# Populations, Activity and Emissions of Diesel Nonroad Equipment in EPA Region 7

United States Environmental Protection Agency

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

Prepared for EPA by
Eastern Research Group, Inc. (ERG)
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## FINAL REPORT

**Prepared for:**

**U.S. Environmental Protection Agency**

**October 19, 2010**

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EPA Contract # EP-C-06-080

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## Acronyms

| | |
|---|---|
| AMBII | Automotive Micro-Bench II |
| BSFC | Brake-Specific Fuel Consumption |
| CAN | Controller Area Network |
| CAT ET | Caterpillar Electronic Technician |
| CATI | Computer Assisted Telephone Interviewing |
| CBS | Comprehensive Business Samples |
| CDT | Central Daylight Time |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| CRC | Coordinating Research Council |
| CVS | Tortoise Concurrent Versions System |
| cQCM | Carousel Quartz Crystal Microbalance |
| CSV | Comma-Separated Variable file |
| DRI | Desert Research Institute |
| EAM | Emissions and Activity Measurements |
| ECU | Electronic Control Unit |
| EDA | Equipment Data Associates, Inc. |
| EFM | Exhaust Flow Meter |
| EOI | Equipment Ownership Interview |
| EPA | United States Environmental Protection Agency |
| ERG | Eastern Research Group |
| ES | Equipment Sample |
| ESI | Equipment Sample Interview |
| FID | Flame Ionization Detector |
| FIPS | Federal Information Processing Standard |
| g | grams |
| GPS | Global Positioning System |
| HP | Horsepower |
| hr | hour |
| kW | Kilowatt |
| mA | Milliamp |
| MOS | Measure of Size |
| MPS | Micro-Proportional Sampler |
| MSOD | Mobile Source Observation Database |
| NDIR | Non-dispersive infrared |
| NOx | Oxides of Nitrogen |
| NTE | Not to Exceed |
| OBD | On-Board Diagnostics |
| OTAQ | Office of Transportation and Air Quality |
| PEMS | Portable Emissions Measurement System |
| PAMS | Portable Activity Measurement System |
| PM | Particulate Matter |
| PPS | Probability Proportional to Size |
| PSU | Primary Sampling Unit |

| | |
|---|---|
| QA | Quality Assurance |
| QAPP | Quality Assurance Project Plan |
| QC | Quality Control |
| QMP | Quality Management Plan |
| RPM | Revolutions Per Minute |
| SAE | Society of Automotive Engineers |
| SAS | Statistical Analysis Software |
| scfm | Standard Cubic Feet per Minute |
| SOPs | Standard Operating Procedures |
| SRI | Southern Research Institute |
| SRS | Simple Random Sampling |
| SSI | Survey Sampling International |
| SSU | secondary sampling unit |
| THC | Total Hydrocarbons |

## Glossary of Terms

**Caller ID:** Establishments that could not be reached due to privacy manager i.e., the number called automatically blocks unknown numbers

**Eligibility rate:** The rate at which fully screened establishments were determined to be eligible for the study (e.g., they were eligible to be invited to participate in the equipment inventory). The denominator is the total number of screened establishments.

**EOI Phase 1:** Equipment Ownership Interview, Phase 1 (telephone interviewing in PSU 1)

**EOI Phase 2:** Equipment Ownership Interview, Phase 2 (telephone interviewing and recruiting in PSUs 1, 2 and 3)

**EOI Phase 3:** Equipment Ownership Interview, Phase 3 (telephone interviewing and recruiting in PSUs 4 and 5)

**ES Phase 1:** Equipment Sample, Phase 1 (inventories and instrumentation fieldwork in PSU 1)

**ES Phase 2:** Equipment Sample, Phase 2 (inventories and instrumentation fieldwork in PSUs 2 and 3)

**ES Phase 3:** Equipment Sample, Phase 3 (inventories and instrumentation fieldwork in PSUs 4 and 5)

**First refusal:** An establishment kindly declined to participate in the interview during the introduction or before screening could begin.

**Final refusal:** Establishment strongly declined to participate during the introduction or before screening could begin.

**General callback:** Establishments wherein the respondent or screener provided a general day and time to call them back.

**Interview response rate:** The rate at which screened and eligible establishments completed the survey (can be used for either the EOI or ESI, depending on context). With regard to the ESI, the recruitment rate and the interview rate represent the same thing. The denominator is the total number of known (screened) eligible establishments.

**Measure of size:** The measure of the units in the target population or another measure of influence that is assumed to correlate fairly strongly with the target population in each sampling unit

**Overall response rate:** This rate is equal to the product of the screening and interview response rates. It reflects net “overall” response from all sources and is typically used to document and assess survey quality (vis a vis the potential for nonresponse bias).

**Partial complete:** Interview was initiated but stopped before it was completed and it was not possible to recontact the establishment to complete the interview. Typically used with EOI survey process

**Partial refusal:** Establishment initiated the interview and refused after the screening for eligibility began.

**Recruitment rate:** The rate at which screened and eligible establishments agreed to the inventory and/or instrumentation phase of the study. The denominator is the total number of known (screened) eligible establishments.

