER project will be of greater value when used to improve the EPA's AP 42 tables to allow more widespread usage of the findings of this study. CE-CERT is in the process of completing that work.

Although it was not studied in this project, it might be of interest to measure emissions from BUGs when biodiesel is substituted for CARB diesel fuel, to study control technologies that were developed after those selected in this project, and to study BUGs smaller than the 300 kilowatts studied in this project, because the smaller size units are quite numerous and of interest to some regulatory agencies.

Benefits to California

This project on diesel backup generators contributed to the PIER program objectives of providing a reliable electricity supply and reducing the cost of California electricity by providing the Energy Commission with accurate information on the emissions, so that BUGs can be evaluated as a viable source of electricity for future outages.

1.0 Introduction

1.1. Background and Overview of Backup Generators in California

Over the years, diesel backup generators (BUGs) have proved to be the main source of emergency backup power in the United States. Diesel BUGs are the prevailing option for backup power in facilities where continuous power is essential due to their reliability, durability, affordability, and overall efficiency. The Ryan et al. (2002) analysis of the California Energy Commission's BUGs inventory (Waterland 2001) provides some insight into locations where BUGs might be sited. She identified four facility types: (1) commercial/industrial, (2) government/utilities, (3) medical, and (4) telecommunications. Sixteen percent of the BUGs were located at medical facilities (mostly hospitals) and 29% were at government and utility sites—including city, county, and state government buildings and offices; prisons; police services; military facilities; municipal water districts; sanitation facilities; and municipal or public utility providers. Figure 1 shows the classes of activities at facilities using BUGs. About half of the BUGs are at commercial/industrial or telecommunications categories, including hotels; entertainment, manufacturing, electronics, financial, and insurance corporations; and communications entities. Backup generator owners rely on backup generation to safeguard against business disruptions. Data centers for banks are a prime example of a business that cannot shut down.

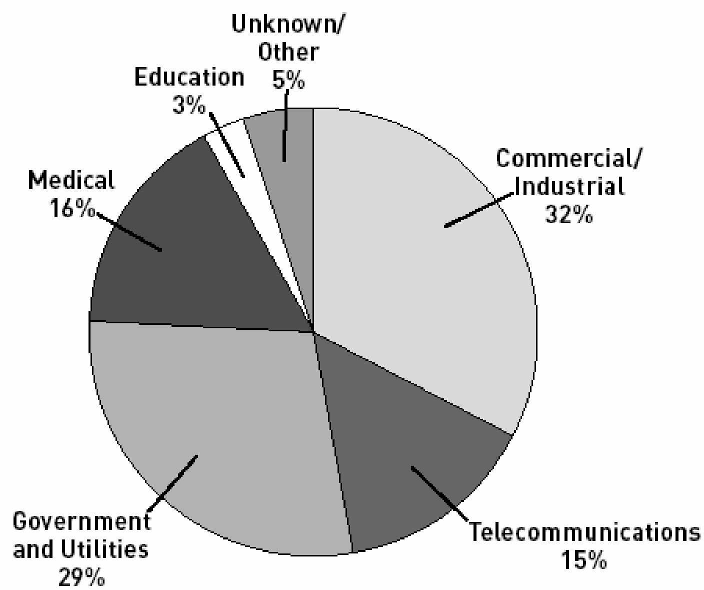


Figure 1. Classification of activities at facilities with BUGs

Surveys show that there are numerous BUGs in California. In 2000, the California Air Resources Board (CARB) (2000) estimated that there were over 11,000 diesel-fueled emergency/standby engines in use in California. Sizes range from 50 to 6,000 horsepower and were typically used for emergency backup electric power generation or emergency water pumping. Estimates suggested that BUGs could generate

5,000 megawatts (MW) of power. Waterland (2001) surveyed the available 4,097 individual permits in the air districts and developed a database with considerable detail on each BUG over 300 kW. He points out that BUGs in five districts account for 86% of the inventory and 87% of the generating capacity. Approximately 85% of the inventory and 84% of the generating capacity is diesel-fueled. Table 1 summarizes the Energy Commission's BUG inventory. Much greater detail is provided on the Energy Commission website.

Table 1. Summary of the California Energy Commission's BUG inventory

Source	**Number of BUGs**			**Total diesel generating capacity (MW)**
	Diesel	Non-Diesel	Total	
South Coast AQMD	1,967	67	2,034	1,694
San Diego County APCD	478	5	483	324
San Joaquin Valley Unified APCD	302	11	313	219
Sacramento Metro AQMD	281	5	286	223
Monterey Bay Unified APCD	111	1	112	76
Mojave Desert AQMD	59	3	62	35
Yolo/Solano AQMD	58	1	59	47
All Other Air Districts	215	69	284	215
Total	3,471	162	3,633	2,833

Source: Waterland (2001)

Note: Only very limited data are available from the Bay Area AQMD. No data exist for Calaveras, Siskiyou, Modoc, Lassen, Tuolumne, Northern Sonoma, or Northern Sierra Air Districts.

The State of California experienced a series of power shortages and localized outages in 2001. Most of the outages were apparently due to the failure of the system of large power generating plants and transmission lines to deliver the electricity to where it was needed. One suggestion was to turn on some of the numerous diesel BUGs to reduce the load on the California system. Many questioned whether diesel BUGs should be turned on while electricity was available, given their relatively high emissions. High emissions would be expected, as many were purchased before EPA first regulated non-road diesel engines and very few had exhaust controls. The fact that BUGs were located in densely populated areas where the power was needed was helpful for electrical supply but problematic from a health perspective. Other issues were that the same areas failed to meet the national ambient air quality standards for ozone, and that most power outages occurred during hot weather, when both electricity demands and ozone peaked.

Ryan et al. (2002) raised the concern that people would be exposed to diesel exhaust—a toxic air contaminant. The U.S. Environmental Protection Agency (EPA) and CARB list more than 40 components of diesel exhaust as toxic air contaminants (TACs). After many years of scientific review, CARB in 1998 identified diesel particulate matter (PM) as a toxic air contaminant[1] and began planning to reduce particulate emissions from all diesel-fueled engines by 85% or to 0.01 grams per brake horsepower-hour. Although BUGs may be a minor contributor to the inventory of diesel PM, the proximity of BUGs and people caused them to become part of the Diesel Risk Reduction Program (CARB 2000).

1.2. Overview — External to California

California was not the only regulatory agency concerned about a more routine use of BUGs and their resulting emissions. Eastern organizations like Northeast States for Coordinated Air Use Management (NESCAUM) and Ozone Transport and Assessment Group (OTAG) issued studies and recommendations about the population, air quality issues and possible controls (NESCAUM 2003; OTC 2001). Perhaps one of the most informative tables of information in the NESCAUM report is the estimated population of engines for that area: Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont. Two independent means—one on sales data and the other on permits—were used to estimate the population. Data indicated most of the engines were < 300 kW (the cutoff for the California study), and that about 80% of the engines and power were from emergency engines. Table 2 shows the estimate based on sales data.

Table 2. Estimates of diesel engines in NESCAUM by number and capacity

Number Totals	Emergency	Peak	Baseload	Total
25-50 kW	1,768	0	0	**1,768**
50-100 kW	5,798	1,375	107	**7,280**
100-250 kW	9,226	2,236	95	**11,557**
250-500 kW	5,918	1,231	7	**7,156**
500-750 kW	1,296	316	47	**1,659**
750-1000 kW	1,164	292	51	**1,507**
1000-1500 kW	641	677	39	**1,357**
1500+ kW	1,073	284	37	**1,394**
Total	**26,884**	**6,411**	**383**	**33,678**

Capacity Totals (MW)	Emergency	Peak	Baseload	Total
25-50 kW	59	0	0	**59**
50-100 kW	462	114	9	**584**
100-250 kW	1,564	371	14	**1,949**
250-500 kW	2,126	443	3	**2,572**
500-750 kW	801	196	29	**1,026**
750-1000 kW	921	230	40	**1,191**
1000-1500 kW	769	837	48	**1,654**
1500+ kW	2,053	615	68	**2,736**
Total	**8,756**	**2,805**	**211**	**11,772**

1.3. Background on Emission Factors

Regulatory agencies often lack actual test results or continuous emission monitoring (CEM) data for a specific source, yet such information is needed to develop the inventories used in air quality management and to asses the potential impacts of the source. Towards meeting that challenge, the EPA created a series of reports (EPA 1995)

[1] The California Air Resources Board identified diesel exhaust as a toxic air contaminant in 1998. See Title 17 CCR Section 93000.

on how to estimate emission factors for various mobile and stationary sources. In general terms, emission factors are expressed as the weight of the pollutant released from a source divided by a unit weight, volume, distance, or duration of the activity that emits the pollutant (e.g., kilograms of particulate matter emitted per gallon of fuel burned). Expressed as an equation:

$$EMFAC = \frac{weight\ \ of\ \ a\ \ pollutant}{weight,\ \ or\ \ duration\ \ of\ \ the\ activity\ \ emiting\ the\ \ pollutant}$$

Although such factors have long been recognized as one of the most cost-effective means for figuring inventories, EPA's caveat is that such factors are meant to represent average emission rates for an entire source category, reflecting age, level of maintenance, and manufacturer—and cannot replace reliable emission measurements from individual sources. However, emission factors are frequently the only method available for estimating emission inventories from new or existing facilities. Source emissions can be estimated quickly and at low cost using emission factors and source activity, as shown in the equation below.

$$E = EMFAC * A * [1-(ER/100)]$$

where:

E = emissions,

EMFAC = uncontrolled emission factor

A = activity rate, and

ER = overall emission reduction efficiency, %.

The primary compilation of emission factor information is EPA's *AP 42,* fifth edition, September 1996 (EPA 1996). It contains emission factors, emission factor ratings, and the analytical protocols for emission testing for more than 200 air pollution source categories. In most cases, the emission factors represent long-term averages for data of acceptable quality for all facilities in the source category (i.e., a population average). In addition to the emission factor, the EPA provides a rating ranging from A (Excellent) to E (Poor) based on the quality of test information and on how well the factor represents the emission source. Higher ratings reflect a number of unbiased observations with widely accepted test procedures. Figure 2 illustrates the EPA rating system and the cost associated with each level.

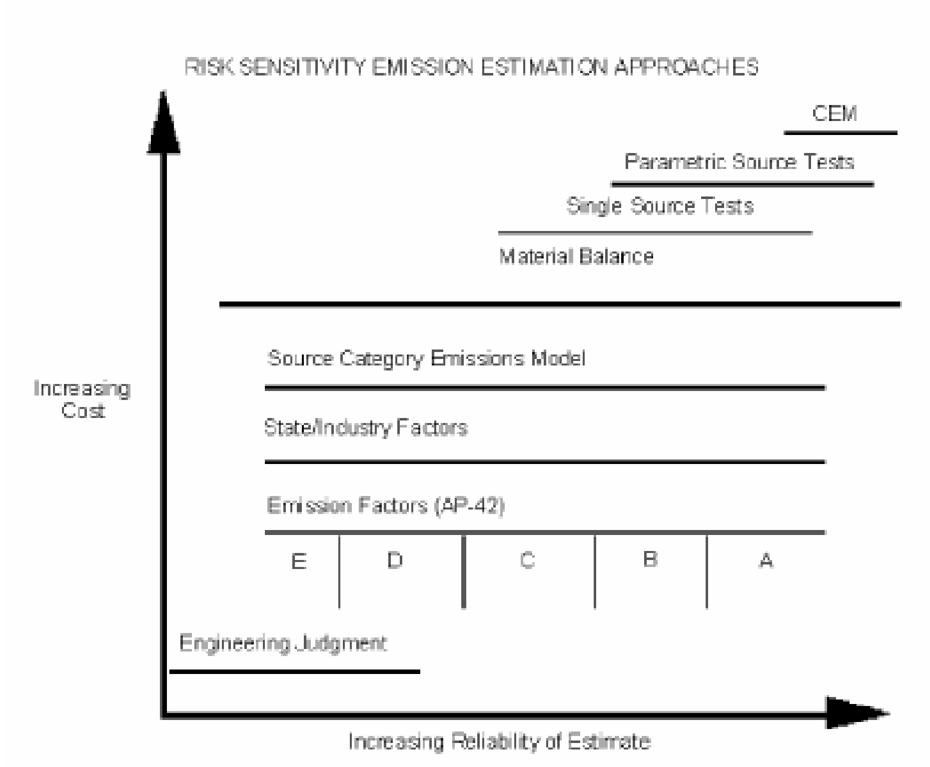


Figure 2. EPA's levels of emission factors and cost

Emission factors in the AP 42 are based on power output and cover a wide range of industrial gasoline- and diesel-fueled IC engines such as generators, pumps, and portable well-drilling equipment, divided into small (< 440 kW) or large (> 440 kW) categories. However, many of the emission factors in the current edition are based on limited data from engines in the 1970s to early 1990s. Accordingly, except for carbon dioxide (CO_2), all of the pollutants have emission factor ratings of D, as seen in Table 3.

Table 3. AP 42 Emission factors and ratings for industrial diesel engines

	Small Engines (< 440 kW)		Large Engines (> 440 kW)	
Pollutant	Factor (g/kW-hr)	Rating	Factor (g/kW-hr)	Rating
NO_x	18.8	D	14.952	B
CO	4.06	D	3.34	C
CO_2	704	B	705.28	B
PM_{10}	1.34	D	0.426	B
HC exhaust	1.50	D		
TOC[1] as CH_4			0.429	C
Aldehydes	0.28	D	0.07	E

1. TOC stands for *total organic compounds,* including all VOCs, methane, ethane, toxics, aldehydes, and semivolatile compounds. "TOC as CH_4" means that the factor was calculated at the molecular weight of methane.

Others have estimated the emission factors for BUGs as a function of the year that the engine was manufactured, as shown in Table 4. The key feature of the table is that the emission rate declines over time and especially after the EPA's regulations for nonroad diesel engines were implemented after 1996.

Table 4. Emission factor based on the year that the engine was manufactured

Year	PM (g/kW-hr)	NO_x (g/kW-hr)
1971–1987	0.71	14.67
1988–1995	0.53	11.20
1996–2001	0.19	7.73
2002	0.16	5.47

1.4. Emission Standards

Prior to 1990, emissions from off-road or non-road sources contributed much less to the air inventory, as compared to mobile sources, and consequently, little attention was placed on precisely determining the emissions from these sources or from making in-use measurements to verify the certification process. This approach was changed with the continued lowering of emissions from mobile sources and the passage of the 1990 Clean Air Act Amendments. Soon after 1990, the EPA launched a major review of the emissions from non-road sources, because these emissions were recognized as a growing and significant contributor to the emissions inventory. The comprehensive review included non-road diesel engines of all sizes used in a wide range of construction, agricultural, and industrial equipment, and in some marine applications. Examples include farm tractors, excavators, diesel lawn tractors, bulldozers, logging equipment, portable generators, road graders, forklifts, and sailboat auxiliary propulsion units.

By 1994, the EPA had adopted the first federal standards (Tier 1) for off-road (or non-road) diesel engines over 37 kW, with a scheduled phased in from 1996 to 2000. On August 27, 1998, the EPA signed the final rule reflecting increasingly more stringent Tier 2/Tier 3 standards for all equipment with phase-in schedules from 2000 to 2008. The Tier 3 standards were expected to lead to implementation of emission control technologies similar to those used by manufacturers of highway heavy-duty engines when complying with the 2004 highway engine standards. The emission standards listed in Table 5 cover the entire useful life, including the application of a deterioration factors (DFs) to all engines. Note the variation in emission standard with engine power and year of manufacture.

Table 5. EPA Nonroad diesel engine emission standards in grams per brake kilowatt-hour (g/bk kW-hr)

Engine Size	Tier	Model Year	NO_x	HC	NMHC + NO_x	CO	PM
kW < 8	Tier 1	2000	-	-	10.5	8.0	1.0
	Tier 2	2005	-	-	7.5	8.0	0.80
8 ≤ kW < 19	Tier 1	2000	-	-	9.5	6.6	0.80
	Tier 2	2005	-	-	7.5	6.6	0.80
19 ≤ kW < 37	Tier 1	1999	-	-	9.5	5.5	0.80
	Tier 2	2004	-	-	7.5	5.5	0.60
37 ≤ kW < 75	Tier 1	1998	9.2	-	-	-	-
	Tier 2	2004	-	-	7.5	5.0	0.40
	Tier 3	2008	-	-	4.7	5.0	TBD
75 ≤ kW < 130	Tier 1	1997	9.2	-	-	-	-
	Tier 2	2003	-	-	6.6	5.0	0.30
	Tier 3	2007	-	-	4.0	5.0	TBD
130 ≤ kW < 225	Tier 1	1996	9.2	1.3	-	11.4	0.54
	Tier 2	2003	-	-	6.6	3.5	0.20
	Tier 3	2006	-	-	4.0	3.5	TBD
225 ≤ kW < 450	Tier 1	1996	9.2	1.3	-	11.4	0.54
	Tier 2	2001	-	-	6.4	3.5	0.20
	Tier 3	2006	-	-	4.0	3.5	TBD
450 ≤ kW < 560	Tier 1	1996	9.2	1.3	-	11.4	0.54
	Tier 2	2002	-	-	6.4	3.5	0.20
	Tier 3	2006	-	-	4.0	3.5	TBD
kW ≥ 560	Tier 1	2000	9.2	1.3	-	11.4	0.54
	Tier 2	2006	-	-	6.4	3.5	0.20

The EPA currently has proposed rules for a Tier 4 standard with new certification requirements and fuel standards. The notice of proposed rule making (EPA 2003) was issued on May 23, 2003 and the final rule was passed May 10, 2004. The new standards will cut emissions from nonroad diesel engines by over 90 percent.

1.5. Project Objectives

The aim and deliverables for the overall project—conducted by University of California, Riverside, Bourns College of Engineering—Center for Environmental Research and Technology (CE-CERT)—were specified during the discussions about the scope of work and approach to achieving those goals. Because the whole project was very large, the original statement of work was divided into a number of tasks and subtasks, with the focus for this work and report being Tasks 9 and 10.

Task 1: Review data developed by start-up contractor and other data

Task 2: Facilitate development and meetings of Steering and Advisory Committee

Task 3: Develop electricity generation scenarios to be analyzed

Task 4: Assess issues associated with interconnection

Task 5: Assess issues associated with dispatch

Task 6: Assess policy and regulatory issues

Task 7: Complete necessary air quality modeling

Task 8: Analyze any health risk issues associated with deployment

Task 9: Assess applicable environmental control technologies

Task 10: Conduct field tests of BUGs units and control alternatives

Task 11: Determine cost, schedules, and approaches to implement

1.6. Report Organization

This report is organized in five chapters. Chapter 1 provides the background for the situation at the time that the Energy Commission and CARB funded this project. Chapter 2 details the processes used to plan the experimental program and selection of the laboratory to make the measurements. Chapter 3 is about the analysis of the data and determination of the emission factors for both the regulated and the toxics. Results are compared with those in the literature. Chapter 4 discusses CARB’s program to demonstrate technology for control of PM emissions from the diesel backup generators. Chapter 5 outlines the lessons learned and the benefits to the Energy Commission and the CARB as a result of the project being completed. Chapter 6 is summarizes the work and makes recommendations for future work.

2.0 Project Approach

The overall project goal was to determine emission factors of BUGs that represented those that were being used in California. Within the main goal were a number of sub-goals and independent actions. Thus, multiple approaches were used as CE-CERT tailored each activity to meet the specific end goal. However, the research team did not lose focus on the key element, namely designing a test matrix that allowed the greatest knowledge of the emission factors from BUGs in California. Towards that end, and knowing that the project was restricted to testing only 20 of the 11,000 BUGs in California, CE-CERT was left few choices: (1) test 20 BUGs selected on a non-random process, (2) use a random selection process, or (3) determine if there was stratification within the BUGs population and then use a filtering process to select the BUGs that would most represent the California situation. The project team rejected the non-random and random selection processes, because those approaches were unlikely to produce the information that was needed. Thus the first part of this section describes the development of a sampling approach based on a stratified population.

A parallel effort was directed to select and develop the testing methods, equipment, and quality assurance methods for the selected BUGs. This path was made straightforward because of the availability of UCR's heavy-duty mobile diesel laboratory. The second section in this section will describe the development of this unique laboratory and the plan for making the measurements.

Finally, an important third element in this project's approach was the involvement of an advisory group who represented the key stakeholders associated with BUGs. The members included representatives from the Engine Manufacturers Association, fuel industry, a non-government organization (the Natural Resources Defense Council, or NRDC), CARB, the Energy Commission, several air districts, and the after-treatment organization (the Manufacturers of Emission Controls Association, or MECA). Appendix A provides a list of the members.

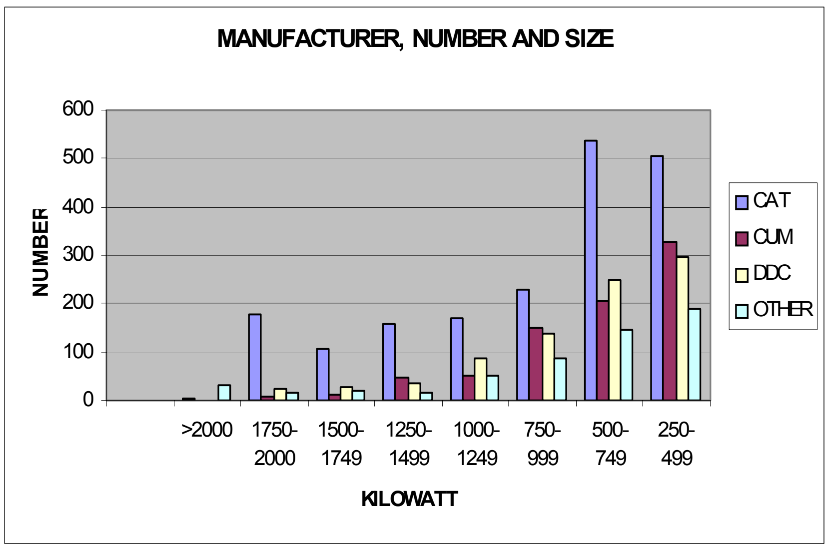
2.1. Identifying a Representative Population of BUGs for the Test Matrix

A number of approaches can be used to select which units to test. A simple and common approach with so many units and so few planned tests is to randomly pick units that are in the field and make the measurements. While easy to do, CE-CERT researchers disregarded this approach as providing very limited information. Instead, researchers proposed using a number of statistical filters to select a representative sample of typical units that were in the field. The approach was based on the knowledge that the population was stratified and that a limited number of parameters would allow the research team to describe the total population. Thus, CE-CERT planned to disaggregate the population by screening or filtering with these variables. The important variables or key characteristics of the population included:

1. Number of like units
2. Size of unit
3. Manufacturer
4. Age of unit (and emission standard)
5. Fuel

Earlier, Table 1 showed information from the AD Little survey of the BUGs that were permitted in the California population. As shown there, more than half of the permitted BUGs were located in SCAQMD, and 30% of the permitted BUGs were in San Diego and San Joaquin Valley. Thus CE-CERT believed that the data for such a large percentage of the California units would be helpful in describing the representative members of the California population. Note that the average BUG was about 450 kilowatts (kW) and 96% of them used diesel fuel. Thus, one screen was to only look at those that used diesel fuel.

CE-CERT further probed the database to develop stratifications that would allow a deeper understanding of the common elements. Engine manufacturer was one of the probed areas; so researchers sorted the Energy Commission data by manufacturer, number, and size of the unit. Results of this sort are arranged using a histogram format in Figure 3.



Note: CAT=Caterpiller, CUM=Cummins, DDC=Detroit Diesel

Figure 3. Manufacturer, number, and size of permitted BUGs in California

The results showed that Caterpillar was the leading seller, with a market share across all units of about 50%. Detroit Diesel and Cummins each have about 20%, others have 5%, and the remaining units did not have an identifiable manufacturer.

CE-CERT decided to take another cut at the data to limit further the number of the units to test. For this cut, researchers assumed that the emissions would be proportional to the power generated in each segment and plotted the product of the power per unit and the number of units, because this would indicate the relative importance of the power sources. These data are plotted in Figure 4.

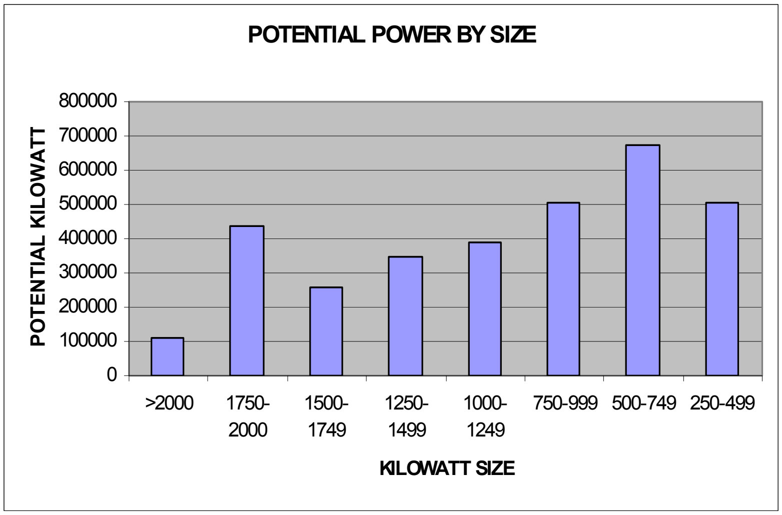


Figure 4. Plot of potential power vs. engine size

In this figure, the peaks for potential power at 1750–2000 kW and at 500–749 kW were notable. These data suggested that a representative sample could be found by simply selecting BUGs from these two size categories. CE-CERT next partitioned the sales penetration by manufacturer in each of these categories and found that Caterpillar sales were > 90% for the units that were 1750–2000 kW and ~50% for the units in the 500–749 kW size. In the smaller, 500–749 kW size, Cummins and Detroit Diesel engines each represented about 20% of the sales. Discussions with local Caterpillar sales offices confirmed the popularity of sales in these size categories and the correctness of limiting the sampling to units that are sized in these bins.

To further limit the number of units in the representative population, CE-CERT hypothesized that units in the South Coast District would be representative of those sold in California. This hypothesis was sound, because over half of the units in the database were from permitted units in the South Coast District. The two plots in Figure 5 visually confirm the validity of the hypothesis that units in South Coast were representative of the whole population. Furthermore, quantitative checks of the market share by manufacturer and of the popular sale units showed that the SC units were representative of the whole of California.

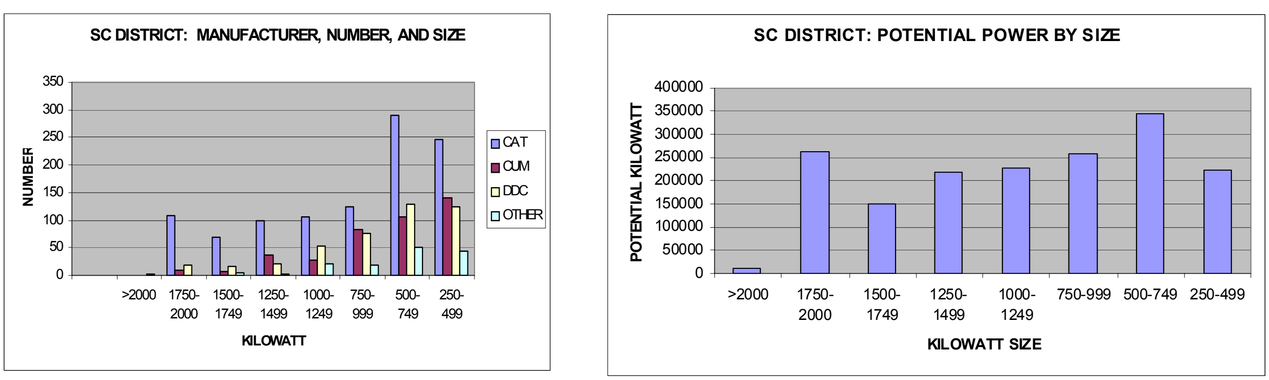


Figure 5. Data for BUGs in the SCAQMD

A final sorting was conducted to establish the number of units within three emission certification periods for diesel engines: 1971–1987, 1987–1995, and 1995+ as emission factors vary significantly for each certification regulation. However, the Energy Commission database and other published information did not show the age distribution of the units. Most of the permits included a serial number, and with help from Caterpillar, CE-CERT researchers were able to get the age and model numbers for the 500–749 and 1750–2000 kW-sized units, as shown in Figure 6.

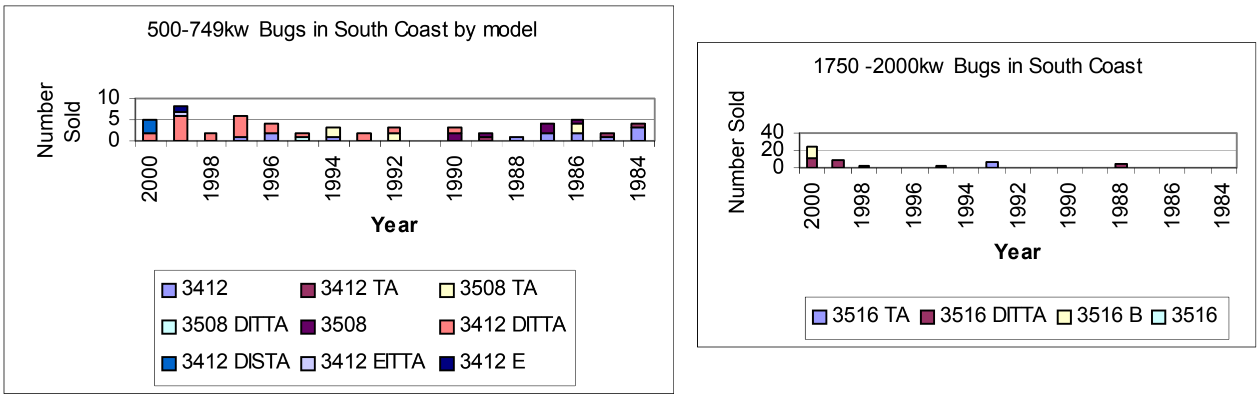


Figure 6. Age and model distribution of BUGs in SCAQMD

Several observations from the charts proved useful in establishing the representative samples for the population of BUGs. First, most of the larger units were installed during the anticipated energy crisis for the year 2000 (i.e., the millennium). However, the smaller units were installed over a longer period of time, and there were active purchasing peaks in the mid-1980s, as well as in the 2000 time frame.

Finally, putting all of this information together allowed us to develop a test population that can statistically represent the whole population. Specifically, the larger, 1750–2000 kW, units are made by Caterpillar and were installed in 1999–2000. For the smaller, 500–749 kW units, these were installed either in the mid-1980s or late 1990s and are primarily Caterpillar units with the remainder being those manufactured by either Cummins or Detroit Diesel. This information was used in the design of the test matrix. An outline of the final test matrix is presented in Table 6. Note that the final matrix included three CAT 3406C units that allowed some measure of the variation that one would detect in field trials. The three units are identified either by the serial number or by the number of hours on the unit.

Table 6. Test matrix of the BUGs tested in the project

Manufacturer	Model	VIN/Serial #	Start Hr	Max kW	Eng Yr.
CAT	3412 C	BPG00177	2,200	545	1998
CAT	3406 B	4RG01632	299	300	1991
DDC 6V92	80837405	BVF149700	273	350	1991
CAT	3406 C	4JK00753	120	350	2000
CAT	3412 C	BPG00177	2,542	545	1998
CAT	3406 C	4JK00706	3,237	350	2000
DDC	Series 60	06RH001775	762	340	1999
Cummins	N14-G2	11964008	1,200	350	1999
CAT	3406B	2WB04221	109	300	1985
Cummins	KTA19G2	68020	62	360	1990
CAT	3406C	4JK00740	663	350	2000
DDC 6V92	6V92	8VF103705	862	300	1985
CAT	3408B	78Z03770	3,002	450	1990
CAT	3508	1FZ01275	443	1000	2000
CAT	3512	1GZ00395	807	1500	2002
CAT	3516	1HZ00388	1,529	2000	2000

2.2. Emission Test Procedures

In general, test procedures consist of following a prescribed sequence of engine operating conditions. For BUGs, the test cycles consist of various steady-state operating modes that include different combinations of engine speeds and loads, with the power output being applied to a resistive electrical load bank. The exhaust gases and particulate matter are sampled for specific component analysis through the analytical train, also according to the CFR protocol. The test procedure is applicable to both uncontrolled engines and those equipped with controls. The test is designed to determine the brake-specific emissions of hydrocarbons, CO, NO_x, and PM. These procedures require the determination of the concentration of each pollutant, exhaust volume and the power output during each mode. The measured emission factors for each mode are weighted and used in the calculation of the overall emission factor in grams of pollutant emitted per kilowatt-hour (g/kW-hr).

Details for testing BUGs can be found in EPA's 40 CFR 89 (EPA 2002a), the section that is used for certifying the nonroad diesel compression engines. The International Standards Organization (ISO) prescribes a similar testing approach (ISO 1996a). Although both EPA and ISO testing procedures are the same, the analysis of the results differ in that the ISO applies a correction factor for moisture to both the PM and NO_x; whereas, the EPA only corrects the NO_x for moisture. The standard test protocol consists of a series of preconditioning cycles to warm and stabilize the engine followed by a sequence of stabilization and testing at five modes, each with a defined speed and load. During the test, the engine is run at rated speed for a minimum period while measuring the regulated emissions. For the CE-CERT testing, the engine was preconditioned at idle then run at full power for at least 30 minutes before measurements were made. Testing begins at the 100% mode and moves from there to the lower power modes with measurements collected for at least 10 minutes at each mode. The currently accepted certification cycle for BUGs is shown in Table 7.

Table 7. Five-mode test cycle for constant-speed engines

Mode number	Engine Speed[1]	Observed Torque[2]	Minimum time in mode, min.	Weighting factors
1	Rated	100	5.0	0.05
2	Rated	75	5.0	0.25
3	Rated	50	5.0	0.30
4	Rated	25	5.0	0.30
5	Rated	10	5.0	0.10

Notes: (1) Engine speed: ± 2% of point. (2) Torque: Throttle fully open for 100% point. Other points: ±2% of engine maximum.

In addition to the standard protocol above, the advisory committee suggested that because many of the BUGs were run routinely for maintenance checks, CE-CERT should measure the transient emissions when the BUGs are started cold. Thus, in addition to the standard five-mode test cycle above, the research team measured the transient gaseous and integrated toxic and PM emissions on the cold start of the engine.

2.3. Emission Test Equipment Provisions

Methods for testing BUGs on-site are also outlined in the ISO standards (ISO 1996b) and can be found in 40 CFR 89, Section D—Emission Test Equipment. Basically the equipment required for the measurement of both gaseous and particulate matter in the diesel exhaust was included in UCR's diesel mobile lab. This included the full-exhaust dilution tunnel; the heated lines from the sampling probes; and the appropriate continuous analyzers for carbon monoxide, carbon dioxide, total hydrocarbons, oxides of nitrogen, and humidity. Analyzer checks were carried out with calibration gases both before and after each test, to check for drift, as required in the CFR. Further, samples were taken from the diluted exhaust and ambient background and stored in bags during the measurement period for post-test comparison with the integrated modal data. Table 8 shows the analyses and reports planned when testing BUGs.

Table 8. Planned analyses and reports when testing BUGs

Equip -ment	Capacity, kW	Gas Measurements							
		Ambient	NO_x	THC	CO	CO_2	Carbonyl	PM	Load
Diesel ICE	300–2000	X	X	X	X	X	X	X	X

The key piece of analytical equipment for measuring the emissions from BUGs was UCR's heavy-duty diesel mobile diesel laboratory. The laboratory was designed to be fitted into the trailer section of a Class 8 tractor/trailer combination and still meet the

CFR standards for measuring emissions from heavy-duty diesel engines. It included a full exhaust dilution tunnel and the suite of analytical instruments required by the CFR. Other specifications since as frequency of calibrations and rate of approach to the final value were tested as the laboratory was outfitted. Figure 7 shows a schematic of the mobile emissions laboratory, and Figure 8 shows the inside of the laboratory during testing. Cocker et al. (2004) provides considerable detail about the laboratory development and application for regulated emissions.

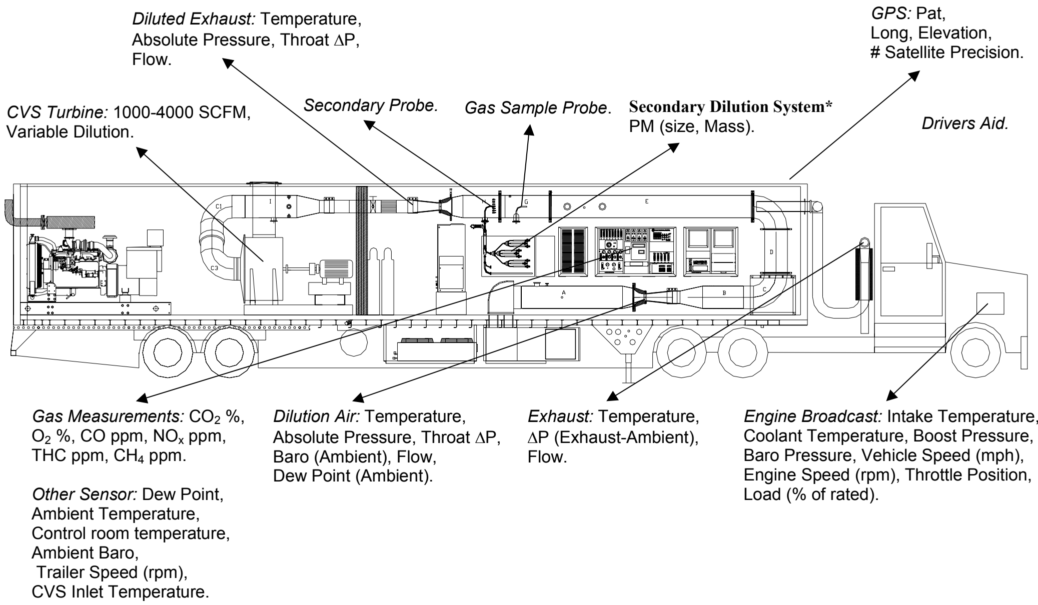


Figure 7. Schematic of UCR's heavy-duty diesel mobile emission laboratory (MEL)

Figure 8. View inside the mobile lab during testing

Figure 9 shows a diagram of the extractive sampling system for gaseous measurements. The system is composed of heated probes, heated filters, and sample conditioning to prevent condensation and remove moisture in the system. Sample probes can be attached to any of ten access ports to the primary tunnel ranging from 2.5 to 10 cm in diameter. The ports are located ten tunnel diameters after sufficient mixing has occurred.

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical devices measure NO_x, methane (CH_4), total hydrocarbons (THC), carbon monoxide (CO), and CO_2 at a frequency of 10 Hz, and were selected based on optimum response time and on-road stability. Two hundred liter (200 L) Tedlar® bags are used to collect tunnel and dilution air samples over a complete test cycle. A total of eight bags are suspended in the MEL, allowing four test cycles to be performed between analyses. Filling of the bags is automated with LabView® 7.0 software (National Instruments, Austin, Texas). Table 9 summarizes the analytical instrumentation used, their range, and their principle of operation. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time.

Table 9. Summary of gas-phase instrumentation in the MEL

Gas Component	Range	Monitoring Method
NO_x	10/30/100/300/1000 (ppm)	Chemiluminescence
CO	50/200/1000/3000 (ppm)	NDIR
CO_2	0.5/2/8/16 (%)	NDIR
THC	10/30/100/300/1000 & 5000 (ppmC)	Heated FID
CH_4	30/100/300/1000 (ppmC)	FID

Ambient dewpoint is measured with a model number 1211hx General Eastern Optical Dewpoint Sensor (Plainville, Connecticut). Resistive thermal devices (RTDs) record temperature along the primary and secondary dilution tunnel, at the dilution air inlet, and at the exhaust outlet. Barometric pressure measured within the tunnel is used to adjust the dynamic flow controller to account for deviations from standard pressure conditions. Daily verification of the barometric reading is performed through comparison of the pressure readings to altitude compensated ATIS (Automated Terminal Information Services) measurements from nearby airports.