**Screening rate:** This rate reflects the fraction of establishments for which we were able to make an eligibility determination. This rate does not consider the actual eligibility status of an establishment. Instead it reflects the fraction of establishments for which sufficient information (via answers to survey questions) was provided to establish whether or not they are eligible to participate in the EOI and/or ESI. The denominator of this rate is the original sample size.

**Short complete:** Those establishments that completed an EOI but did not complete the ESI.

**Specific callback respondent:** Establishments wherein the respondent or screener provided a specific day and time to call them back.

## Acknowledgements

This multi-year pilot study was made possible through funding provided by the U.S. Environmental Protection Agency (EPA) and the Coordinating Research Council (CRC). ERG greatly appreciates having had the opportunity work on this complex and exciting project and wishes to acknowledge the significant contributions of EPA and CRC was well as those of integral partners NuStats, Sensors, Inc., the Urban Institute, Southern Research Institute and the Desert Research Institute. The contributions of all our team members along with the project design, planning and oversight support provided by EPA and CRC have been critical in this study's success.

We must thank EPA management and technical expertise from John Koupal, Carl Fulper, Connie Hart, Jim Warila and Bob Giannelli for their continual support throughout the study. Several other EPA personnel also provided valuable project field support such as Ethan Schauer, Brian Ratkos, Robert Caldwell, Chris Bahn, and Tim Quast; Nancy Tschirhart and Rosemary Gehyk for the fuel analyses; Zuimdie Guerra for the PM filter analyses; and Donna Reinhart for her contractual support.

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# Executive Summary

This study was a multi-year pilot project to develop recruitment and data collection protocols as part of a broad effort to understand the population, emissions and activities of nonroad equipment in various economic sectors. This study, which was supported by the U.S. Environmental Protection Agency (EPA) and the Coordinating Research Council (CRC), focused on commercial establishments within the construction sector. Statistical sampling was applied to randomize the recruitment and screening of participants and the selection of equipment pieces, with weighting applied toward size and usage history. Fieldwork involved the installation and operation of portable on-board instruments to measure exhaust emissions and equipment usage in EPA's Region 7 area (states of Iowa, Kansas and Missouri). Data was collected during normal operation at construction worksites in three different phases over a 17 month period between June 2007 and October 2008.

Inventories were conducted at 79 worksites, with testing at 29 of those sites. Emissions and activity data was collected on approximately 29 pieces of equipment each. Gaseous and particulate-matter emissions data were collected over a typical working day using a specially constructed enclosure housing a SEMTECH-DS, a micro-proportional Sampler (MPS), a three-chamber 47mm gravimetric sampler and various-sized exhaust flowmeters, all manufactured by Sensors, Inc. Activity measurements (1 Hz date / time / engine speed) were collected over a period of approximately one month using Isaac and Corsa dataloggers.

Recruiting, technical and logistical challenges encountered during the study resulted in a refinement of equipment and procedures for conducting future studies of this nature. These challenges and the steps taken to address them are described in detail in this report. Data collected have been subjected to extensive review, analysis and validation / correction. Emissions are presented on a work basis, fuel basis and time basis. Although uncertainties are presented with the emission results, these "in-use" duty cycles differ from certification test cycles, and a comparison of these "in-use" emissions with emission standards would not be appropriate.

This report and the associated data collected throughout the study represent a first step in the process of improving the quantity and representativeness of data available for nonroad engine inventory modeling. EPA will continue this process by performing additional review, including comparison of this data with data from other EPA and non-EPA emission test programs. It is anticipated that these data will finally be used to develop relationships and emission rates in a non-road version of the MOVES model. This report and data from this study will be released to

the general public after EPA's comprehensive review has been completed and approval from sponsors and EPA senior management has been granted, and findings from EPA's review will be included in subsequent EPA reports.

## Test Program Overview

### Introduction

Previous work has shown that nonroad equipment contributes substantially to mobile-source emissions, with their contribution in relative terms expected to increase as emissions from highway vehicles are controlled (Kean, Sawyer & Harley 2000). Generally, nonroad equipment includes vehicles powered by combustion engines, designed to perform a wide variety of tasks other than street or highway transportation. Thus, the term "nonroad equipment" covers a broad variety of machines including forklifts, graders, crawler dozers, backhoe loaders, excavators and other equipment.

A report published by the National Academy of Sciences emphasized the need for EPA to design and implement programs to expand and improve the data used to support emissions inventory estimates from nonroad equipment. This and other NRC report recommendations have influenced the concept and design of EPA's new inventory model for highway vehicles, the Motor Vehicle Emissions Simulator (MOVES). Therefore, this study was intended as the first step in a program to respond to recommendations concerning the quantity and representativeness of the data supporting inventory modeling for nonroad engines.

The Nonroad PEMS and PAMS study was a multi-year pilot study funded and supported by the U.S. Environmental Protection Agency (EPA) and the Coordinating Research Council (CRC) which was intended to refine methods of developing larger-scale estimations of populations, usage and emissions of heavy-duty non-road diesel equipment in various economic sectors. During this pilot study, the ERG team, consisting of ERG, Sensors, Inc., NuStats, the Urban Institute, Southern Research Institute and the Desert Research Institute worked with the United States Environmental Protection Agency (EPA) to integrate statistical sampling techniques, the latest activity and emissions measurement technology and rigorous quality assurance and quality control methods to characterize in-use, real-world emissions from nonroad diesel engines within the commercial construction sector in EPA Region 7 (work was performed in the states of Iowa, Kansas and Missouri).

The study focused on commercial establishments within the construction sector, with the objective of developing recruitment and data collection protocols for ultimately expanding the study to other commercial sectors that operate fleets of nonroad diesel engines (owned or leased) in their daily operations such as agriculture, mining, and utility sectors. These protocols included:

- Sample Frame – the list from which a sample of commercial establishments is drawn.
- Sample Design – the approach for randomly selecting commercial establishments within the sample frame to meet a specified sampling target.
- Recruitment Protocols – the process and materials used to (1) provide advance notice to prospective participants about the study, (2) screen establishments for eligibility as a study participant, and (3) recruit qualified establishments to participate in the study (this later process includes the use of monetary incentives).
- Data Processing and Statistical Analysis– procedures for processing and analyzing the dispositions or outcomes of sampling and recruitment stages for the purposes of data weighting and analysis.

While these protocols and data collection processes were developed, tested and modified within the construction sector, it is reasonable to expect that they will generally apply to other commercial sectors with some modifications needed to address nuances with sample frames and fleet operations that may be specific to a particular commercial sector.

In total, 549 establishments were interviewed regarding their equipment ownership and usage. From those establishments, 119 volunteered to allow project team members to conduct onsite inventories and emissions and activity measurements on their eligible nonroad equipment. Inventories were conducted at sites of 79 of those establishments, and emissions and/or activity measurements were performed at sites of 29 establishments. Emissions tests were ultimately conducted on 58 different pieces of nonroad equipment, and activity information was collected from 30 pieces of nonroad equipment. Statistical sampling was applied prior to and during fieldwork in order to randomize the recruitment and screening of participants and the selection of equipment to be instrumented, and various ways of establishing a rapport with and minimizing our testing burden on participants were explored throughout the study.

For the emissions measurements, portable on-board emission measurement systems (PEMS) were used to perform 40 CFR 1065-compliant onboard measurements of gaseous and aggregate particulate matter (PM) exhaust emissions on 50 horsepower or greater diesel engines in nonroad construction equipment. In order to withstand the rigors of testing in a nonroad environment, equipment had to be “ruggedized”, and equipment modifications and enhancements were made throughout the course of the study to achieve test goals.

For the activity measurements, various commercially-available portable activity measurement systems (PAMS) were evaluated, three different types of systems purchased, and these systems were used during the work assignment to collect activity (date / time / engine speed) over a period of approximately one month. This activity testing provided information on long-term equipment usage patterns of this equipment and also provided an opportunity to test and evaluate the performance of PAMS equipment and data quality during the work assignment.

Study data was analyzed, quality assured and processed for input into the EPA Office of Transportation and Air Quality's (OTAQ's) Mobile Source Observation Database (MSOD), where it may be used to help expand and improve the data currently supporting emission inventory modeling for nonroad engines.

**Multi-Stage Sample Plan**

The sample design for this pilot study employed stratified multi-stage probability sampling with probabilities proportional to size. The number of selection stages varied by the type of data collection (i.e., establishment vs. equipment samples). The survey of establishments employed two-stages of selection, while the equipment samples involved a three-stage design, as follows:

- First Stage (Primary) County level
- Second Stage (Secondary) Establishment level (within county)
- Third Stage (Tertiary) Equipment piece (within establishment)

Because the first- and second-stage sampling units were different sizes, in terms of the numbers of equipment expected within each unit, the second-stage samples were drawn with probability proportional to size (PPS). In PPS, the first and second-state selection probabilities would then be managed to compensate for the fact that third-stage probabilities cannot be managed.

The measure of size (MOS) is ideally a measure of the units in the target population (equipment pieces—or diesel engines—in this case), or alternatively, another measure of influence that is assumed to correlate fairly strongly with the target population in each sampling unit. Lacking direct estimates of equipment populations by county or establishment, the number of employees per establishment was selected because it was assumed to be correlated to equipment population.

In the third stage, one or more eligible equipment pieces would be drawn from each selected establishment using simple random sampling (SRS). Specifics of the design at each stage are discussed below.

**First Stage.** The first stage of selection was utilized by all samples in the study and involved a sample of 5 counties (primary sampling units or PSUs) with probabilities proportional to size from the collection of counties selected within EPA Region 7. EPA designed the sample and selected these counties, which are shown in Table OV-1.