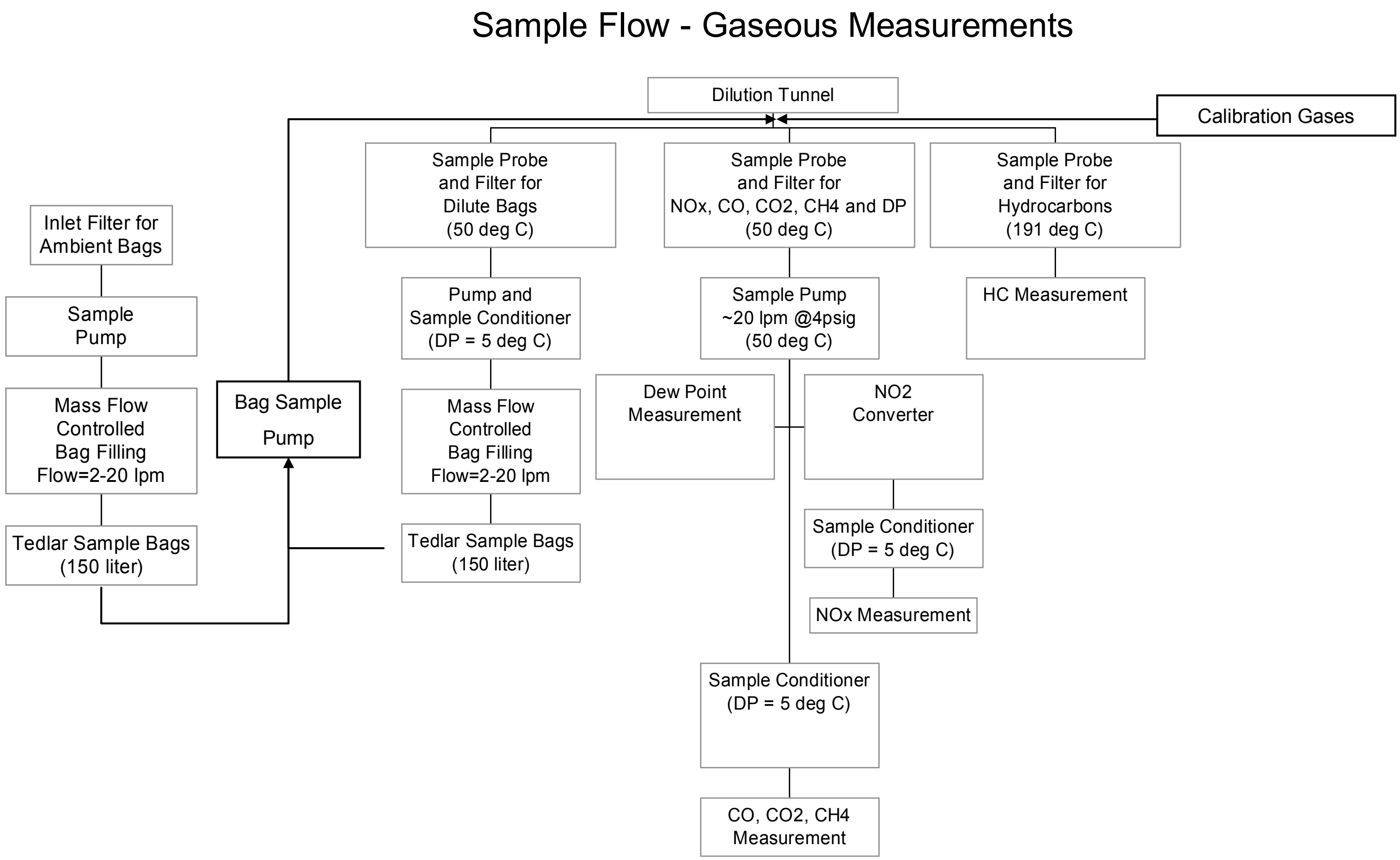


Figure 9. Schematic of the gaseous analytical equipment within the mobile diesel laboratory

Particulate matter was measured in addition to the regulated and speciated gaseous emissions. The laboratory was designed to measure PM according to the requirements of the 2007 standard (EPA 2002b). The key element of the measurement was the design of a secondary dilution tunnel to control the temperature of the filter face to the 47.5°C (118°F) that is specified in the CFR. Figure 10 shows a schematic of the tunnel. Cocker et al. (2004) provides other details of the design and analysis of the PM, including the determination of elemental and organic carbon, speciated VOCs (including carbonyls, benzene, toluene, and xylene compounds), and speciated semi-volatile organic compounds (SVOCs).

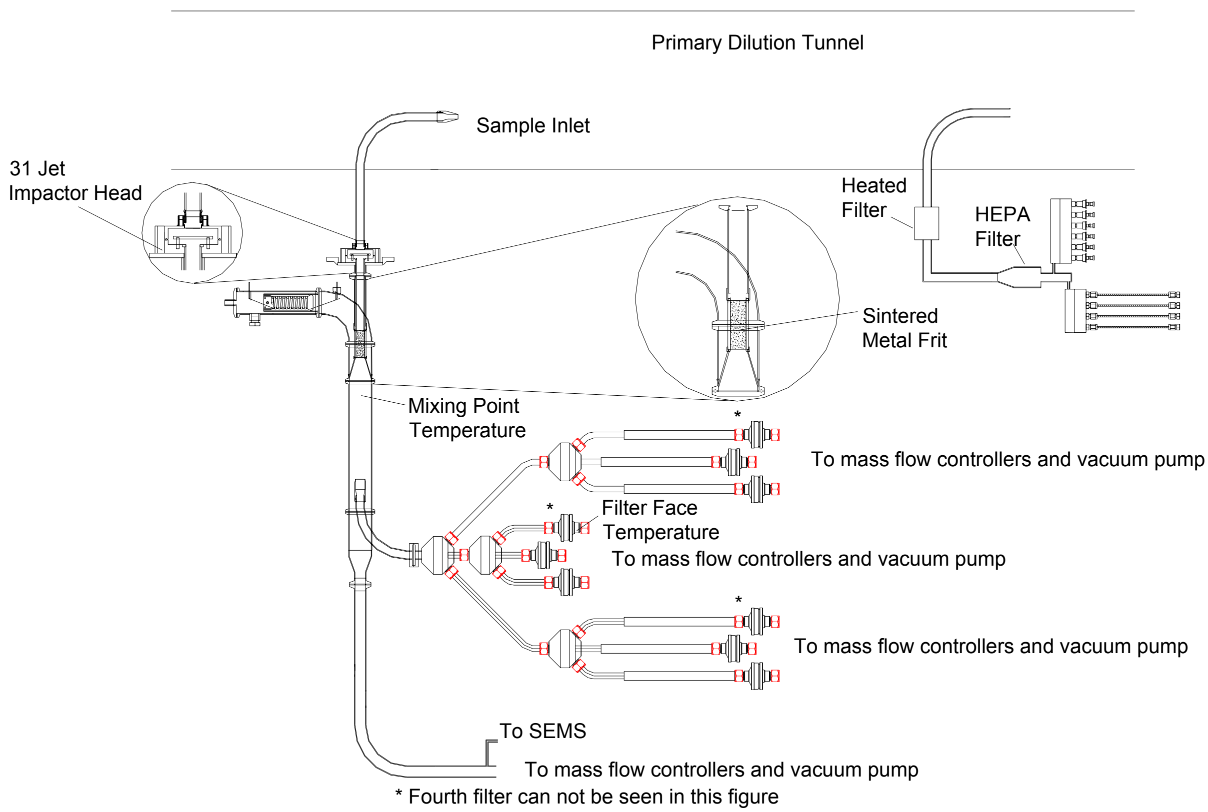


Figure 10. Detailed schematic of the SDS. Further detail of the impactor system and sintered metal frit used to deliver dilution air are given in the inset

In addition to measuring PM, carbonyl (i.e., aldehyde and ketone) emissions were measured in some tests by initially withdrawing a controlled volume from the secondary tunnel through a cartridge of silica coated with 2,4-dinitrophenylhydrazine (DNPH) (Waters Corp., Milford, Massachusetts) and a 0 to 1.0 LPM Unit Series 7301 mass flow controller. Later samples were withdrawn from the primary system to improve the signal/noise ratio. The cartridges were extracted with 5 mL of acetonitrile and injected into a Shimadzu (Torrance, California) high performance liquid chromatograph (HPLC) equipped with an SPD-10AV UV-VIS detector. The HPLC sample injection, column, and operating conditions are set up according to the specifications of the SAE 930142HP protocol (Siegl et al. 1993). A separate port is used for collecting a sample of dilution air for background correction.

2.4. Testing BUGs with a Power Rating over 600kW

Because of temperature and flow limitations, the heavy-duty MEL was restricted to full-dilution tunnel testing for BUGs with a power rating below 600 kW. Accordingly, when CE-CERT wanted to test the BUGs listed in Table 6 with power ratings from 1,000 to 2,000 kW, researchers needed to use a different technique. For units > 1,000 kW, CE-CERT used partial dilution sampling; meaning that only a portion of the exhaust was captured and directed for analysis into the MEL. To ensure that researchers sampled a representative sample, a metal probe with the same geometry as the exhaust outlet was inserted along the centerline of the exhaust stream.

For subsequent analysis of these data, it was important to know the exact fraction of the exhaust that was sampled or the dilution ratio. The dilution ratio was determined by two methods. In the first method, CE-CERT measured the gravimetric rate of fuel consumption by putting a 55-gallon drum of fuel on a digital scale. The mass-rate of fuel intake was compared with the mass emission rate of CO_2, and the dilution ratio was calculated. To confirm the dilution ratio measured with CO_2, a second and independent method was used. Researchers injected propane into the exhaust stream at the muffler inlet at a know rate and measured the rate of propane recovery in the diluted stream. Previous work with full dilution systems showed that propane injected in the muffler inlet was totally recovered at the rate of injection and none was lost as the result of a reaction with the oxygen in the exhaust stream. A comparison of the two methods indicated an agreement within 3%.

2.5. CARB Verification of the Heavy-duty Diesel Mobile Laboratory

A cross-lab correlation check was performed with a Freightliner tractor equipped with a 475 hp, MY2000 Caterpillar C-15 diesel engine at CARB's heavy-duty chassis dynamometer facility located at the Metropolitan Transit Authority (MTA) facilities in Los Angeles, California. The vehicle was loaded using the chassis dynamometer, and emissions measurements were made using either the CARB laboratory or the MEL. The truck was tested on the Urban Dynamometer Driving Schedule (UDDS) and two steady-speed tests. Table 10 shows the results of these tests. It should be noted that all MEL emissions data were submitted to CARB, which returned them with the correlation. A cross-laboratory check performed by other heavy-duty diesel (HDD) laboratories reported (Traver 2002) similar deviations, as this study found.

Table 10. Cross-laboratory test performed at CARB's heavy-duty diesel truck (HDDT) test facility (January 31, 2002)

Test Cycle	THC	CO	NO_X	CO_2
Hot UDDS	10.1%	13.0%	8.9%	5.2%
SS @40 mph	7.4%	12.3%	4.0%	4.9%
SS @ 55 mph	16.4%	3.7%	4.0%	5.5%

After the installation of the secondary system, a number of internal and external confirmation tests were carried out. For example, the masses of $PM_{2.5}$ collected on two parallel samples holders were compared and the results were within 5%. Also a cross-lab correlation check was performed with the same Freightliner tractor at the CARB heavy-duty chassis dynamometer facility while operating on the UDDS. Emission measurements were made using the MEL and CARB measurement benches on consecutive days. Table 11 shows the results of these tests. For these tests, the filter face temperature in the MEL was adjusted to 27 °C (81°F) to match the CARB PM collection system. A retest in the MEL with the filter face temperature set to 47 °C (117°F) recovered ~11% less PM mass than the MEL test at 27 °C (81°F). Following the tests, the MEL emissions data were submitted blind to CARB, who provided the percent differences between the labs, as shown in Table 11. A cross-lab check performed by other HDD laboratories reported similar deviations as those found in Table 11 (Traver 2002).

Table 11. Cross-laboratory test performed at CARB's HDDT test facility. (March 19, 2002)

Test Cycle	THC	CO	NO_x	CO_2	PM
Hot UDDS	11.8%	18.4%	8.0%	2.7%	0.1%

2.6. Engine Operation Data Collection

Measurements of engine load performance and ambient conditions were included for all tests because of the impact of engine inlet temperature and humidity on emissions and BUG performance. Ideally, the CE-CERT research team would have had an independent means of measuring fuel consumption so as to compute the emissions either on a heat input or power output basis. However, this equipment was not available, so CE-CERT did not measure the fuel flow for most of the tests. The CE-CERT team did take samples of the diesel fuel used in each BUG tested and CARB's laboratory in El Monte analyzed the samples for sulfur, aromatics, polynuclear aromatics, and cetane index. In this testing, the BUG output was connected to a 600 kW resistive load bank made by Crestchic Ltd. (Burton upon Trent, Staffordshire, UK) to dissipate the power generated and load.

Measurement of ambient conditions was very important to the proper interpretation of the test data as ambient temperature, pressure and humidity affect the quantity of air introduced to the engine and therefore influence the air/fuel ratio. If temperature is lower, greater mass of air can be introduced in the engine, which can allow for greater fuel combustion rate, in effect boosting the output power of the engine. Greater A/F, higher humidity, or increased pressure affect peak combustion temperatures and can influence the emission levels of NO_x, CO, and THC (McCormick et al. 1997). Therefore, for each test run, the ambient temperature, pressure, and relative humidity were measured.

2.7. Quality Assurance and Quality Control Requirements

Internal calibration and verification procedures are performed regularly in accordance with the CFR. A partial summary of routine calibrations performed by the MEL as part of the data quality assurance/quality control program is listed in Table 12. The MEL uses precision gas blending to obtain required calibration gas concentrations. Calibration gas cylinders, certified to 1%, are obtained from Scott-Marrin Inc. (Riverside, California). By using precision blending, the number of calibration gas cylinders in the lab was reduced to 5, and cylinders need to be replaced less frequently. The gas divider contains a series of mass flow controllers that are calibrated regularly with a Bios Flow Calibrator (Butler, New Jersey) and produces the required calibration gas concentrations within the required ±1.5% accuracy.

In addition to weekly propane recovery checks, which yield > 98% recovery, CO_2 recovery checks are also performed. A calibrated mass of CO_2 is injected into the primary dilution tunnel and is measured downstream by the CO_2 analyzer. These tests also yield > 98% recovery. The results of each recovery check are all stored in an internal QA/QC graph that allows for the immediate identification of problems and/or sampling bias.

Table 12. Verification and calibration table

EQUIPMENT	FREQUENCY	VERIFICATION PERFORMED	CALIBRATION PERFORMED
Constant Volume Sample (CVS)	Daily Weekly Per Set-up Second by second	Propane Injection CO_2 Injection CVS Leak Check Back pressure tolerance ±5 inH_20	Throat Pressure Absolute Pressure
Calibration System	Semi-Annual	Primary Standard 1% Bottle Check	Mass flow controllers (MFCs): Drycal Bios Meter
Analyzers	Pre/Post Test Daily Monthly	Zero span drifts Linearity Check	Zero Span
Secondary System	Daily Testly Weekly Semi-Annual	Leak Check CO_2: Secondary vs. Primary Propane Injection: 6-point primary vs. secondary check	MFC: Drycal Bios Meter and TSI Mass Meter
Data Validation	Testly	CO_2 Balance Modal vs. Integrated Bag Mass Standard Check all sensors limits/mode	
PM Sample Media	Testly	Static, tunnel, and dynamic blanks	
Temperature, Barometric Pressure, and Dewpoint Sensors	Daily	Checks w/Automatic Terminal Information Service (ATIS); Psychrometer	Performed when verification fails

2.8. Data Acquisition and Reporting

The testing of BUGs required a PC-based data acquisition and recording system to automate the process of data taking and reducing potential erroneous recordings. The PC and interface electronic input hardware receives streaming data from separate data acquisition subsystems: (1) generator output meter, (2) continuous emission monitors (CEMs), (3) ambient data, and (4) the BUG itself.

The CEM analytical bench will provide data on continuously monitored emissions only, such as CO_2, NO_x, CH_4, THC, and CO. Other sampled emissions, such as aldehydes and PM required manual data input from the analytical labs. Test data from the BUG equipment will include revolutions per minute (RPM), compressor discharge pressure and temperature for ISO correction, exhaust gas temperature and flow rate, and other vital DG operational settings deemed necessary by the original equipment manufacturer (OEM) and testing personnel.

2.9. Field Issues

Even with everything in place with respect to the design of the test matrix and the selection of the test conditions, there were a number of issues related to field-testing that complicated the implementation of the plan. First was the identification of a test site that had a BUG from the test matrix and whose owner was willing to let us test the unit. The identification of a willing participating partner became a critical element in the execution of the plan. One obstacle was the permit and the limited number of hours included on the permit. An approach to the air districts indicated that it was not easy to get an exception to the permitted hours, thus many of the first BUGs that were tested came from rental companies.

Once a BUG was located, the next step was a site visit to see if the mobile lab would fit into their facility and whether there were any operational problems that could be anticipated on the site. For example, CE-CERT often had to fabricate parts so that the exhaust of the BUG would fit the input for MEL. Next, the load bank was installed and the calibration for the dilution tunnels and the analytical equipment were completed on the site. Figure 11 shows a typical setup.

Figure 11. Typical field setup of the BUG, load cell, and the MEL

3.0 In-Field Testing for Regulated and Toxic Emissions

3.1. Data Analysis

Raw data from the testing were analyzed to develop emission rates and emission factors for the various BUGs that were tested. The CFR (EPA 2002c) provides details on how to treat raw data and convert it into useful emission rates and emission factors. A key factor in the final determination of the emission factor is the adjustments needed for the NO_x and PM for moisture. A question arose as to whether to correct the PM for moisture, as required by the ISO requirements, or to leave the measured value unaltered, as specified in the CFR. Because CE-CERT wanted the calculated values to be directly compared to those in the EPA's AP 42 and manufacturer's engine certification, researchers decided to follow the CFR method and not correct the PM for moisture. NO_x was corrected for moisture as required by the CFR. The final reported emission test results are computed by use of the following formula:

$$A_{WM} = \frac{\sum_{i=1}^{i=n}\left(g_i \times WF_i\right)}{\sum_{i=1}^{i=n}\left(P_i \times WF_i\right)}$$

Where:

A_{WM} = Weighted mass emission level (HC, CO, CO_2, PM, or NO_x) in g/kW-hr

g_i = Mass flow in grams per hour,

P_i = Power measured during each mode, including auxiliary loads, and

WF_i = Effective weighing factor.

Another issue that came up during the discussions with several of the members of the advisory board was the power measured at each mode. The above equation indicates that it is the output power and not the brake horsepower. However, the brake horsepower value is used to certify the engines. From CE-CERT's work, researchers could only estimate the brake horsepower that is the standard used to certify engines. Thus, the power value shown in this project's raw data is probably about 3%–5% high, based on the fan plus other auxiliaries, and another 3%–5% high, based on the losses associated with the generator where the engine output is converted into electrons. Hence overall, the CE-CERT emission factors should probably be reduced by 6%–10% to reflect the values on a brake horsepower basis when compared to the certification values. CE-CERT has reported the values on the basis of the power measured at the load bank.

3.2. Test-to-Test Reproducibility

Repeatability and precison are important indicators of the quality of any experimental data. Figure 12 shows the results of three emission results obtained for NO_x for the 5-mode cycle emission test for CAT 3406B during the same day. Listed across the bottom of the figure is the the coefficient of variance (COV) for the different modes (% load). COV ranged from 1.70% to 4.24%. Here the COV was below 5%. Similar results were obtained for all other criteria pollutants and generators.

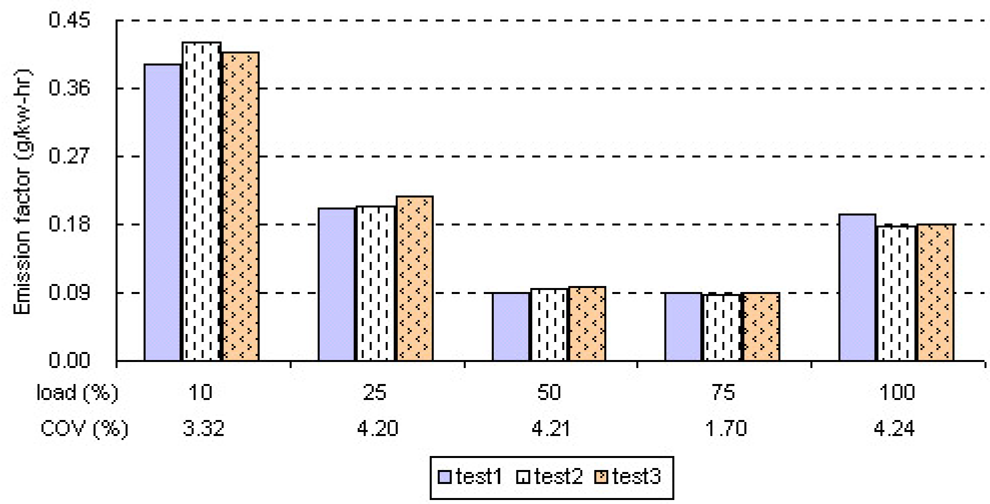


Figure 12. Test-to-test precision for emissions of NO_x with a CAT 3406B

Because some emission tests were conducted on different days or months, the CE-CERT team examined the COV for those tests as well. Results showed very low emission test variability from day to day and month to month for all pollutants and all engines. Examples of these are shown in Figures 13 and Figure 14. Figure 13 shows the day-by-day reproducibility of the NO_x emissions obtained for a CAT 3406C and an example of the month-by-month variablity is provided in Figure 14 for the NO_x emissions from a CAT 3412C. The emission tests of CAT 3412C were taken after the unit was in the field for 2.5 months and had accumulated about another 350 hours of operation. An interesting observation is the low deterioration factor for this particular BUG.

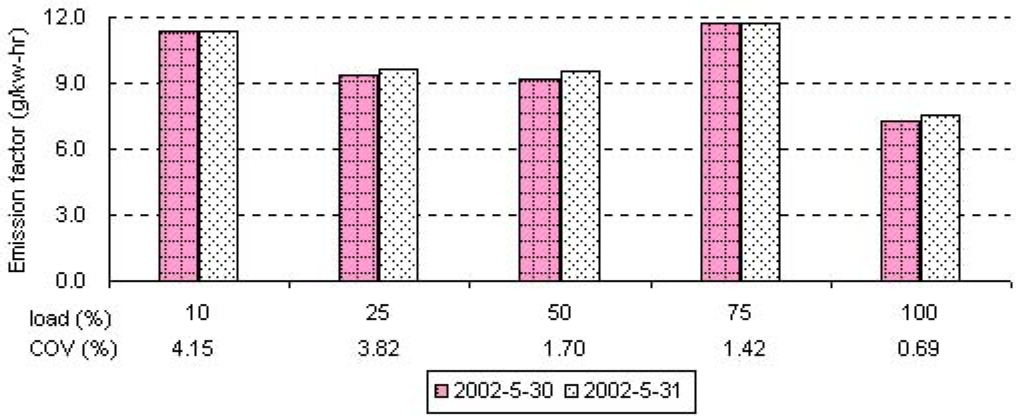


Figure 13. Day-to-day precision for emissions of NO_x with a CAT 3406C

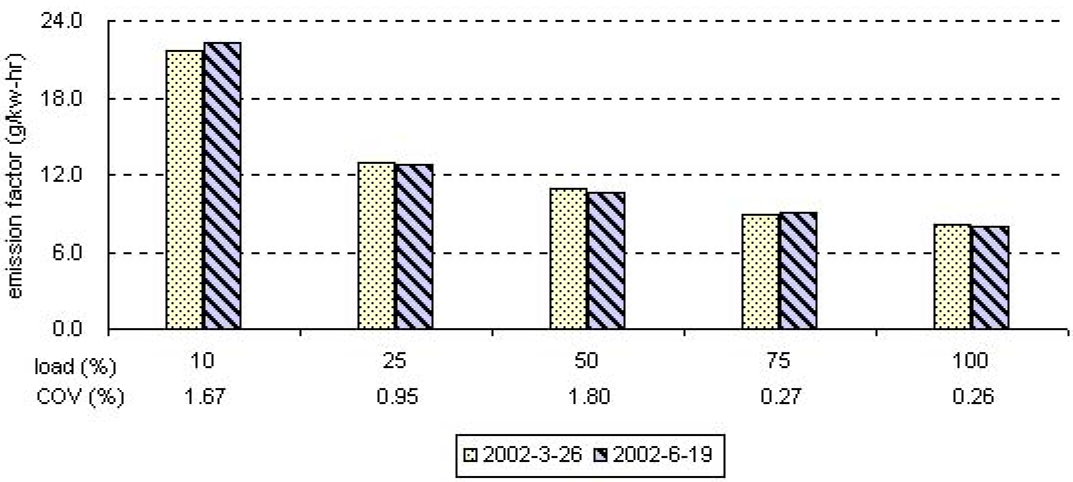


Figure 14. Month-to-month precision for emissions of NO_x with a CAT 3412C

3.3. CO_2 Emissions and Generator Power

Another useful internal check of the consistency of the overall emission testing, including the analytical equipment associated with the emission tests, is the correlation of the CO_2 emissions with generator power. Assuming a constant effieciency, CO_2 emissions should be directly related (linear) to fuel consumption and power. Figure 15 displays a very good fit of the expected linear realationship. When the coefficient of determination, R^2, is > 0.90, then the correlation is statistically strong. CO_2 emission rates versus power were checked for three other generators, and a strong correlation was found for them as well (see Figures 16–18).

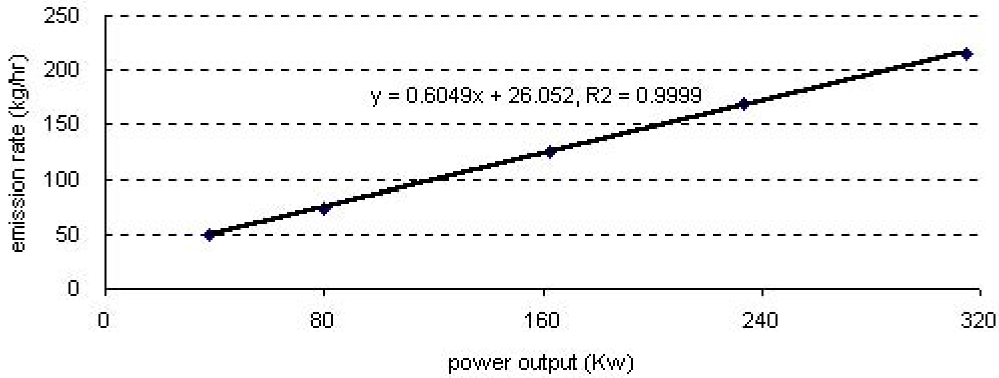


Figure 15. CAT3406B CO_2 emission rate versus generator power output

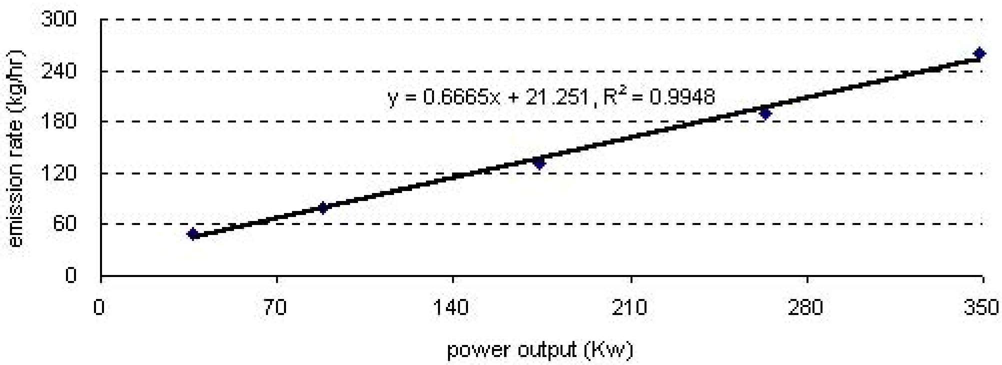


Figure 16. CAT3406C CO_2 emission rates versus generator power output

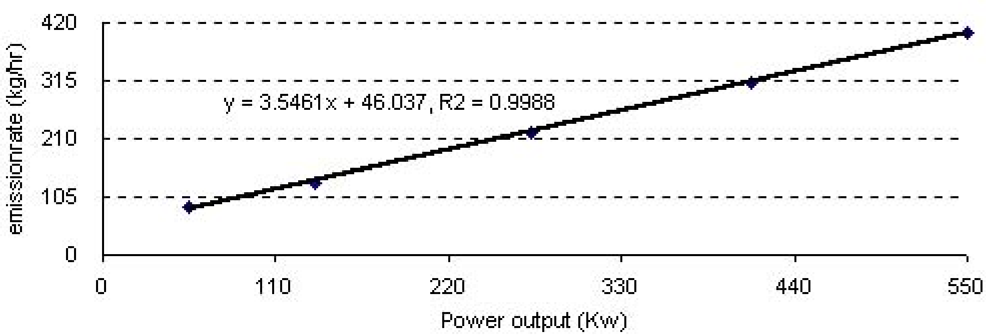


Figure 17. CAT3412C CO_2 emission rate versus generator power output

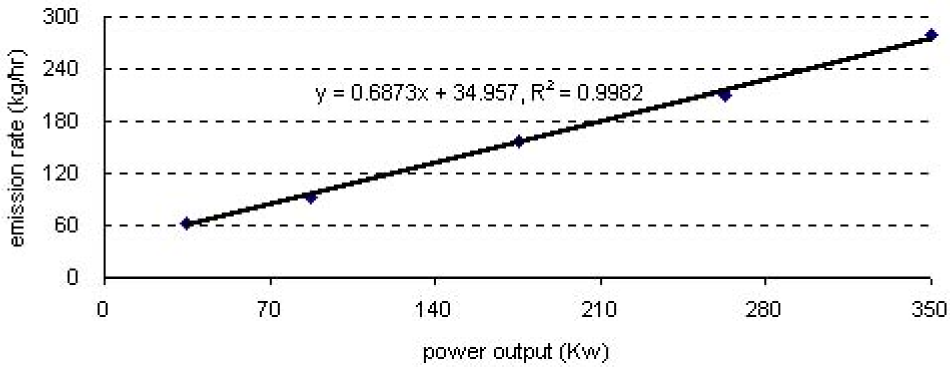


Figure 18. DDC8V92 CO_2 emission rate versus generator power output

3.4. Emission Factors for the Transient Cold Start

For each of the BUGs, the raw data were compiled during the testing, then adjustments were made to correct for ambient values and moisture. One of the data sets that was unique to this work was the measurement of transient emissions during the cold start. A representative example of the startup transient data is shown in Figure 19. The salient features are the high CO, total hydrocarbons, and the low NO_x initial values for about the first 30 seconds, and then a leveling out of the emissions.

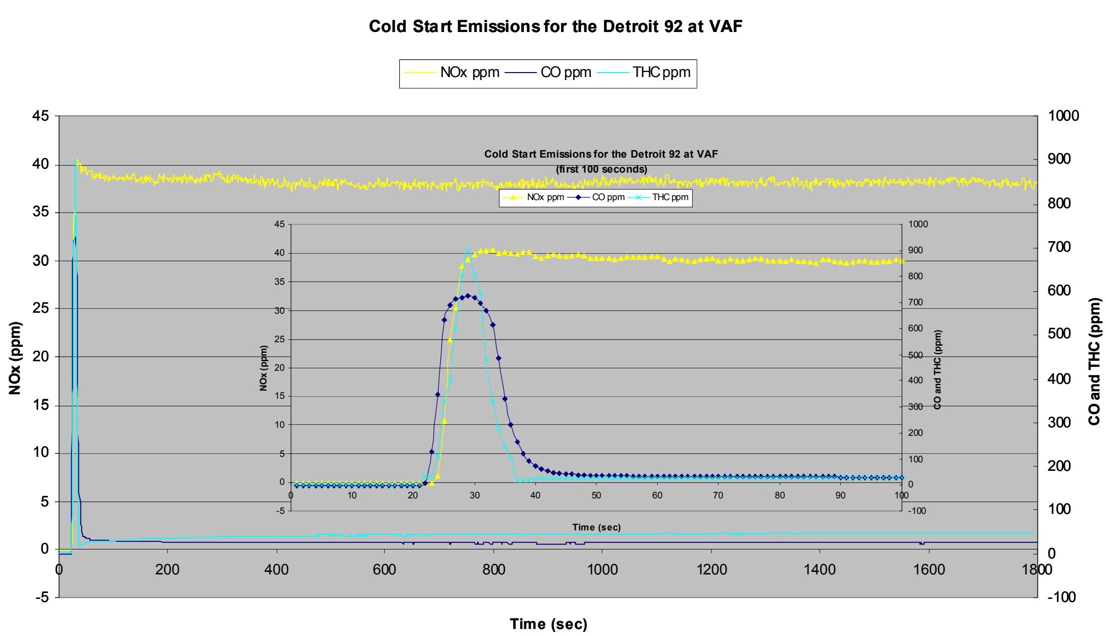


Figure 19. Cold-start emissions for CO and NO_X as a function of time

Although no electrical load is applied to the generator when the BUG was started, there are measurable emissions. For example, in the case shown in Figure 20, the emission factors in grams per kilowatt-hour were 24.3, 22.5, 55.4 and 17.7 for CO, THC, NO_x and

PM, respectively. The load on the engine was about 5 kW and emissions were averaged over the first 30 minutes.

3.5. Emission Factors for Regulated Species and Carbon Dioxide, CO_2

As mentioned in the introduction to this section, the emission factors were calculated from the raw data by following the methods prescribed in the CFR. For each BUG, the CE-CERT team developed emission rates in terms of the actual measured grams per hour at a specific power setting and then calculated the emission factor in terms of grams per measured kW-hour. The overall emission factor was figured using the formula and weighting factors shown in the CFR. Table 13 lists the weighted emission factors for the uncontrolled BUGs.

Table 13. Summary of weighted emission factors in g/kW-hr for uncontrolled BUGS

Mfg/Model/Yr	Eng Hr	Fuel	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406B/'91	300	CARB	0.15	0.03	0.12	1.21	12.95		777	0.13
DDC/V92/'91	273	CARB	0.63	0.05	0.59	1.26	10.48		868	0.29
CAT/3406C/00	120	CARB	0.10	0.02	0.08	1.90	8.80	0.30	765	0.25
CAT/3412C/'98	2200	CARB	0.15	0.04	0.12	1.46	10.42		824	0.21
CAT/3412C/98	2542	CARB	0.14	0.04	0.11	1.53	10.35	0.44	821	0.26
CAT/3406C/00	3237	CARB	0.22	0.04	0.37	1.68	8.89	0.37	745	0.22
DDC/60/99	762	CARB	0.09	0.01	0.08	0.75	10.19	0.39	871	0.08
CUM/N14/99	1200	CARB	0.30	0.03	0.27	0.63	8.25	0.26	803	0.09
CAT/3406B/86	110	CARB	0.23	0.04	0.19	0.90	15.37	0.40	773	0.14
CUM/KTA19G2/90	64	CARB	0.52	0.05	0.48	0.93	9.37	0.37	733	0.32
CAT/3406C/00	664	CARB	0.11	0.02	0.09	1.96	9.08	0.33	755	0.25
CAT/3406C/00	1018	ECD	0.10	0.02	0.08	2.07	7.98	0.31	762	0.22
CAT/3406C/00	130	CARB	0.12	0.02	0.10	1.39	8.86	0.28	747	0.20
DDC/V92/85	863	CARB	0.88	0.07	0.82	2.11	14.46	0.76	957	0.28
CAT/3408B/90	3004	CARB	0.19	0.05	0.14	2.30	7.16	0.35	799	0.47
CAT/3512/00	808	CARB	0.42	0.03	0.39	0.77	6.93	0.42	798	0.18
CAT/3508/02	443	CARB	0.43	0.04	0.37	0.74	6.41	0.32	798	0.22
CAT/3516/00	1530	CARB	0.40	0.02	0.36	0.66	6.80	0.38	745	0.17

A graphical representation of the NO_x emission factors for all the uncontrolled BUGs is shown in Figure 20. Manufacturer, year, and size are used as filters to separate the data. The first three bar charts are data with Detroit Diesel engines, the next two with Cummins engines, and the remainder with Caterpillar engines. The striped bars indicate those engines that the EPA classifies in AP 42 as large units, or > 440 kW. The engine model and the year are listed as the legend on the x-axis, with the emission factor listed on the y-axis. Note that the measured NO_x emission factors values are well below those shown in the EPA's AP 42 tables of 18.8 and 14.95 g/kW-hr for the small and large units, respectively. Note also that the emissions for most engines made after 1996 were well within the 9.2 grams per brake kilowatt-hour (g/bk kW-hr) certification limit. Note that the numbers shown in Figure 20 are in actual kW, as opposed to brake kW, as specified in the regulation. With auxiliary losses as high as 10%, a measured value of 10 g/kW-hr would be reduced to 9 g/bk kW-hr.

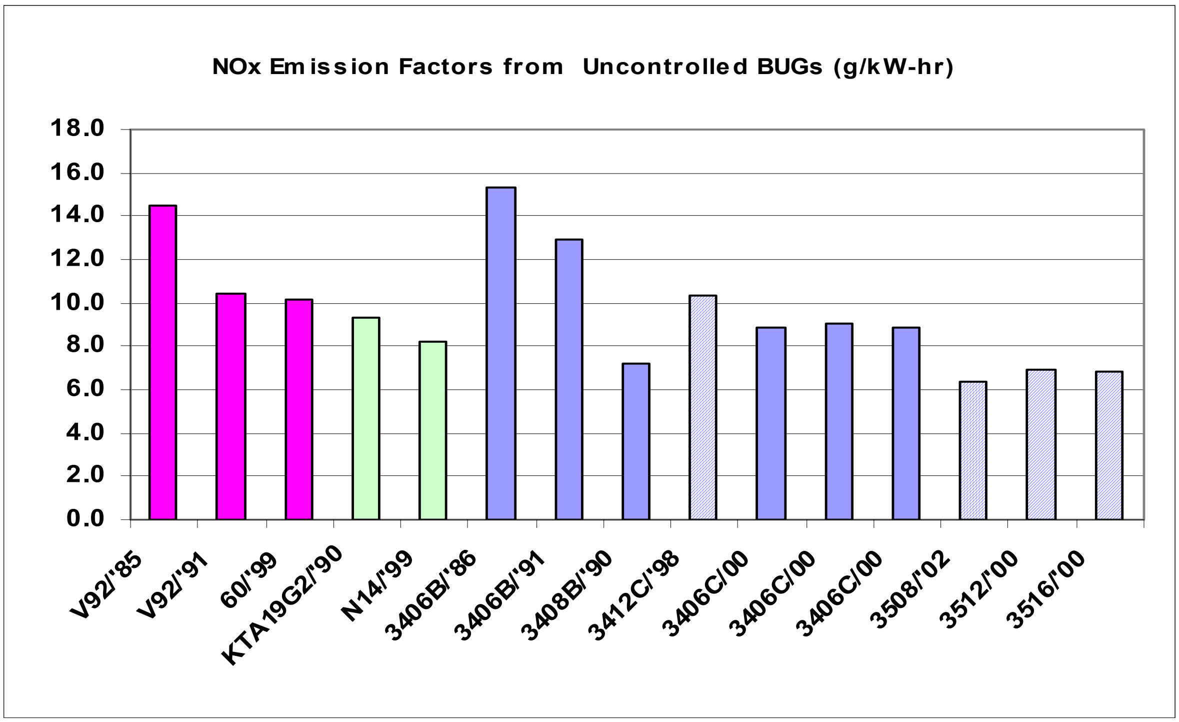


Figure 20. NO_X emission factors in g/kW-hr from uncontrolled BUGs

A chart using the same legends as for the NO_x emission factors is constructed in Figure 21 for the PM emissions. The main observation is the striking, large difference between the measured emission factors and those in EPA's AP 42 of 1.34 and 0.43 for the small and large engines, respectively; or with the compliance value of 0.54-g/bk kW-hr for small engines made after 1996. Also noteworthy are the very low emission factors for the largest BUGs in the CAT 3500 engine series.