**Table OV-1 Primary Sampling Units for the Pilot Study**

| PSU | FIPS | STATE | COUNTY | EST. NO. EMPLOYEES | SAMPLING PROBABILITY |
|---|---|---|---|---|---|
| 1 | 29095 | MO | Jackson | 63,800 | 0.3063 |
| 2 | 19113 | IA | Linn | 25,400 | 0.1216 |
| 3 | 19163 | IA | Scott | 18,500 | 0.4277 |
| 4 | 29047 | MO | Clay | 16,500 | 0.3813 |
| 5 | 20177 | KS | Shawnee | 13,000 | 0.3006 |

**Second Stage.** Within each PSU, commercial establishments were the secondary sampling unit (SSU), drawn with selection probabilities based on the same measure of size used to draw the first-stage sample. For construction establishments, the establishment MOS was the estimated number of employees, as derived for use in the first stage. After compiling the establishment frame for each PSU, an estimated number of employees was assigned to each establishment (MOS), based on its assigned size class.

**Third Stage.** The third stage of selection was relevant to the sampling of equipment from the equipment inventory performed prior to instrumentation.

### Overview of Study Plan

Unlike motor vehicles, for which registration databases exist, it is not practical to construct or obtain sample frames listing individual equipment pieces. To compensate for this difficulty, coverage was expressed in terms of the owners or users of equipment within the construction sector. Thus, for this pilot study, coverage of the target population included engines owned, rented or leased by commercial establishments in the construction sector that employed at least one person on a full-time or part-time basis during the previous twelve months. Elements of the target population were identified and selected through the constituent establishments that operated this equipment.[1]

At the onset of this study, the ERG team employed the Comprehensive Business Samples (CBS) supplied by Survey Sampling International (SSI) of Fairfield, Connecticut as the sampling frame. SSI compiles listings from telephone directories and additional industry-specific sources including government listings, bank records, trade directories, city directories and proprietary sources. Listings are verified and updated on a continuous basis.

The study objectives called for the collection of emissions and activity data from 50 nonroad diesel engines operated within the study area. To achieve this, it was necessary to collect a total of 550 observations from two independent samples:

- Establishment sample – a sample of 500 establishments for a telephone survey, referred to as the Equipment Ownership Interview (EOI), involving the administration of an equipment ownership survey to screen and qualify establishments for the study.

- Equipment sample – a sample of establishments from which inventories, 25 emissions measurements and 25 activity measurements would be drawn. These were establishments qualified in the Establishment sample who agreed to participate in an inventory and emissions and activity testing of their equipment fleet.[2]

The administration of the EOI was intended as a predecessor to the administration of the Equipment Sample Interview (ESI) to recruit participants for an equipment inventory and random selection of equipment for instrumentation.

Specific targets were provided for the numbers of establishments and pieces of equipment for which data were collected. Table OV-2 presents the study goals by measurement type.

**Table OV-2 Study Goals by Measurement Type**

| | MEASUREMENT TYPE | ESTABLISHMENT SAMPLE | EQUIPMENT SAMPLE |
|---|---|---|---|

[1] Government and other non-commercial establishments were excluded from the target population.

[2] For the 50 observations involving equipment measurements, an experiment was embedded to test for response rate effects associated with incentives. The incentive was offered to a random half of the eligible Equipment Sample subjects upon completion of the EOI (telephone) portion of the survey (and as part of the recruitment process into the inventory and measurement components of data collection).

| Economic Sector | Total—EOI and Instrumentations | Equipment Ownership Interview | Emissions Measurement | Activity Measurement |
|---|---|---|---|---|
| Construction | 550 | 500 | 25 | 25 |

This pilot study was planned to be implemented in two phases for the Establishment Sample and three phases for the Equipment Samples. The Pilot would commence with the first phase of the Establishment Sample (involving conduct of only the EOI). EOI data collection would start in one of the five study areas: Primary Sampling Unit 1 (PSU1) followed by Phase 2 of the Establishment Sample (EOI Phase 2). The Equipment Sample would be conducted following completion of the Establishment Sample. The rollout of both planned phases of the Establishment Sample and all three phases of the Equipment Sample are shown in Table OV-3 below. A total of 185 EOI interviews were expected to be needed in order to secure 60 total equipment emissions and activity measurements. This table also presents the by-phase distribution of inventories and instrumentations which were expected. Oversampling was employed to ensure emissions and activity measurement test targets were met.

**Table OV-3 Expected Distribution of Completions by Sample and Measurement Type**

| COMPLETES BY TYPE | EOI PHASE 1 (PSU 1) | EOI PHASE 2 (PSUs 2-5) | ES PHASE 1 (PSU 1) | ES PHASE 2 (PSUs 2,3) | ES PHASE 3 (PSUs 4,5) | TOTAL |
|---|---|---|---|---|---|---|
| EOI - Establishment Sample | 100 | 400 | | | | 500 |
| EOI - Equipment Sample | | | 37 | 74 | 74 | 185 |
| Inventory | 0 | 0 | 12 | 24 | 24 | 60 |
| Emissions measurements | 0 | 0 | 6 | 12 | 12 | 30 |
| Activity measurements | 0 | 0 | 6 | 12 | 12 | 30 |

## PEMS and PAMS Equipment Used in Study

The ERG team used SEMTECH-DS PEMS manufactured by Sensors, Inc. and provided by the EPA for collection of emissions data for this work assignment, and researched and acquired from commercial vendors the PAMS used for collection of activity measurements.