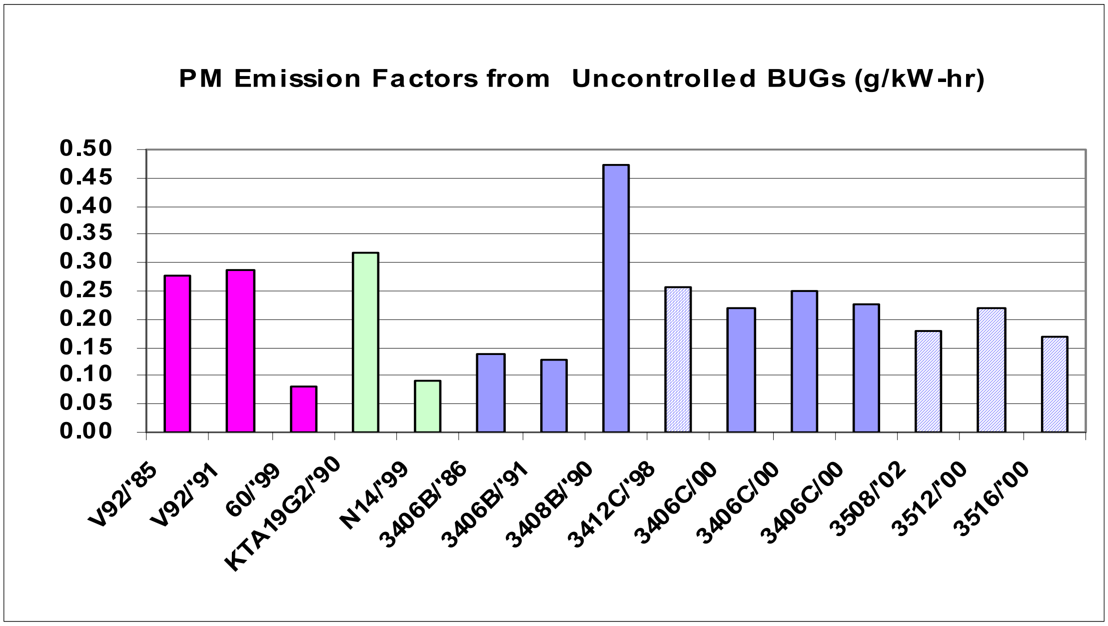


Figure 21. PM emission factors in g/kW-hr from uncontrolled BUGs

The large difference between the AP 42 value of 1.34-g/kW hr for small engines and the measured value became a source of further investigation. Several factors were obvious, including that the AP 42 value was derived using older engines with higher fuel sulfur content, and that a different method may have been used for measuring the emissions. CE-CERT's discussion with EPA uncovered that a contractor did the work a long time ago with older engines and their workers were retired. However, from some other work, CE-CERT researchers believe that the main difference is in the measurement method, as shown in Figure 22. Measurements made with a full dilution tunnel using the methods as specified in 40 CFR 89 are 3 to 5 times lower than measurements made with EPA's Field Method 5. The latter method uses impingers for the recovery of the condensable PM, and that is where significant mass is recovered. More work is needed to confirm this hypothesis.

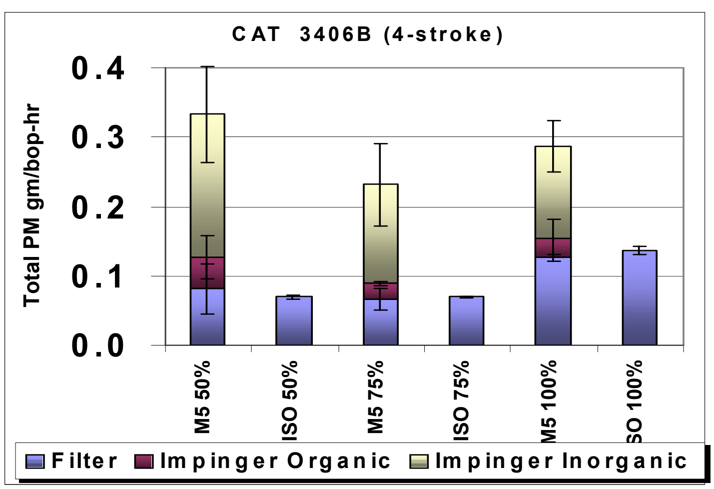


Figure 22. Mass emissions measured by 40 CFR 89 and CARB's Method 5

3.6. Emissions Data by Manufacturer

The next series of figures provides more detailed information on the emission factors by the manufacturer of the engine. The reader is cautioned that these data are for only a few engines and are unlikely to be statistically representative of the whole population of diesel engines for these manufacturers. Instead, the few measured BUGs represent a snapshot for that manufacturer and give indications of the evolution of the technology and reduced emissions over time. Figure 23 shows BUGs using Detroit Diesel engines and represents engines from 1985, 1991, and 1999. Three emission factors are represented: NO_x, PM, and non-methane hydrocarbons. A key difference in these data is that the 6V92 engines (from 1985 and 1991) use a 2-stroke design, and the Series 60 (from 1999) uses a 4-stroke design. The significant reduction in the non-methane hydrocarbons was as expected when changing from the 2-stroke to the 4-stroke technology. Also note that the NO_x drop in the 1991 off-road unit was probably a consequence of the on-road specification in 1988. Technology developed for the on-road application migrated to the non-road application.

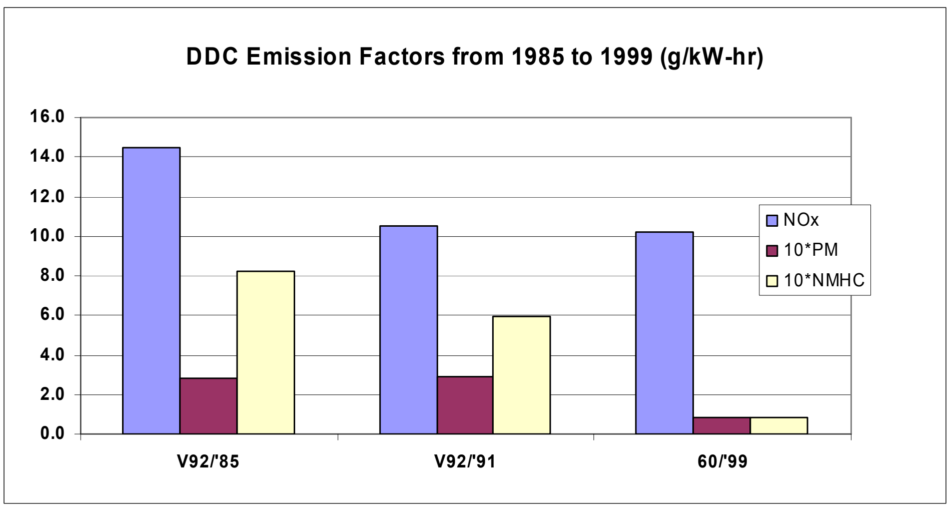


Figure 23. Emission factors for DDC engines from 1985, 1991, and 1999 (g/kW-hr)

Figure 24 shows the change in engine technology for BUGs with Cummins engines. Both used 4-stroke technology and the main difference is the significant lowering of the PM levels as the NO_x was already in compliance with the non-road EPA regulation. Because the N14 engine was used in on-road/mobile applications, the CE-CERT research team believes that the improvements needed to meet the EPA's 1998 on-road regulation were carried over to the off-road applications.

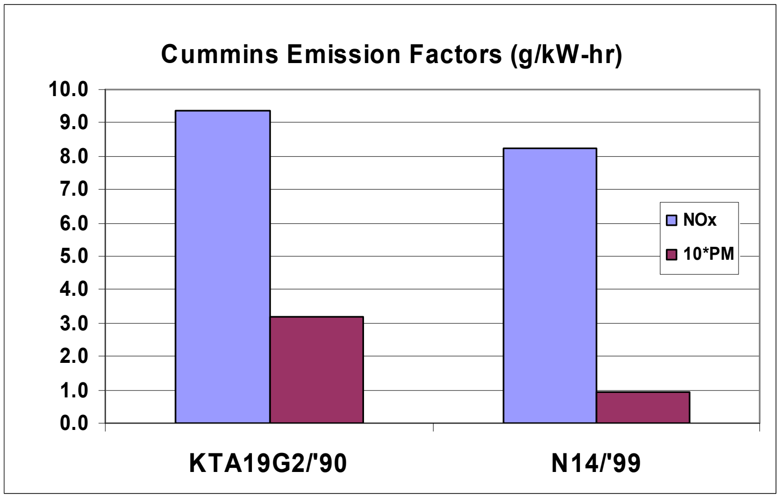


Figure 24. Emission factors for Cummins engines for 1990 and 1999 (g/kW-hr)

The final set of figures capture the changes in the emissions from BUGs that used Caterpillar engines. As stated in the introduction, more Caterpillar engines were tested in this project than any other manufacturer's engine, because Caterpillar units led the market in California.

Figure 25 shows the changes in emission factors for NO_x and PM for BUGs that used the 3406 Series of engines from 1985 to 2000. The 3400 series has 4-stroke engine technology and was used in both on-road and off-road applications. Thus, changes in engine technology to meet on-road regulations would be carried over to the nonroad applications. Therefore, the lower NO_x emission factor in 1991 may have been attributable to technology that was carried over from the changes in 1988 to meet the EPA regulation. However, it appears that the timing was retarded in the 3406C engines after 1996, so they would meet the meet the new off-road regulations. One interesting result from the three randomly selected 3406C units is that they have nearly the same emission factor, even though the age or hours of use ranged from 120 to 600 to 3200 hours. These data confirm the usual hypotheses that the deterioration factor is small for diesel engines.

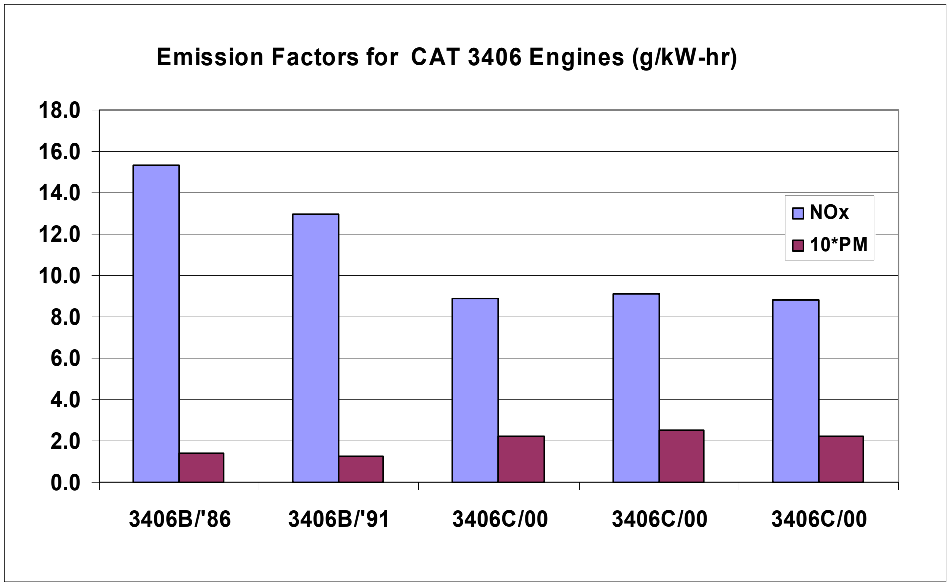


Figure 25. Emission factors for CAT 3406 series from 1985 to 2000 (g/kW-hr)

Figure 26 shows the emission factors for Caterpillar engines made after 1996, when the non-road regulation went into effect. Included in the figure are the emission factors for the largest 3500-Series, that range to 2,000 kW, even though they do not have to meet the same requirements until a later year. Note the low emission factors for the largest engines.

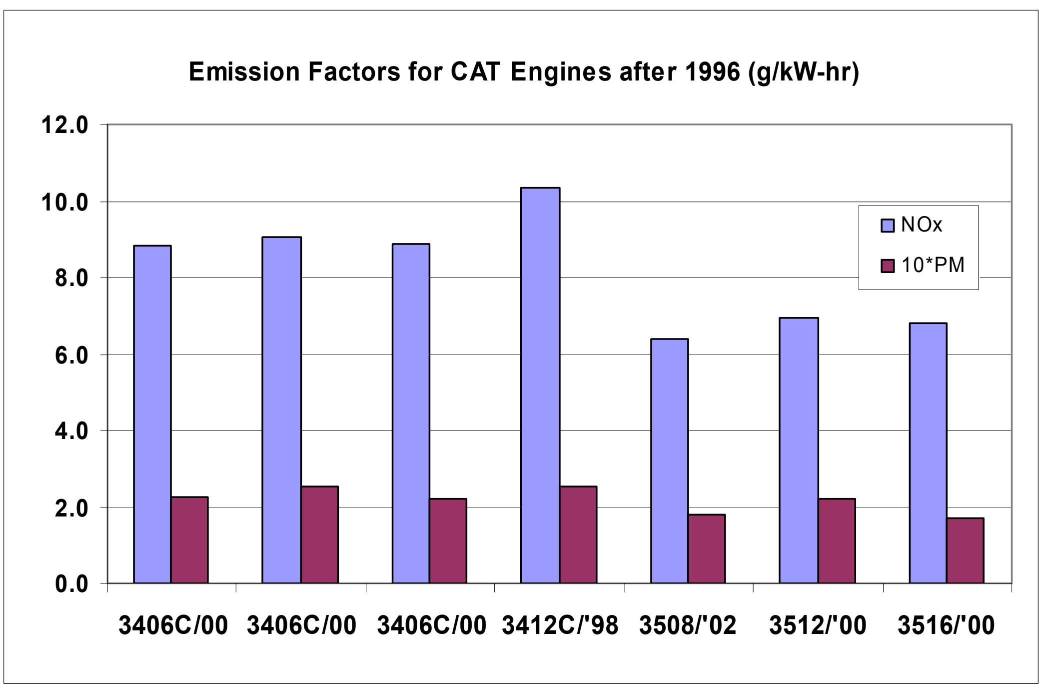


Figure 26. Emission factors for CAT engines (g/kW-hr) made after 1996

3.7. Emission Factors for Carbonyls from BUGs

The carbonyl emissions from selected BUGs were measured using the techniques described earlier in Section 2.3. Table 14 shows the emission factors for several carbonyls and the coefficient of variation based on multiple test runs in two cases. Few data exist in the literature on the emissions values for formaldehyde and the rest of the carbonyl group. As shown in Table 3, the AP 42 factors for formaldehyde are 280 mg/kW-hr and 70 mg/kW-hr for small and large BUGs, respectively. EPA confidence ratings for these emissions were very low. As can be seen in the Table 15, the emission factors from this study ranged from 21 to 100 mg/kW-hr for uncontrolled units. Values in Table 15 are uncorrected for the ambient contribution and a cursory review of some measurements indicate that the correction factor is < 3% and within the noise of the measurements. The complete data are provided in Appendix F.

The data show that the carbonyl emissions factors are much less than the emission factors for PM, NO_x, or THC, as expected. The carbonyls represent a fraction of the THC and the fraction ranges from 5% to 45%, with an average of about 25% in this data set.

Another parameter of interest is the relative portions of the carbonyls. Formaldehyde is the largest carbonyl constituent, representing about 64% of the total carbonyls. Acetaldehyde is the second largest carbonyl concentration, at about 15% of the total. Acetone, acrolein, and propionaldhyde represent 7%, 2%, and 3% respectively.

Some indication of the repeatability of the measurements can be gained from tests where multiple measurements were made and an indication of the covariance is shown in the table below. More data are available in Appendix F to gather a fuller understanding of the relative error associated with the measurement of carbonyls.

Table 14. Emission factors in mg/kW-hr for several carbonyls and the coefficient of variation based on multiple test runs in two cases

Mfg/Model/Yr	Fuel		Formal	Acetal	Acetone	Acrolein	Total
CAT/3406C/00	CARB		14	5	4	0.3	25
			13	5	5	0.3	27
			13	5	4	0.6	22
		AVE	13	5	4	0.4	25
		STDEV	0.6	0.2	0.8	0.2	2.6
		COV	4%	5%	18%	36%	10%
DDC/V92/85	CARB		30	8	2	0.1	45
			32	9	3	0.5	52
		AVE	31	8	3	0.3	48
		STDEV	0.8	0.6	0.1	0.1	2.2
		COV	3%	7%	4%	50%	5%

Table 15. Carbonyl emission factors calculated based on 40 CFR 89 for selected BUGs in mg/kW-hr

Mfg/Model/Yr	Fuel	Catalyst	Formal	Acetal	Acetone	Acrolein	Propional	Crotonal	MEK	Methac	Butyral	Benzal	Valeral	Tolual	Hexanal	Total
CAT/3406B/1991	CARB	none	18	5	3	1	0	0	0	0	0	0	0	0	0	28
DDC/V92/86	CARB	none	18	6	3	0	1	0	0	0	2	0	1	0	0	33
CAT/3406C/00	CARB	none	13	5	4	0	0	0	0	0	1	0	0	0	0	25
CAT/3412C/##	CARB	none	15	6	8	0	1	0	1	0	3	0	2	0	1	37
CAT/3406C/00	CARB	none	27	16	23	1	7	1	7	1	11	3	1	0	3	93
CAT/3406C/00	JBRIZ(	none	35	18	21	1	12	1	12	1	13	2	3	1	3	100
DDC/60/99	CARB	none	21	6	7	0	0	0	0	0	0	0	1	0	0	35
CUM/N14/99	CARB	none	18	5	2	1	1	0	0	0	1	0	0	0	1	30
CAT/3406B/86	CARB	none	35	8	3	0	1	0	1	0	1	1	0	1	2	53
CAT/3406B/86	JBRIZ(	none	36	8	4	1	1	0	1	0	1	1	1	1	2	55
CUM/KTA19G2/9	CARB	none	44	5	1	1	1	0	0	0	1	0	1	0	2	58
CAT/3406C/00	CARB	none	21	5	2	1	1	0	0	0	0	0	0	0	1	33
CAT/3406C/00	CARB	DOC1	17	1	1	0	0	0	0	0	0	1	0	0	0	21
DDC/V92/85	CARB	none	31	8	3	0	1	0	0	0	1	1	1	1	1	48
DDC/V92/85	CARB	DOC2	23	8	4	0	1	0	0	0	0	0	0	0	1	39

4.0 Demonstration of Control Technologies

The initial goal of the project funded by the Energy Commission was to demonstrate commercial exhaust cleanup controls; presumably technology from on-road applications that could be adapted for an off-road application—the backup generators. Although the initial plan in the scope of work was to briefly test and demonstrate both PM and NO_x control technologies, the plan changed. The demonstration program was significantly enhanced by the participation of a team from the Stationary Source Division of CARB. The addition of the CARB team changed the direction from a simple demonstration program of both NO_x and PM control technologies to one that focused on PM and included demonstration and durability under typical operating conditions. The durability time was set to 167 hours, to allow the control technology participants to obtain a conditional verification with CARB, assuming that the program plan was pre-approved by the appropriate Verification Branch. The information from the demonstration program was included in CARB's Technical Support Documents that were used to develop an air toxic control measure (ATCM) regulation for backup generators. Accordingly, the CARB technical support documents can also be reviewed for more detail on the combined effort.

4.1. Technologies for PM Control and Demonstration

The demonstration project planned to test controls, consisting of:

- fuel technology,
- after-treatment devices, and
- combination of fuel and after treatment technology.

The CARB, the Energy Commission, and UCR openly solicited technology for the project, because the emission testing would be without cost to the participants. As a result, there were more vendors interested in participating than available slots. A scorecard was developed to objectively weight the submissions and to help decide on which technologies to include in the demonstration program. The key elements were: the technology's state of commercialization, the willingness of the vendor to supply the technology at no cost, and the need for that technology type in the demonstration matrix. From this process, emerged a number of technologies, which are detailed in Table 16. The bold items in Table 16 refer to the shortened description of the control used.

Table 16. Control strategies Included in the demonstration program

Manufacturer of Control	Product	Product Description
Lubrizol	PuriNO$_x$™ technology	Water emulsified fuel (20% water emulsification) utilizes Lubrizol's (**Emulsified Fuel**).
Süd Chemie	SC-DOC	**Diesel Oxidation Catalyst** (DOCs).
Lubrizol-Engine Control Systems	Sequentially Regenerated Combifilter	Triple bank silicon carbide particulate filter with online filter regeneration by electrical heating (**Active DPF**).
Johnson Matthey	Continuously Regenerating Trap (CRT)	Catalyzed diesel particulate filter (**Passive DPF**).
CleanAir Systems: Flow-Thru-Filter System with Clean Diesel Technologies (CDT) Fuel-Borne Catalyst	Flow-Thru-Filter System combined with CDT Fuel-Borne Catalyst	Combined system includes a DOC, flow through filter used with a CDT fuel-borne catalyst. The flow through filter component was removed prior to testing due to lower than required exhaust temperatures (**Fuel-Borne Catalyst** with **DOC** or FBC/DOC).
Catalytic Exhaust Products Particulate Filter with Clean Diesel Technologies Fuel-Borne Catalyst	SXS-B/FA combined with CDT Fuel-Borne Catalyst	CDT fuel-borne catalyst used with an uncatalyzed diesel particulate filter (**Fuel-Borne Catalyst with Particulate Filter** or FBC/DPF).

4.2. Development of Test Protocol

The CARB has developed procedures for verifying control technologies for diesel engines, these are collectively known as the verification program.[2] The full approval process requires several sets of emissions tests and 500 hours of durability testing for emergency BUGs and 1000 hours for other diesel equipment. As a preliminary step in

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[2] See CARB web page: *Diesel Emission Control Strategies Verification*, at http://www.arb.ca.gov/diesel/verdev/verdev.htm.

the approval process, manufacturers could apply for a "conditional approval" based on results from one-third of the testing time. However, when the technologies were selected for this demonstration program, only draft protocols were available for verifying a BUG, and the recommended durability cycle was developed later.

Informal surveys indicated that most BUGs were tested monthly for a short period of time and then shut off. There was some concern about whether a diesel particulate filter (DPF) would plug up in the maintenance cycle, because the light-off temperature was not being reached to burn off the carbonaceous material. Furthermore, a question was raised on whether the DPF would survive if suddenly it reached the light off temperature and all the accumulated carbonaceous material was burned. From such discussions, the final protocol for the verification and demonstration program was developed. It was based on four phases:

1. Baseline emissions testing
2. Zero hour control device emissions testing
3. Control device durability testing
4. Control device emissions testing after durability testing

4.2.1. Baseline Emissions Testing

Emissions are measured emissions based on steady-state cycles described in 40 CFR 89 and as described earlier in Table 7 of this report. Electrical loading for the BUG was provided by a resistive-type load bank that is capable of providing 100% of the maximum load listed by the BUG manufacturer. One set of triplicate tests will be performed using the base diesel fuel. Table 17 lists the measurements made and reported in this phase of the program.

Table 17. Measurements made during testing

Parameter	Units
Particulate Matter	g/hr, g/kW-hr (average modal and overall)
Gaseous Emissions NO_x, NO_2, CO, CO_2 THC, CH_4, NMHC	ppm, g/hr, g/kW-hr (average modal and overall)
Exhaust Temperature	$^{\circ}$F, $^{\circ}$C (average modal)
Exhaust Backpressure	inches H_2O (average modal)

4.2.2. Zero Hour Control Device Emissions Testing

After at least 24 hours of degreening (break-in) on the BUG, an operational checkout was performed to ensure the proper operation of the installed control device. One triplicate set of emissions tests were performed according to the procedures described in the baseline section. The results represented the zero hour emissions and operating parameters of the control device, as applied to the selected BUG.

4.2.3. Control Device Durability Testing

As part of the CARB conditional approval process, manufacturers must provide durability test data representing a minimum of 33% of the total required for full approval of a control technology. For emergency backup generators, full approval requires 500 hours of durability testing. Thus, the 33% required for conditional approval represents 167 hours. The durability testing for this application class is broken into two operating conditions: (1) simulated maintenance cycles, and (2) simulated operating cycles. According to CARB procedures, the 167-hour accumulation should occur as shown in Section 4.2.3.1.

4.2.3.1. Recommended Durability Test Cycle for an Emergency Standby Generator

Part 1: Simulated Maintenance: Emergency Standby Generator

- Cold-start engine and run engine at no-load for no more than 1 hour.
- Shutdown engine and cool until engine reaches cold-start conditions.
- Run these tests consecutively and repeat 24 times.

Part 2: Simulated Operation

A. Low-Load Operation

- Run engine at low-load (25%) for a total of 24 hours.
- Can be broken into separate runs of two hours or more

B. Mid-Load Operation

- Run engine at mid-load (65%) for a total of 24 hours.
- Can be broken into separate runs of two hours or more

C. High-Load Operation

- Run engine at high-load (80%) for 24 consecutive hours.
- Can be broken into separate runs of two hours or more

Repeat Parts 1 and Part 2 so the accumulated hours are greater than the 168 hours that is needed for the conditional verification of a device. During accumulation testing, a thermocouple and pressure transducer was installed in the exhaust stream between the exhaust manifold and control device to monitor exhaust temperature and exhaust backpressure at 1 Hz intervals. Figure 27 shows an example of data from the maintenance cycle portion.

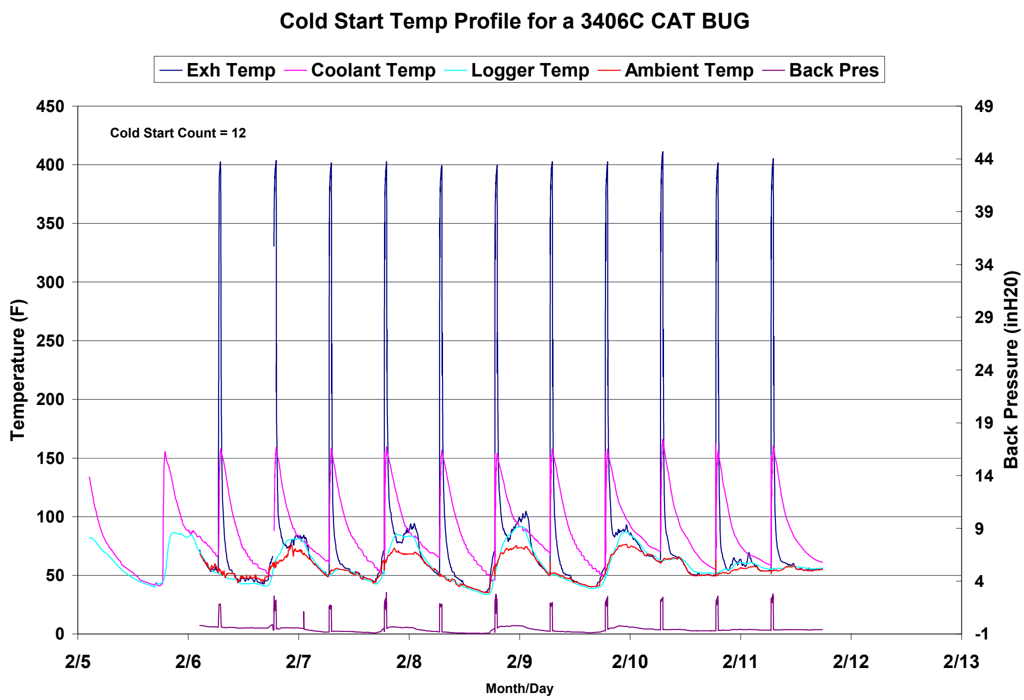

Figure 27. Sample data for a typical maintenance cycle

4.2.4. Control Device Emissions Testing After Durability Testing

After completion of the durability testing, one triplicate set of emissions tests were performed according to the procedures described earlier. The results represent the 167-hour (33% point) emissions and operating parameters of the control device as applied to the selected BUG.

4.3. Results of Demonstration Program – Emulsified Fuel

Lubrizol's PuriNOx™ was used as an example of an emulsified fuel. It consists of a blend of water, conventional diesel fuel, and a mixture of special compounds that is added to the fuel to maintain the emulsion, enhance cetane number and lubricity, inhibit corrosion, and protect against freezing. The formulated fuel contains 77% diesel fuel, 20% water, and 3% additive package. This fuel might not be of interest for applications like emergency generators, because the fuel needs to be circulated in order to prevent the suspension from breaking down into hydrocarbon and water phases.

CE-CERT tested the emulsified fuel in two engines—first a modern and post-control (after 1996) unit, and second, a unit from 1986 from the same manufacturer. Results for a modern BUG are illustrated in Figure 28. The fuel showed reductions for all load points and an overall reduction in the emission factors of 69% and 13% for PM and NO_x, respectively.

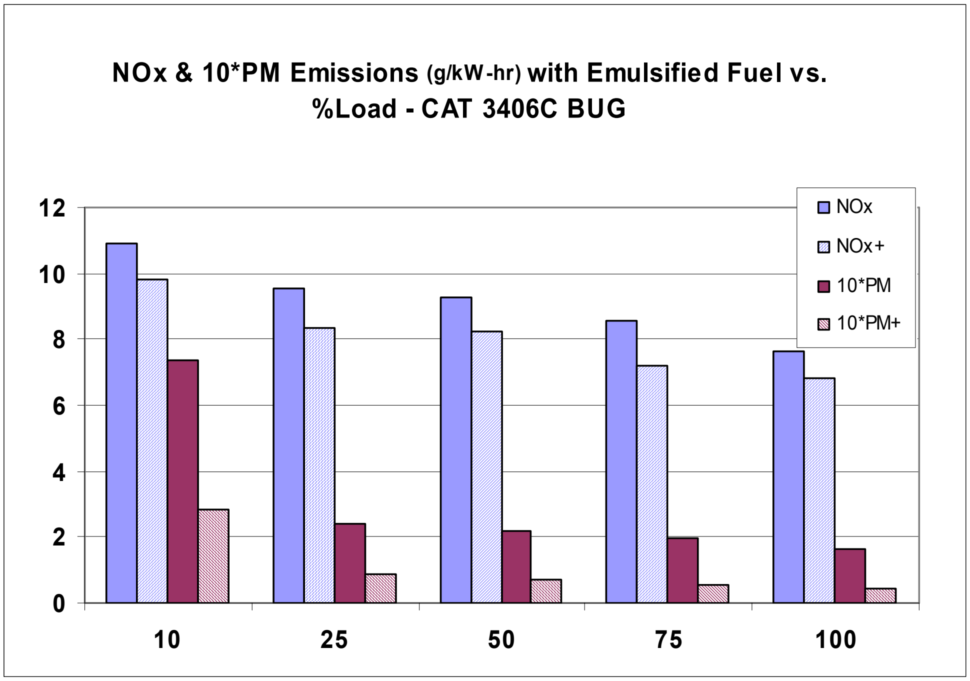

Figure 28. NO_X and PM emissions with emulsified fuel and a CAT 3406C

Tests with the second BUG, a 1986 CAT 3406B, proved to have different results. Results are shown in Figure 29. They indicate that the earlier BUG achieved less of a reduction in both PM and NO_x than the modern BUG. For this case, the overall reduction in the emission factors were 25% and 4% respectively. Because PM reduction is believed to be linked to a reduction in the diesel oil droplet size in the cylinder and to the injection pressure, CE-CERT believes that the much lower injector pressure used on the earlier unit did not provide the same capability of reducing droplet size; hence, the reduced effectiveness in reducing PM and NO_x.

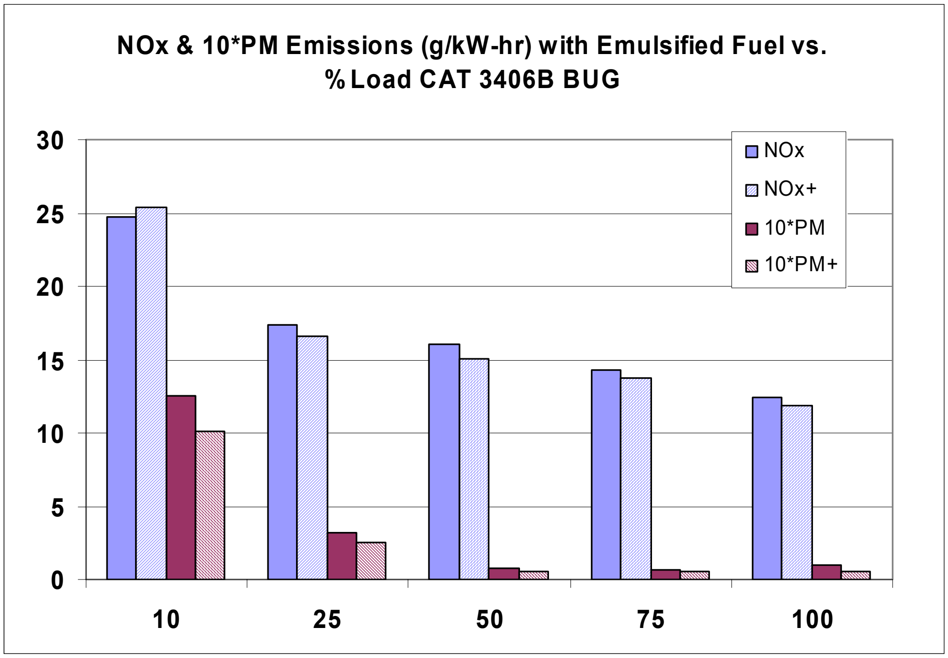

Figure 29. NO_X and PM emissions with emulsified fuel and a CAT 3406B

4.4. Results for a BUG Tested with CARB and CARB-ULSD Fuels

A review of the data indicated that the 2000 CAT 3406B unit was tested with both CARB and CARB-ULSD (ultra-low sulfur diesel) fuel. A comparison of the results indicated that the CARB-ULSD had 10% lower THC, 5% lower PM, and 12% NO_x. Although the differences for PM and THC are probably within the experimental variability, the last figure for NO_x is significant. Tests of the fuel composition are still pending, but there is no reason to suspect that the lower sulfur content is solely related to the observed emission benefit.

4.5. Results of Demonstration Program – Diesel Oxidation Catalysts (DOC)

Phillips et al. (1999) discusses modern diesel oxidation catalysts (DOCs) as flow-through devices that were fitted to diesel passenger vehicles in Europe since 1989. The primary purposes are to oxidize hydrocarbon (HC), CO, and to some extent, PM in the exhaust gas. PM mass reduction is achieved by oxidation of the lube oil and fuel portion (volatile organic fraction, or VOF) of the PM. Under the lean conditions of diesel exhaust gas Platinum (Pt)-based catalysts show high activity for oxidation reactions. Other non-precious metal catalytic components (such as alkaline-earth or lanthanide-based materials) can also facilitate oxidation of the VOF of the PM, particularly for catalysts with relatively low Pt content. Although high activity for oxidation of carbon-based emissions is required, oxidation of sulfur oxides at higher temperatures is undesirable, because high oxidation levels of sulfur dioxide can lead to significant increase of PM weight, as the result of sulfate and water binding to the PM.

Süd-Chemie provided two diesel oxidation catalysts designed to promote chemical oxidation of CO and HC, including the semi-volatile organic compounds (SVOCs) that are associated with the PM in diesel exhaust. Diesel oxidation catalysts are not expected to be very effective in reducing the solid or elemental carbon portion of the diesel exhaust associated with PM. Thus the overall reduction effectiveness of DOCs depends on the proportion of the PM that is volatile, and this ratio can be gauged by measuring the organic carbon (OC) in a PM sample that is collected on a quartz filter. Figure 30 shows the effectiveness of DOC-1 and DOC-2 for reducing the PM from a BUG with a modern CAT 3406C engine.

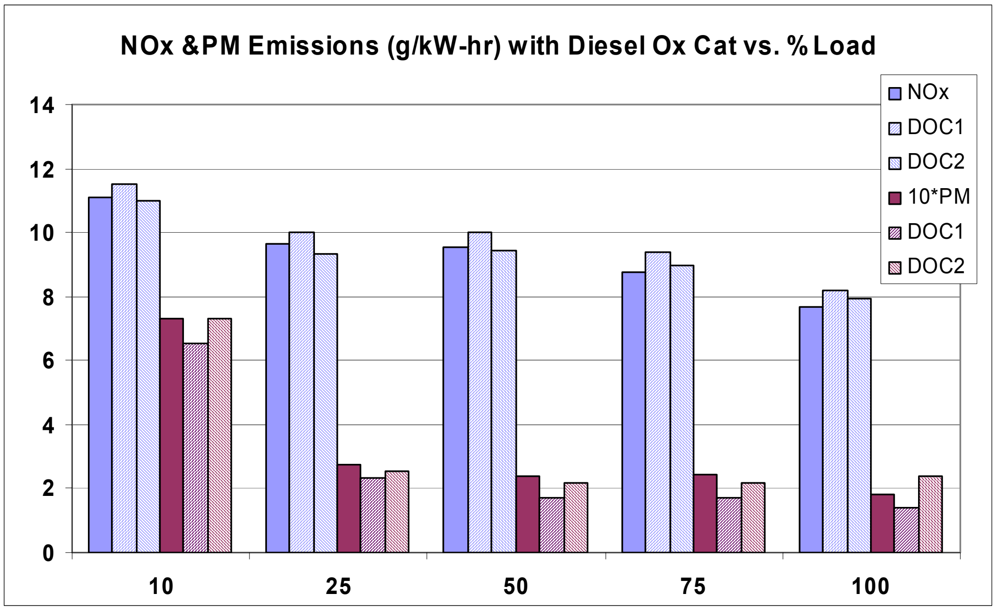

Figure 30. NO_x and PM emissions for a Cat 3406C BUG with DOC installed

Emission reductions depended on whether the unit was using DOC-1 or DOC-2. PM was reduced 25% and 6% and NO_x increased 6%, and showed no change for DOCs-1 and DOC-2, respectively.

4.5.1. Effect of Back Pressure on DOC Operation

Because the NO_x increase for DOC-1 was unexpected, CE-CERT researchers checked the operating conditions of the engine and noted that the backpressure on the engine at 50% load was reduced from 10.8 inches of water with the muffler to 4.9 inches when the muffler was removed and replaced with the DOC-1. Therefore, the research team added a choke plate to the outlet after the DOC-1, to increase the backpressure to about 12 inches of water. Results as seen in Figure 31 showed that NO_x was 4% below the uncontrolled version, or a total reduction of about 9%. The results can be explained as follows: the higher backpressure establishes an exhaust gas recirculation effect, so higher backpressure should reduce NO_x. Although NO_x was reduced, PM at the 50% load increased from –27% to –11%, presumably due to the well-known NO_x/PM tradeoff.

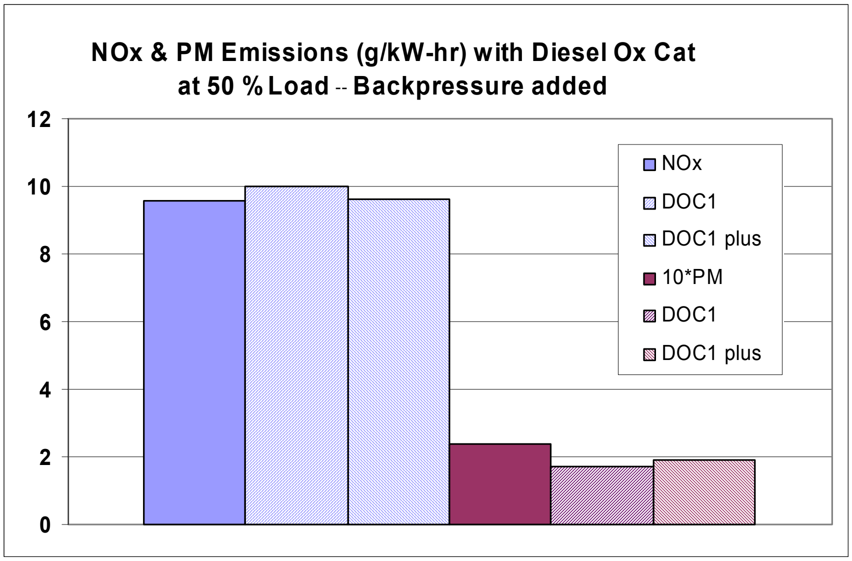

Figure 31. DOC-1 with backpressure added to match muffler

Both DOC-1 and DOC-2 were very effective (> 85%) in reducing the CO and total gaseous hydrocarbons (THCs) due to the active metals, as Figure 32 illustrates.