For PEMS testing, the ERG team leased a trailer from Sensors, Inc. which was used to house, transport and maintain the PEMS and all associated support equipment. Sensors personnel transported this trailer to and from EPA Region 7 and the various work locations within the region using a flatbed truck with a boom lift, which was also part of the lease agreement. This boom lift allowed the PEMS installation team members to place the approximately 400-pound PEMS rack onto each piece of equipment being tested.

For emissions measurements, the PEMS rack collected the following information in one-second intervals, as specified in the work assignment:

- engine speed (revolutions per minute, rpm),
- oxygen concentration in the exhaust stream ([$O_2$], percent by weight, wt%),
- carbon-dioxide concentration in the exhaust stream ([CO2], percent by weight, wt%),
- oxides of nitrogen concentration in the exhaust stream ([$NO_x$], parts per million, ppm),
- carbon monoxide concentration in the exhaust stream ([CO], percent by weight, wt%)
- total hydrocarbon concentration in the exhaust stream, ([THC] parts per million, ppm)
- aggregate particulate matter by gravimetric methods (g),
- ambient temperature (°C),
- exhaust temperature (°C),
- exhaust mass flow rate (via the Sensors EFM)
- relative humidity (%), and
- barometric pressure (kilo-Pascals, kPa).
- date/time stamp.

The following derived measurements, also specified in the work assignment, were provided for all emissions measurements:

- exhaust flow volume (adjusted to standard temperature and pressure, cu. ft/min (scfm)),
- fuel flow volume (g/sec, gal/sec),
- carbon dioxide emission rate (g/sec, g/kg fuel),
- pollutant emission rates for NOx, CO, THC, and PM, (g/sec, g/gal).

The PEMS rack consisted of the EPA-provided SEMTECH-DS PEMS (as well as a backup SEMTECH-DS PEMS), a Sensors micro-proportional Sampler (MPS), a Sensors Gravimetric Filter Sampler and 2", 3", 4" and 5" diameter exhaust flowmeters (EFMs). Flowmeter diameter selection was based on each particular installation. A small air compressor and filtration unit was used to operate the MPS, and to automatically back-purge the EFM pressure lines at specified intervals. This air compressor operated using A/C power provided by a Honda portable generator. Automated zero calibrations of the SEMTECH-DS analyzers were performed throughout the sampling period using ambient air which was scrubbed with a carbon filter and a particulate filter.

All emissions measurements throughout the study included gravimetric filter sampling using a micro-proportional sampling system (MPS) and Sensors' 3-chamber gravimetric filter sampler provided by EPA. The SEMTECH MPS is a two-stage dilute proportional sampler in which a proportional sample flow is extracted from the exhaust flow. This sample flow is controlled to be a constant fraction of the varying exhaust flow by way of a two-stage dilution system.  The first stage performs a fine "valving" function and the second stage is a venturi which adds the major part of the dilution flow and forces the sample plus the primary dilution flow to exit the MPS (Fulper, Giannelli, et al., 2010).  The MPS total flow (sample flow plus primary and secondary dilution) was held to a constant rate of approximately 12.5 liters per minute in this study.  Maximum exhaust flowrates and major and minor dilution ratios were tailored for each installation based on engine size and anticipated workload according to guidelines in the PEMS installation SOPs (Appendix F).  Additional information regarding flowrates and system settings are available in Appendix F (PEMS Installation SOPS) and Appendix I (PEMS Data QC Criteria).

Gravimetric PM samples were collected on 47mm Teflon filters housed in the gravimetric filter sampling unit which was heated to 1065 specifications.  Filter flow was maintained at a rate of approximately 18 liters per minute.  The filter sampler automatically switched between the three gravimetric filters, based on an integral timer, input voltage signal indicating engine start, or the filter could also be switched by a wireless remote electrical signal. One filter was used to capture the first start at the beginning of the day or shift (generally a 10-minute cold-start), and the second and third filters captured continued warm operation or hot start emissions (20-minutes sampling for the second filter and 30-minutes sampling for the third filter).  Each "start" episode was defined as the first ten (10) minutes of operation after the engine was turned on.

ERG acquired "core" portable activity measurement systems (PAMS) conforming to the PAMS specifications outlined in the work assignment.  These systems measured and recorded engine on and off times, engine speed and associated date and time stamps over an approximately one month period for each activity instrumentation.

**Initial Surveys and Phase 1 of Field Testing**

The Establishment Sample EOI was administered to Phase 1 (PSU 1) survey participants from April 20, 2007 through June 20, 2007.  Data was collected under a pledge of confidentiality that responses would be used for statistical purposes only. During collection, storage and reporting, steps were taken to protect the identity of respondents or establishments with the information collected, as required by the workplan and the QAPP.

Prior to the administering the EOI survey, the study team conducted a number of activities with the purpose of improving response and participation rates.  These included securing study support from area trade associations, conducting an advance mailing of a letter and brochure to prospective respondents and performing cognitive testing / structured interviews (these followed Phase 1 of the EOI surveys).