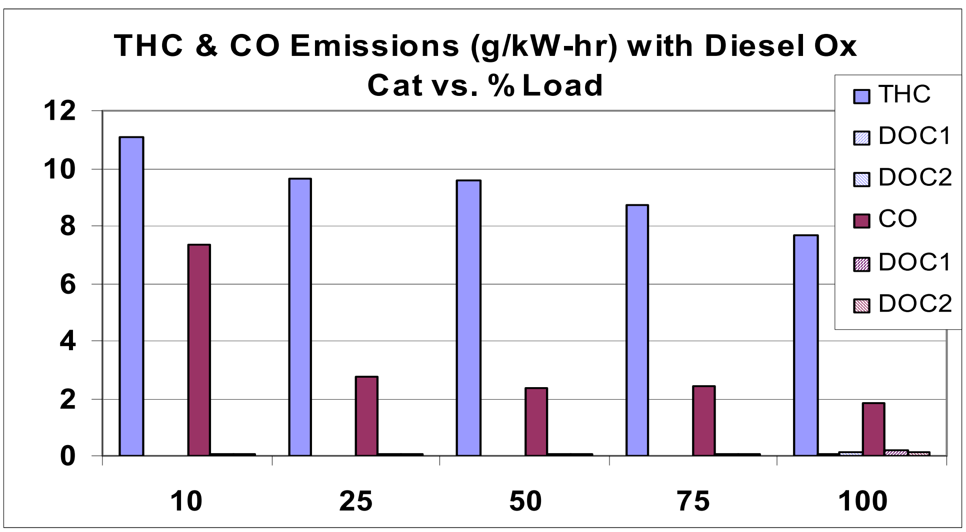

Figure 32. THC and CO are significantly reduced with a diesel oxidation catalyst

This section's introduction mentioned that greater PM reductions would be achieved with greater SVOCs or organic carbon (OC) in the gas phase. A subsequent demonstration with a DOC-2 confirmed this hypothesis. DOC-2 was retrofitted onto a MY1985, two-stroke Detroit Diesel 6V92—an engine known for its high levels of organic carbon. The measured reductions were: 44% for PM, 55% for non-methane hydrocarbons (NMHC), and 89% for CO. NO_x increased about 2%. Overall PM reduction effectiveness of DOC-2 was increased from 6% for the modern, 4-stroke engine to 44% for the older, 2-stroke engine. The significant increase in effectiveness was expected, because the diesel exhaust for a 2-stroke is rich in OC when compared to the OC from a modern 4-stroke engine. High levels of OC lead to higher levels of PM reduction with a DOC. At 100% load, the DOC-2 reduction was 62%; however, the effectiveness was reduced for lower loads, as shown in Figure 33.

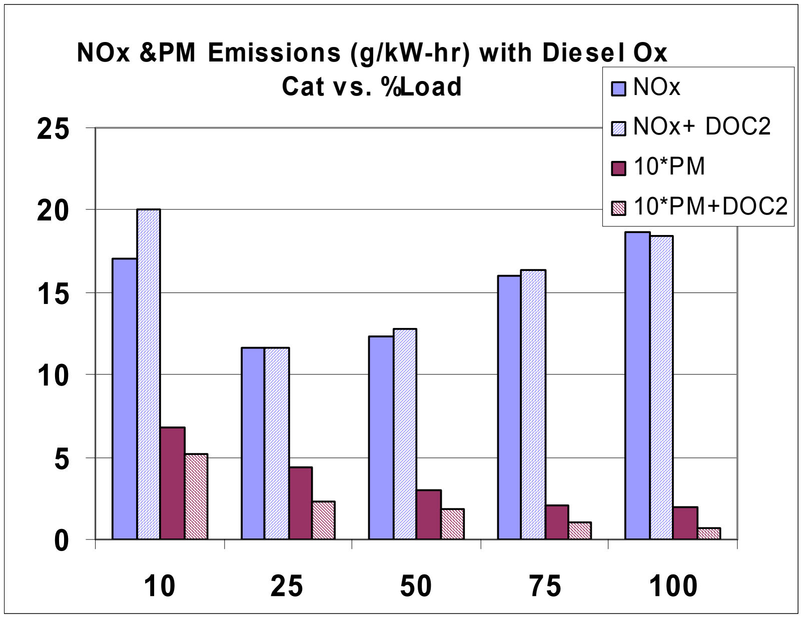

Figure 33. NO_X and PM emissions for BUG with 2-stroke engine technology (before and after a DOC is installed)

Figure 34 shows a BUG outfitted with a DOC.

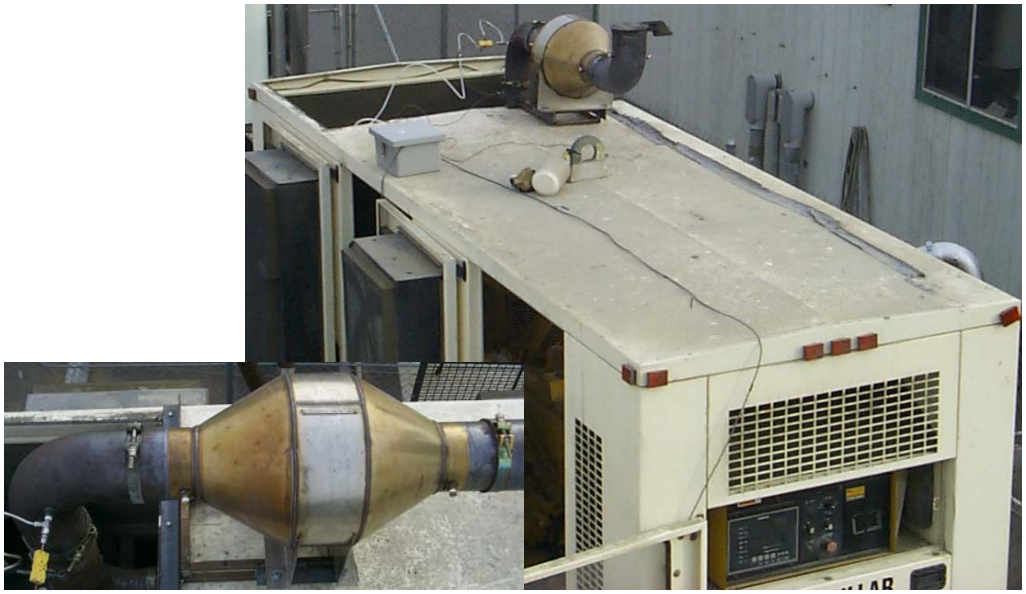

Figure 34. Example of a 350 kW BUG outfitted with a DOC

4.6. Results of Demonstration Program – Passive Diesel Particle Filter (DPF)

Proposals to further lower particulate matter standards for heavy-duty, diesel-powered engines have prompted interest in particulate-filter-based, after-treatment solutions. Allansson et al. (2000) described the commercial experience of continuously regenerating traps designed to control PM, CO, and HC emissions in those countries that have promoted the use of diesel fuel with less than 50 parts per million by weight (ppmw) sulfur. The CRT system is comprised of a proprietary platinum-based oxidation catalyst installed upstream of a wall-flow particulate filter typically made of cordierite. The platinum catalyst oxidizes a proportion of the NO in the exhaust stream to form NO_2, and this NO_2 is utilized to combust the soot trapped in the DPF. It is well known that NO_2 combusts soot at a significantly lower temperature than does O_2, so the system continuously regenerates (i.e., combusts) the trapped soot under standard heavy-duty diesel engine conditions where temperatures (~200°C–450°C, or ~390°F–840°F) are favorable for NO_2 production, and thus complete soot destruction is achieved (Figure 35). The formation of NO_2 is problematic because NO_2 levels for CARB-verified control devices were limited to 20% of the total engine baseline NO_x emissions.

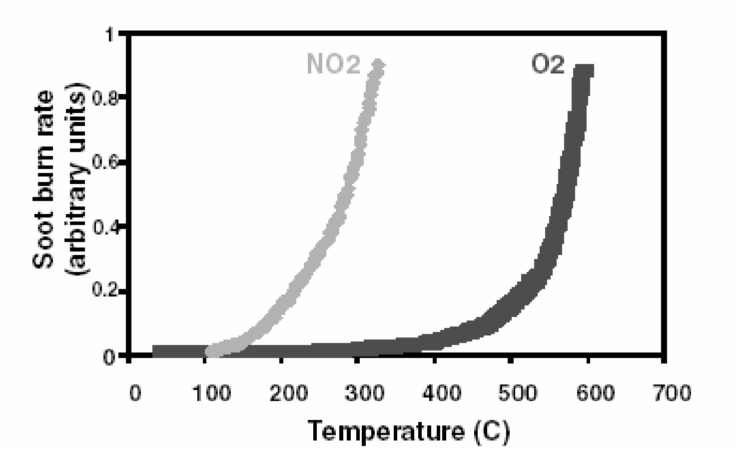

Figure 35. Combustion temperatures for diesel soot in oxygen and nitrogen dioxide

A Johnson Matthey CRT was retrofitted on a MY2000 Caterpillar 3406C diesel generator. Initial emission testing of the JM CRT (noted as DPF-1) resulted in control efficiencies for PM of just below 85%—a value lower than expected. Upon opening the device, black streaks were noted on the white filter, indicative of a leak around the ceramic monolithic filter and housing. Adding a bead of special caulking around the active element repaired the leak. After repair, durability cycling began for DPF-2 but was stopped in order to retest the zero-control efficiencies. The control efficiency of DPF-2 was measured at 91% for PM, 98% for NMHC, and 76% for the CO. Total NO_x for DPF-2 decreased about 9% from the uncontrolled BUG's emissions (Figures 36 and 37). However, as compared with baseline, the level of NO_2 was about 7 times higher than baseline for DPF-2.

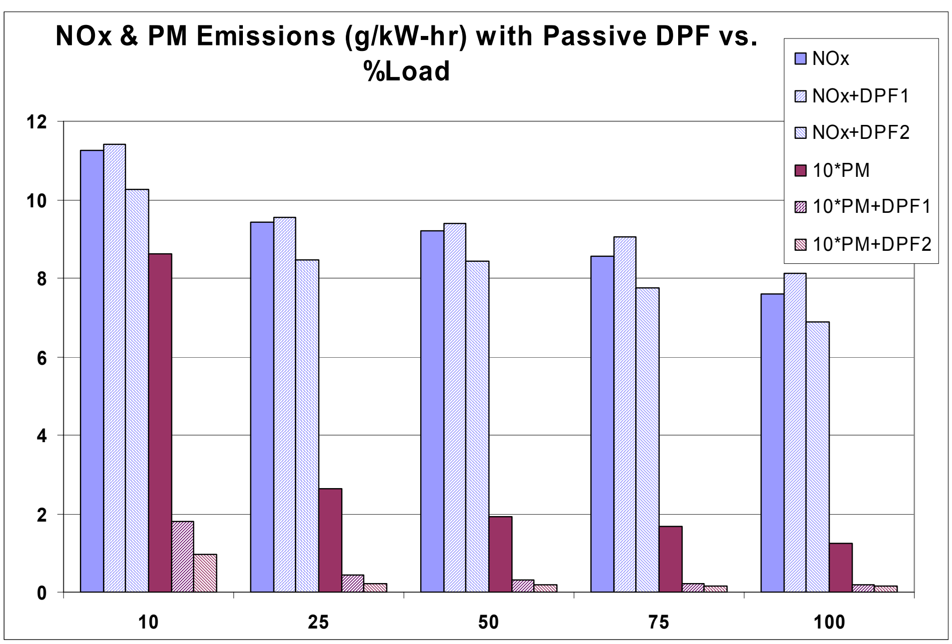

Figure 36. NO_X and PM emissions (g/kW-hr) with passive DPF vs. %Load

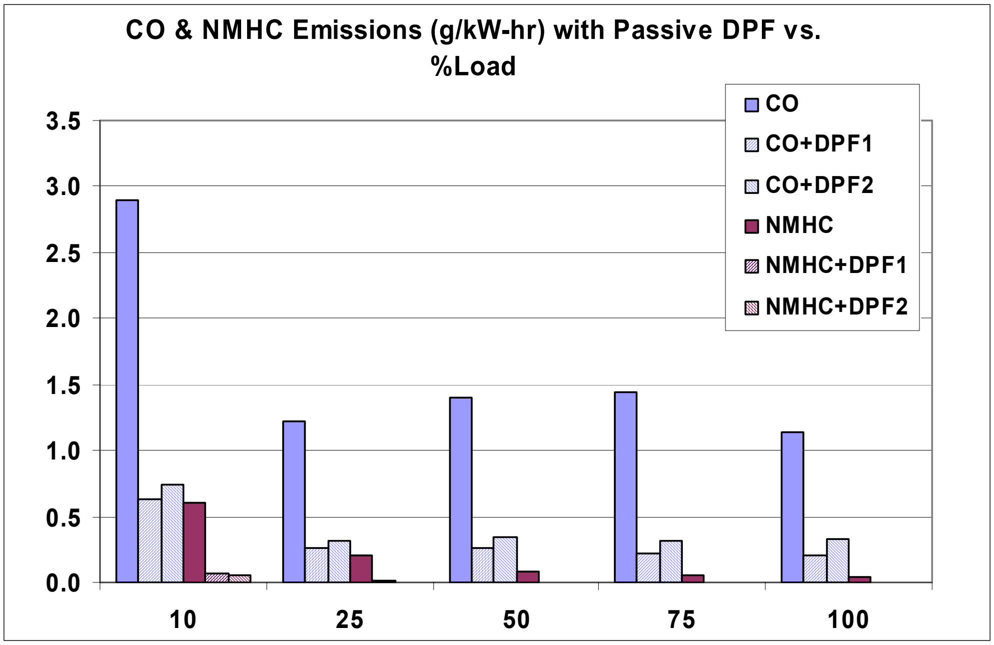

Figure 37. CO and NMHC emissions (g/kW-hr) with passive DPF vs. %Load

4.7. Results of Demonstration Program – Active Diesel Particle Filter

The Lubrizol-Engine Control Systems (ECS) electrically regenerated Combifilter™ was retrofitted on a MY2000 Caterpillar 3406C generator. This control system includes three silicon carbide diesel particulate filters with an electrical regeneration system designed to provide continuous PM control. The triple-filter system provides uninterrupted emission filtration during regeneration by switching the exhaust flow between filters. The regeneration system was electronically controlled and entirely automatic. The main components of the system are the ceramic wall-flow filter elements, electronic control unit (ECU), electrical heater system, compressed air blower system, and valve system to switch the exhaust flow between filters. The system provides online regeneration by isolating one filter at a time from the exhaust stream to allow for electrical regeneration of that filter. Electrical heating combined with a low flow of compressed air regenerates the filter. Upon completion of the regeneration cycle, the filter is brought back online for operation. The system operates in two modes: a soot cycle where all three filters are open to exhaust and a regeneration mode where one filter is isolated for regeneration. These two cycles continue throughout operation, sequentially regenerating one filter during each regeneration cycle. This design provides continuous filtration, with regeneration automated by the timed control system.

Because the system operates in two distinct modes—soot and regeneration—emission testing was performed in triplicate for both modes. The emission test results show a > 99% reduction in PM for both modes. In addition, NMHC was reduced by about 45% and NO_x by 10%. Although the particulate matter reduction was very high, this system had two areas of concern. First, backpressure levels measured during durability were higher than anticipated. During the durability cycling, average backpressure was measured at approximately 50 inches H_2O at 65% and 85% loads, with a maximum of approximately 70 inches H_2O. Considering that the unit was originally designed for a smaller, four-stroke CAT engine (3300-Series), the device manufacturer attributes the higher-than-anticipated backpressure to differences in engine exhaust flows and exhaust hardware between the Caterpillar 3300 and 3400 Series engines. Presumably, the issue associated with the higher backpressure could easily be addressed during the design phase of stationary source retrofitting.

The second issue of concern was the regeneration control system; specifically the timing of regeneration. The UCR researchers found that during the intermittent cold start portion of durability cycling, the soot mode (all three filters open) was longer than had been indicated by the manufacturer. The result was that the filters were not regenerating as often as described during cold start operation, and backpressure increased. Because the regeneration system is controlled strictly by timing and not by backpressure sensors, this control scheme may need optimization for applications with multiple cold starts. The manufacturer indicated that both backpressure and regeneration cycling would be addressed and corrected within the control system design.

4.8. Results of Demonstration Program – Fuel-borne Catalyst and DOC

The CleanAIR Flow Through Filter (FTF™) System was retrofitted on a MY1985, 2-stroke Detroit Diesel V92. This system was projected to reduce PM by 50% without increasing NO_2 emissions. This system is a passive, flow-through-filter (FTF) combined with a Clean Diesel Technology (CDT), fuel-borne catalyst to reduce diesel particulate emissions. A diesel oxidation catalyst, also part of the system, reduces CO and HC emissions. This system experienced regeneration problems during degreening operation (no load operation for 25 hours). The exhaust temperatures were not sufficient for regeneration, and the FTF clogged. It was removed and the DOC, combined with the fuel-borne catalyst, was tested. The control efficiency of the DOC and FBC system was 38% for PM and 69% for NMHC, while NO_x increased by approximately 4.8%.

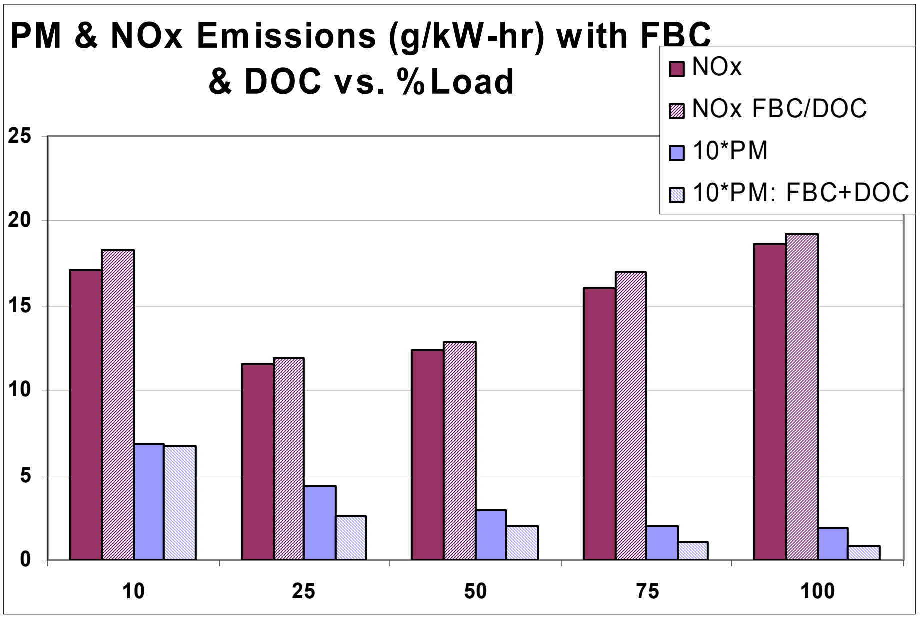

Figure 38. PM and NO_x Emissions (g/kW-hr) with FBC and DOC vs. %Load

4.9. Results of Demonstration Program – Fuel-borne Catalyst and DPF

The Catalytic Exhaust Products SXS-B/FA diesel particulate filter is an uncatalyzed ceramic wall flow filter combined with Clean Diesel Technology fuel-borne catalyst. It was operated on the exhaust of a MY2000, Caterpillar 3406C diesel generator. This system combines a ceramic monolith trap with a Clean Diesel Technology fuel-borne catalyst to facilitate regeneration of the diesel particulate filter. The bare wall flow diesel particulate filter requires a minimum exhaust gas temperature of approximately 550ºC to 600 ºC (1,020ºF to 1,110ºF) for 20% of operation, in order for the particulate filter to regenerate properly. Addition of a fuel-borne catalyst will assist in regeneration and allow the diesel particulate filter to regenerate at exhaust temperatures in the range of 320 ºC to 350ºC (610ºF to 660ºF) or about 225°C (437ºF) less than without the fuel-borne catalyst.

Results from the testing showed that the fuel/after-treatment combination reduced PM by > 99% for both the initial test and after the durability testing, as shown in Figure 39. Removal of the PM is about complete, so it does not show up on the figure. Hydrocarbons were reduced as well.

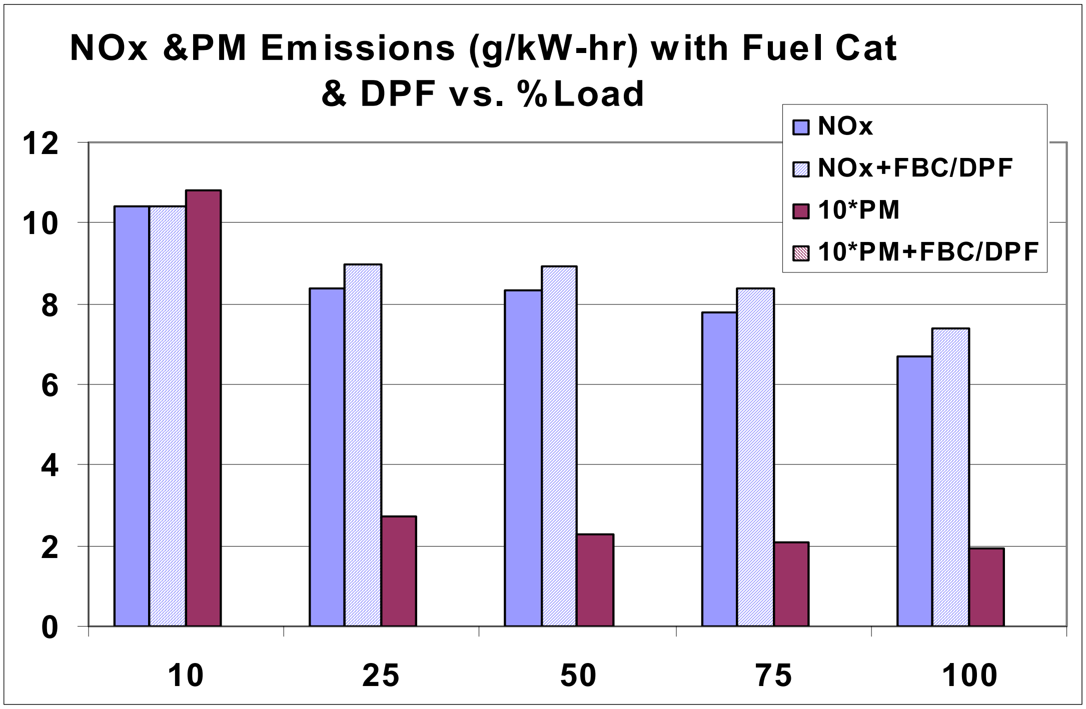

Figure 39. PM and NO_x Emissions (g/kW-hr) with FBC and DPF vs. %Load

4.10. Measurement of the Diesel Particulate Number Size Distribution

Smaller particles penetrate deeper into lungs. Based on the growing interest in the particle size distribution for number (as well as for mass) in the diesel exhaust, CE-CERT measured the particle size distribution for several of the control devices using a scanning mobility particle sizer (SMPS). Because this testing involved steady-state cycle, the SMPS had enough time to accumulate the data needed for this portion of the study. Figure 40 shows SMPS data for the PM number distribution as a function of load and for both without and with a passive diesel particulate filter with 91+% PM mass removal. The figure depicts the classic accumulation modes as the particulate matter is cooled in the full dilution tunnel. Note that the PM particulate numbers are the highest for the uncontrolled exhaust. Other data on the number distribution of particle sizes were collected and are provided in Appendix G. Note the differences in the number distribution for the DOC applied to an engine with “wet” and “dry” soot.

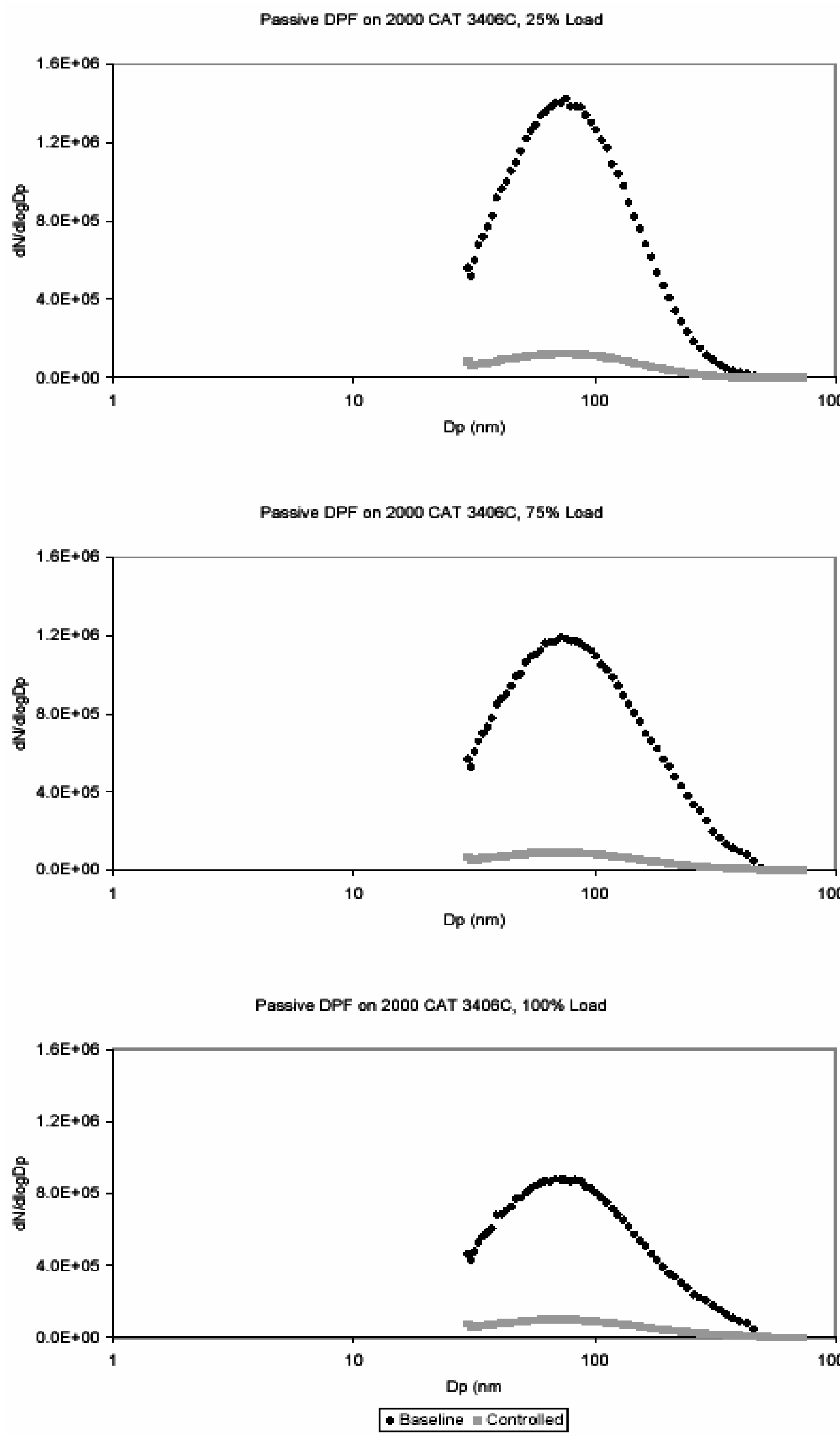

Figure 40. PM number distributions at three modes, for a backup generator equipped with a passive diesel filter

4.11. Examples of Data wherein the PM is Corrected for Moisture

This section's introduction pointed out that the analyses would be done following the CFR method. One consequence of following the CFR method is that only the NO_x emissions will be corrected for moisture. In this last section, some of the PM values are corrected for moisture in accordance with the method indicated in the International Standards Organization (ISO) 8178-1 (ISO 1996c). This section is added for completeness, because CARB is considering the inclusion of a moisture correction for the verification procedures.

The ISO document states: "As the particulate emission of diesel engines depends on ambient air conditions, the particulate concentration shall be corrected for ambient air humidity with the factor ***KP***."

KP is calculated based on the humidity of the air, the total barometric pressure, and the relative humidity. Examples of the effect of the humidity correction are provided in Tables 18 and 19. Note that the correction factors range from 81% to 96%. Thus, the real overall PM is reduced by about 12%, due to the moisture correction, and the reduction attributable to the DOC is reduced from 25% to 20%, because the moisture levels were different on both test days.

Table 18. PM moisture correction factors and their effect on DOC reduction

		Baseline						With DOC				
		Correct	PM	PM*	sec	kW		Correct	PM	PM*	sec	kW
CAT/3406(	M100	0.89	7.96	7.07	400	347		*0.96*	*5.33*	*5.13*	400	348
CAT/3406(	M75	0.88	7.95	6.99	450	259		*0.96*	*5.51*	*5.28*	450	259
CAT/3406(	M50	0.87	5.52	4.82	500	171		*0.95*	*4.23*	*4.03*	500	172
CAT/3406(	M25	0.87	3.43	2.97	500	86		*0.92*	*2.99*	*2.75*	500	86
CAT/3406(	M10	0.88	3.83	3.36	500	37		*0.85*	*3.21*	*2.73*	500	36
CAT/3406(	M100	0.81	6.82	5.52	400	346		*0.93*	*5.41*	*5.02*	400	348
CAT/3406(	M75	0.81	8.08	6.55	450	261		*0.92*	*5.48*	*5.07*	450	259
CAT/3406(	M50	0.82	5.76	4.71	500	172		*0.92*	*4.12*	*3.78*	500	171
CAT/3406(	M25	0.84	3.28	2.75	500	86		*0.90*	*2.88*	*2.58*	500	89
CAT/3406(	M10	0.88	3.63	3.18	500	36		*0.85*	*3.38*	*2.87*	500	37
CAT/3406(	M100	0.91	6.16	5.61	400	347		*0.91*	*5.69*	*5.17*	400	346
CAT/3406(	M75	0.90	7.62	6.84	450	261		*0.91*	*5.40*	*4.90*	450	259
CAT/3406(	M50	0.89	5.75	5.13	500	172		*0.90*	*4.02*	*3.63*	500	170
CAT/3406(	M25	0.88	3.31	2.93	500	89		*0.88*	*2.75*	*2.43*	500	89
CAT/3406(	M10	0.91	3.87	3.51	500	38		*0.84*	*3.41*	*2.88*	500	37
	M100		6.98	6.07	400	347			5.48	5.11	400	347
	M75		7.88	6.79	450	260			5.46	5.08	450	259
	M50		5.68	4.89	500	172			4.12	3.81	500	171
	M25		3.34	2.88	500	87			2.87	2.59	500	88
	M10		3.78	3.35	500	37			3.33	2.83	500	37
			0.24	0.21					0.18	0.16		
							%Reduction		25%	20%		

Table 19. Summary of percentage reductions in emission factors (EMFAC in g/kW-hr) from baseline for the various controls

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	THC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	3237	CARB	none	0.22	1.68	8.89	0.37	745	0.22
	3237	LUBRIZOL	none	0.18	1.14	7.73	0.34	747	0.07
			%red	18.1%	32.3%	13.0%	8.6%	-0.2%	68.7%
CAT/3406B/86	110	CARB	none	0.23	0.90	15.37	0.40	773	0.14
	114	LUBRIZOL	none	0.22	0.67	14.68	0.45	769	0.10
			%red	4.0%	25.5%	4.5%	-12.9%	0.5%	24.7%
CAT/3406C/00	1018	ULSD	none	0.10	2.07	7.98	0.31	762	0.24
	1026	LUBRIZOL	none	0.13	1.11	7.01	0.30	750	0.05
			%red	-34.3%	46.5%	12.2%	2.1%	1.6%	77.3%
	1029	LUBRIZOL	DOC2	0.01	0.02	7.17	0.13	747	0.05
			%red	84.9%	99.1%	10.2%	56.8%	1.9%	79.6%
CAT/3406C/00	664	CARB	none	0.11	1.96	9.08	0.33	755	0.25
	688	CARB	DOC-1	0.01	0.08	9.61	0.63	747	0.19
			%red	86.7%	96.0%	-5.8%	-89.8%	1.0%	24.6%
	733	CARB	DOC-2	0.01	0.07	9.10	0.28	751	0.24
			%red	92.0%	96.5%	-0.2%	14.2%	0.5%	5.6%
DDC/V92/85	863	CARB	none	0.88	2.11	14.46	0.76	957	0.28
			DOC-2	0.40	0.23	14.78	-0.17	927	0.16
			%red	54.9%	88.9%	-2.2%	122.3%	3.1%	44.3%
CAT/3406C/00	155	CARB	none	0.12	1.39	8.86	0.28	747	0.20
	185	ULSD	DPF1	0.01	0.25	9.19	3.03	743	0.03
			%red	91.2%	82.2%	-3.8%	-976.1%	0.4%	84.2%
	349	ULSD	DPF2	0.01	0.33	8.04	2.09	761	0.02
			%red	94.2%	76.2%	9.2%	-639.8%	-1.9%	90.8%
CAT/3406C/00	772	ULSD	none	0.11	1.96	9.08	0.33	755	0.25
			Act/DOC	0.04	1.65	8.11	0.02	774	0.00
			%red	63.2%	15.8%	10.7%	93.9%	-2.5%	99.8%
	780		Act/Reg	0.07	2.61	8.01	0.07	748	0.00
			%red	35.4%	-32.8%	11.8%	77.3%	1.0%	99.7%
	810		Act/soot	0.07	2.08	8.14	0.09	741	0.00
			%red	35.3%	-5.9%	10.4%	74.1%	1.9%	99.9%
	987		Act/Reg	0.07	2.53	7.64	0.01	762	0.01
			%red	40.1%	-28.7%	15.9%	96.8%	-0.9%	97.5%
	1006		Act/soot	0.07	1.99	7.82	0.00	766	0.01
			%red	38.1%	-1.5%	13.9%	98.9%	-1.5%	97.7%
DDC/V92/85	863	CARB	none	0.88	2.11	14.46	0.76	957	0.28
	916	ULSD-FBC	DOC3	0.27	0.13	15.17	0.26	931	0.17
			%red	69.5%	93.6%	-4.9%	65.4%	2.7%	38.2%
	1090		DOC3	0.24	0.14	14.64	0.56	954	0.16
			%red	72.4%	93.6%	-1.3%	26.4%	0.3%	43.6%
CAT/3406C/00	1018	ULSD	none	0.10	2.07	7.98	0.31	762	0.24
	1061	ULSD+FBC	DPF	0.01	0.03	8.58	1.40	755	0.00
			%red	94.2%	98.7%	-7.5%	-353.4%	0.9%	99.7%
	1244			0.00	0.03	8.64	1.50	755.89	0.00
				96.7%	98.7%	-8.2%	-383.8%	0.8%	99.7%

4.12. Control of NO_x Emissions from BUGs

The major focus of this project was to demonstrate PM control technology, rather than NO_x control technology. Although CE-CERT contacted a number of leading vendors for the proven Selective Catalytic Reduction (SCR) technology using ammonia derived from urea, the research team was unable to include SCR technology in this program. One site near San Diego even had a combined SCR-DPF system, but by the time that CE-CERT contacted them, the control technology was disassembled and the owners were not willing to reassemble it. In general, the vendors said they were revising the expensive control system that is required with these systems to properly remove NO_x and minimize ammonia (NH_3) slippage. Hence, they were not thoroughly tested enough during CE-CERT 's demonstration program. Recently, SCR systems were installed by Cummins on a large BUG used in snow-making operations in the San Bernardino Mountains and by Johnson Matthey for a prime generator on Catalina Island.

The chemistry for the SCR process is rather straightforward, with three major reactions occurring between the NO_x species and ammonia on the vanadium-based SCR catalysts as described by Walker et al. (2004).

1. $4\ NH_3 + 4\ NO + O_2 \rightarrow 4\ N_2 + 6\ H_2O$
2. $4\ NH_3 + 2\ NO + 2\ NO_2 \rightarrow 4\ N_2 + 6\ H_2O$
3. $8\ NH_3 + 6\ NO_2 \rightarrow 7\ N_2 + 12\ H_2O$

In the absence of NO_2, Reaction (1) is fast and dominates. With NO_2 and for NO_2/NO ratios < 1, then Reaction (2), which is very fast, is dominant. However, for NO_2/NO ratios > 1, then the activity falls sharply, because the very slow Reaction (3) becomes important. Johnson Matthey reports that vanadium-based SCR systems are used extensively to control NO_x emissions in the stationary source market, because vanadium has very high selectivity to nitrogen and has a wide operating temperature window. Vanadium-based SCR catalysts also have a very high sulfur tolerance. Within the stationary source market, the temperature of vanadium-based applications are controlled to avoid the high temperatures that could induce catalyst deactivation and selectivity loss.

Future work should review the status of the SCR units installed on BUGs in the San Bernardino Mountains and on Catalina Island.

5.0 Project Outcomes

Researchers noted the following project outcomes:

1. Over 700 individual tests of BUGs were run, including background checks. As a result, a significant database was created for regulated and non-regulated emissions from the 16 diesel BUGs that were selected to represent California units based on market share, size, age, and contribution to the emissions inventory. The power output varied from 300 to 2,000 kW.

2. For units manufactured prior to the introduction of the non-road regulations, the measured emissions for PM compared well with manufacture's values but were up to 80% lower than values listed in EPA's AP 42, probably due to the method of measuring emissions. NO_x values were lower, but within 20% of the EPA factors. Emission values for units built after the implementation of non-road standards met the regulatory values.

3. The measurements for the carbonyl emissions from BUGs in this PIER program now comprise the largest database available and provide new information on the emission levels of formaldehyde and other carbonyls. Formaldehyde comprises about 65% of the carbonyls, and values vary over a wide range and are dependent on the unit and operating power.

4. A number of emission control options were demonstrated during the project and the impact of several of these technologies on the particle size distribution was measured. The eight PM control technologies that were demonstrated included fuel modification, addition of after-control technology, and combinations of both. Most of the effort centered on controlling particulate matter, and control or reduction in PM ranged from about 15% to 99%+. Although not demonstrated, some discussion is provided on the adoption of a technology for control of NO_x.

5. A report following EPA's AP 42 format was drafted for EPA and sent to them for review and acceptance.

6.0 Conclusions and Recommendations

6.1. Conclusions

The in-field test results determined that the criteria pollutants or their precursors were significantly lower than the values in EPA's AP 42 for older units and close to the regulatory limits for the newer units. In addition, a new understanding was provided on the emissions of carbonyls, such as formaldehyde. Thus, the values from this study will provide a greater insight into the emissions if BUGs are activated in non-attainment areas.

Control technology based on fuel change or the addition of after-treatment units was effective in reducing the PM levels and other emissions from older and newer BUGs. The data from this PIER effort will allow the BUG owner and the local air districts to evaluate the impact of operating diesel BUGs both without and with controls. Although the main focus of this project was on the use of PM control technology, some discussion addresses the available technologies to reduce NO_x to low levels.

6.2. Benefits to California

This project on diesel backup generators contributed to the PIER program objectives of providing a reliable electricity supply and reducing the cost of California electricity by providing the Energy Commission with accurate information on the emissions, so that BUGs can be evaluated as a viable source of electricity for future outages.

6.3. Recommendations

The information gained from this PIER project will be of greater value when it is integrated into EPA's AP 42 tables, so that the emission values identified in this work can be more widely used. Researchers at the University of California, Riverside, are in the process of completing that work.

While not studied in this project, it might be of interest to measure emissions where biodiesel is substituted for CARB diesel fuel and also to study BUGs that are smaller than the 300 kW units studied in this project, because the smaller size units are quite numerous and of keen interest to some air districts.

7.0 References

Allansson, R., B. J. Cooper, J. E. Thoss, A. Uusimäki, A. P. Walker, and J. P. Warren. 2000. *European Experience of High Mileage Durability of Continuously Regenerating Diesel Particulate Filter Technology*. SAE paper 2000-01-0480.

Cocker, D. R., K. J. Johnson, S. D. Shah, X. Zhu, J. W. Miller, and J. M Norbeck. 2004. *Development and Application of a Mobile Laboratory for Measuring Emissions From Diesel Engines. II. Sampling for Toxics and Particulate Matter.* Submitted to *Environmental Science & Technology*.

California Air Resources Board. 2000. *Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-Fueled Engines and Vehicles.* October.

Cocker, D. R., K. J. Johnson, S. D. Shah, J. W. Miller, and J. M. Norbeck. 2004. *Development and Application of a Mobile Laboratory for Measuring Emissions From Diesel Engines I. Regulated Gaseous Emissions*. Accepted for publication by *Environmental Science & Technology*.

International Standards Organization. 1996a. *IS0 8178-4, Reciprocating internal combustion engines - Exhaust emission measurement -Part 4: Test cycles for different engine applications.* First edition. 1996-08-l5.

International Standards Organization. 1996b. *IS0 8178-2. Reciprocating internal combustion engines - Exhaust emission measurement - Part 2:Measurement of gaseous and particulate exhaust emissions at site.* First edition. 1996-08-l5.

International Standards Organization. 1996c. *IS0 8178-1 Reciprocating internal combustion engines - Exhaust emission measurement - Part 1*: First edition. 1996-08-I5.

McCormick, R. L., M. S. Graboski, M. S. Newlin, and J. D. Ross. 1997. "Effect of Humidity on Heavy-Duty Transient Emissions from Diesel and Natural Gas Engines at High Altitude." *J. Air & Waste Manage. Assoc.* 47: 784–791.

Northeast States for Coordinated Air Use Management (NESCAUM). 2003. *Stationary Diesel Engines in the Northeast: An Initial Assessment of the Regional Population, Control Technology Options and Air Quality Policy Issues.* June.

Ozone Transport Commission. 2001. *Distributed Generation Initiative*. March 6, 2001.

Phillips, P. R., G. R. Chandler, D. M. Jollie, A. J. J. Wilkins, and M. V. Twigg. 1999. *Development of Advanced Diesel Oxidation Catalysts.* SAE paper 1999-01-3075 E, VII International Mobility Technology Conference & Exhibit, Sao Paulo, Brazil. October 4–6.

Ryan, N. E., K. M. Larsen, and P. C. Black. 2002. *Smaller, Closer, Dirtier: Diesel Backup Generators in California*. Environmental Defense Report.

Siegl, W.O., J. F. O. Richert, T. E. Jensen, D. Schuetzle, S. J. Swarin, J. F. Loo, A. Prostak, D. Nagy, and A. M. Schlenker. 1993. *Improved emissions speciation methodology for phase II of the auto/oil air quality improvement research program-hydrocarbons and oxygenates*. SAE Technical Paper 930142.

Traver, M. L. May 2002. *Interlaboratory Crosscheck of Heavy-Duty Vehicle Chassis Dynamometers.* Final Report. East Liberty, Ohio. CRC Project No. E-55-1.

U.S. Environmental Protection Agency. 1995. *Introduction to AP 42*, Volume I, 5th Edition. Office of Air Quality Planning and Standards, Office of Air and Radiation. Research Triangle Park. U. S. EPA. January.

U.S. Environmental Protection Agency. 1996. *AP 42, Emission Factors for Uncontrolled Industrial Diesel Engines, Section 3.3 Small Engines, Updated 5th Edition*. Contract No. 68-D2-0160, Work Assignment 50. Office of Air Quality Planning and Standards. Research Triangle Park. U. S. EPA. October.

U.S. Environmental Protection Agency. 2002a. *40 Code of Federal Regulations (CFR) Part 89 – Control of Emissions from New and In-use Nonroad Compression Ignition Engines.* June 28, 2002.

U.S. Environmental Protection Agency. 2002b. *40 Code of Federal Regulations (CFR) Part 86 — Control of Emissions from New and In-use Highway Vehicles and Engines, §86.1310-2007 Exhaust gas sampling and analytical system for gaseous emissions from heavy-duty diesel-fueled engines and particulate emissions from all engines.* June 28, 2002.

U.S. Environmental Protection Agency. 2002c. *40 Code of Federal Regulations (CFR) Part 89 – Control of Emissions from New and In-use Nonroad Compression Ignition Engines, Subpart E Exhaust Emission Test Procedures 89.424 Dilute emission sampling calculations.* June 28, 2002.

U.S. Environmental Protection Agency. 2003. *40 CFR Parts 69, 80, 89, et al. Control of Emissions of Air Pollution From Nonroad Diesel Engines and Fuel; Proposed Rule.* Federal Register. Vol. 68, No. 100. Friday, May 23.

Waterland, L. 2001. *Inventory of Backup Generators in the State of California*. California Energy Commission. P500-01-027. December.

Walker, A. P., P. G. Blakeman, T. Ilkenhans, B. Magnusson, A. C. McDonald, P. Kleijwegt, F. Stunnenberg, and M. Sanchez. 2004. *The Development and In-Field Demonstration of Highly Durable SCR Catalyst Systems*. SAE paper 2004-01-1289, 2004 SAE World Congress. Detroit, Michigan. March 8–11.

Glossary

AB 2588	Air Toxics “Hot Spots” Information and Assessment Program
APCD	Air Pollution Control District
AQMD	Air Quality Management District
ASTM	American Society of Testing & Materials
ATCM	Air Toxic Control Measure
ATIS	Automated Terminal Information Services
BACT	Best Available Control Technology
BC	Bottom-Center
BTX	Benzene, toluene, and xylene
BUG	Backup Generator
CAA	Clean Air Act
CARB	California Air Resources Board
CAT	Caterpillar Corporation
CCR	California Code of Regulations
CDT	Clean Diesel Technology
CE-CERT	Center for Environmental Research and Technology
CEM	Continuous emission monitor
CFR	Code of Federal Regulations
CFV	Critical Flow Venturi
CH4	Methane
CO	Carbon Monoxide
CO2	Carbon Dioxide
COV	Coefficient of variance
CRT	Continuously regenerating trap
CUM	Cummins
CVS	Constant Volume Sample
DDC	Detroit Diesel Corporation
DI	Direct Injection
DNPH	2, 4- dinitrophenylhydrazine
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DPM	Diesel Particulate Matter
DRRP	Diesel Risk Reduction Plan
EC	Elemental Carbon
EMA	Engine Manufacturers Association
EMFAC	CARB emissions model for calculating on-road vehicle emissions
EPA	U.S. Environmental Protection Agency
FEL	Family Emission Limits
FTF	Flow-through-filter
g/hr	Grams per hour
g/kW-hr	Grams per kilowatt-hour
g/bk kW-hr	Grams per brake kilowatt-hour
GC	Gas Chromatography
GC-FID	Flame Ionization Detector
GC-MS	Gas Chromatography Mass Spectroscopy

HAP	Hazard Air Pollutant
HC	Hydrocarbon
HDD	Heavy duty diesel
HDDT	Heavy duty diesel truck
HFID	Heated Flame Ionization Detector
Hp.	Horsepower
HPLC	High Performance Liquid Chromatography
IC	Internal Combustion
IDI	Indirect Injection
kW	Kilowatt
MDL	Mobile Diesel Laboratory
MECA	Manufacturers of Emission Controls Association
MEL	Mobile Emission Laboratory
MFC	Mass flow controller
MY	Model Year
NAAQS	National Ambient Air Quality Standards
NDIR	Non-dispersive Infrared
NESCAUM	Northeast States for Coordinated Air Use Management
NIST	National Institute of Standards and Technology
NMHC	Non-Methane Hydrocarbons
NO	Nitric Oxide
NO2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
NRDC	Natural Resources Defense Council
O2	Oxygen
O3	Ozone
OEMFAC	Overall Emission Factor
OTAG	Ozone Transport and Assessment Group
PAH	Polycyclic Aromatic Hydrocarbon
PM	Particulate Matter
ppb	Parts per billion
ppm	Parts per million
ppmw	Parts per million by weight
QA	Quality Assurance
QC	Quality Control
RTD	Resistive Thermal Device
SCR	Selective catalytic reduction
SMPS	Scanning Mobility Particle Sizer
SVOCs	Semi-volatile Organic Compounds
TAC	Toxic Air Contaminant
THC	Total Hydrocarbons
VOC	Volatile Organic Compounds
UCR	University of California, Riverside
UDDS	Urban Dynamometer Driving Schedule
ULSD	Ultra Low Sulfur Diesel
WSPA	Western States Petroleum Association

Appendix A. List of Advisory Members

Affiliation	Position	Name: First	Name: Last	Title	email
Calif Energy Com. (CEC)	Prime	Marla	Mueller	Air Quality Manager, CEC	mmueller@energy.state.ca.us
Calif Air Resources Board (CARB)	Prime	Alberto	Ayala	Research Division, CARB	aayala@arb.ca.gov
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Calif Air Resources Board (CARB)	Prime	Alex	Santos	Stationary Source Div., CARB	asantos@arb.ca.gov
Calif Air Pollution Control Officers Assoc.	Prime	Barbara	Lee	Chair (2001)	nsc@sonic.net
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Appendix B. Description Diesel Generators Tested

		<-- Engine Detail -->				<-- Generator Detail -->				
No	**Manufacturer**	**Model**	**VIN/Serial #**	**Start Hr**	**Fuel**	**Make**	**Model**	**Max kW**	**Serial #**	**Eng Yr.**
1	CAT	3412 C	BPG00177	2,200	RFD#2	CAT	SR4B	545	9FG01162	1998
2	CAT	3406 B	4RG01632	299	RFD#2	CAT	5R2	300	7CF00704	1991
3	DDC 6V92	80837405	BVF149700	273	RFD#2	Kohler	350R0ZD71	350	289576	1991
4	CAT	3406 C	4JK00753	120	RFD#2	CAT	SR4B	350	SCK01230	2000
5	CAT	3412 C	BPG00177	2,542	RFD#2	CAT	SR4B	545	9FG01162	1998
6	CAT	3406 C	4JK00706	3,237	RFD#2	CAT	SR4B	350	5CK01183	2000
8	DDC	Series 60	06RH001775	762	RFD#2	MEC ALTE SPA	ECO37-3174	340	779592	1999
9	Cummins	N14-G2	11964008	1,200	RFD#2			350	964008	1999
10	CAT	3406B	2WB04221	109	RFD#2	CAT	SR4	300	6BA0224A	1985
11	Cummins	KTA19G2	68020	62	RFD#2	CUM.	400DFEB	360	I900350538	1990
12	CAT	3406C	4JK00740	663	RFD#2	CAT	SR4B	350	5CK01218	2000
14	DDC 6V92	6V92	8VF103705	862	CARB + Add	LEROY SUMER	TZ3160MZ	300	64157/2	1985
20	CAT	3408B	78Z03770	3,002	CARB	CAT		450		1990
22	CAT	3508	1FZ01275	443	RED-Carb	CAT	NNGLK	1000	2DN01635	2000
21	CAT	3512	1GZ00395	807	RED-Carb	CAT	SR4B	1500	6DW01075	2002
23	CAT	3516	1HZ00388	1,529	RED-Carb	CAT	?	2000	4FN01665	2000

Appendix C. Description of Data Recorded for Each Test per 40 CFR 89.405 and Test Cycle for the Demonstration/Durability Testing

Data recorded

(a) Engine description and specification

(1) Engine-system combination.

(2) Engine identification numbers.

(3) Number of hours of operation accumulated on engine.

(4) Rated maximum horsepower and torque.

(5) Maximum horsepower and torque speeds.

(6) Engine displacement.

(7) Governed speed.

(8) Idle rpm.

(9) Fuel consumption at maximum power and torque.

(10) Maximum airflow.

(11) Air inlet restriction.

(12) Exhaust pipe diameter(s).

(13) Maximum exhaust system back pressure.

(b) *Test data, general*

(1) Engine-system combination.

(2) Engine identification number.

(3) Instrument operator.

(4) Engine operator.

(5) Number of hours of operation accumulated on the engine prior to beginning the warm-up portion of the test.

(6) Fuel identification.

(7) Date of most recent analytical assembly calibration.

(c) *Test data, pre-test*

(1) Date and time of day.

(2) Test number.

(3) Intermediate speed and rated speed as defined in §89.2 and maximum observed torque for these speeds.

(4) Recorder chart or equivalent. Identify the zero traces for each range used, and span traces for each range used.

(5) Air temperature after and pressure drop across the charge air cooler (if applicable) at maximum observed torque and rated speed.

(d) *Test data, modal*

(1) Recorder chart or equivalent. Identify for each test mode the emission concentration traces and the associated analyzer range(s). Identify the start and finish of each test.

(2) Observed engine torque.

(3) Observed engine rpm.

(4) Record engine torque and engine rpm continuously during each mode with a chart recorder or equivalent recording device.

(5) Intake air flow (for raw mass flow sampling method only) and depression for each mode.

(6) Engine intake air temperature at the engine intake or turbocharger inlet for each mode.

(7) Mass fuel flow (for raw sampling) for each mode.

(8) Engine intake humidity.

(9) Coolant temperature outlet.

(10) Engine fuel inlet temperature at the pump inlet.

(e) *Test data; post-test*

(1) Recorder chart or equivalent. Identify the zero traces for each range used and the span traces for each range used. Identify hang up check, if performed.

(2) Total number of hours of operation accumulated on the engine.

Test plan for demonstration/durability testing and verification of a control device for a backup generator (BUG)

Activity	Time (days)
Baseline test of BUG	2
Install device	1
Degreen device	2
Baseline test of device	2
24 cold starts at 2/day	12
Load for 1 day at 25%, 65%, 80% load	3
24 cold starts at 2/day	12
Load for 1 day at 25%, 65%, 80%	3
Emission test (optional) unless needed for conditional verification	2
24 cold starts at 2/day	12
Load for 1 day at 25%, 65%, 80% load	3
24 cold starts at 2/day	12
Load for 1 day at 25%, 65%, 80% load	3
24 cold starts at 2/day	12
Load for 1 day at 25%, 65%, 80% load	3
24 cold starts at 2/day	12
Load for 1 day at 25%, 65%, 80% load	3
Final verification testing	2

Appendix D. Uncontrolled BUGs: Calculated Emission Factors for Each Load and for Overall BUG in grams/kW-hour as per 40 CFR 89

Cummins engines

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CUM/KTA19G2/	64	CARB	none	M90	353	0.51	0.09	0.44	1.17	12.75	0.21	671	0.26
CUM/KTA19G2/	64	CARB	none	M75	296	0.48	0.06	0.43	0.91	11.01	0.29	678	0.27
CUM/KTA19G2/	64	CARB	none	M50	201	0.53	0.05	0.49	0.91	8.34	0.37	718	0.36
CUM/KTA19G2/	64	CARB	none	M25	98	0.63	0.05	0.59	0.89	6.27	0.48	872	0.37
CUM/KTA19G2/	64	CARB	none	M10	41	1.31	0.09	1.23	1.72	6.41	0.73	1303	0.69
CUM/KTA19G2/	66	CARB	none	M90	353	0.48	0.08	0.41	1.15	12.89	0.38	667	0.25
CUM/KTA19G2/	66	CARB	none	M75	295	0.47	0.06	0.42	0.89	10.81	0.42	665	0.28
CUM/KTA19G2/	66	CARB	none	M50	200	0.46	0.04	0.43	0.82	8.09	0.33	726	0.31
CUM/KTA19G2/	66	CARB	none	M25	100	0.60	0.04	0.56	0.90	6.17	0.41	867	0.36
CUM/KTA19G2/	66	CARB	none	M10	40	1.22	0.10	1.13	1.77	6.29	0.71	1305	0.66
					353	0.50	0.08	0.42	1.16	12.82	0.30	669	0.25
					296	0.47	0.06	0.42	0.90	10.91	0.36	671	0.28
					201	0.50	0.05	0.46	0.87	8.22	0.35	722	0.34
					99	0.61	0.04	0.58	0.89	6.22	0.45	869	0.37
					41	1.27	0.10	1.18	1.75	6.35	0.72	1304	0.68
						0.52	0.05	0.48	0.93	9.37	0.37	733	0.32
CUM/N14/99	1200	CARB	none	M100	343	0.19	0.04	0.16	0.70	11.09	0.24	704	0.06
CUM/N14/99	1200	CARB	none	M75	256	0.19	0.02	0.17	0.40	9.11	0.22	726	0.06
CUM/N14/99	1200	CARB	none	M50	170	0.28	0.02	0.26	0.57	7.00	0.19	795	0.09
CUM/N14/99	1200	CARB	none	M25	87	0.56	0.04	0.53	1.13	5.65	0.31	991	0.19
CUM/N14/99	1200	CARB	none	M10	36	1.17	0.06	1.12	1.34	14.58	0.98	1370	0.29
CUM/N14/99	1200	CARB	none	M100	342	0.19	0.04	0.16	0.72	11.18	0.28	707	0.05
CUM/N14/99	1200	CARB	none	M75	256	0.19	0.02	0.17	0.41	9.24	0.26	729	0.07
CUM/N14/99	1200	CARB	none	M50	171	0.28	0.02	0.26	0.58	7.01	0.23	793	0.07
CUM/N14/99	1200	CARB	none	M25	87	0.54	0.04	0.51	1.13	5.63	0.32	987	0.13
CUM/N14/99	1200	CARB	none	M10	36	1.17	0.06	1.12	1.39	14.58	0.90	1376	0.44
					342	0.19	0.04	0.16	0.71	11.13	0.26	705	0.06
					256	0.19	0.02	0.17	0.41	9.18	0.24	727	0.07
					170	0.28	0.02	0.26	0.57	7.00	0.21	794	0.08
					87	0.55	0.04	0.52	1.13	5.64	0.32	989	0.16
					36	1.17	0.06	1.12	1.36	14.58	0.94	1373	0.36
						0.30	0.03	0.27	0.63	8.25	0.26	803	0.09

2-Stroke DDC engines

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
DDC/V92/91	273	CARB	none	M10	35	2.77	0.19	2.60	3.30	12.70		1812	0.78
DDC/V92/91	273	CARB	none	M25	88	1.13	0.07	1.07	1.60	8.21		1063	0.51
DDC/V92/91	273	CARB	none	M50	175	0.59	0.05	0.55	1.25	9.11		864	0.38
DDC/V92/91	273	CARB	none	M75	263	0.43	0.04	0.39	1.04	11.35		779	0.18
DDC/V92/91	273	CARB	none	M100	350	0.36	0.06	0.31	1.17	14.42		776	0.11
DDC/V92/91	273	CARB	none	M10	35	2.58	0.13	2.47	3.71	12.45		1739	0.77
DDC/V92/91	273	CARB	none	M25	88	1.10	0.06	1.05	1.69	8.06		1010	0.45
DDC/V92/91	273	CARB	none	M50	175	0.54	0.02	0.52	1.25	9.23		853	0.34
DDC/V92/91	273	CARB	none	M75	263	0.43	0.03	0.41	1.07	11.26		773	0.18
DDC/V92/91	273	CARB	none	M100	350	0.35	0.04	0.32	1.07	14.20		764	0.10
DDC/V92/91	273	CARB	none	M10	35	2.82	0.22	2.64	3.45	12.60		1822	0.76
DDC/V92/91	273	CARB	none	M25	88	1.21	0.08	1.13	1.67	8.27		1065	0.46
DDC/V92/91	273	CARB	none	M50	175	0.62	0.05	0.58	1.21	9.29		870	0.35
DDC/V92/91	273	CARB	none	M75	263	0.44	0.04	0.40	1.03	11.25		784	0.18
DDC/V92/91	273	CARB	none	M100	350	0.36	0.05	0.32	1.00	14.19		770	0.10
					35	2.72	0.18	2.57	3.49	12.58		1791	0.77
					88	1.15	0.07	1.08	1.65	8.18		1046	0.48
					175	0.58	0.04	0.55	1.24	9.21		863	0.36
					263	0.43	0.04	0.40	1.05	11.29		779	0.18
					350	0.36	0.05	0.31	1.08	14.27		770	0.11
						0.63	0.05	0.59	1.26	10.48		868.3	0.29
DDC/V92/85	863	CARB	none	M100	291	0.26	0.04	0.22	1.77	18.48	0.41	820	0.23
DDC/V92/85	863	CARB	none	M75	221	0.47	0.04	0.43	1.25	15.82	0.56	860	0.23
DDC/V92/85	863	CARB	none	M50	148	0.97	0.06	0.91	8.49	12.30	0.71	931	0.30
DDC/V92/85	863	CARB	none	M25	74	1.78	0.13	1.67	1.93	11.55	1.36	1207	0.46
DDC/V92/85	863	CARB	none	M10	34	3.63	0.33	3.34	4.28	16.54	2.96	1908	0.70
DDC/V92/85	865	CARB	none	M100	291	0.26	0.00	0.27	2.03	18.65	0.31	823	0.20
DDC/V92/85	865	CARB	none	M75	222	0.47	0.00	0.47	1.31	16.10	0.47	861	0.20
DDC/V92/85	865	CARB	none	M50	148	0.95	-0.01	0.95	1.26	12.32	0.74	933	0.29
DDC/V92/85	865	CARB	none	M25	74	1.68	0.29	1.43	1.92	11.65	1.42	1212	NA
DDC/V92/85	865	CARB	none	M10	33	3.56	0.72	2.94	4.35	16.87	2.97	1926	NA
DDC/V92/85	867	CARB	none	M100	290	0.28	0.05	0.24	2.01	18.42	0.35	813	0.16
DDC/V92/85	867	CARB	none	M75	221	0.50	0.05	0.46	1.33	16.02	0.56	855	0.18
DDC/V92/85	867	CARB	none	M50	147	0.95	0.06	0.89	1.27	12.24	0.69	927	0.30
DDC/V92/85	867	CARB	none	M25	73	1.71	0.12	1.60	1.90	11.60	1.39	1206	0.43
DDC/V92/85	867	CARB	none	M10	31	3.68	0.32	3.41	4.55	17.36	2.91	1963	0.66
DDC/V92/85	868	CARB	none	M100	291	0.29	0.05	0.24	2.22	18.90	0.32	824	0.18
DDC/V92/85	868	CARB	none	M75	222	0.51	0.05	0.46	1.37	16.21	0.50	857	0.20
DDC/V92/85	868	CARB	none	M50	147	0.96	0.06	0.90	1.26	12.56	0.72	933	0.29
DDC/V92/85	868	CARB	none	M25	75	1.63	0.12	1.53	1.84	11.62	1.34	1193	0.42
DDC/V92/85	868	CARB	none	M10	31	3.63	0.32	3.36	4.39	17.66	2.98	2003	NA
					291	0.27	0.03	0.24	2.01	18.61	0.35	820	0.19
					222	0.49	0.03	0.46	1.32	16.04	0.52	858	0.20
					148	0.96	0.05	0.92	3.07	12.35	0.71	931	0.30
					74	1.70	0.16	1.56	1.90	11.60	1.38	1205	0.43
					32	3.62	0.42	3.26	4.39	17.11	2.95	1950	0.68
						0.88	0.07	0.82	2.11	14.46	0.76	957	0.28

DDC engines: 4-Stroke (Series 60) and 2-Stroke compared

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
DDC/60/99	762	CARB	none	M100	294	0.09	0.02	0.07	0.89	8.65	0.24	736	0.09
DDC/60/99	762	CARB	none	M75	222	0.08	0.01	0.07	0.80	8.20	0.23	743	0.09
DDC/60/99	762	CARB	none	M50	145	0.09	0.01	0.08	0.62	8.98	0.27	778	0.09
DDC/60/99	762	CARB	none	M25	73	0.15	0.01	0.14	0.68	16.56	0.71	901	0.07
DDC/60/99	762	CARB	none	M10	31	0.46	0.04	0.42	2.57	25.12	2.00	1338	0.19
DDC/60/99	762	CARB	none	M100	293	0.07	0.01	0.06	0.89	8.84	0.35	992	0.07
DDC/60/99	762	CARB	none	M75	222	0.06	0.01	0.05	0.82	8.19	0.21	1014	0.08
DDC/60/99	762	CARB	none	M50	144	0.07	0.01	0.07	0.58	8.92	0.28	1081	0.08
DDC/60/99	762	CARB	none	M25	72	0.15	0.01	0.14	0.66	16.42	0.66	973	0.08
DDC/60/99	762	CARB	none	M10	32	0.46	0.04	0.42	2.46	24.17	1.92	1454	0.18
DDC/60/99	762	CARB	none	M100	292	0.06	0.01	0.05	0.74	8.67	0.15	729	0.07
DDC/60/99	762	CARB	none	M75	217	0.06	0.01	0.05	0.73	8.42	0.44	746	0.07
DDC/60/99	762	CARB	none	M50	146	0.07	0.01	0.06	0.57	8.93	0.31	771	0.08
DDC/60/99	762	CARB	none	M25	73	0.13	0.01	0.12	0.64	16.30	0.67	873	0.06
DDC/60/99	762	CARB	none	M10	31	0.43	0.04	0.39	2.54	25.14	1.89	1308	0.14
					293	0.07	0.01	0.06	0.84	8.72	0.25	819	0.07
					220	0.06	0.01	0.06	0.78	8.27	0.30	834	0.08
					145	0.08	0.01	0.07	0.59	8.94	0.29	877	0.09
					73	0.14	0.01	0.13	0.66	16.43	0.68	916	0.07
					32	0.45	0.04	0.41	2.52	24.81	1.94	1366	0.17
						0.09	0.01	0.08	0.75	10.19	0.39	870.88	0.08
DDC/V92/91	273	CARB	none	M10	35	2.77	0.19	2.60	3.30	12.70		1812	0.78
DDC/V92/91	273	CARB	none	M25	88	1.13	0.07	1.07	1.60	8.21		1063	0.51
DDC/V92/91	273	CARB	none	M50	175	0.59	0.05	0.55	1.25	9.11		864	0.38
DDC/V92/91	273	CARB	none	M75	263	0.43	0.04	0.39	1.04	11.35		779	0.18
DDC/V92/91	273	CARB	none	M100	350	0.36	0.06	0.31	1.17	14.42		776	0.11
DDC/V92/91	273	CARB	none	M10	35	2.58	0.13	2.47	3.71	12.45		1739	0.77
DDC/V92/91	273	CARB	none	M25	88	1.10	0.06	1.05	1.69	8.06		1010	0.45
DDC/V92/91	273	CARB	none	M50	175	0.54	0.02	0.52	1.25	9.23		853	0.34
DDC/V92/91	273	CARB	none	M75	263	0.43	0.03	0.41	1.07	11.26		773	0.18
DDC/V92/91	273	CARB	none	M100	350	0.35	0.04	0.32	1.07	14.20		764	0.10
DDC/V92/91	273	CARB	none	M10	35	2.82	0.22	2.64	3.45	12.60		1822	0.76
DDC/V92/91	273	CARB	none	M25	88	1.21	0.08	1.13	1.67	8.27		1065	0.46
DDC/V92/91	273	CARB	none	M50	175	0.62	0.05	0.58	1.21	9.29		870	0.35
DDC/V92/91	273	CARB	none	M75	263	0.44	0.04	0.40	1.03	11.25		784	0.18
DDC/V92/91	273	CARB	none	M100	350	0.36	0.05	0.32	1.00	14.19		770	0.10
					35	2.72	0.18	2.57	3.49	12.58		1791	0.77
					88	1.15	0.07	1.08	1.65	8.18		1046	0.48
					175	0.58	0.04	0.55	1.24	9.21		863	0.36
					263	0.43	0.04	0.40	1.05	11.29		779	0.18
					350	0.36	0.05	0.31	1.08	14.27		770	0.11
						0.63	0.05	0.59	1.26	10.48		868.3	0.29

CAT 3406B Engines

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406B/91	300	CARB	none	M10	38	0.48	0.12	0.37	3.75	22.51		1324	0.39
CAT/3406B/91	300	CARB	none	M25	79	0.25	0.06	0.20	1.69	15.30		926	0.20
CAT/3406B/91	300	CARB	none	M50	161	0.15	0.03	0.13	0.76	13.61		745	0.09
CAT/3406B/91	300	CARB	none	M75	231	0.10	0.03	0.10	1.02	11.80		731	0.09
CAT/3406B/91	300	CARB	none	M100	317	0.05	0.03	0.00	1.83	10.30		701	0.19
CAT/3406B/91	300	CARB	none	M10	38	0.43	0.07	0.36	3.73	22.04		1336	0.42
CAT/3406B/91	300	CARB	none	M25	80	0.25	0.04	0.22	1.69	15.30		936	0.20
CAT/3406B/91	300	CARB	none	M50	162	0.16	0.03	0.13	0.83	13.34		755	0.10
CAT/3406B/91	300	CARB	none	M75	236	0.11	0.03	0.08	1.03	11.75		711	0.09
CAT/3406B/91	300	CARB	none	M100	316	0.07	0.03	0.04	1.86	10.18		714	0.18
CAT/3406B/91	300	CARB	none	M10	38	0.43	0.07	0.37	3.72	21.88		1333	0.41
CAT/3406B/91	300	CARB	none	M25	80	0.26	0.04	0.22	1.67	15.08		935	0.22
CAT/3406B/91	300	CARB	none	M50	164	0.16	0.03	0.14	0.82	13.24		747	0.10
CAT/3406B/91	300	CARB	none	M75	233	0.11	0.03	0.09	0.99	11.76		711	0.09
CAT/3406B/91	300	CARB	none	M100	312	0.07	0.03	0.04	1.78	10.36		714	0.18
					38	0.45	0.09	0.37	3.74	22.14		1331	0.41
					80	0.25	0.05	0.21	1.68	15.23		932	0.21
					163	0.16	0.03	0.13	0.80	13.40		749	0.10
					233	0.11	0.03	0.09	1.02	11.77		718	0.09
					315	0.06	0.03	0.03	1.82	10.28		710	0.18
						0.15	0.03	0.12	1.21	12.95		777	0.13
CAT/3406B/86	110	CARB	none	M100	296	0.19	0.04	0.15	0.93	12.38	0.24	711	0.10
CAT/3406B/86	110	CARB	none	M75	220	0.15	0.04	0.12	0.56	14.46	0.24	714	0.07
CAT/3406B/86	110	CARB	none	M50	147	0.26	0.05	0.21	0.65	16.33	0.37	759	0.08
CAT/3406B/86	110	CARB	none	M25	73	0.45	0.09	0.37	1.57	17.47	0.76	935	0.35
CAT/3406B/86	110	CARB	none	M10	30	1.05	0.15	0.93	4.76	24.79	2.01	1412	1.34
CAT/3406B/86	111	CARB	none	M100	296	0.15	0.04	0.12	0.92	12.38	0.25	704	0.09
CAT/3406B/86	111	CARB	none	M75	225	0.11	0.03	0.09	0.62	14.19	0.19	708	0.07
CAT/3406B/86	111	CARB	none	M50	148	0.17	0.03	0.15	0.65	15.78	0.36	746	0.06
CAT/3406B/86	111	CARB	none	M25	73	0.38	0.06	0.33	1.65	17.18	0.88	922	0.30
CAT/3406B/86	111	CARB	none	M10	31	1.05	0.15	0.92	4.73	24.68	2.00	1405	1.16
					296	0.17	0.04	0.14	0.92	12.38	0.24	708	0.10
					223	0.13	0.03	0.10	0.59	14.33	0.22	711	0.07
					147	0.21	0.04	0.18	0.65	16.05	0.37	753	0.07
					73	0.42	0.08	0.35	1.61	17.33	0.82	929	0.32
					31	1.05	0.15	0.92	4.74	24.73	2.00	1409	1.25
						0.23	0.04	0.19	0.90	15.37	0.40	773	0.14

CAT 3406C engines

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	120	CARB	none	M10	35	0.63	0.07	0.57	2.88	11.75	NA	1339	0.67
CAT/3406C/00	120	CARB	none	M25	88	0.23	0.02	0.21	1.30	9.66	NA	871	0.24
CAT/3406C/00	120	CARB	none	M50	172	0.09	0.02	0.07	2.05	9.28	NA	745	0.26
CAT/3406C/00	120	CARB	none	M75	261	0.04	0.01	0.03	2.12	8.37	NA	715	0.27
CAT/3406C/00	120	CARB	none	M100	346	0.06	0.03	0.03	1.72	7.35	NA	732	0.20
CAT/3406C/00	120	CARB	none	M10	36	0.61	0.07	0.55	3.02	11.10	0.94	1302	0.80
CAT/3406C/00	120	CARB	none	M25	88	0.22	0.02	0.20	1.43	9.22	0.41	863	0.29
CAT/3406C/00	120	CARB	none	M50	175	0.08	0.02	0.06	2.14	9.05	0.27	744	0.27
CAT/3406C/00	120	CARB	none	M75	264	0.03	0.01	0.02	2.00	8.16	0.23	718	0.23
CAT/3406C/00	120	CARB	none	M100	352	0.06	0.03	0.04	1.85	7.22	0.29	733	0.21
CAT/3406C/00	120	CARB	none	M10	36	0.55	0.03	0.52	2.86	11.33	0.92	1297	0.75
CAT/3406C/00	120	CARB	none	M25	88	0.21	0.01	0.20	1.30	9.69	0.39	874	0.24
CAT/3406C/00	120	CARB	none	M50	175	0.08	0.02	0.07	1.94	9.46	0.24	749	0.24
CAT/3406C/00	120	CARB	none	M75	264	0.04	0.01	0.03	1.88	8.62	0.28	719	0.20
CAT/3406C/00	120	CARB	none	M100	348	0.06	0.03	0.04	1.60	7.62	0.33	736	0.18
					36	0.60	0.06	0.55	2.92	11.39	0.93	1313	0.74
					88	0.22	0.02	0.20	1.34	9.52	0.40	869	0.26
					174	0.08	0.02	0.07	2.05	9.26	0.26	746	0.26
					263	0.04	0.01	0.03	2.00	8.38	0.25	717	0.23
					349	0.06	0.03	0.04	1.72	7.40	0.31	734	0.20
						0.10	0.02	0.08	1.90	8.80	0.30	765	0.25
CAT/3406C/00	664	CARB	none	M100	347	0.11	0.04	0.08	1.71	7.71	0.24	716	0.21
CAT/3406C/00	664	CARB	none	M75	259	0.08	0.03	0.06	2.28	8.88	0.27	710	0.25
CAT/3406C/00	664	CARB	none	M50	171	0.10	0.02	0.08	1.97	9.91	0.33	740	0.23
CAT/3406C/00	664	CARB	none	M25	86	0.22	0.02	0.20	1.38	9.87	0.41	867	0.29
CAT/3406C/00	664	CARB	none	M10	37	0.56	0.04	0.53	2.74	11.22	0.88	1259	0.74
CAT/3406C/00	666	CARB	none	M100	346	0.08	0.04	0.05	1.72	7.64	0.49	722	0.18
CAT/3406C/00	666	CARB	none	M75	261	0.06	0.02	0.04	2.24	8.74	0.20	710	0.25
CAT/3406C/00	666	CARB	none	M50	172	0.09	0.02	0.07	1.97	9.36	0.40	733	0.24
CAT/3406C/00	666	CARB	none	M25	86	0.21	0.02	0.19	1.41	9.55	0.35	871	0.27
CAT/3406C/00	666	CARB	none	M10	36	0.59	0.06	0.54	2.80	11.35	0.83	1288	0.72
CAT/3406C/00	669	CARB	none	M100	347	0.09	0.03	0.06	1.60	7.61	0.32	715	0.16
CAT/3406C/00	669	CARB	none	M75	261	0.06	0.02	0.05	2.18	8.63	0.23	707	0.23
CAT/3406C/00	669	CARB	none	M50	172	0.09	0.02	0.07	1.95	9.40	0.41	731	0.24
CAT/3406C/00	669	CARB	none	M25	89	0.16	0.02	0.15	1.35	9.47	0.41	852	0.27
CAT/3406C/00	669	CARB	none	M10	38	0.48	0.04	0.44	2.64	10.71	0.79	1232	0.73
					347	0.09	0.03	0.06	1.68	7.65	0.35	718	0.18
					260	0.07	0.02	0.05	2.23	8.75	0.23	709	0.24
					172	0.09	0.02	0.07	1.97	9.56	0.38	735	0.24
					87	0.20	0.02	0.18	1.38	9.63	0.39	864	0.28
					37	0.54	0.05	0.50	2.73	11.09	0.83	1260	0.73
						0.11	0.02	0.09	1.96	9.08	0.33	755	0.25

CAT 3406C engine and CAT 3408C engine

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	3237	CARB	none	M100	347	NA	0.05	NA	1.63	7.59	0.29	707	0.17
CAT/3406C/00	3237	CARB	none	M75	257	NA	0.04	NA	1.83	8.61	0.31	701	0.20
CAT/3406C/00	3237	CARB	none	M50	171	NA	0.04	NA	1.61	9.28	0.26	725	0.22
CAT/3406C/00	3237	CARB	none	M25	86	NA	0.05	NA	1.28	9.46	0.47	864	0.25
CAT/3406C/00	3237	CARB	none	M10	38	NA	0.11	NA	2.86	10.88	1.07	1233	0.76
CAT/3406C/00	3237	CARB	none	M100	348	0.17	0.05	0.13	1.69	7.64	0.33	702	0.16
CAT/3406C/00	3237	CARB	none	M75	258	0.17	0.04	0.14	1.87	8.54	0.34	697	0.19
CAT/3406C/00	3237	CARB	none	M50	171	0.21	0.04	0.17	1.63	9.22	0.35	719	0.21
CAT/3406C/00	3237	CARB	none	M25	85	0.33	0.04	0.30	1.23	9.59	0.67	864	0.23
CAT/3406C/00	3237	CARB	none	M10	37	0.80	0.12	0.70	2.86	10.96	0.98	1241	0.72
					348	0.17	0.05	0.13	1.66	7.61	0.31	704	0.16
					258	0.17	0.04	0.14	1.85	8.57	0.33	699	0.20
					171	0.21	0.04	0.17	1.62	9.25	0.30	722	0.22
					85	0.33	0.04	0.30	1.26	9.52	0.57	864	0.24
					37	0.80	0.12	0.70	2.86	10.92	1.02	1237	0.74
						0.22	0.04	0.19	1.68	8.89	0.37	745	0.22
CAT/3408B/90	3004	CARB	none	M100	390.8	0.10	0.05	0.06	3.14	NA	NA	761	0.75
CAT/3408B/90	3004	CARB	none	M75	294.5	0.07	0.03	0.05	2.32	NA	NA	746	0.42
CAT/3408B/90	3004	CARB	none	M50	196.6	0.16	0.05	0.12	1.81	NA	NA	784	0.42
CAT/3408B/90	3004	CARB	none	M25	98.7	0.34	0.10	0.25	3.16	NA	NA	935	0.64
CAT/3408B/90	3004	CARB	none	M10	40.7	1.31	0.35	1.01	8.84	NA	NA	1425	1.37
CAT/3408B/90	3005	CARB	none	M100	391.6	0.11	0.03	0.08	2.95	6.27	0.35	748	0.59
CAT/3408B/90	3005	CARB	none	M75	294.5	0.10	0.03	0.08	2.29	6.61	0.29	737	0.39
CAT/3408B/90	3005	CARB	none	M50	197.0	0.19	0.04	0.15	1.35	7.52	0.29	777	0.35
CAT/3408B/90	3005	CARB	none	M25	98.1	0.38	0.10	0.30	2.50	7.87	0.51	938	0.61
CAT/3408B/90	3005	CARB	none	M10	41.6	1.30	0.31	1.04	6.62	11.61	1.42	1405	1.26
CAT/3408B/90	3005	CARB	none	M100	394.1	0.12	0.04	0.08	3.01	6.26	0.40	751	0.60
CAT/3408B/90	3005	CARB	none	M75	295.4	0.07	0.02	0.05	2.25	6.69	0.25	739	0.38
CAT/3408B/90	3005	CARB	none	M50	198.3	0.19	0.04	0.15	1.43	7.47	0.33	777	0.38
CAT/3408B/90	3005	CARB	none	M25	99.6	0.35	0.09	0.27	2.42	7.59	0.45	922	0.62
CAT/3408B/90	3005	CARB	none	M10	41.5	1.35	0.33	1.07	6.63	11.44	1.47	1377	1.28
					392	0.11	0.04	0.08	3.04	6.27	0.38	754	0.65
					295	0.08	0.03	0.06	2.29	6.65	0.27	741	0.40
					197	0.18	0.04	0.14	1.53	7.50	0.31	780	0.38
					99	0.36	0.10	0.27	2.69	7.73	0.48	932	0.62
					41	1.32	0.33	1.04	7.36	11.52	1.44	1403	1.31
						0.19	0.05	0.14	2.30	7.16	0.35	799	0.47