Following the initial EOI PSU 1 survey, the EOI Phase 1 EOI / ESI interview was conducted (initial surveys followed by recruiting of eligible establishments). To accomplish this, a sample of businesses was drawn, the EOI was administered (survey only, not recruiting), followed by the administration of an incentive experiment, and finally the administration of the Equipment Sample Interview (ESI) with the objective of recruiting qualified establishments to participate in the inventory and instrumentation phase of the study. During the ESI, data on the qualified businesses (e.g., business name, site address selected for the inventory, contact name and phone number, etc.) that completed the EOI and agreed to be inventoried were electronically transferred to ERG by way of a secure FTP site. Personnel in ERG's Kansas City office retrieved the establishment information from the secure FTP site and contacted the participating establishments to schedule the inventory appointments.

Inventories were conducted at one or two sites for each establishment. For each site inventoried, information regarding all equipment belonging to, leased by, or used by a particular establishment was collected on a site inventory form. Sufficient information was gathered for each piece of equipment in order to allow determination of equipment model year and engine power using supplemental information, such as EquipmentWatch or other commercially available equipment specification resources. Equipment serial number and cumulative hours of use (from the equipment's hour meter) were recorded and each piece of equipment's PEMS and PAMS testability was also assessed. Digital photographs of equipment, serial numbers and equipment specification tags were taken whenever possible to help clarify or correct any ambiguous or inaccurate information recorded during on-site inventories. Inventory information collected in the field was entered into a master spreadsheet posted on an ERG-internal project-specific secure server. In Austin, equipment horsepower and model year information was determined using equipment specification literature. Information pertaining to the equipment's age, engine size, and cumulative usage was used to assign each piece of equipment to a specific weighted bin for PEMS and PAMS selection. After equipment was classified in the weighted stratification bins, individual pieces of equipment were selected for PEMS and PAMS instrumentation. Each eligible piece of equipment was selected either as a primary, or "first choice" selection, or as "backup" equipment in case one or more of the primary pieces of equipment could not be tested. After the equipment information entry was verified and PEMS and PAMS instrumentation selections were made, this information was posted back to the project-specific secure server for onsite field staff to retrieve.

After retrieval of the equipment selections, the ERG onsite installation manager scheduled instrumentations with appropriate establishment contacts. If a site contact indicated the selected equipment was not to be used or not available for testing during the anticipated measurement period, an alternate piece of equipment was selected for instrumentation from the list of secondary selections.

At the outset of fieldwork, the sampling plan permitted up to four pieces of equipment (two emissions measurements and two activity measurements) to be sampled per establishment. However, EPA and the ERG team decided to allow some of the sampled pieces of equipment to be measured for *both* activity and emissions, and during the course of the work assignment, the teams discovered that fewer establishments used PEMS-eligible equipment than originally anticipated. Because of this, PEMS sampling requirements were relaxed to allow up to five pieces of equipment to be sampled per establishment (three emissions and two activity measurements), again with some equipment possibly having both PEMS and PAMS installed.

PAMS installations were performed at the outset of each phase of testing, prior to the start of PEMS testing. PAMS units were then revisited, monitored and maintained throughout the PEMS test period for each phase of the study. Teams of two to three people performed the PAMS installations, and on average installed two PAMS per day (typically at the same site or establishment). Both Corsa and Isaac PAMS units were used during each phase, and engine speed (revolutions per minute, or RPM) was collected in several different ways, including via a Capelec voltage processor connected to the equipment's battery, an optical sensor directed at a rotating object to which reflective tape was applied, a magnetic pickup mounted near a rotating object to which a magnet was affixed, or by non-destructively tapping into the equipment's electronic tachometer signal. Non-destructive taps were accomplished using supplemental connectors with harnesses which connected inline with the equipment's original harness.

After PAMS installations were complete (or nearly complete), PEMS emissions measurements were commenced. PEMS emissions measurements were usually performed by three person teams, with a fourth field technician providing fieldwork management, PEMS rack mounting support, testing oversight and other fieldwork logistic support. Emission measurements were typically gathered over a one-day period in an effort to collect emissions information throughout the equipment's entire work day. PEMS installation, operation and maintenance was scheduled and performed in such a way as to minimize interruption of equipment use. PEMS instrumentation teams generally performed installations during each site's non-working hours (after the equipment was no longer needed for that working day). Hence, PEMS installations usually took place the evening prior to the day of testing, and the instrumentation team would then arrive the next morning at least two hours prior to site operations to warm-up, calibrate and verify the equipment's operation prior to emissions testing. This schedule usually allowed the PEMS instrumentation team to obtain cold-start emissions data for both gaseous pollutants and PM.

For every PEMS and PAMS instrumentation, detailed information pertaining to the equipment being instrumented as well as calibration, filter sampling and other PEMS and PAMs test details were collected on PEMS and PAMS instrumentation forms.

Field staff followed the methodology provided in the project QAPP and associated standard operating procedures (SOPs) for both PEMS and PAMS testing. Significant detail was associated with PEMS and PAMS instrumentations, and procedural training was provided to all team members prior to fieldwork. Daily calibrations of PEMS equipment were performed, and laboratory calibration and verification of flowmeter measurements and SEMTECH gaseous measurement linearity results were performed by Sensors, Inc. prior to and following each phase of fieldwork.

Operation of all PEMS test equipment was continuously monitored by PEMS instrumentation teams throughout the test day. During breaks in usage of the construction equipment, team members would attempt to access the PEMS to refill the generator, replace the gravimetric filters and calibrate the SEMTECH-DS, as necessary. Real-time monitoring of test parameters was performed using remote laptops connected to the PEMS rack wirelessly in order to identify and correct any data or equipment issues. In addition, test files were extracted during and immediately after each test, processed and reviewed for data quality issues or problems.

PEMS installation teams attempted to collect diesel fuel and crankcase lubricating oil samples on all pieces of equipment that received emissions measurements. Fuels samples were gathered so that adjustments can be made to the emission measurements based on fuel properties (i.e density, C/H ratios, etc). Oil samples were taked because they might be able to determine the engine status or wear. All fuel and oil samples which were collected were stored and shipped in appropriate containers provided by EPA.

Phase 1 fieldwork, which was performed in the county of Jackson, Missouri, began June $4^{th}$ 2007 and continued through July $24^{th}$, 2007. At the completion of ES Phase 1fieldwork, the team revised the Emissions and Activity Measurement sections of the QAPP (as well as the associated SOPS) based on field-testing experience. SOPs were continually revised and redistributed throughout each phase of testing as procedural and equipment refinements were made.

### Phase 2 Surveys and Field Testing in PSUs 2 and 3

According to our study design, Phase 2 was to proceed with conducting the establishment sample EOI with PSUs 2 through 5. However, partly due to the skewed nature of the establishments according to the measure of size (MOS) and also due to the lower than expected amount of eligible pieces of equipment to test, a full integration of the Phase 2 Establishment and Equipment Samples (i.e., the EOI & ESI) into a single, unified design was performed. In addition, due to the lower than anticipated yield rate of establishments, it was discovered that a census of all construction establishments in the region would be needed in order to achieve the goals of the study. Therefore, the study design was modified to integrate the establishment and equipment sample into a single, integrated interview process, as shown in Table OV-4. This table shows the revised sample size goals by showing censuses conducted for Inventory and Instrumentation for Phases II (PSUs 2&3) and III (PSUs 4&5). As shown in Table OV-4, a total of 3541 selections were expected to be needed to complete the EOIs for the Establishment Sample and the EOI portion of the Equipment Sample.

**Table OV-4 Revised Total Sample Needed to Achieve Sample Targets**

| TYPE OF DATA COLLECTION | ESTABLISHMENT SAMPLE | | EQUIPMENT SAMPLE | | | TOTAL |
|---|---|---|---|---|---|---|
| | PHASE 1 | PHASE 2 | PHASE 1 | PHASE 2 | PHASE 3 | |
| EOIs | 243 | n/a | 404 | 1522 | 1372 | 3541 |
| Inventory & Instrumentations | 0 | 0 | 37 | 74 | 74 | 185 |

With the exception of some changes made to establishment eligibility criteria (relaxing eligibility in an effort to increase recruitment yield), the process for the integrated sample mirrored the establishment sample process for the first PSU. However, following the initial EOI survey, the extended recruitment interview was performed with all eligible establishments in order to select a site at which an in-field equipment inventory would be conducted and equipment selected for instrumentation.

Field testing in PSUs 2 and 3 mirrored that performed in PSU1, but targeted establishments located in the counties of Linn and Scott, Iowa. Fieldwork in PSUs 2 and 3 began September 5, 2007 and continued through October 27$^{th}$, 2007.

### Study Enhancements Made Prior to Phase 3

As a pilot project, the design strategy was to capitalize on experience with previous phases of the project and build upon that experience before proceeding with the subsequent phase. Previous enhancements to the study design included revising eligibility criteria[3] and integrating the establishment sample EOI and equipment sample ESI into a single survey application. As a result of the EOI Phase 2 effort, in order to meet data collection goals, a decision was made to explore the viability and utility of drawing a supplemental sample from a database provided by Equipment Data Associates, Inc. (EDA).[4] To that end, EDA data was purchased using the same specifications employed by EPA in its earlier acquisition of EDA data for PSU 1 (Jackson, MO). The data set structure was organized and merged with the existing SSI data set. The result of this assessment was a merged data set of 2,209 records, comprising the sample frame for Phase 3. Accordingly, all 2,209 records in the combined SSI-EDA frame were loaded into the sample management system for the issuance of advance letters and subsequent calling by the telephone facility.

In addition to enhancements made to the establishment sample frame, data collection equipment and procedures were refined prior to ES Phase 3 fieldwork, based on information learned during ES Phase 1 and II testing. The team considered several changes, but eventually focused on enhancing PEMS RPM collection and PEMS ECU data collection.