Initial and subsequent retest of CAT 3412C after 350 hours in rental service

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3412C/##	2200	CARB	none	M10	57	0.96	0.21	0.78	5.56	21.76		1584	0.62
CAT/3412C/##	2200	CARB	none	M25	138	0.29	0.08	0.23	2.05	12.90		1018	0.26
CAT/3412C/##	2200	CARB	none	M50	268	0.17	0.04	0.14	1.03	10.86		820	0.17
CAT/3412C/##	2200	CARB	none	M75	407	0.05	0.02	0.03	1.25	8.94		737	0.20
CAT/3412C/##	2200	CARB	none	M100	540	0.06	0.02	0.04	2.14	7.61		699	0.30
CAT/3412C/##	2200	CARB	none	M10	58	0.94	0.21	0.77	5.46	22.14		1601	0.51
CAT/3412C/##	2200	CARB	none	M25	137	0.30	0.08	0.23	2.04	13.15		1025	0.25
CAT/3412C/##	2200	CARB	none	M50	265	0.16	0.04	0.13	0.97	11.08		825	0.16
CAT/3412C/##	2200	CARB	none	M75	403	0.06	0.02	0.05	1.15	9.05		734	0.19
CAT/3412C/##	2200	CARB	none	M100	537	0.06	0.02	0.04	1.98	7.84		689	0.26
					57	0.95	0.21	0.77	5.51	21.95		1593	0.57
					137	0.30	0.08	0.23	2.04	13.02		1022	0.26
					266	0.17	0.04	0.13	1.00	10.97		823	0.17
					405	0.06	0.02	0.04	1.20	8.99		735	0.20
					539	0.06	0.02	0.04	2.06	7.73		694	0.28
						0.15	0.04	0.12	1.46	10.42		824	0.21
CAT/3412C/##	2542	CARB	none	M50	256	0.19	0.04	0.16	1.05	11.29	0.42	826	0.23
CAT/3412C/##	2542	CARB	none	M75	412	0.05	0.01	0.04	1.27	9.08	0.28	774	0.32
CAT/3412C/##	2542	CARB	none	M100	548	0.06	0.02	0.04	2.20	8.09	0.35	769	0.41
CAT/3412C/##	2542	CARB	none	M50	256	0.15	0.04	0.12	1.03	10.91	0.33	817	0.20
CAT/3412C/##	2542	CARB	none	M75	412	0.05	0.02	0.03	1.21	9.08	0.33	760	0.20
CAT/3412C/##	2542	CARB	none	M100	548	0.06	0.02	0.04	2.26	8.06	0.35	762	0.36
CAT/3412C/##	2542	CARB	none	M100	550	0.07	0.02	0.05	2.05	8.09	0.38	734	0.28
CAT/3412C/##	2542	CARB	none	M75	412	0.05	0.02	0.03	1.13	8.97	0.33	739	0.19
CAT/3412C/##	2542	CARB	none	M50	272	0.12	0.04	0.09	0.98	10.67	0.42	788	0.18
CAT/3412C/##	2542	CARB	none	M25	135	0.30	0.09	0.23	2.31	12.77	0.77	960	0.25
CAT/3412C/##	2542	CARB	none	M10	55	1.06	0.27	0.83	6.00	22.45	2.13	1521	0.84
CAT/3412C/##	2542	CARB	none	M100	549	0.06	0.02	0.05	2.25	8.03	0.29	752	0.33
CAT/3412C/##	2542	CARB	none	M75	412	0.04	0.01	0.03	1.23	8.90	0.26	750	0.21
CAT/3412C/##	2542	CARB	none	M50	274	0.12	0.03	0.09	1.00	10.51	0.39	794	0.20
CAT/3412C/##	2542	CARB	none	M25	135	0.27	0.08	0.21	2.25	12.72	0.71	973	0.34
CAT/3412C/##	2542	CARB	none	M10	56	0.98	0.24	0.77	5.76	22.17	2.19	1510	0.56
CAT/3412C/##	2542	CARB	none	M100	549	0.06	0.02	0.04	2.29	7.99	0.35	744	0.35
					55	1.02	0.25	0.80	5.88	22.3	2.2	1516	0.70
					135	0.29	0.08	0.22	2.28	12.7	0.7	966	0.30
					265	0.15	0.04	0.11	1.01	10.8	0.4	806	0.20
					412	0.05	0.02	0.03	1.21	9.0	0.3	756	0.23
					549	0.06	0.02	0.04	2.21	8.0	0.3	752	0.35
						0.14	0.04	0.11	1.53	10.35	0.44	821	0.26

CAT 3500-Series engines with CARB fuel

Mfg/Model/Yr	Eng Hr	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3508/02	443	M100	998	0.28	0.04	0.25	0.37	8.20	0.25	706	0.08
CAT/3508/02	443	M75	752	0.33	0.02	0.31	0.44	6.29	0.30	729	0.10
CAT/3508/02	443	M50	501	0.41	0.02	0.32	0.66	5.57	0.34	783	0.19
CAT/3508/02	443	M25	251	0.66	0.05	0.57	1.37	6.29	0.56	964	0.38
CAT/3508/02	443	M10	100	1.64	0.22	1.25	3.92	10.96	1.29	1395	0.87
CAT/3508/02	446	M100	999	0.26	0.04	0.23	0.41	8.18	0.30	700	0.07
CAT/3508/02	446	M75	746	0.31	0.01	0.29	0.46	6.47	0.28	736	0.10
CAT/3508/02	446	M50	500	0.43	0.02	0.39	0.68	5.68	0.35	786	0.19
CAT/3508/02	446	M25	250	0.63	0.14	0.50	1.42	6.26	0.56	966	0.34
CAT/3508/02	446	M10	100	1.56	0.18	1.37	4.10	11.17	1.32	1445	0.86
			999	0.27	0.04	0.24	0.39	8.19	0.27	703	0.07
			749	0.32	0.02	0.30	0.45	6.38	0.29	733	0.10
			500	0.42	0.02	0.36	0.67	5.62	0.35	785	0.19
			250	0.64	0.10	0.54	1.40	6.27	0.56	965	0.36
			100	1.60	0.20	1.31	4.01	11.06	1.30	1420	0.86
		EMFAC		0.43	0.04	0.37	0.74	6.41	0.37	798	0.18
CAT/3512/00	808	M100	1503	0.25	0.03	0.22	0.40	8.56	0.31	702	0.10
CAT/3512/00	808	M75	1116	0.33	0.03	0.29	0.50	6.22	0.24	744	0.14
CAT/3512/00	808	M50	744	0.42	0.01	0.40	0.71	6.58	0.31	780	0.23
CAT/3512/00	808	M25	381	0.59	0.07	0.56	1.35	7.43	0.52	938	0.39
CAT/3512/00	808	M10	149	1.10	0.07	1.01	2.88	8.58	4.65	962	0.93
CAT/3512/00	810	M100	1511	0.25	0.04	0.22	0.40	8.62	0.28	704	0.08
CAT/3512/00	810	M75	1117	0.33	0.03	0.30	0.49	6.16	0.28	738	0.13
CAT/3512/00	810	M50	745	0.43	0.02	0.40	0.73	6.68	0.35	789	0.23
CAT/3512/00	810	M25	381	0.61	0.02	0.58	1.35	7.46	0.59	942	0.38
CAT/3512/00	810	M10	149	1.63	0.13	1.51	4.27	13.11	1.59	1453	0.88
			1507	0.25	0.04	0.22	0.40	8.59	0.30	703	0.09
			1116	0.33	0.03	0.30	0.50	6.19	0.26	741	0.14
			744	0.43	0.02	0.40	0.72	6.63	0.33	785	0.23
			381	0.60	0.05	0.57	1.35	7.44	0.55	940	0.39
			149	1.37	0.10	1.26	3.58	10.84	3.12	1207	0.90
		EMFAC		0.42	0.03	0.39	0.76	6.88	0.39	793	0.22
CAT/3516/00	1530	M100	2007	0.28	0.08	0.21	0.36	9.01	0.27	693	0.08
CAT/3516/00	1530	M75	1502	0.31	0.03	0.27	0.39	7.05	0.28	688	0.09
CAT/3516/00	1530	M50	1002	0.38	0.02	0.34	0.60	5.85	0.34	731	0.18
CAT/3516/00	1530	M25	497	0.60	0.00	0.58	1.32	6.00	0.60	889	0.34
CAT/3516/00	1530	M10	197	1.58	0.06	1.49	4.14	9.17	1.63	1356	1.03
CAT/3516/00	1532	M100	2001	0.26	0.04	0.24	0.37	8.74	0.21	685	0.07
CAT/3516/00	1532	M75	1505	0.32	0.01	0.28	0.36	7.30	0.36	684	0.09
CAT/3516/00	1532	M50	1000	0.38	0.01	0.36	0.61	6.14	0.34	756	0.18
CAT/3516/00	1532	M25	503	0.53	0.02	0.51	1.20	5.61	0.53	833	0.34
CAT/3516/00	1532	M10	199	1.44	0.13	1.29	3.80	8.39	1.24	1274	0.93
			2004	0.27	0.06	0.22	0.37	8.88	0.24	689	0.07
			1504	0.31	0.02	0.28	0.37	7.17	0.32	686	0.09
			1001	0.38	0.01	0.35	0.60	6.00	0.34	743	0.18
			500	0.57	0.01	0.55	1.26	5.81	0.56	861	0.34
			198	1.51	0.10	1.39	3.97	8.78	1.44	1315	0.98
		EMFAC		0.40	0.02	0.36	0.66	6.80	0.38	745	0.17

Appendix E. Controlled BUGs: Calculated Emission Factors for Each Load and for Overall BUG in grams/kW-hour as per 40 CFR 89

CAT 3406C engine using emulsified fuel (PuriNOx)

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	3237	CARB	none	M100	347	NA	0.05	NA	1.63	7.59	0.29	707	0.17
CAT/3406C/00	3237	CARB	none	M75	257	NA	0.04	NA	1.83	8.61	0.31	701	0.20
CAT/3406C/00	3237	CARB	none	M50	171	NA	0.04	NA	1.61	9.28	0.26	725	0.22
CAT/3406C/00	3237	CARB	none	M25	86	NA	0.05	NA	1.28	9.46	0.47	864	0.25
CAT/3406C/00	3237	CARB	none	M10	38	NA	0.11	NA	2.86	10.88	1.07	1233	0.76
CAT/3406C/00	3237	CARB	none	M100	348	0.17	0.05	0.13	1.69	7.64	0.33	702	0.16
CAT/3406C/00	3237	CARB	none	M75	258	0.17	0.04	0.14	1.87	8.54	0.34	697	0.19
CAT/3406C/00	3237	CARB	none	M50	171	0.21	0.04	0.17	1.63	9.22	0.35	719	0.21
CAT/3406C/00	3237	CARB	none	M25	85	0.33	0.04	0.30	1.23	9.59	0.67	864	0.23
CAT/3406C/00	3237	CARB	none	M10	37	0.80	0.12	0.70	2.86	10.96	0.98	1241	0.72
					348	0.17	0.05	0.13	1.66	7.61	0.31	704	0.16
					258	0.17	0.04	0.14	1.85	8.57	0.33	699	0.20
					171	0.21	0.04	0.17	1.62	9.25	0.30	722	0.22
					85	0.33	0.04	0.30	1.26	9.52	0.57	864	0.24
					37	0.80	0.12	0.70	2.86	10.92	1.02	1237	0.74
						0.22	0.04	0.19	1.68	8.89	0.37	745	0.22
CAT/3406C/00	3237	_UBRIZOI	none	M85	293	0.17	0.04	0.14	1.00	6.81	0.26	707	0.05
CAT/3406C/00	3237	_UBRIZOI	none	M75	256	0.15	0.04	0.12	1.18	7.15	0.25	704	0.05
CAT/3406C/00	3237	_UBRIZOI	none	M50	171	0.20	0.05	0.16	1.12	8.23	0.43	723	0.07
CAT/3406C/00	3237	_UBRIZOI	none	M25	86	0.27	0.05	0.23	1.04	8.35	0.34	860	0.08
CAT/3406C/00	3237	_UBRIZOI	none	M10	36	0.67	0.12	0.57	2.60	9.80	0.97	1261	0.27
CAT/3406C/00	3237	_UBRIZOI	none	M85	295	0.15	0.04	0.12	1.01	6.83	0.22	705	0.04
CAT/3406C/00	3237	_UBRIZOI	none	M75	256	0.12	0.03	0.10	1.12	7.20	0.29	701	0.05
CAT/3406C/00	3237	_UBRIZOI	none	M50	171	0.16	0.03	0.13	1.12	8.28	0.33	723	0.07
CAT/3406C/00	3237	_UBRIZOI	none	M25	85	0.22	0.02	0.21	1.03	8.29	0.47	853	0.10
CAT/3406C/00	3237	_UBRIZOI	none	M10	36	0.56	0.05	0.51	2.58	9.79	1.00	1246	0.29
					294	0.16	0.04	0.13	1.00	6.82	0.24	706	0.04
					256	0.14	0.03	0.11	1.15	7.18	0.27	702	0.05
					171	0.18	0.04	0.15	1.12	8.25	0.38	723	0.07
					85	0.25	0.03	0.22	1.03	8.32	0.41	857	0.09
					36	0.61	0.09	0.54	2.59	9.79	0.99	1253	0.28
						0.18	0.04	0.15	1.14	7.73	0.34	747	0.07
					% Red	18.1%	11.4%	20.3%	32.3%	13.0%	8.6%	-0.2%	68.7%

CAT 3406B engine using emulsified fuel (PuriNOx)

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406B/86	110	CARB	none	M100	296	0.19	0.04	0.15	0.93	12.38	0.24	711	0.10
CAT/3406B/86	110	CARB	none	M75	220	0.15	0.04	0.12	0.56	14.46	0.24	714	0.07
CAT/3406B/86	110	CARB	none	M50	147	0.26	0.05	0.21	0.65	16.33	0.37	759	0.08
CAT/3406B/86	110	CARB	none	M25	73	0.45	0.09	0.37	1.57	17.47	0.76	935	0.35
CAT/3406B/86	110	CARB	none	M10	30	1.05	0.15	0.93	4.76	24.79	2.01	1412	1.34
CAT/3406B/86	111	CARB	none	M100	296	0.15	0.04	0.12	0.92	12.38	0.25	704	0.09
CAT/3406B/86	111	CARB	none	M75	225	0.11	0.03	0.09	0.62	14.19	0.19	708	0.07
CAT/3406B/86	111	CARB	none	M50	148	0.17	0.03	0.15	0.65	15.78	0.36	746	0.06
CAT/3406B/86	111	CARB	none	M25	73	0.38	0.06	0.33	1.65	17.18	0.88	922	0.30
CAT/3406B/86	111	CARB	none	M10	31	1.05	0.15	0.92	4.73	24.68	2.00	1405	1.16
					296	0.17	0.04	0.14	0.92	12.38	0.24	708	0.10
					223	0.13	0.03	0.10	0.59	14.33	0.22	711	0.07
					147	0.21	0.04	0.18	0.65	16.05	0.37	753	0.07
					73	0.42	0.08	0.35	1.61	17.33	0.82	929	0.32
					31	1.05	0.15	0.92	4.74	24.73	2.00	1409	1.25
						0.23	0.04	0.19	0.90	15.37	0.40	773	0.14
CAT/3406B/86	114	LUBRIZOL	none	M90	287	0.14	0.03	0.12	0.42	11.46	0.12	645	0.05
CAT/3406B/86	114	LUBRIZOL	none	M75	223	0.12	0.02	0.11	0.41	13.84	0.22	708	0.05
CAT/3406B/86	114	LUBRIZOL	none	M50	147	0.12	0.02	0.10	0.38	15.18	0.42	748	0.05
CAT/3406B/86	114	LUBRIZOL	none	M25	73	0.49	0.07	0.43	1.40	16.73	0.90	928	0.23
CAT/3406B/86	114	LUBRIZOL	none	M10	30	1.74	0.26	1.52	5.05	25.55	2.24	1437	0.94
CAT/3406B/86	115	LUBRIZOL	none	M90	269	0.13	0.03	0.11	0.45	12.18	0.25	704	0.05
CAT/3406B/86	115	LUBRIZOL	none	M75	219	0.12	0.03	0.09	0.41	13.70	0.31	707	0.05
CAT/3406B/86	115	LUBRIZOL	none	M50	147	0.12	0.02	0.10	0.41	14.90	0.41	750	0.05
CAT/3406B/86	115	LUBRIZOL	none	M25	72	0.50	0.07	0.44	1.41	16.51	0.94	938	0.26
CAT/3406B/86	115	LUBRIZOL	none	M10	30	1.85	0.30	1.59	5.29	25.31	2.31	1471	1.08
					278	0.14	0.03	0.11	0.43	11.82	0.19	674	0.05
					221	0.12	0.02	0.10	0.41	13.77	0.26	708	0.05
					147	0.12	0.02	0.10	0.40	15.04	0.41	749	0.05
					72	0.50	0.07	0.44	1.40	16.62	0.92	933	0.25
					30	1.79	0.28	1.56	5.17	25.43	2.27	1454	1.01
						0.22	0.04	0.19	0.67	14.68	0.45	769	0.10
					% Red	4.0%	20.4%	0.6%	25.5%	4.5%	-12.9%	0.5%	24.7%

CAT 3406B engine using CARB and CARB-ULSD fuels

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst Ty	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	664	CARB	none	M100	347	0.11	0.04	0.08	1.71	7.71	0.24	716	0.21
CAT/3406C/00	664	CARB	none	M75	259	0.08	0.03	0.06	2.28	8.88	0.27	710	0.25
CAT/3406C/00	664	CARB	none	M50	171	0.10	0.02	0.08	1.97	9.91	0.33	740	0.23
CAT/3406C/00	664	CARB	none	M25	86	0.22	0.02	0.20	1.38	9.87	0.41	867	0.29
CAT/3406C/00	664	CARB	none	M10	37	0.56	0.04	0.53	2.74	11.22	0.88	1259	0.74
CAT/3406C/00	666	CARB	none	M100	346	0.08	0.04	0.05	1.72	7.64	0.49	722	0.18
CAT/3406C/00	666	CARB	none	M75	261	0.06	0.02	0.04	2.24	8.74	0.20	710	0.25
CAT/3406C/00	666	CARB	none	M50	172	0.09	0.02	0.07	1.97	9.36	0.40	733	0.24
CAT/3406C/00	666	CARB	none	M25	86	0.21	0.02	0.19	1.41	9.55	0.35	871	0.27
CAT/3406C/00	666	CARB	none	M10	36	0.59	0.06	0.54	2.80	11.35	0.83	1288	0.72
CAT/3406C/00	669	CARB	none	M100	347	0.09	0.03	0.06	1.60	7.61	0.32	715	0.16
CAT/3406C/00	669	CARB	none	M75	261	0.06	0.02	0.05	2.18	8.63	0.23	707	0.23
CAT/3406C/00	669	CARB	none	M50	172	0.09	0.02	0.07	1.95	9.40	0.41	731	0.24
CAT/3406C/00	669	CARB	none	M25	89	0.16	0.02	0.15	1.35	9.47	0.41	852	0.27
CAT/3406C/00	669	CARB	none	M10	38	0.48	0.04	0.44	2.64	10.71	0.79	1232	0.73
					347	0.09	0.03	0.06	1.68	7.65	0.35	718	0.18
					260	0.07	0.02	0.05	2.23	8.75	0.23	709	0.24
					172	0.09	0.02	0.07	1.97	9.56	0.38	735	0.24
					87	0.20	0.02	0.18	1.38	9.63	0.39	864	0.28
					37	0.54	0.05	0.50	2.73	11.09	0.83	1260	0.73
						0.11	0.02	0.09	1.96	9.08	0.33	755	0.25
CAT/3406C/00	1018	ECD	none	M100	350	0.04	0.03	0.02	2.00	6.61	0.28	705	0.18
CAT/3406C/00	1018	ECD	none	M75	263	0.04	0.02	0.03	2.20	7.61	0.29	708	0.21
CAT/3406C/00	1018	ECD	none	M50	174	0.09	0.02	0.07	2.04	8.15	0.30	742	0.23
CAT/3406C/00	1018	ECD	none	M25	86	0.23	0.01	0.22	1.33	8.18	0.37	890	0.27
CAT/3406C/00	1018	ECD	none	M10	34	0.70	0.04	0.66	3.42	10.05	0.93	1376	1.09
CAT/3406C/00	1019	ECD	none	M100	352	0.04	0.02	0.02	2.18	6.83	0.33	711	0.20
CAT/3406C/00	1019	ECD	none	M75	267	0.04	0.01	0.03	2.27	7.93	0.25	716	0.21
CAT/3406C/00	1019	ECD	none	M50	174	0.09	0.02	0.07	2.20	8.49	0.26	744	0.23
CAT/3406C/00	1019	ECD	none	M25	86	0.24	0.02	0.23	1.34	8.59	0.43	881	0.27
CAT/3406C/00	1019	ECD	none	M10	34	0.73	0.06	0.68	3.56	10.78	0.87	1388	1.08
					351	0.04	0.02	0.02	2.09	6.72	0.30	708	0.19
					265	0.04	0.01	0.03	2.24	7.77	0.27	712	0.21
					174	0.09	0.02	0.07	2.12	8.32	0.28	743	0.23
					86	0.23	0.02	0.22	1.34	8.39	0.40	885	0.27
					34	0.71	0.05	0.67	3.49	10.41	0.90	1382	1.08
						0.10	0.02	0.08	2.07	7.98	0.31	762	0.24
					%red	10.9%	23.9%	7.9%	-5.3%	12.1%	5.9%	-0.9%	4.1%

CAT 3406C engine and a diesel oxidation catalyst (DOC-1)

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	664	CARB	none	M100	347	0.11	0.04	0.08	1.71	7.71	0.24	716	0.21
CAT/3406C/00	664	CARB	none	M75	259	0.08	0.03	0.06	2.28	8.88	0.27	710	0.25
CAT/3406C/00	664	CARB	none	M50	171	0.10	0.02	0.08	1.97	9.91	0.33	740	0.23
CAT/3406C/00	664	CARB	none	M25	86	0.22	0.02	0.20	1.38	9.87	0.41	867	0.29
CAT/3406C/00	664	CARB	none	M10	37	0.56	0.04	0.53	2.74	11.22	0.88	1259	0.74
CAT/3406C/00	666	CARB	none	M100	346	0.08	0.04	0.05	1.72	7.64	0.49	722	0.18
CAT/3406C/00	666	CARB	none	M75	261	0.06	0.02	0.04	2.24	8.74	0.20	710	0.25
CAT/3406C/00	666	CARB	none	M50	172	0.09	0.02	0.07	1.97	9.36	0.40	733	0.24
CAT/3406C/00	666	CARB	none	M25	86	0.21	0.02	0.19	1.41	9.55	0.35	871	0.27
CAT/3406C/00	666	CARB	none	M10	36	0.59	0.06	0.54	2.80	11.35	0.83	1288	0.72
CAT/3406C/00	669	CARB	none	M100	347	0.09	0.03	0.06	1.60	7.61	0.32	715	0.16
CAT/3406C/00	669	CARB	none	M75	261	0.06	0.02	0.05	2.18	8.63	0.23	707	0.23
CAT/3406C/00	669	CARB	none	M50	172	0.09	0.02	0.07	1.95	9.40	0.41	731	0.24
CAT/3406C/00	669	CARB	none	M25	89	0.16	0.02	0.15	1.35	9.47	0.41	852	0.27
CAT/3406C/00	669	CARB	none	M10	38	0.48	0.04	0.44	2.64	10.71	0.79	1232	0.73
					347	0.09	0.03	0.06	1.68	7.65	0.35	718	0.18
					260	0.07	0.02	0.05	2.23	8.75	0.23	709	0.24
					172	0.09	0.02	0.07	1.97	9.56	0.38	735	0.24
					87	0.20	0.02	0.18	1.38	9.63	0.39	864	0.28
					37	0.54	0.05	0.50	2.73	11.09	0.83	1260	0.73
						0.11	0.02	0.09	1.96	9.08	0.33	755	0.25
CAT/3406C/00	688	CARB	DOC1	M100	348	0.01	0.00	0.01	0.09	8.21	0.57	700	0.14
CAT/3406C/00	688	CARB	DOC1	M75	259	0.01	0.00	0.01	0.09	9.57	0.72	696	0.17
CAT/3406C/00	688	CARB	DOC1	M50	172	0.01	0.00	0.01	0.06	10.09	0.70	725	0.18
CAT/3406C/00	688	CARB	DOC1	M25	86	0.02	0.00	0.02	0.07	10.00	0.33	869	0.25
CAT/3406C/00	688	CARB	DOC1	M10	36	0.08	0.01	0.08	0.20	11.75	0.16	1301	0.64
CAT/3406C/00	689	CARB	DOC1	M100	348	0.01	0.00	0.01	0.09	8.20	0.66	703	0.14
CAT/3406C/00	689	CARB	DOC1	M75	259	0.01	0.00	0.01	0.08	9.30	0.74	699	0.17
CAT/3406C/00	689	CARB	DOC1	M50	171	0.01	0.00	0.01	0.06	10.00	0.66	726	0.17
CAT/3406C/00	689	CARB	DOC1	M25	89	0.03	0.00	0.03	0.07	10.02	0.32	861	0.23
CAT/3406C/00	689	CARB	DOC1	M10	37	0.08	0.01	0.08	0.18	11.40	0.12	1271	0.66
CAT/3406C/00	690	CARB	DOC1	M100	346	0.01	0.00	0.01	0.09	8.22	0.67	704	0.15
CAT/3406C/00	690	CARB	DOC1	M75	259	0.01	0.00	0.01	0.09	9.30	0.76	699	0.17
CAT/3406C/00	690	CARB	DOC1	M50	170	0.01	0.00	0.01	0.06	9.92	0.66	730	0.17
CAT/3406C/00	690	CARB	DOC1	M25	89	0.02	0.00	0.02	0.07	10.05	0.30	862	0.22
CAT/3406C/00	690	CARB	DOC1	M10	37	0.09	0.01	0.07	0.19	11.41	0.15	1268	0.66
CAT/3406C/00	706	CARB	DOC1+DP	M50	173	0.01	0.01	0.01	0.05	9.14	1.04	727	0.21
CAT/3406C/00	706	CARB	DOC1+DP	M50	173	0.01	0.01	0.01	0.05	9.16	0.95	727	0.21
CAT/3406C/00	706	CARB	DOC1+DP	M50	173	0.01	0.01	0.01	0.05	9.18	0.91	727	0.21
						0.01	0.01	0.01	0.05	9.16	0.97	727	0.21
					347	0.01	0.00	0.01	0.09	8.21	0.63	702	0.14
					259	0.01	0.00	0.01	0.09	9.39	0.74	698	0.17
					171	0.01	0.00	0.01	0.06	10.01	0.67	727	0.17
					88	0.02	0.00	0.02	0.07	10.03	0.32	864	0.24
					37	0.08	0.01	0.08	0.19	11.52	0.14	1280	0.65
						0.01	0.00	0.01	0.08	9.61	0.63	747	0.19
					% Red	86.7%	90.3%	85.8%	96.0%	-5.8%	-89.8%	1.0%	24.6%

CAT 3406C engine and a diesel oxidation catalyst (DOC-2)

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	664	CARB	none	M100	347	0.11	0.04	0.08	1.71	7.71	0.24	716	0.21
CAT/3406C/00	664	CARB	none	M75	259	0.08	0.03	0.06	2.28	8.88	0.27	710	0.25
CAT/3406C/00	664	CARB	none	M50	171	0.10	0.02	0.08	1.97	9.91	0.33	740	0.23
CAT/3406C/00	664	CARB	none	M25	86	0.22	0.02	0.20	1.38	9.87	0.41	867	0.29
CAT/3406C/00	664	CARB	none	M10	37	0.56	0.04	0.53	2.74	11.22	0.88	1259	0.74
CAT/3406C/00	666	CARB	none	M100	346	0.08	0.04	0.05	1.72	7.64	0.49	722	0.18
CAT/3406C/00	666	CARB	none	M75	261	0.06	0.02	0.04	2.24	8.74	0.20	710	0.25
CAT/3406C/00	666	CARB	none	M50	172	0.09	0.02	0.07	1.97	9.36	0.40	733	0.24
CAT/3406C/00	666	CARB	none	M25	86	0.21	0.02	0.19	1.41	9.55	0.35	871	0.27
CAT/3406C/00	666	CARB	none	M10	36	0.59	0.06	0.54	2.80	11.35	0.83	1288	0.72
CAT/3406C/00	669	CARB	none	M100	347	0.09	0.03	0.06	1.60	7.61	0.32	715	0.16
CAT/3406C/00	669	CARB	none	M75	261	0.06	0.02	0.05	2.18	8.63	0.23	707	0.23
CAT/3406C/00	669	CARB	none	M50	172	0.09	0.02	0.07	1.95	9.40	0.41	731	0.24
CAT/3406C/00	669	CARB	none	M25	89	0.16	0.02	0.15	1.35	9.47	0.41	852	0.27
CAT/3406C/00	669	CARB	none	M10	38	0.48	0.04	0.44	2.64	10.71	0.79	1232	0.73
					347	0.09	0.03	0.06	1.68	7.65	0.35	718	0.18
					260	0.07	0.02	0.05	2.23	8.75	0.23	709	0.24
					172	0.09	0.02	0.07	1.97	9.56	0.38	735	0.24
					87	0.20	0.02	0.18	1.38	9.63	0.39	864	0.28
					37	0.54	0.05	0.50	2.73	11.09	0.83	1260	0.73
						0.11	0.02	0.09	1.96	9.08	0.33	755	0.25
CAT/3406C/00	733	CARB	DOC2	M100	355	0.01	0.00	0.00	0.08	8.06	0.46	710	0.24
CAT/3406C/00	733	CARB	DOC2	M75	260	0.00	0.00	0.00	0.08	8.91	0.31	711	0.22
CAT/3406C/00	733	CARB	DOC2	M50	172	0.00	0.00	0.00	0.06	9.38	0.06	736	0.22
CAT/3406C/00	733	CARB	DOC2	M25	86	0.01	0.00	0.01	0.07	9.39	0.08	879	0.25
CAT/3406C/00	733	CARB	DOC2	M10	36	0.11	0.01	0.10	0.16	11.16	0.01	1303	0.76
CAT/3406C/00	735	CARB	DOC2	M100	353	0.01	0.00	0.00	0.06	7.80	0.49	716	0.23
CAT/3406C/00	735	CARB	DOC2	M75	264	0.00	0.00	0.00	0.07	8.74	0.32	702	0.23
CAT/3406C/00	735	CARB	DOC2	M50	173	0.01	0.00	0.00	0.06	9.22	0.25	727	0.23
CAT/3406C/00	735	CARB	DOC2	M25	86	0.01	0.00	0.01	0.06	9.14	0.07	864	0.27
CAT/3406C/00	735	CARB	DOC2	M10	36	0.11	0.01	0.10	0.15	10.88	0.01	1282	0.74
CAT/3406C/00	737	CARB	DOC2	M100	354	0.01	0.00	0.00	0.06	7.94	0.49	709	0.24
CAT/3406C/00	737	CARB	DOC2	M75	262	0.01	0.00	0.00	0.07	9.18	0.39	696	0.19
CAT/3406C/00	737	CARB	DOC2	M50	172	0.01	0.00	0.00	0.06	9.78	0.50	727	0.20
CAT/3406C/00	737	CARB	DOC2	M25	88	0.01	0.00	0.01	0.07	9.42	0.06	857	0.24
CAT/3406C/00	737	CARB	DOC2	M10	38	0.11	0.01	0.10	0.14	10.90	0.00	1248	0.68
					354	0.01	0.00	0.00	0.07	7.93	0.48	712	0.24
					262	0.00	0.00	0.00	0.07	8.94	0.34	703	0.22
					172	0.01	0.00	0.00	0.06	9.46	0.27	730	0.22
					87	0.01	0.00	0.01	0.06	9.32	0.07	867	0.25
					37	0.11	0.01	0.10	0.15	10.98	0.00	1278	0.73
						0.01	0.00	0.01	0.07	9.10	0.28	751	0.24
					% Red	92.0%	86.6%	93.1%	96.5%	-0.2%	14.2%	0.5%	5.6%

DDC engine (2-stroke) and with a diesel oxidation catalyst (DOC-2)

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
DDC/V92/85	863	CARB	none	M100	291	0.26	0.04	0.22	1.77	18.48	0.41	820	0.23
DDC/V92/85	863	CARB	none	M75	221	0.47	0.04	0.43	1.25	15.82	0.56	860	0.23
DDC/V92/85	863	CARB	none	M50	148	0.97	0.06	0.91	8.49	12.30	0.71	931	0.30
DDC/V92/85	863	CARB	none	M25	74	1.78	0.13	1.67	1.93	11.55	1.36	1207	0.46
DDC/V92/85	863	CARB	none	M10	34	3.63	0.33	3.34	4.28	16.54	2.96	1908	0.70
DDC/V92/85	865	CARB	none	M100	291	0.26	0.00	0.27	2.03	18.65	0.31	823	0.20
DDC/V92/85	865	CARB	none	M75	222	0.47	0.00	0.47	1.31	16.10	0.47	861	0.20
DDC/V92/85	865	CARB	none	M50	148	0.95	-0.01	0.95	1.26	12.32	0.74	933	0.29
DDC/V92/85	865	CARB	none	M25	74	1.68	0.29	1.43	1.92	11.65	1.42	1212	NA
DDC/V92/85	865	CARB	none	M10	33	3.56	0.72	2.94	4.35	16.87	2.97	1926	NA
DDC/V92/85	867	CARB	none	M100	290	0.28	0.05	0.24	2.01	18.42	0.35	813	0.16
DDC/V92/85	867	CARB	none	M75	221	0.50	0.05	0.46	1.33	16.02	0.56	855	0.18
DDC/V92/85	867	CARB	none	M50	147	0.95	0.06	0.89	1.27	12.24	0.69	927	0.30
DDC/V92/85	867	CARB	none	M25	73	1.71	0.12	1.60	1.90	11.60	1.39	1206	0.43
DDC/V92/85	867	CARB	none	M10	31	3.68	0.32	3.41	4.55	17.36	2.91	1963	0.66
DDC/V92/85	868	CARB	none	M100	291	0.29	0.05	0.24	2.22	18.90	0.32	824	0.18
DDC/V92/85	868	CARB	none	M75	222	0.51	0.05	0.46	1.37	16.21	0.50	857	0.20
DDC/V92/85	868	CARB	none	M50	147	0.96	0.06	0.90	1.26	12.56	0.72	933	0.29
DDC/V92/85	868	CARB	none	M25	75	1.63	0.12	1.53	1.84	11.62	1.34	1193	0.42
DDC/V92/85	868	CARB	none	M10	31	3.63	0.32	3.36	4.39	17.66	2.98	2003	NA
					291	0.27	0.03	0.24	2.01	18.61	0.35	820	0.19
					222	0.49	0.03	0.46	1.32	16.04	0.52	858	0.20
					148	0.96	0.05	0.92	3.07	12.35	0.71	931	0.30
					74	1.70	0.16	1.56	1.90	11.60	1.38	1205	0.43
					32	3.62	0.42	3.26	4.39	17.11	2.95	1950	0.68
						0.88	0.07	0.82	2.11	14.46	0.76	957	0.28
DDC/V92/85	929	CARB	DOC2	M100	291	0.1	0.0	0.0	0.1	18.5	0.0	801	0.07
DDC/V92/85	929	CARB	DOC2	M75	224	0.1	0.0	0.1	0.1	16.4	0.0	827	0.09
DDC/V92/85	929	CARB	DOC2	M50	147	0.4	0.0	0.4	0.1	12.8	0.0	909	0.18
DDC/V92/85	929	CARB	DOC2	M25	75	1.0	0.1	0.9	0.4	11.6	0.0	1159	0.22
DDC/V92/85	929	CARB	DOC2	M10	32	2.7	0.3	2.5	3.0	19.8	0.3	1968	0.51
DDC/V92/85	929	CARB	DOC2	M100	294	0.1	0.0	0.1	0.1	18.7	0.0	812	0.07
DDC/V92/85	929	CARB	DOC2	M75	224	0.2	0.0	0.1	0.1	16.4	0.0	825	0.10
DDC/V92/85	929	CARB	DOC2	M50	147	0.4	0.0	0.3	0.1	12.8	0.1	907	0.19
DDC/V92/85	929	CARB	DOC2	M10	32	2.9	0.3	2.7	2.8	20.1	0.7	1972	0.49
DDC/V92/85	931	CARB	DOC2	M100	288	0.1	0.0	0.1	0.2	18.0	0.0	797	0.08
DDC/V92/85	931	CARB	DOC2	M75	229	0.1	0.0	0.1	0.1	16.3	0.0	830	0.11
DDC/V92/85	931	CARB	DOC2	M50	148	0.4	0.0	0.3	0.1	12.6	0.0	901	0.20
DDC/V92/85	931	CARB	DOC2	M25	74	1.0	0.1	0.9	0.4	11.7	0.0	1153	0.24
DDC/V92/85	931	CARB	DOC2	M10	32	2.7	0.3	2.5	3.1	20.1	0.3	1966	0.54
					291	0.07	0.01	0.06	0.14	18.43	-0.01	803	0.07
					226	0.14	0.01	0.13	0.12	16.37	0.00	827	0.10
					147	0.36	0.02	0.35	0.13	12.74	0.03	906	0.19
					75	0.98	0.06	0.92	0.40	11.66	0.00	1156	0.23
					32	2.80	0.26	2.57	2.93	20.00	0.42	1969	0.51
						0.40	0.03	0.37	0.23	14.78	0.02	927	0.16
					%red	54.9%	59.6%	54.5%	88.9%	-2.2%	97.7%	3.1%	44.3%

CAT 3406C engine and a diesel particulate filter (DPF-1)

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	130	CARB	none	M100	348	0.06	0.02	0.05	1.29	7.67	0.21	711	0.14
CAT/3406C/00	130	CARB	none	M75	255	0.06	0.02	0.05	1.62	8.55	-0.02	700	0.18
CAT/3406C/00	130	CARB	none	M50	170	0.11	0.02	0.09	1.53	9.45	0.33	730	0.21
CAT/3406C/00	130	CARB	none	M25	85	0.24	0.02	0.22	1.25	9.66	0.44	865	0.27
CAT/3406C/00	130	CARB	none	M10	36	0.70	0.07	0.65	2.92	11.65	0.90	1299	0.90
CAT/3406C/00	133	CARB	none	M100	348	0.07	0.02	0.05	1.07	7.55	0.24	699	0.12
CAT/3406C/00	133	CARB	none	M75	255	0.07	0.02	0.06	1.42	8.65	0.31	695	0.16
CAT/3406C/00	133	CARB	none	M50	170	0.11	0.02	0.09	1.34	9.18	0.25	728	0.19
CAT/3406C/00	133	CARB	none	M25	85	0.23	0.02	0.21	1.21	9.42	0.52	869	0.27
CAT/3406C/00	133	CARB	none	M10	36	0.64	0.06	0.59	2.90	11.29	0.92	1301	0.90
CAT/3406C/00	134	CARB	none	M100	347	0.06	0.02	0.05	1.08	7.65	0.18	705	0.12
CAT/3406C/00	134	CARB	none	M75	255	0.07	0.02	0.05	1.38	8.59	0.25	696	0.16
CAT/3406C/00	134	CARB	none	M50	172	0.10	0.02	0.08	1.38	9.08	0.31	724	0.18
CAT/3406C/00	134	CARB	none	M25	85	0.24	0.03	0.22	1.23	9.28	0.33	862	0.26
CAT/3406C/00	134	CARB	none	M10	36	0.65	0.06	0.60	2.84	11.02	0.89	1278	0.81
CAT/3406C/00	136	CARB	none	M100	348	0.06	0.02	0.05	1.10	7.47	0.21	702	0.13
CAT/3406C/00	136	CARB	none	M75	255	0.07	0.02	0.05	1.36	8.47	0.27	692	0.16
CAT/3406C/00	136	CARB	none	M50	169	0.10	0.02	0.08	1.35	9.10	0.28	726	0.19
CAT/3406C/00	136	CARB	none	M25	85	0.21	0.02	0.20	1.21	9.30	0.41	863	0.25
CAT/3406C/00	136	CARB	none	M10	36	0.61	0.06	0.55	2.95	11.08	0.92	1290	0.83
					347	0.06	0.02	0.05	1.13	7.59	0.21	704	0.13
					255	0.07	0.02	0.05	1.45	8.56	0.20	696	0.17
					170	0.10	0.02	0.09	1.40	9.20	0.29	727	0.19
					85	0.23	0.02	0.21	1.22	9.42	0.43	865	0.26
					36	0.65	0.06	0.60	2.90	11.26	0.91	1292	0.86
						0.12	0.02	0.10	1.39	8.86	0.28	747	0.20
CAT/3406C/00	185	ECD	Passive D	M100	346	0.01	0.01	0.00	0.20	8.10	0.80	712	0.02
CAT/3406C/00	185	ECD	Passive D	M75	265	0.01	0.01	0.00	0.23	9.06	2.07	695	0.02
CAT/3406C/00	185	ECD	Passive D	M50	171	0.01	0.01	0.00	0.27	9.34	3.27	727	0.03
CAT/3406C/00	185	ECD	Passive D	M25	87	0.01	0.00	0.00	0.28	9.53	5.59	863	0.04
CAT/3406C/00	185	ECD	Passive D	M10	36	0.05	0.02	0.04	0.62	11.39	6.99	1296	0.15
CAT/3406C/00	191	ECD	Passive D	M100	346	0.01	0.00	0.00	0.21	8.20	0.87	702	0.02
CAT/3406C/00	191	ECD	Passive D	M75	259	0.01	0.00	0.00	0.23	9.15	2.06	691	0.02
CAT/3406C/00	191	ECD	Passive D	M50	172	0.01	0.00	0.01	0.24	9.45	3.37	719	0.03
CAT/3406C/00	191	ECD	Passive D	M25	85	0.02	0.00	0.01	0.25	9.55	5.91	864	0.05
CAT/3406C/00	191	ECD	Passive D	M10	36	0.09	0.01	0.08	0.62	11.47	7.03	1292	0.19
CAT/3406C/00	196	ECD	Passive D	M100	346	0.01	0.00	0.01	0.20	8.08	0.83	704	0.02
CAT/3406C/00	196	ECD	Passive D	M75	264	0.01	0.00	0.01	0.22	8.98	2.07	690	0.02
CAT/3406C/00	196	ECD	Passive D	M50	172	0.01	0.00	0.01	0.26	9.35	3.37	719	0.03
CAT/3406C/00	196	ECD	Passive D	M25	85	0.02	0.00	0.02	0.26	9.53	5.95	873	0.05
CAT/3406C/00	196	ECD	Passive D	M10	36	0.08	0.01	0.07	0.65	11.37	7.19	1301	0.20
					346	0.01	0.00	0.00	0.20	8.13	0.83	706	0.02
					263	0.01	0.00	0.00	0.22	9.06	2.07	692	0.02
					172	0.01	0.00	0.01	0.26	9.38	3.34	722	0.03
					86	0.01	0.00	0.01	0.26	9.54	5.82	867	0.04
					36	0.07	0.01	0.06	0.63	11.41	7.07	1296	0.18
						0.01	0.00	0.01	0.25	9.19	3.03	743	0.03
					% Red	91.2%	81.8%	92.9%	82.2%	-3.8%	-976.1%	0.4%	84.2%

CAT 3406C and diesel particulate filter (DPF-2) after caulking DPF-1 to reduce by-pass around the active element

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	130	CARB	none	M100	348	0.06	0.02	0.05	1.29	7.67	0.21	711	0.14
CAT/3406C/00	130	CARB	none	M75	255	0.06	0.02	0.05	1.62	8.55	-0.02	700	0.18
CAT/3406C/00	130	CARB	none	M50	170	0.11	0.02	0.09	1.53	9.45	0.33	730	0.21
CAT/3406C/00	130	CARB	none	M25	85	0.24	0.02	0.22	1.25	9.66	0.44	865	0.27
CAT/3406C/00	130	CARB	none	M10	36	0.70	0.07	0.65	2.92	11.65	0.90	1299	0.90
CAT/3406C/00	133	CARB	none	M100	348	0.07	0.02	0.05	1.07	7.55	0.24	699	0.12
CAT/3406C/00	133	CARB	none	M75	255	0.07	0.02	0.06	1.42	8.65	0.31	695	0.16
CAT/3406C/00	133	CARB	none	M50	170	0.11	0.02	0.09	1.34	9.18	0.25	728	0.19
CAT/3406C/00	133	CARB	none	M25	85	0.23	0.02	0.21	1.21	9.42	0.52	869	0.27
CAT/3406C/00	133	CARB	none	M10	36	0.64	0.06	0.59	2.90	11.29	0.92	1301	0.90
CAT/3406C/00	134	CARB	none	M100	347	0.06	0.02	0.05	1.08	7.65	0.18	705	0.12
CAT/3406C/00	134	CARB	none	M75	255	0.07	0.02	0.05	1.38	8.59	0.25	696	0.16
CAT/3406C/00	134	CARB	none	M50	172	0.10	0.02	0.08	1.38	9.08	0.31	724	0.18
CAT/3406C/00	134	CARB	none	M25	85	0.24	0.03	0.22	1.23	9.28	0.33	862	0.26
CAT/3406C/00	134	CARB	none	M10	36	0.65	0.06	0.60	2.84	11.02	0.89	1278	0.81
CAT/3406C/00	136	CARB	none	M100	348	0.06	0.02	0.05	1.10	7.47	0.21	702	0.13
CAT/3406C/00	136	CARB	none	M75	255	0.07	0.02	0.05	1.36	8.47	0.27	692	0.16
CAT/3406C/00	136	CARB	none	M50	169	0.10	0.02	0.08	1.35	9.10	0.28	726	0.19
CAT/3406C/00	136	CARB	none	M25	85	0.21	0.02	0.20	1.21	9.30	0.41	863	0.25
CAT/3406C/00	136	CARB	none	M10	36	0.61	0.06	0.55	2.95	11.08	0.92	1290	0.83
					347	0.06	0.02	0.05	1.13	7.59	0.21	704	0.13
					255	0.07	0.02	0.05	1.45	8.56	0.20	696	0.17
					170	0.10	0.02	0.09	1.40	9.20	0.29	727	0.19
					85	0.23	0.02	0.21	1.22	9.42	0.43	865	0.26
					36	0.65	0.06	0.60	2.90	11.26	0.91	1292	0.86
						0.12	0.02	0.10	1.39	8.86	0.28	747	0.20
CAT/3406C/00	338	ECD	Passive D	M100	349	0.01	0.01	0.00	0.30	7.41	0.42	714	0.01
CAT/3406C/00	338	ECD	Passive D	M75	258	0.00	0.00	0.00	0.28	8.32	1.25	703	0.01
CAT/3406C/00	338	ECD	Passive D	M50	173	0.01	0.00	0.00	0.30	9.10	2.78	731	0.02
CAT/3406C/00	338	ECD	Passive D	M25	87	0.01	0.00	0.01	0.31	9.23	5.27	878	0.02
CAT/3406C/00	338	ECD	Passive D	M10	35	0.09	0.01	0.08	0.76	11.13	7.37	1335	0.09
CAT/3406C/00	343	ECD	Passive D	M100	349	0.01	0.01	0.00	0.31	6.83	0.40	718	0.01
CAT/3406C/00	343	ECD	Passive D	M75	261	0.00	0.00	0.00	0.29	7.67	1.04	709	0.01
CAT/3406C/00	343	ECD	Passive D	M50	174	0.01	0.00	0.00	0.32	8.45	2.40	738	0.02
CAT/3406C/00	343	ECD	Passive D	M25	84	0.01	0.00	0.01	0.29	8.28	4.79	892	0.02
CAT/3406C/00	343	ECD	Passive D	M10	35	0.08	0.01	0.07	0.67	9.95	6.27	1326	0.09
CAT/3406C/00	349	ECD	Passive D	M100	349	0.01	0.01	0.00	0.37	6.38	0.26	733	0.02
CAT/3406C/00	349	ECD	Passive D	M75	263	0.00	0.01	0.00	0.36	7.29	0.79	717	0.02
CAT/3406C/00	349	ECD	Passive D	M50	170	0.00	0.01	0.00	0.40	7.77	1.88	748	0.02
CAT/3406C/00	349	ECD	Passive D	M25	89	0.00	0.01	0.00	0.36	7.87	4.25	875	0.02
CAT/3406C/00	349	ECD	Passive D	M10	34	0.04	0.03	0.01	0.82	9.74	6.11	1371	0.11
					349	0.01	0.01	0.00	0.32	6.87	0.36	722	0.01
					261	0.00	0.00	0.00	0.31	7.76	1.03	710	0.01
					172	0.01	0.01	0.00	0.34	8.44	2.35	739	0.02
					87	0.01	0.00	0.01	0.32	8.46	4.77	882	0.02
					35	0.07	0.02	0.06	0.75	10.28	6.58	1344	0.10
						0.01	0.01	0.00	0.33	8.04	2.09	761	0.02
					% Red	94.2%	72.4%	96.0%	76.2%	9.2%	-639.8%	-1.9%	90.8%

CAT 3406C engine using an active particulate filter with DOC-4 – Baseline data and initial control results

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	664	CARB	none	M100	347	0.11	0.04	0.08	1.71	7.71	0.24	716	0.21
CAT/3406C/00	664	CARB	none	M75	259	0.08	0.03	0.06	2.28	8.88	0.27	710	0.25
CAT/3406C/00	664	CARB	none	M50	171	0.10	0.02	0.08	1.97	9.91	0.33	740	0.23
CAT/3406C/00	664	CARB	none	M25	86	0.22	0.02	0.20	1.38	9.87	0.41	867	0.29
CAT/3406C/00	664	CARB	none	M10	37	0.56	0.04	0.53	2.74	11.22	0.88	1259	0.74
CAT/3406C/00	666	CARB	none	M100	346	0.08	0.04	0.05	1.72	7.64	0.49	722	0.18
CAT/3406C/00	666	CARB	none	M75	261	0.06	0.02	0.04	2.24	8.74	0.20	710	0.25
CAT/3406C/00	666	CARB	none	M50	172	0.09	0.02	0.07	1.97	9.36	0.40	733	0.24
CAT/3406C/00	666	CARB	none	M25	86	0.21	0.02	0.19	1.41	9.55	0.35	871	0.27
CAT/3406C/00	666	CARB	none	M10	36	0.59	0.06	0.54	2.80	11.35	0.83	1288	0.72
CAT/3406C/00	669	CARB	none	M100	347	0.09	0.03	0.06	1.60	7.61	0.32	715	0.16
CAT/3406C/00	669	CARB	none	M75	261	0.06	0.02	0.05	2.18	8.63	0.23	707	0.23
CAT/3406C/00	669	CARB	none	M50	172	0.09	0.02	0.07	1.95	9.40	0.41	731	0.24
CAT/3406C/00	669	CARB	none	M25	89	0.16	0.02	0.15	1.35	9.47	0.41	852	0.27
CAT/3406C/00	669	CARB	none	M10	38	0.48	0.04	0.44	2.64	10.71	0.79	1232	0.73
					347	0.09	0.03	0.06	1.68	7.65	0.35	718	0.18
					260	0.07	0.02	0.05	2.23	8.75	0.23	709	0.24
					172	0.09	0.02	0.07	1.97	9.56	0.38	735	0.24
					87	0.20	0.02	0.18	1.38	9.63	0.39	864	0.28
					37	0.54	0.05	0.50	2.73	11.09	0.83	1260	0.73
						0.11	0.02	0.09	1.96	9.08	0.33	755	0.25
CAT/3406C/00	772	ECD	Active DP	MS100	340	0.00	0.01	0.00	1.28	6.50	-0.01	739	0.00
CAT/3406C/00	772	ECD	Active DP	MR75	263	0.01	0.01	0.00	1.63	7.65	0.02	730	0.00
CAT/3406C/00	772	ECD	Active DP	MS50	177	0.02	0.02	0.01	1.71	8.69	0.01	751	0.00
CAT/3406C/00	772	ECD	Active DP	MR25	86	0.12	0.03	0.10	1.54	8.82	0.04	895	0.00
CAT/3406C/00	772	ECD	Active DP	MS10	37	0.50	0.08	0.43	2.98	10.51	0.05	1244	0.00
CAT/3406C/00	772	ECD	Active DP	MR100	340	0.00	0.01	0.00	1.63	6.44	0.03	715	0.00
					340	0.00	0.01	0.00	1.45	6.47	0.01	727	0.001
					263	0.01	0.01	0.00	1.63	7.65	0.02	730	0.001
					177	0.02	0.02	0.01	1.71	8.69	0.01	751	0.000
					86	0.12	0.03	0.10	1.54	8.82	0.04	895	0.000
					37	0.50	0.08	0.43	2.98	10.51	0.05	1244	0.002
						0.04	0.01	0.03	1.65	8.11	0.02	774	0.00
					% Red	63.2%	38.4%	68.4%	15.8%	10.7%	93.9%	-2.5%	99.8%

CAT 3406C engine with an active particulate filter without a diesel oxidation catalyst – Initial results – Both regeneration and soot modes

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	780	ECD	Active DP	MS100	342	0.03	0.02	0.01	2.85	6.43	0.01	771	0.000
CAT/3406C/00	780	ECD	Active DP	MR75	266	0.02	0.01	0.01	3.15	7.34	0.00	769	0.001
CAT/3406C/00	780	ECD	Active DP	MS50	177	0.05	0.02	0.03	2.63	8.42	0.07	743	0.001
CAT/3406C/00	780	ECD	Active DP	MR25	89	0.18	0.03	0.15	3.02	8.51	0.20	848	0.000
CAT/3406C/00	780	ECD	Active DP	MS10	38	0.63	0.12	0.53	3.05	9.95	0.40	1203	0.008
CAT/3406C/00	786	ECD	Active DP	MR100	343	0.03	0.02	0.01	2.55	6.66	0.07	699	0.001
CAT/3406C/00	786	ECD	Active DP	MS75	263	0.02	0.01	0.01	2.36	7.74	0.06	686	0.000
CAT/3406C/00	786	ECD	Active DP	MR50	171	0.06	0.02	0.04	2.75	8.36	0.03	720	0.002
CAT/3406C/00	786	ECD	Active DP	MS25	89	0.19	0.06	0.14	1.43	8.27	0.20	823	0.000
CAT/3406C/00	790	ECD	Active DP	MS100	345	0.04	0.03	0.02	1.83	6.91	0.05	702	0.000
CAT/3406C/00	790	ECD	Active DP	MR75	260	0.02	0.01	0.01	2.44	7.69	0.05	692	0.000
CAT/3406C/00	790	ECD	Active DP	MS50	176	0.07	0.02	0.05	2.02	8.58	0.03	715	0.000
CAT/3406C/00	790	ECD	Active DP	MR25	87	0.18	0.02	0.16	2.46	8.39	0.13	847	0.000
CAT/3406C/00	790	ECD	Active DP	MS10	37	0.59	0.07	0.53	3.11	10.32	0.44	1232	0.001
CAT/3406C/00	795	ECD	Active DP	MR100	345	0.03	0.02	0.02	2.22	6.71	0.06	702	0.000
CAT/3406C/00	795	ECD	Active DP	MS75	261	0.02	0.01	0.01	2.09	7.87	0.08	689	0.000
CAT/3406C/00	795	ECD	Active DP	MR50	177	0.05	0.02	0.03	2.45	8.49	0.05	717	0.001
CAT/3406C/00	795	ECD	Active DP	MS25	88	0.16	0.03	0.14	1.52	8.70	0.09	850	0.000
CAT/3406C/00	795	ECD	Active DP	MR10	36	0.57	0.07	0.51	5.49	10.43	0.59	1249	0.001
CAT/3406C/00	802	ECD	Active DP	MS100	349	0.04	0.02	0.02	1.88	6.89	0.06	700	0.000
CAT/3406C/00	802	ECD	Active DP	MR75	262	0.03	0.01	0.02	2.40	7.75	0.06	682	0.000
CAT/3406C/00	802	ECD	Active DP	MS50	171	0.06	0.02	0.05	1.88	8.71	0.05	721	0.000
CAT/3406C/00	802	ECD	Active DP	MR25	86	0.17	0.02	0.15	2.50	8.55	0.12	888	0.002
CAT/3406C/00	802	ECD	Active DP	MS10	38	0.58	0.06	0.53	3.05	10.20	0.52	1220	0.003
CAT/3406C/00	805	ECD	Active DP	MR100	344	0.03	0.02	0.01	2.12	6.72	0.07	693	0.000
CAT/3406C/00	805	ECD	Active DP	MS75	261	0.03	0.01	0.02	2.17	7.89	0.07	687	0.000
CAT/3406C/00	805	ECD	Active DP	MR50	170	0.07	0.02	0.05	2.33	8.57	0.08	721	0.001
CAT/3406C/00	805	ECD	Active DP	MS25	85	0.17	0.01	0.16	1.38	8.54	0.14	858	0.000
CAT/3406C/00	805	ECD	Active DP	MR10	36	0.63	0.05	0.58	5.58	10.41	0.57	1264	0.003
CAT/3406C/00	810	ECD	Active DP	MS100	346	0.03	0.03	0.01	1.83	6.91	0.00	695	0.001
CAT/3406C/00	810	ECD	Active DP	MR75	259	0.02	0.02	0.00	2.54	7.77	0.01	697	0.001
CAT/3406C/00	810	ECD	Active DP	MS50	177	0.06	0.03	0.03	1.90	8.80	0.08	723	0.001
CAT/3406C/00	810	ECD	Active DP	MR25	87	0.16	0.04	0.13	2.20	8.73	0.19	861	0.001
CAT/3406C/00	810	ECD	Active DP	MS10	38	0.53	0.10	0.44	2.99	10.32	0.45	1257	0.002

	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
Regeneration	344	0.03	0.02	0.01	2.29	6.70	0.07	698	0.000
	262	0.02	0.01	0.01	2.63	7.64	0.03	710	0.000
	173	0.06	0.02	0.04	2.51	8.48	0.05	719	0.002
	87	0.17	0.03	0.15	2.55	8.54	0.16	861	0.001
	36	0.60	0.06	0.55	5.53	10.42	0.58	1257	0.002
		0.07	0.02	0.05	2.61	8.01	0.07	748	0.00
	% Red	35.4%	13.9%	40.2%	-32.8%	11.8%	77.3%	1.0%	99.7%
Sooting	346	0.03	0.02	0.01	2.18	6.74	0.02	722	0.00
	262	0.02	0.01	0.01	2.21	7.83	0.07	687	0.00
	175	0.06	0.02	0.04	2.14	8.64	0.07	729	0.00
	87	0.17	0.04	0.14	1.45	8.50	0.14	843	0.00
	38	0.58	0.09	0.51	3.05	10.20	0.45	1228	0.00
		0.07	0.02	0.05	2.08	8.14	0.09	741.09	0.00
	% Red	35.3%	4.0%	42.3%	-5.9%	10.4%	74.1%	1.9%	99.9%

CAT 3406C engine with an active particulate filter without a diesel oxidation catalyst – Final results – Both regeneration and soot modes

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	987	ECD	Active DP	MR100	342.0	0.02	0.02	0.00	2.59	6.22	0.00	730.3	0.01
CAT/3406C/00	987	ECD	Active DP	MS75	264.9	0.01	0.01	0.00	2.43	7.25	0.00	735.7	0.01
CAT/3406C/00	987	ECD	Active DP	MR50	175.9	0.04	0.02	0.02	2.63	7.89	0.00	750.7	0.01
CAT/3406C/00	987	ECD	Active DP	MS25	90.1	0.15	0.02	0.13	1.43	8.23	0.00	867.4	0.00
CAT/3406C/00	987	ECD	Active DP	MR10	38.3	0.54	0.08	0.47	4.67	9.14	0.23	1244.8	0.00
CAT/3406C/00	992	ECD	Active DP	MS100	344.3	0.03	0.02	0.01	2.07	6.40	0.00	720	0.01
CAT/3406C/00	992	ECD	Active DP	MR75	264.6	0.02	0.01	0.01	2.71	7.02	0.00	723	0.00
CAT/3406C/00	992	ECD	Active DP	MS50	175.9	0.08	0.05	0.04	2.17	8.04	0.00	744	0.01
CAT/3406C/00	992	ECD	Active DP	MR25	85.9	0.18	0.02	0.16	2.94	7.95	0.00	875	0.00
CAT/3406C/00	992	ECD	Active DP	MS10	37.4	0.63	0.06	0.59	3.01	9.23	0.19	1250	0.01
CAT/3406C/00	997	ECD	Active DP	MR100	341.7	0.01	0.01	0.01	2.47	6.45	0.00	718	0.00
CAT/3406C/00	997	ECD	Active DP	MS75	262.4	0.02	0.02	0.00	2.21	7.58	0.00	720	0.00
CAT/3406C/00	997	ECD	Active DP	MR50	176.4	0.05	0.03	0.02	2.64	8.07	0.00	745	0.01
CAT/3406C/00	997	ECD	Active DP	MS25	85.7	0.16	0.03	0.13	1.39	8.26	0.00	878	0.00
CAT/3406C/00	997	ECD	Active DP	MR10	37.3	0.53	0.07	0.47	5.37	9.50	0.22	1263	0.01
CAT/3406C/00	1002	ECD	Active DP	MS100	343.6	0.03	0.02	0.01	1.87	6.74	0.00	736	0.01
CAT/3406C/00	1002	ECD	Active DP	MR75	261.8	0.02	0.01	0.01	2.47	7.46	0.00	718	0.01
CAT/3406C/00	1002	ECD	Active DP	MS50	176.4	0.06	0.02	0.04	1.95	8.29	0.00	737	0.01
CAT/3406C/00	1002	ECD	Active DP	MR25	84.9	0.17	0.02	0.15	2.60	8.30	0.06	881	0.00
CAT/3406C/00	1002	ECD	Active DP	MS10	37.3	0.59	0.05	0.54	3.04	9.61	0.13	1259	0.01
CAT/3406C/00	1006	ECD	Active DP	MR100	343.6	0.02	0.02	0.01	1.85	n/a	0.00	616	0.00
CAT/3406C/00	1006	ECD	Active DP	MS75	261.8	0.03	0.03	0.01	1.87	7.71	0.00	717	0.00
CAT/3406C/00	1006	ECD	Active DP	MR50	169.6	0.04	0.01	0.03	2.25	8.30	0.00	744	0.01
CAT/3406C/00	1006	ECD	Active DP	MS25	85.9	0.13	0.00	0.13	1.31	8.71	0.00	880	0.00
CAT/3406C/00	1006	ECD	Active DP	MR10	37.3	0.47	0.02	0.45	5.08	9.51	0.31	1262	0.00
CAT/3406C/00	1006	ECD	Active DP	MS100	343.6	0.03	0.02	0.01	2.05	6.77	0.00	718	0.01
CAT/3406C/00	1006	ECD	Active DP	MR75	263.2	0.02	0.01	0.01	2.63	7.41	0.00	718	0.01
CAT/3406C/00	1006	ECD	Active DP	MS50	173.0	0.06	0.02	0.04	1.89	8.18	0.00	748	0.01
CAT/3406C/00	1006	ECD	Active DP	MR25	85.9	0.18	0.03	0.15	2.47	n/a	n/a	888	0.00
CAT/3406C/00	1006	ECD	Active DP	MS10	36.9	0.63	0.08	0.56	3.12	n/a	n/a	1293	0.01

	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
Regeneration	342	0.02	0.01	0.01	2.30	6.33	0.00	688	0.01
	263	0.02	0.01	0.01	2.60	7.30	0.00	720	0.01
	175	0.05	0.03	0.03	2.26	8.13	0.00	745	0.01
	86	0.17	0.02	0.15	2.67	8.13	0.03	881	0.00
	38	0.51	0.05	0.47	5.04	9.38	0.25	1257	0.00
		0.07	0.02	0.05	2.53	7.64	0.01	762	0.01
	% Red	40.1%	16.6%	45.4%	-28.7%	15.9%	96.8%	-0.9%	97.5%
Sooting	344	0.03	0.02	0.01	2.00	6.64	0.00	725	0.01
	263	0.02	0.02	0.00	2.17	7.52	0.00	724	0.01
	175	0.07	0.03	0.04	2.00	8.17	0.00	743	0.01
	87	0.15	0.02	0.13	1.38	8.40	0.00	875	0.00
	37	0.62	0.06	0.56	3.06	9.42	0.16	1267	0.01
		0.07	0.02	0.05	1.99	7.82	0.00	766	0.01
	% Red	38.1%	-2.1%	46.9%	-1.5%	13.9%	98.9%	-1.5%	97.7%

CAT 3406C engine using emulsified fuel and a diesel oxidation catalyst (DOC-2)

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	1018	ECD	none	M100	350	0.04	0.03	0.02	2.00	6.61	0.28	705	0.18
CAT/3406C/00	1018	ECD	none	M75	263	0.04	0.02	0.03	2.20	7.61	0.29	708	0.21
CAT/3406C/00	1018	ECD	none	M50	174	0.09	0.02	0.07	2.04	8.15	0.30	742	0.23
CAT/3406C/00	1018	ECD	none	M25	86	0.23	0.01	0.22	1.33	8.18	0.37	890	0.27
CAT/3406C/00	1018	ECD	none	M10	34	0.70	0.04	0.66	3.42	10.05	0.93	1376	1.09
CAT/3406C/00	1019	ECD	none	M100	352	0.04	0.02	0.02	2.18	6.83	0.33	711	0.20
CAT/3406C/00	1019	ECD	none	M75	267	0.04	0.01	0.03	2.27	7.93	0.25	716	0.21
CAT/3406C/00	1019	ECD	none	M50	174	0.09	0.02	0.07	2.20	8.49	0.26	744	0.23
CAT/3406C/00	1019	ECD	none	M25	86	0.24	0.02	0.23	1.34	8.59	0.43	881	0.27
CAT/3406C/00	1019	ECD	none	M10	34	0.73	0.06	0.68	3.56	10.78	0.87	1388	1.08
					351	0.04	0.02	0.02	2.09	6.72	0.30	708	0.19
					265	0.04	0.01	0.03	2.24	7.77	0.27	712	0.21
					174	0.09	0.02	0.07	2.12	8.32	0.28	743	0.23
					86	0.23	0.02	0.22	1.34	8.39	0.40	885	0.27
					34	0.71	0.05	0.67	3.49	10.41	0.90	1382	1.08
						0.10	0.02	0.08	2.07	7.98	0.31	762	0.24
CAT/3406C/00	1026	LUBRIZO	none	M85	295	0.08	0.02	0.06	1.05	6.22	0.23	691	0.03
CAT/3406C/00	1026	LUBRIZO	none	M75	259	0.08	0.02	0.06	1.22	6.54	0.27	695	0.04
CAT/3406C/00	1026	LUBRIZO	none	M50	175	0.15	0.02	0.13	0.94	7.44	0.27	731	0.06
CAT/3406C/00	1026	LUBRIZO	none	M25	86	0.20	0.01	0.19	0.96	7.50	0.42	881	0.08
CAT/3406C/00	1026	LUBRIZO	none	M10	36	0.53	0.03	0.50	2.74	8.74	0.86	1301	0.19
						0.13	0.02	0.11	1.11	7.01	0.30	750	0.05
					%Red	-34.3%	-13.6%	-38.0%	46.5%	12.2%	2.1%	1.6%	77.3%
CAT/3406C/00	1029	LUBRIZO	DOC2	M85	285	0.01	0.00	0.01	0.04	6.55	0.23	683	0.03
CAT/3406C/00	1029	LUBRIZO	DOC2	M75	258	0.01	0.00	0.01	0.02	6.69	0.19	699	0.04
CAT/3406C/00	1029	LUBRIZO	DOC2	M50	172	0.02	0.00	0.02	0.02	7.66	0.11	731	0.05
CAT/3406C/00	1029	LUBRIZO	DOC2	M25	86	0.02	0.00	0.03	0.01	7.51	0.01	861	0.06
CAT/3406C/00	1029	LUBRIZO	DOC2	M10	36	0.09	0.00	0.11	0.00	8.85	0.00	1279	0.19
						0.01	0.00	0.01	0.02	7.17	0.13	747	0.05
					%Red	84.9%	91.1%	82.0%	99.1%	10.2%	56.8%	1.9%	79.6%

DDC engine (2-stroke) with fuel-based catalyst and a diesel oxidation catalyst (DOC-3) – Initial results

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
DDC/V92/85	863	CARB	none	M100	291	0.26	0.04	0.22	1.77	18.48	0.41	820	0.23
DDC/V92/85	863	CARB	none	M75	221	0.47	0.04	0.43	1.25	15.82	0.56	860	0.23
DDC/V92/85	863	CARB	none	M50	148	0.97	0.06	0.91	8.49	12.30	0.71	931	0.30
DDC/V92/85	863	CARB	none	M25	74	1.78	0.13	1.67	1.93	11.55	1.36	1207	0.46
DDC/V92/85	863	CARB	none	M10	34	3.63	0.33	3.34	4.28	16.54	2.96	1908	0.70
DDC/V92/85	865	CARB	none	M100	291	0.26	0.00	0.27	2.03	18.65	0.31	823	0.20
DDC/V92/85	865	CARB	none	M75	222	0.47	0.00	0.47	1.31	16.10	0.47	861	0.20
DDC/V92/85	865	CARB	none	M50	148	0.95	-0.01	0.95	1.26	12.32	0.74	933	0.29
DDC/V92/85	865	CARB	none	M25	74	1.68	0.29	1.43	1.92	11.65	1.42	1212	NA
DDC/V92/85	865	CARB	none	M10	33	3.56	0.72	2.94	4.35	16.87	2.97	1926	NA
DDC/V92/85	867	CARB	none	M100	290	0.28	0.05	0.24	2.01	18.42	0.35	813	0.16
DDC/V92/85	867	CARB	none	M75	221	0.50	0.05	0.46	1.33	16.02	0.56	855	0.18
DDC/V92/85	867	CARB	none	M50	147	0.95	0.06	0.89	1.27	12.24	0.69	927	0.30
DDC/V92/85	867	CARB	none	M25	73	1.71	0.12	1.60	1.90	11.60	1.39	1206	0.43
DDC/V92/85	867	CARB	none	M10	31	3.68	0.32	3.41	4.55	17.36	2.91	1963	0.66
DDC/V92/85	868	CARB	none	M100	291	0.29	0.05	0.24	2.22	18.90	0.32	824	0.18
DDC/V92/85	868	CARB	none	M75	222	0.51	0.05	0.46	1.37	16.21	0.50	857	0.20
DDC/V92/85	868	CARB	none	M50	147	0.96	0.06	0.90	1.26	12.56	0.72	933	0.29
DDC/V92/85	868	CARB	none	M25	75	1.63	0.12	1.53	1.84	11.62	1.34	1193	0.42
DDC/V92/85	868	CARB	none	M10	31	3.63	0.32	3.36	4.39	17.66	2.98	2003	NA
					291	0.27	0.03	0.24	2.01	18.61	0.35	820	0.19
					222	0.49	0.03	0.46	1.32	16.04	0.52	858	0.20
					148	0.96	0.05	0.92	3.07	12.35	0.71	931	0.30
					74	1.70	0.16	1.56	1.90	11.60	1.38	1205	0.43
					32	3.62	0.42	3.26	4.39	17.11	2.95	1950	0.68
						0.88	0.07	0.82	2.11	14.46	0.76	957	0.28
DDC/V92/85	916	ECD+FBC	DOC3	M100	291	0.04	0.01	0.04	0.04	19.43	0.68	812	0.08
DDC/V92/85	916	ECD+FBC	DOC3	M75	223	0.09	0.01	0.08	0.03	16.79	0.21	831	0.11
DDC/V92/85	916	ECD+FBC	DOC3	M50	148	0.22	0.01	0.21	0.05	12.69	-0.07	905	0.20
DDC/V92/85	916	ECD+FBC	DOC3	M25	75	0.73	0.03	0.71	0.33	11.88	0.18	1155	0.25
DDC/V92/85	916	ECD+FBC	DOC3	M10	33	2.34	0.15	2.20	2.56	17.10	1.78	1870	0.64
DDC/V92/85	916	ECD+FBC	DOC3	M100	290	0.03	0.00	0.03	0.04	19.46	0.87	820	0.08
DDC/V92/85	916	ECD+FBC	DOC3	M75	223	0.08	0.01	0.07	0.03	17.09	0.25	829	0.11
DDC/V92/85	916	ECD+FBC	DOC3	M50	148	0.19	0.01	0.18	0.04	12.86	-0.04	904	0.20
DDC/V92/85	916	ECD+FBC	DOC3	M25	74	0.70	0.06	0.65	0.21	11.85	0.03	1150	0.25
DDC/V92/85	916	ECD+FBC	DOC3	M10	31	2.50	0.21	2.32	2.97	19.99	1.87	1986	0.71
DDC/V92/85	916	ECD+FBC	DOC3	M100	295	0.03	0.00	0.03	0.05	18.87	1.01	819	0.09
DDC/V92/85	916	ECD+FBC	DOC3	M75	223	0.07	0.01	0.07	0.03	17.17	0.42	839	0.11
DDC/V92/85	916	ECD+FBC	DOC3	M50	146	0.18	0.01	0.17	0.04	13.16	0.03	916	0.21
DDC/V92/85	916	ECD+FBC	DOC3	M25	74	0.70	0.04	0.66	0.23	12.02	0.21	1158	0.26
DDC/V92/85	916	ECD+FBC	DOC3	M10	32	2.50	0.20	2.32	2.69	17.86	1.75	1923	0.66
					292	0.04	0.01	0.03	0.04	19.25	0.85	817	0.08
					223	0.08	0.01	0.07	0.03	17.02	0.30	833	0.11
					147	0.20	0.01	0.19	0.04	12.91	-0.03	908	0.20
					74	0.71	0.05	0.67	0.26	11.92	0.14	1154	0.25
					32	2.45	0.19	2.28	2.74	18.32	1.80	1926	0.67
						0.27	0.02	0.25	0.13	15.17	0.26	931	0.17
					%red	69.5%	72.7%	69.3%	93.6%	-4.9%	65.4%	2.7%	38.2%

DDC engine (2-stroke) with fuel-based catalyst and a diesel oxidation catalyst (DOC-3) – Final results

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
DDC/V92/85	863	CARB	none	M100	291	0.26	0.04	0.22	1.77	18.48	0.41	820	0.23
DDC/V92/85	863	CARB	none	M75	221	0.47	0.04	0.43	1.25	15.82	0.56	860	0.23
DDC/V92/85	863	CARB	none	M50	148	0.97	0.06	0.91	8.49	12.30	0.71	931	0.30
DDC/V92/85	863	CARB	none	M25	74	1.78	0.13	1.67	1.93	11.55	1.36	1207	0.46
DDC/V92/85	863	CARB	none	M10	34	3.63	0.33	3.34	4.28	16.54	2.96	1908	0.70
DDC/V92/85	865	CARB	none	M100	291	0.26	0.00	0.27	2.03	18.65	0.31	823	0.20
DDC/V92/85	865	CARB	none	M75	222	0.47	0.00	0.47	1.31	16.10	0.47	861	0.20
DDC/V92/85	865	CARB	none	M50	148	0.95	-0.01	0.95	1.26	12.32	0.74	933	0.29
DDC/V92/85	865	CARB	none	M25	74	1.68	0.29	1.43	1.92	11.65	1.42	1212	NA
DDC/V92/85	865	CARB	none	M10	33	3.56	0.72	2.94	4.35	16.87	2.97	1926	NA
DDC/V92/85	867	CARB	none	M100	290	0.28	0.05	0.24	2.01	18.42	0.35	813	0.16
DDC/V92/85	867	CARB	none	M75	221	0.50	0.05	0.46	1.33	16.02	0.56	855	0.18
DDC/V92/85	867	CARB	none	M50	147	0.95	0.06	0.89	1.27	12.24	0.69	927	0.30
DDC/V92/85	867	CARB	none	M25	73	1.71	0.12	1.60	1.90	11.60	1.39	1206	0.43
DDC/V92/85	867	CARB	none	M10	31	3.68	0.32	3.41	4.55	17.36	2.91	1963	0.66
DDC/V92/85	868	CARB	none	M100	291	0.29	0.05	0.24	2.22	18.90	0.32	824	0.18
DDC/V92/85	868	CARB	none	M75	222	0.51	0.05	0.46	1.37	16.21	0.50	857	0.20
DDC/V92/85	868	CARB	none	M50	147	0.96	0.06	0.90	1.26	12.56	0.72	933	0.29
DDC/V92/85	868	CARB	none	M25	75	1.63	0.12	1.53	1.84	11.62	1.34	1193	0.42
DDC/V92/85	868	CARB	none	M10	31	3.63	0.32	3.36	4.39	17.66	2.98	2003	NA
					291	0.27	0.03	0.24	2.01	18.61	0.35	820	0.19
					222	0.49	0.03	0.46	1.32	16.04	0.52	858	0.20
					148	0.96	0.05	0.92	3.07	12.35	0.71	931	0.30
					74	1.70	0.16	1.56	1.90	11.60	1.38	1205	0.43
					32	3.62	0.42	3.26	4.39	17.11	2.95	1950	0.68
						0.88	0.07	0.82	2.11	14.46	0.76	957	0.28
DDC/V92/85	1089	ECD+FB(	DOC3	M100	293	0.06	0.01	0.05	0.05	18.49	0.61	820	0.07
DDC/V92/85	1089	ECD+FB(	DOC3	M75	223	0.10	0.00	0.10	0.05	16.28	0.46	860	0.11
DDC/V92/85	1089	ECD+FB(	DOC3	M50	148	0.20	0.00	0.20	0.06	12.37	0.04	943	0.19
DDC/V92/85	1089	ECD+FB(	DOC3	M25	75	0.63	0.02	0.61	0.25	11.49	0.15	1185	0.22
DDC/V92/85	1089	ECD+FB(	DOC3	M10	33	2.18	0.13	2.07	2.32	16.63	1.88	1943	0.56
DDC/V92/85	1089	ECD+FB(	DOC3	M100	293	0.04	0.00	0.04	0.05	18.41	1.14	836	0.07
DDC/V92/85	1089	ECD+FB(	DOC3	M75	223	0.08	0.00	0.08	0.03	16.78	0.97	857	0.10
DDC/V92/85	1089	ECD+FB(	DOC3	M50	148	0.18	0.01	0.18	0.07	12.65	0.16	934	0.18
DDC/V92/85	1089	ECD+FB(	DOC3	M25	75	0.57	0.01	0.56	0.17	12.08	0.10	1175	0.20
DDC/V92/85	1089	ECD+FB(	DOC3	M10	32	2.16	0.13	2.05	2.85	19.93	1.73	2022	0.67
DDC/V92/85	1091	ECD+FB(	DOC3	M100	293	0.04	0.01	0.04	0.05	17.62	1.14	811	0.07
DDC/V92/85	1091	ECD+FB(	DOC3	M75	223	0.08	0.01	0.08	0.04	16.35	1.17	846	0.11
DDC/V92/85	1091	ECD+FB(	DOC3	M50	148	0.17	0.01	0.16	0.07	12.26	0.30	923	0.19
DDC/V92/85	1091	ECD+FB(	DOC3	M25	74	0.55	0.02	0.53	0.17	11.30	0.06	1183	0.22
DDC/V92/85	1091	ECD+FB(	DOC3	M10	31	2.43	0.17	2.28	3.13	19.32	2.26	2051	0.73
					293	0.05	0.01	0.04	0.05	18.18	0.96	822	0.07
					223	0.09	0.00	0.09	0.04	16.47	0.86	854	0.10
					148	0.18	0.00	0.18	0.06	12.42	0.17	933	0.19
					75	0.58	0.02	0.57	0.20	11.62	0.10	1181	0.21
					32	2.26	0.14	2.13	2.77	18.63	1.96	2006	0.65
						0.24	0.01	0.23	0.14	14.64	0.56	954	0.16
					%red	72.4%	85.4%	71.5%	93.6%	-1.3%	26.4%	0.3%	43.6%

CAT 3406C engine with a fuel-based catalyst and a diesel particulate filter (FBC/DPF) – Initial results

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	1018	ECD	none	M100	350	0.04	0.03	0.02	2.00	6.61	0.28	705	0.18
CAT/3406C/00	1018	ECD	none	M75	263	0.04	0.02	0.03	2.20	7.61	0.29	708	0.21
CAT/3406C/00	1018	ECD	none	M50	174	0.09	0.02	0.07	2.04	8.15	0.30	742	0.23
CAT/3406C/00	1018	ECD	none	M25	86	0.23	0.01	0.22	1.33	8.18	0.37	890	0.27
CAT/3406C/00	1018	ECD	none	M10	34	0.70	0.04	0.66	3.42	10.05	0.93	1376	1.09
CAT/3406C/00	1019	ECD	none	M100	352	0.04	0.02	0.02	2.18	6.83	0.33	711	0.20
CAT/3406C/00	1019	ECD	none	M75	267	0.04	0.01	0.03	2.27	7.93	0.25	716	0.21
CAT/3406C/00	1019	ECD	none	M50	174	0.09	0.02	0.07	2.20	8.49	0.26	744	0.23
CAT/3406C/00	1019	ECD	none	M25	86	0.24	0.02	0.23	1.34	8.59	0.43	881	0.27
CAT/3406C/00	1019	ECD	none	M10	34	0.73	0.06	0.68	3.56	10.78	0.87	1388	1.08
					351	0.04	0.02	0.02	2.09	6.72	0.30	708	0.19
					265	0.04	0.01	0.03	2.24	7.77	0.27	712	0.21
					174	0.09	0.02	0.07	2.12	8.32	0.28	743	0.23
					86	0.23	0.02	0.22	1.34	8.39	0.40	885	0.27
					34	0.71	0.05	0.67	3.49	10.41	0.90	1382	1.08
						0.10	0.02	0.08	2.07	7.98	0.31	762	0.24
CAT/3406C/00	1061	ECD+FB(	Passive D	M100	351	0.00	0.00	0.00	0.03	7.06	0.65	691	0.005
CAT/3406C/00	1061	ECD+FB(	Passive D	M75	263	0.02	0.02	0.00	0.01	8.12	1.13	702	0.001
CAT/3406C/00	1061	ECD+FB(	Passive D	M50	173	0.00	0.00	0.00	0.01	8.81	1.38	740	0.00
CAT/3406C/00	1061	ECD+FB(	Passive D	M25	86	0.00	0.00	0.00	0.04	8.78	1.58	889	0.000
CAT/3406C/00	1061	ECD+FB(	Passive D	M10	36	0.00	0.00	0.01	0.03	10.34	1.69	1353	0.002
CAT/3406C/00	1066	ECD+FB(	Passive D	M100	349	0.01	0.01	0.00	0.07	7.37	0.74	690	0.003
CAT/3406C/00	1066	ECD+FB(	Passive D	M75	262	0.00	0.00	0.00	0.04	8.46	1.25	700	0.00
CAT/3406C/00	1066	ECD+FB(	Passive D	M50	173	0.01	0.00	0.00	0.02	8.96	1.40	735	0.000
CAT/3406C/00	1066	ECD+FB(	Passive D	M25	85	0.00	0.00	0.00	0.00	8.96	1.63	900	0.007
CAT/3406C/00	1066	ECD+FB(	Passive D	M10	36	0.02	0.00	0.03	0.00	10.53	1.68	1351	0.00
CAT/3406C/00	1071	ECD+FB(	Passive D	M100	349	0.00	0.00	0.00	0.06	7.44	0.86	692	0.002
CAT/3406C/00	1071	ECD+FB(	Passive D	M75	262	0.00	0.00	0.00	0.04	8.40	1.27	697	0.000
CAT/3406C/00	1071	ECD+FB(	Passive D	M50	174	0.01	0.00	0.01	0.02	8.85	1.46	734	0.000
CAT/3406C/00	1071	ECD+FB(	Passive D	M25	86	0.05	0.04	0.01	0.00	9.00	1.76	897	0.000
CAT/3406C/00	1071	ECD+FB(	Passive D	M10	37	0.02	0.00	0.04	0.00	10.05	1.84	1302	0.00
					350	0.00	0.00	0.00	0.05	7.29	0.75	691	0.003
					262	0.01	0.01	0.00	0.03	8.33	1.22	699	0.000
					173	0.00	0.00	0.00	0.02	8.87	1.42	737	0.000
					85	0.02	0.01	0.01	0.01	8.91	1.66	895	0.003
					36	0.01	0.00	0.03	0.01	10.31	1.74	1335	0.001
						0.01	0.01	0.00	0.03	8.52	1.31	755	0.00
					%red	91.8%	64.9%	95.5%	98.7%	-6.8%	-323.0%	0.9%	99.6%

CAT 3406C engine with a fuel-based catalyst and a diesel particulate filter (FBC/DPF) – Final results

Mfg/Model/Yr	Eng Hr	Fuel	Catalyst T	mode	Kw	THC	CH4	NMHC	CO	NOx	NO2	CO2	PM Mass
CAT/3406C/00	1018	ECD	none	M100	350	0.04	0.03	0.02	2.00	6.61	0.28	705	0.18
CAT/3406C/00	1018	ECD	none	M75	263	0.04	0.02	0.03	2.20	7.61	0.29	708	0.21
CAT/3406C/00	1018	ECD	none	M50	174	0.09	0.02	0.07	2.04	8.15	0.30	742	0.23
CAT/3406C/00	1018	ECD	none	M25	86	0.23	0.01	0.22	1.33	8.18	0.37	890	0.27
CAT/3406C/00	1018	ECD	none	M10	34	0.70	0.04	0.66	3.42	10.05	0.93	1376	1.09
CAT/3406C/00	1019	ECD	none	M100	352	0.04	0.02	0.02	2.18	6.83	0.33	711	0.20
CAT/3406C/00	1019	ECD	none	M75	267	0.04	0.01	0.03	2.27	7.93	0.25	716	0.21
CAT/3406C/00	1019	ECD	none	M50	174	0.09	0.02	0.07	2.20	8.49	0.26	744	0.23
CAT/3406C/00	1019	ECD	none	M25	86	0.24	0.02	0.23	1.34	8.59	0.43	881	0.27
CAT/3406C/00	1019	ECD	none	M10	34	0.73	0.06	0.68	3.56	10.78	0.87	1388	1.08
					351	0.04	0.02	0.02	2.09	6.72	0.30	708	0.19
					265	0.04	0.01	0.03	2.24	7.77	0.27	712	0.21
					174	0.09	0.02	0.07	2.12	8.32	0.28	743	0.23
					86	0.23	0.02	0.22	1.34	8.39	0.40	885	0.27
					34	0.71	0.05	0.67	3.49	10.41	0.90	1382	1.08
						0.10	0.02	0.08	2.07	7.98	0.31	762	0.24
CAT/3406C/00	1244	ECD+FB(	Passive D	M100	346	0.01	0.00	0.01	0.05	7.62	0.95	692	0.002
CAT/3406C/00	1244	ECD+FB(	Passive D	M75	262	0.00	0.00	0.00	0.04	8.56	1.40	700	0.001
CAT/3406C/00	1244	ECD+FB(	Passive D	M50	174	0.01	0.00	0.01	0.02	9.11	1.57	737	0.002
CAT/3406C/00	1244	ECD+FB(	Passive D	M25	85	0.00	0.00	0.01	0.00	9.16	1.74	895	0.00
CAT/3406C/00	1244	ECD+FB(	Passive D	M10	36	0.04	0.00	0.04	0.00	10.74	2.22	1364	0.000
CAT/3406C/00	1249	ECD+FB(	Passive D	M100	349	0.00	0.00	0.00	0.04	7.45	0.92	700	0.002
CAT/3406C/00	1249	ECD+FB(	Passive D	M75	261	0.00	0.00	0.00	0.04	8.42	1.45	700	0.000
CAT/3406C/00	1249	ECD+FB(	Passive D	M50	173	0.00	0.00	0.00	0.02	9.02	1.64	735	0.001
CAT/3406C/00	1249	ECD+FB(	Passive D	M25	86	0.00	0.00	0.00	0.00	9.01	1.76	883	0.00
CAT/3406C/00	1249	ECD+FB(	Passive D	M10	36	0.02	0.00	0.02	0.00	10.73	2.14	1350	0.005
CAT/3406C/00	1254	ECD+FB(	Passive D	M100	349	0.00	0.00	0.01	0.05	7.39	0.86	701	0.001
CAT/3406C/00	1254	ECD+FB(	Passive D	M75	262	0.00	0.00	0.00	0.04	8.30	1.39	706	0.000
CAT/3406C/00	1254	ECD+FB(	Passive D	M50	174	0.00	0.00	0.00	0.01	8.76	1.64	740	0.000
CAT/3406C/00	1254	ECD+FB(	Passive D	M25	85	0.00	0.00	0.00	0.00	8.92	1.89	894	0.00
CAT/3406C/00	1254	ECD+FB(	Passive D	M10	36	0.00	0.00	0.02	0.00	10.00	2.06	1297	0.001
					348	0.00	0.00	0.00	0.04	7.48	0.91	697	0.002
					262	0.00	0.00	0.00	0.04	8.43	1.41	702	0.000
					174	0.00	0.00	0.00	0.02	8.96	1.61	737	0.001
					85	0.00	0.00	0.00	0.00	9.03	1.79	890	0.000
					36	0.02	0.00	0.03	0.00	10.49	2.14	1337	0.002
						0.00	0.00	0.00	0.03	8.64	1.50	756	0.001
					%red	96.7%	100.0%	95.0%	98.7%	-8.2%	-383.8%	0.8%	99.7%

Appendix F. Calculated Carbonyl Emission Factors in mg/kW-hour at Each Load and Overall Emission Factor (EMFAC) as per 40 CFR 89 for Some Uncontrolled and Controlled BUGs

CAT 3406B/'91 using CARB fuel

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M10	38	41	16	9	1	1	0	1	0	0	0	0	0	0	69
M25	79	18	7	5	0	0	0	0	0	0	0	0	0	0	31
M50	161	na	na	na	na	na	na	na	na	na	na	na	na	na	na
M75	231	18	5	3	0	1	0	0	3	0	0	0	0	0	31
M100	317	22	0	2	1	0	0	0	0	1	0	0	0	0	27
M10	38	39	12	8	0	0	0	0	0	0	0	0	0	0	58
M25	80	20	7	5	0	1	0	0	0	0	0	0	0	0	32
M50	162	17	5	3	1	0	0	0	0	2	0	0	0	0	29
M75	236	11	2	2	0	0	0	0	0	0	0	0	0	0	15
M100	316	33	9	4	0	1	0	0	1	0	0	0	0	0	46
M10	38	34	12	8	0	0	0	0	0	0	0	0	0	0	54
M25	80	18	7	5	1	0	0	0	0	0	0	0	0	0	31
M50	164	16	5	3	1	0	0	0	0	0	0	0	0	0	24
M75	233	19	5	3	1	0	0	0	0	0	0	0	0	0	28
M100	312	17	4	3	1	0	0	0	0	0	0	0	0	0	26
	38	38	13	8	0	0	0	0	0	0	0	0	0	0	60
	80	19	7	5	0	0	0	0	0	0	0	0	0	0	31
	163	16	5	3	1	0	0	0	0	1	0	0	0	0	26
	233	16	4	3	0	0	0	0	1	0	0	0	0	0	25
	315	24	4	3	1	0	0	0	0	0	0	0	0	0	33
EMFAC		18	5	3	1	0	0	0	0	0	0	0	0	0	28

DDC6V92/'91 using CARB fuel

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M10	35	81	34	17	1	6	2	4	0	17	4	12	0	6	184
M25	88	26	11	6	0	2	0	1	0	5	1	3	0	0	55
M50	175	16	6	3	0	1	0	0	0	0	0	0	0	0	27
M75	263	16	6	2	1	1	0	0	0	1	0	0	0	0	27
M100	350	23	6	2	0	1	1	0	0	4	1	1	0	0	40
M10	35	89	31	18	4	4	1	1	0	0	3	0	0	5	156
M25	88	27	10	6	0	2	0	0	0	0	2	0	0	0	47
M50	175	14	6	3	0	1	0	0	0	3	0	1	0	0	30
M75	263	14	5	3	0	1	0	0	0	3	1	1	0	0	28
M100	350	20	5	2	0	1	0	0	0	4	1	1	0	0	35
M10	35	90	31	19	4	4	0	0	0	0	0	0	0	0	148
M25	88	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M50	175	15	6	3	0	1	0	0	0	3	1	1	0	0	30
M75	263	16	5	3	0	1	0	0	0	0	0	0	0	0	25
M100	350	22	6	3	1	1	0	0	0	0	1	0	0	0	33
	35	87	32	18	3	4	1	2	0	0	2	0	0	4	163
	88	17	7	4	0	1	0	0	0	2	1	1	0	0	34
	175	15	6	3	0	1	0	0	0	2	0	1	0	0	29
	263	15	5	3	0	1	0	0	0	1	0	0	0	0	27
	350	21	6	2	0	1	0	0	0	3	1	1	0	0	36
EMFAC		18	6	3	0	1	0	0	0	2	0	1	0	0	33

CAT 3406C (120hrs) using CARB fuel

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M10	35	43	20	15	1	3	0	1	0	8	2	3	0	1	98
M25	88	14	6	5	0	0	0	0	0	0	0	0	0	0	26
M50	172	13	4	4	0	0	0	0	0	2	0	1	0	0	26
M75	261	12	4	3	1	0	0	0	0	0	0	0	0	0	20
M100	346	16	4	3	0	0	0	1	0	3	0	1	0	0	29
		14	5	4	0	0	0	0	0	1	0	0	0	0	25
M10	36	44	21	18	1	3	0	2	0	9	2	4	0	1	104
M25	88	15	7	7	0	1	0	1	0	3	1	1	0	0	37
M50	175	13	5	5	1	0	0	0	0	0	0	0	0	0	24
M75	264	9	4	4	0	0	0	0	0	2	0	0	0	0	21
M100	352	14	4	4	0	0	0	0	0	2	0	1	0	0	26
		13	5	5	0	1	0	0	0	2	0	0	0	0	27
M10	36	38	15	14	2	1	0	0	0	0	0	0	0	0	71
M25	88	15	6	5	0	0	0	0	0	0	0	0	0	0	26
M50	175	12	5	3	1	0	0	0	0	0	0	0	0	0	21
M75	264	10	4	3	1	0	0	0	0	0	0	0	0	0	17
M100	348	14	5	3	1	0	0	0	1	0	0	0	0	0	23
		13	5	4	1	0	0	0	0	0	0	0	0	0	22
	36	42	19	16	1	2	0	1	0	6	2	2	0	1	91
	88	15	7	6	0	0	0	0	0	1	0	0	0	0	29
	174	13	5	4	0	0	0	0	0	1	0	0	0	0	24
	263	11	4	3	0	0	0	0	0	1	0	0	0	0	19
	349	14	4	3	1	0	0	0	0	2	0	1	0	0	26
EMFAC		13	5	4	0	0	0	0	0	1	0	0	0	0	25

CAT 3412 using CARB fuel

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M50	256	20	8	9	0	1	0	2	0	4	1	5	0	1	51
M75	412	11	5	7	0	1	0	2	0	1	0	0	0	1	29
M100	548	13	6	9	0	1	0	1	0	2	1	2	0	0	36
M50	256	16	9	14	0	3	0	2	0	1	1	1	0	2	48
M75	412	9	5	7	0	1	0	1	0	2	0	2	0	0	26
M100	548	11	5	8	0	1	0	1	0	2	0	2	0	0	30
M100	550	14	6	6	0	1	0	1	0	3	0	2	0	0	33
M75	412	7	3	5	0	0	0	1	0	1	0	1	0	0	20
M50	272	15	6	7	0	1	0	1	0	3	0	2	0	0	37
M25	135	30	11	10	1	2	0	1	0	5	0	3	0	1	66
M10	55	53	21	22	1	3	1	2	0	10	1	8	0	1	123
M100	549	11	5	6	0	1	0	1	0	2	0	1	0	0	28
M75	412	7	3	5	0	0	0	0	0	1	0	1	0	0	19
M50	274	13	5	6	0	1	0	1	0	2	0	2	0	0	31
M25	135	17	7	7	0	1	0	0	0	3	0	2	0	0	39
M10	56	69	27	21	2	4	1	2	0	12	2	9	0	2	150
M100	549	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	55	61	24	21	1	3	1	2	0	11	2	8	0	2	137
	135	24	9	8	1	1	0	1	0	4	0	3	0	1	52
	265	16	7	9	0	1	0	1	0	3	1	2	0	1	41
	446	9	4	6	0	1	0	1	0	2	0	1	0	0	25
	549	10	4	6	0	1	0	1	0	2	0	1	0	0	25
EMFAC		15	6	8	0	1	0	1	0	3	0	2	0	1	37

DDC S60/'99 using CARB fuel

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M100	294	20	6	5	0	1	0	0	0	1	0	0	0	1	34
M75	222	18	6	5	0	0	0	0	0	0	0	0	0	1	30
M50	145	21	9	6	0	0	0	0	0	0	0	0	0	0	36
M25	73	33	10	12	0	0	0	0	0	0	0	3	0	0	58
M10	31	78	35	33	0	3	0	0	0	0	0	9	0	0	158
M100	293	17	4	5	0	0	0	0	0	0	0	0	0	1	27
M75	222	14	4	5	0	0	0	0	0	0	0	2	0	0	25
M50	144	16	4	5	0	0	0	0	0	0	0	0	0	0	24
M25	72	33	9	10	0	0	0	0	0	0	0	0	0	0	51
M10	32	74	21	20	0	0	0	0	0	4	0	7	0	0	126
M100	292	18	4	4	0	0	0	0	0	0	0	1	0	0	27
M75	217	16	4	5	0	0	0	0	0	0	0	2	0	0	27
M50	146	17	6	8	0	1	0	1	0	0	0	2	0	0	36
M25	73	32	8	8	0	0	0	0	0	0	0	0	0	0	48
M10	31	78	26	27	0	5	0	0	0	0	0	7	0	0	142
	32	77	27	27	0	3	0	0	0	1	0	7	0	0	142
	73	33	9	10	0	0	0	0	0	0	0	1	0	0	53
	145	18	6	6	0	0	0	0	0	0	0	1	0	0	32
	220	16	5	5	0	0	0	0	0	0	0	1	0	0	27
	293	18	5	4	0	0	0	0	0	0	0	0	0	1	29
EMFAC		21	6	7	0	0	0	0	0	0	0	1	0	0	35

CUM N14/'99 using CARB fuel

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M100	343	19	2	0	0	0	0	0	0	0	0	0	0	0	23
M75	256	13	3	1	0	0	0	0	0	0	1	0	0	1	20
M50	170	15	5	2	0	1	0	1	0	1	0	0	0	1	26
M25	87	31	11	4	1	2	1	1	1	1	1	1	0	2	57
M10	36	48	17	9	2	3	1	2	1	2	2	1	1	4	92
M100	342	17	1	0	0	0	0	0	0	0	0	0	0	0	19
M75	256	13	3	1	1	0	0	0	0	0	0	0	0	1	21
M50	171	15	4	2	0	1	0	1	0	1	0	0	0	1	26
M25	87	29	11	4	1	2	1	1	1	1	0	1	0	2	54
M10	36	46	17	8	2	3	1	2	1	2	1	1	1	4	87
	36	47	17	8	2	3	1	2	1	2	1	1	1	4	90
	87	30	11	4	1	2	1	1	1	1	1	1	0	2	56
	170	15	5	2	0	1	0	1	0	1	0	0	0	1	26
	256	13	3	1	0	0	0	0	0	0	0	0	0	1	21
	342	18	2	0	0	0	0	0	0	0	0	0	0	0	21
EMFAC		18	5	2	1	1	0	0	0	1	0	0	0	1	30

CAT 3406C (3300hrs) with: (1) CARB fuel, and (2) an emulsified fuel

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M100	347	34	12	14	0	3	1	3	1	6	1	1	0	3	80
M75	257	*32*	15	18	0	4	0	4	1	10	1	1	1	3	91
M50	171	29	15	19	0	4	0	5	1	12	1	1	0	3	91
M25	86	21	10	15	0	3	0	4	0	15	2	0	0	2	71
M10	38	67	27	39	0	8	1	11	2	38	3	1	0	6	204
M100	348	37	22	32	0	8	1	8	1	8	1	2	0	3	125
M75	258	13	12	21	0	4	1	4	0	2	3	0	0	1	64
M50	171	26	25	41	0	10	1	10	1	13	1	2	0	3	133
M25	85	27	52	99	3	26	3	26	2	26	23	5	1	6	299
M10	37	94	28	43	0	7	3	11	0	34	2	0	0	5	226
	37	81	28	41	0	7	2	11	1	36	3	1	0	5	215
	85	24	10	15	1	14	1	15	1	20	13	3	1	4	71
	171	28	20	30	0	7	1	7	1	13	1	2	0	3	112
	258	23	14	20	0	4	0	4	1	6	2	1	1	2	*78*
	348	35	17	23	0	5	1	5	1	7	1	1	0	3	102
EMFAC		27	16	23	1	7	1	7	1	11	3	1	0	3	93
M85	293	36	52	92	3	27	3	23	2	17	1	5	2	6	268
M75	256	30	8	7	0	1	0	2	0	5	0	0	0	1	55
M50	171	27	12	16	0	3	0	4	1	10	3	1	0	2	81
M25	86	31	46	90	1	23	2	23	2	26	3	5	2	6	261
M10	36	109	30	43	0	8	2	11	0	35	8	0	0	5	250
M85	295	39	14	6	0	1	0	2	1	6	0	1	0	1	72
M75	256	14	11	13	0	3	0	3	0	8	1	1	0	2	55
M50	171	56	91	163	1	44	4	39	3	21	4	8	4	7	444
M25	85	61	40	39	1	7	1	10	1	19	2	2	0	5	186
M10	36	86	70	73	1	14	1	18	2	45	2	3	0	7	322
	36	98	50	58	1	11	2	15	1	40	5	2	0	6	286
	85	46	40	39	1	15	2	17	2	23	2	4	1	6	186
	171	42	12	16	1	24	2	22	2	15	3	5	2	4	81
	256	22	10	10	0	2	0	2	0	6	1	0	0	1	55
	294	37	33	49	1	14	1	12	1	11	1	3	1	4	170
EMFAC		35	18	21	1	12	1	12	1	13	2	3	1	3	100

CAT 3406B/1986 with 1) CARB fuel and 2) an emulsified fuel

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M100	296	38	7	0	1	1	0	0	0	0	1	0	0	2	50
M75	220	28	5	2	0	1	0	0	0	0	1	0	0	2	39
M50	147	31	8	3	0	1	1	1	0	1	1	1	0	2	50
M25	73	47	14	4	0	3	1	1	0	2	1	1	0	3	77
M10	30	102	32	12	1	6	3	4	0	4	3	4	0	7	177
M100	296	27	5	0	0	1	0	0	0	0	0	0	0	1	35
M75	225	32	5	2	0	1	0	0	0	0	0	0	2	1	44
M50	148	28	4	2	0	1	0	0	0	0	0	0	0	1	38
M25	73	56	17	15	1	5	1	4	0	2	1	1	0	3	106
M10	31	121	31	14	4	6	2	3	1	4	2	3	1	5	197
	31	112	31	13	3	6	2	3	1	4	2	3	0	6	187
	73	51	15	10	1	4	1	2	0	2	1	1	0	3	91
	147	30	6	2	0	1	0	0	0	1	1	0	0	1	44
	223	30	5	2	0	1	0	0	0	0	0	0	1	1	42
	296	32	6	0	0	1	0	0	0	0	0	0	0	1	42
EMFAC		35	8	3	0	1	0	1	0	1	1	0	1	2	53
M90	287	35	7	3	1	1	0	0	0	1	1	0	0	2	52
M75	223	31	6	3	1	1	0	0	0	0	1	0	0	1	45
M50	147	27	5	2	0	1	0	0	0	1	0	0	0	1	38
M25	73	60	14	6	2	3	1	1	0	2	2	1	0	3	95
M10	30	165	45	23	5	9	4	5	2	6	4	5	1	8	283
M90	269	31	7	2	1	1	0	1	0	1	1	0	0	2	46
M75	219	28	6	3	1	1	0	0	0	1	0	0	0	1	41
M50	147	25	4	2	0	1	0	0	0	0	0	0	3	1	40
M25	72	57	14	7	2	3	1	1	0	2	1	1	0	3	91
M10	30	157	42	20	6	8	3	3	1	5	2	4	1	7	259
	30	161	43	22	5	9	3	4	1	5	3	4	1	8	271
	72	58	14	7	2	3	1	1	0	2	1	1	0	3	93
	147	26	5	2	0	1	0	0	0	1	0	0	2	1	39
	221	29	6	3	1	1	0	0	0	0	0	0	0	1	43
	278	33	7	3	1	1	0	0	0	1	1	0	0	2	49
EMFAC		36	8	4	1	1	0	1	0	1	1	1	1	2	55

CUM KTA19G2/'90 using CARB fuel

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M90	353	35	2	2	1	1	0	0	0	0	0	0	0	2	44
M75	296	*22*	1	0	0	0	0	0	0	0	0	2	0	1	27
M50	201	40	3	0	1	1	0	0	0	1	0	1	0	1	49
M25	98	51	12	4	2	3	1	1	0	2	1	1	1	2	82
M10	41	87	19	7	3	4	2	2	1	2	1	3	1	3	135
M90	353	39	1	0	2	0	0	0	0	0	0	0	0	2	46
M75	295	48	4	0	2	1	0	0	0	1	0	1	0	2	59
M50	200	33	5	0	1	1	0	0	0	1	0	1	1	2	44
M25	100	42	11	0	4	2	1	1	0	2	1	1	1	2	68
M10	40	80	19	8	4	4	2	2	1	2	2	3	1	3	129
	41	84	19	7	4	4	2	2	1	2	2	3	1	3	132
	99	47	12	2	3	3	1	1	0	2	1	1	1	2	75
	201	37	4	0	1	1	0	0	0	1	0	1	0	1	47
	296	48	2	0	1	1	0	0	0	1	0	1	0	1	*59*
	353	37	2	1	2	0	0	0	0	0	0	0	0	2	45
EMFAC		44	5	1	1	1	0	0	0	1	0	1	0	2	58

CAT 3406C (666hrs) with CARB fuel and after adding DOC-2 oxidation catalyst

Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M100	347	29	6	2	3	2	1	0	0	0	1	0	0	1	46
M75	259	21	4	2	1	1	0	0	0	0	0	0	0	1	32
M50	171	16	4	2	1	1	0	0	0	0	0	1	0	1	26
M25	86	25	7	3	1	1	0	1	0	1	0	1	4	1	45
M10	37	62	16	7	2	3	2	2	0	2	1	2	0	3	103
M100	346	27	5	2	2	1	1	0	0	0	1	0	0	1	39
M75	261	17	3	1	1	0	0	0	0	0	0	0	0	1	25
M50	172	18	4	2	1	1	0	0	0	0	0	0	0	1	27
M25	86	18	7	3	1	1	0	1	0	1	0	1	1	1	36
M10	36	47	18	8	3	4	1	2	1	2	1	3	1	4	94
	37	54	17	8	2	3	1	2	1	2	1	3	1	3	99
	86	22	7	3	1	1	0	1	0	1	0	1	2	1	40
	172	17	4	2	1	1	0	0	0	0	0	0	0	1	27
	260	19	4	2	1	0	0	0	0	0	0	0	0	1	28
	347	28	6	2	2	1	1	0	0	0	1	0	0	1	42
EMFAC		21	5	2	1	1	0	0	0	0	0	0	0	1	33
M100	348	10	0	0	0	0	0	0	0	0	0	0	0	0	11
M75	259	13	0	0	0	0	0	0	0	0	1	0	0	0	15
M50	172	20	1	0	0	0	0	0	0	0	1	0	0	0	23
M25	86	23	3	1	0	0	0	0	0	0	0	0	1	0	29
M10	36	35	13	6	0	1	0	1	0	0	0	0	0	1	58
M100	346	10	0	0	0	0	0	0	0	0	1	0	0	0	12
M75	259	11	0	0	0	0	0	0	0	0	1	0	0	0	12
M50	170	25	1	0	0	0	0	0	0	0	1	0	1	0	28
M25	89	25	3	2	0	0	0	0	0	0	0	0	0	0	32
M10	37	32	11	5	0	1	0	0	0	0	0	0	2	0	53
															0
	37	34	12	6	0	1	0	0	0	0	0	0	1	0	55
	87	24	3	2	0	0	0	0	0	0	0	0	1	0	31
	171	23	1	0	0	0	0	0	0	0	1	0	0	0	26
	259	12	0	0	0	0	0	0	0	0	1	0	0	0	13
	347	10	0	0	0	0	0	0	0	0	1	0	0	0	11
EMFAC		17	1	1	0	0	0	0	0	0	1	0	0	0	21

DDC 6V92/'85 with: (1) CARB fuel, and (2) a fuel-borne catalyst in ULSD and DOC-3, an oxidation catalyst

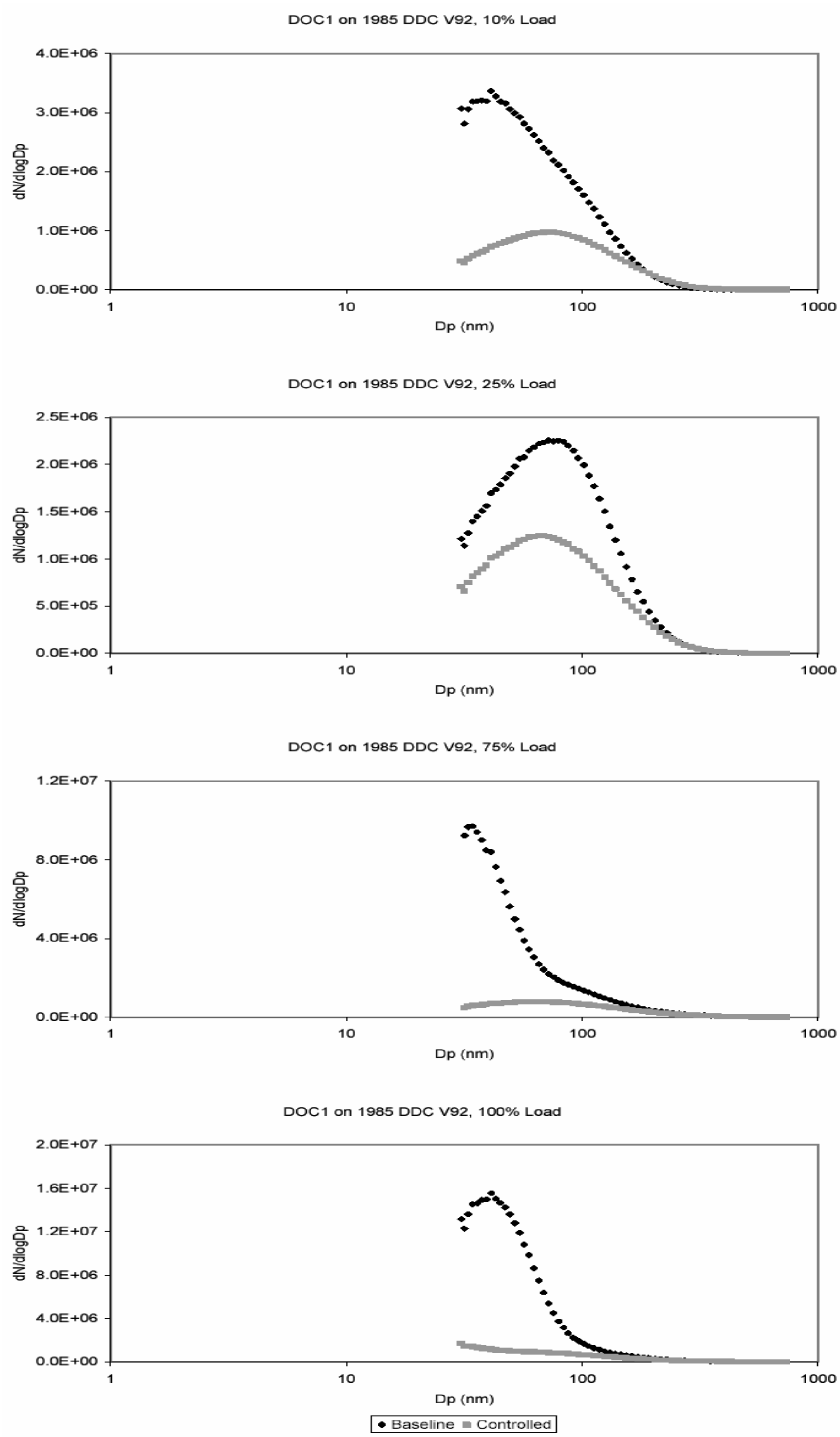
Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M100	290	16	1	0	0	0	0	0	0	0	0	0	0	0	18
M75	221	21	3	0	0	0	0	0	0	1	0	1	0	0	26
M50	147	28	9	2	0	2	0	0	0	1	1	1	0	0	46
M25	73	51	16	8	0	3	0	1	0	2	1	1	1	1	84
M10	31	134	44	21	0	7	1	3	4	3	3	3	1	11	236
M100	291	21	1	0	0	0	0	0	0	0	0	0	0	1	24
M75	223	26	7	1	0	1	0	0	0	1	1	0	0	1	39
M50	148	28	9	2	0	1	0	0	0	1	1	1	1	1	45
M25	75	48	14	6	1	3	0	1	0	2	1	1	1	4	81
M10	33	133	53	23	9	10	5	2	5	13	7	2	3	13	278
															0
	290	18	1	0	0	0	0	0	0	0	0	0	0	0	21
	222	23	5	1	0	1	0	0	0	1	1	0	0	0	32
	147	28	9	2	0	2	0	0	0	1	1	1	1	1	45
	74	49	15	7	0	3	0	1	0	2	1	1	1	2	83
	32	134	48	22	5	9	3	3	4	8	5	2	2	12	257
EMFAC		31	8	3	0	1	0	0	0	1	1	1	1	1	48
M100	290	1	0	0	0	0	0	0	0	0	0	0	0	0	1
M75	223	1	0	0	0	0	0	0	0	0	0	0	0	0	1
M50	148	16	5	1	0	1	0	0	0	0	0	0	0	0	24
M25	74	36	13	7	1	3	0	2	2	1	1	4	0	2	71
M10	31	98	34	16	1	7	0	2	0	4	2	3	1	2	170
M100	295	0	0	0	0	0	0	0	0	0	0	0	0	0	1
M75	223	1	0	0	0	0	0	0	0	0	0	0	0	0	2
M50	146	15	4	0	0	1	0	0	0	0	0	0	0	0	21
M25	74	33	12	7	0	3	0	2	0	2	0	1	0	0	60
M10	32	110	40	15	1	7	1	2	0	5	2	1	9	5	196
M100	295	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M75	223	0	0	0	0	0	0	0	0	0	0	0	0	0	1
M50	146	12	1	0	0	0	0	0	0	0	0	0	0	0	13
M25	74	22	9	5	0	2	0	0	1	1	0	1	0	1	42
M10	32	100	37	17	3	7	1	2	1	4	4	1	9	5	189
	294	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	223	1	0	0	0	0	0	0	0	0	0	0	0	0	1
	147	14	3	1	0	1	0	0	0	0	0	0	0	0	19
	74	31	11	6	0	2	0	1	1	1	1	2	0	1	58
	32	103	37	16	2	7	1	2	0	4	3	2	6	4	185
EMFAC		12	4	2	0	1	0	0	0	0	0	0	0	0	20

DDC 6V92/'85 with: (1) CARB fuel, and (2) CARB fuel and DOC-2, an oxidation catalyst

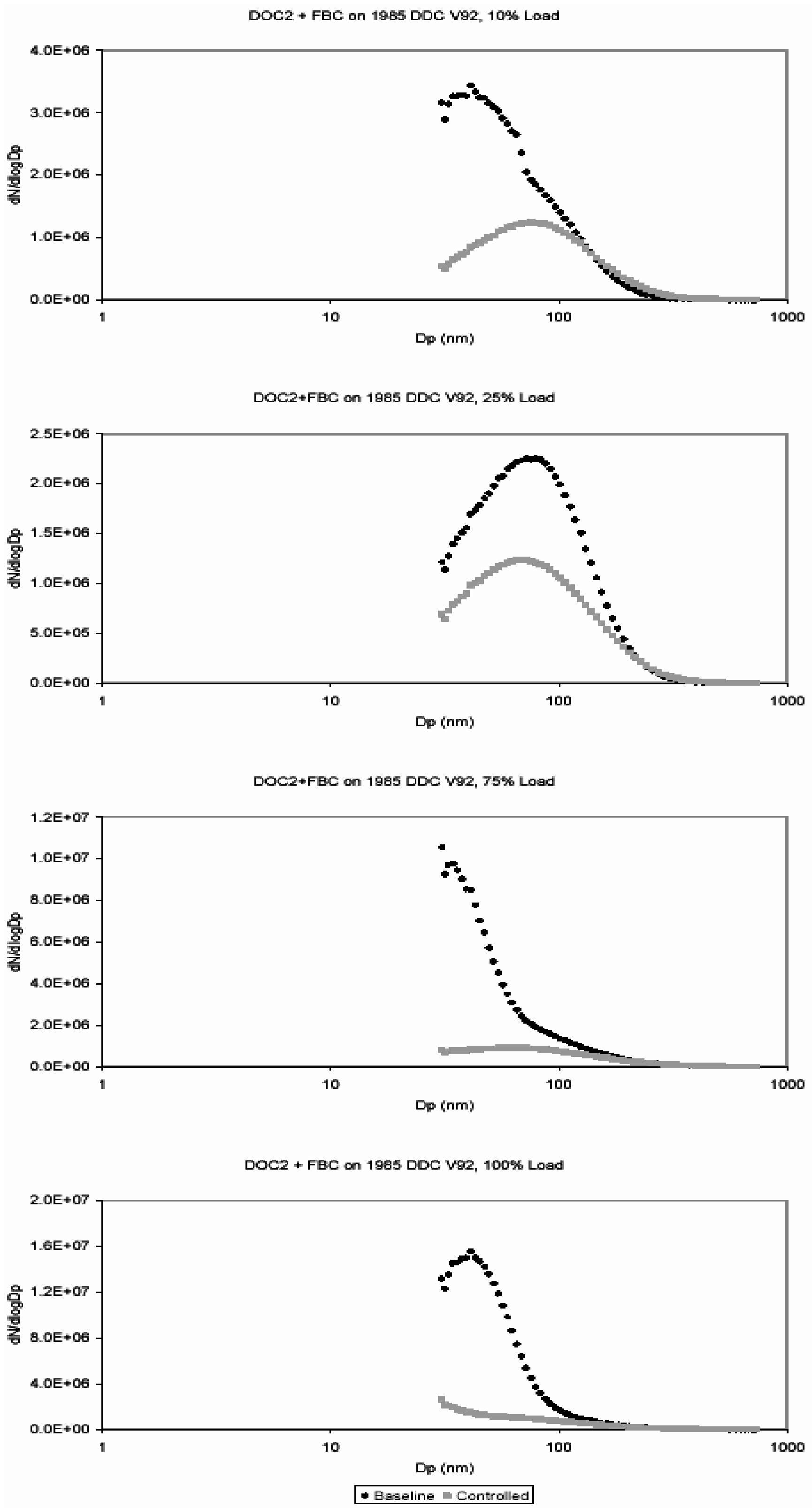
Mode	kW	formal	acetal	acetone	acrolein	propional	crotonal	MEK	methac	butyral	benzal	valeral	tolual	hexanal	Total
M100	290	16	1	0	0	0	0	0	0	0	0	0	0	0	18
M75	221	21	3	0	0	0	0	0	0	1	0	1	0	0	26
M50	147	28	9	2	0	2	0	0	0	1	1	1	0	0	46
M25	73	51	16	8	0	3	0	1	0	2	1	1	1	1	84
M10	31	134	44	21	0	7	1	3	4	3	3	3	1	11	236
M100	291	21	1	0	0	0	0	0	0	0	0	0	0	1	24
M75	223	26	7	1	0	1	0	0	0	1	1	0	0	1	39
M50	148	28	9	2	0	1	0	0	0	1	1	1	1	1	45
M25	75	48	14	6	1	3	0	1	0	2	1	1	1	4	81
M10	33	133	53	23	9	10	5	2	5	13	7	2	3	13	278
	290	18	1	0	0	0	0	0	0	0	0	0	0	0	21
	222	23	5	1	0	1	0	0	0	1	1	0	0	0	32
	147	28	9	2	0	2	0	0	0	1	1	1	1	1	45
	74	49	15	7	0	3	0	1	0	2	1	1	1	2	83
	32	134	48	22	5	9	3	3	4	8	5	2	2	12	257
EMFAC		31	8	3	0	1	0	0	0	1	1	1	1	1	48
M100	291	4	0	0	0	0	0	0	0	0	0	0	0	0	5
M75	224	14	3	1	0	0	0	0	0	0	0	0	1	0	20
M50	147	19	7	3	0	1	0	0	0	0	0	0	0	0	32
M25	75	41	20	9	1	2	0	1	1	1	1	0	2	2	82
M10	32	150	64	28	8	11	3	4	2	6	10	4	2	7	300
M100	288	5	0	0	0	0	0	0	0	0	0	0	0	0	5
M75	229	14	2	1	0	0	0	0	0	0	0	1	0	0	19
M50	148	25	9	4	0	1	0	0	0	0	0	0	0	0	41
M25	74	40	18	9	0	2	0	0	1	1	1	0	0	1	76
M10	32	143	64	28	8	11	3	6	2	6	9	5	2	2	289
	32	147	64	28	8	11	3	5	2	6	9	4	2	5	294
	75	40	19	9	1	2	0	1	1	1	1	0	1	2	79
	147	22	8	4	0	1	0	0	0	0	0	0	0	0	36
	227	14	3	1	0	0	0	0	0	0	0	1	0	0	19
	290	5	0	0	0	0	0	0	0	0	0	0	0	0	5
EMFAC		23	8	4	0	1	0	0	0	0	0	0	0	1	39

Appendix G. Number size distribution for particulate matter (PM) for various control devices

A Diesel Oxidation Catalyst on a 2-stroke engine (6V92/1985)



A Diesel Oxidation Catalyst on a 2-stroke engine (6V92/1985) with a fuel-borne catalyst



An active trap system with 97+% removal of PM