For PEMS RPM collection enhancements, the team abandoned use of "Capelec" RPM measurement devices (which were the primary RPM measurement device used during PEMS tests in ES Phases 1 and 2 of this study) as the method of RPM collection during PEMS testing. This decision was made because only limited success was achieved obtaining an accurate and reliable RPM signal. Instead, the ERG team and EPA decided to use optical sensors for PEMS RPM acquisition during ES Phase 3 testing. The ERG team and EPA worked together to identify dedicated optical sensor holders which could be attached to high-powered rare-earth magnets (acquired separately). These high-powered mounts proved to be capable of securely attaching the optical sensors for both day-long PEMS testing and month-long PAMS testing. This provided a much more reliable RPM signal during the third phase of fieldwork.

In addition to the RPM collection enhancement, the team focused efforts on supplementing PEMS test procedures and equipment in order to allow the collection of

[3] Certain eligibility criteria were revised, including establishments that (according to the SSI sample frame) reported having zero employees were no longer excluded from the study as a result of Phase 1 and establishments that were non-prime contractors were considered eligible during Phase 2.
[4] The EDA data provide a list of establishments that have financed construction equipment purchases. The data set contains identifying company information, equipment pieces financed (by equipment type) and date of transaction.

Caterpillar ECU data from electronically-controlled equipment that would be PEMS-tested throughout the remainder of this work assignment. Therefore, ERG, EPA and Sensors worked with Caterpillar in acquiring "CAT ET" (Caterpillar Electronic Technician) equipment and software necessary for ECU data collection on nonroad equipment, and the project team established training sessions with Caterpillar for use of this equipment and software. New procedures were developed to allow this data to be collected in the field during emissions testing (rather than collection of data during engine diagnosis or repairs, the typical application for this equipment). The CAT ET software was installed on a remote laptop for which the "sleep" power mode was disabled (allowing the laptop to operate with the lid closed). This laptop was placed in the cab of the equipment being tested, connected directly to the ECU CAN port (via the Cat ET communication module) and to a power supply (taken from the PEMS onboard generator). Since acquisition could not start until after the equipment was turned on, remote control of the acquisition laptop was necessary and was achieved by way of a standard Wi-Fi computer transmitter/receiver. Preliminary testing showed this configuration adequate for remotely collecting ECU data from electronically-controlled Caterpillar equipment. This data could then later be merged and time-aligned with the PEMS data for the same test.

**Phase 3 Surveys and Field Testing in PSUs 4 and 5**

Phase 3 EOIs and Equipment Sample recruitment were performed with the integrated sample and merged SSI-EDA frame. Phase 3 fieldwork was conducted with establishments located in the counties of Clay, Missouri and Shawnee, Kansas. Because of the distance which separated these two counties, inventories, emissions and activity measurements were conducted independently in each county (work for each task was completed in Clay, Missouri before moving on to Shawnee, Kansas). Phase 3 fieldwork began June 30th 2008 and continued through October 10th 2008. The quality of RPM data collected during ES Phase 3 was higher than that in ES Phases 1 and 2, and although only one piece of electronically-controlled Caterpillar equipment was tested, ECU data collection was successful for this test. Several weeks of CRC-funded PEMS testing were added to the scope of work during ES Phase 3, increasing the total number of PEMS tests collected during the study, as shown in the next section.

**Summary of EOI Surveys and Equipment Sample Recruitment**

A hierarchical disposition analysis was conducted using the survey data to determine the data collection performance and instrumentation recruitment rates throughout the study. Specifically, the analysis provided documentation of the screening rate, eligibility rates, interview rates, and overall response rates for each of the study phases. The response rates that had been expected during the planning phase are shown in Table OV-5 below. In Table OV-5, an "eligible establishment" was an establishment which had verified that it was the establishment that had been selected for the sample, operated in the construction industry, used diesel powered equipment and employed one or more persons (although the "one or more persons employed" eligibility requirement was later eliminated in an effort to yield more Equipment Sample). If a determination was made regarding eligibility, an establishment was "screened". If insufficient information was obtained to determine eligibility; the establishment disposition was "not screened."

**Table OV-5 *Expected* Dispositions for each Sample Frame and Study Phase**

| | ESTABLISHMENT SAMPLE | | EQUIPMENT SAMPLE | | |
|---|---|---|---|---|---|
| | PHASE 1 | PHASE 2 | PHASE1 | PHASE 2 | PHASE 3 |
| | PSU1 | PSU 2-5 | PSU1 | PSU 2+3 | PSU 4+5 |
| **Screening Response** | 75% | 75% | 75% | 75% | 75% |
| **Interview Response** | 85% | 85% | 85% | 85% | 85% |
| **Overall Response*** | 64% | 64% | 26% | 26% | 26% |
| **Eligibility Rate** | 85% | 85% | 75% | 75% | 75% |
| **Total Sample** | 304 | 1214 | 318 | 635 | 635 |
| **Total Interviewed (EOI)** | 100 | 400 | 93 | 185 | 185 |
| **Total Agreeing to Instrumentation** | NA | NA | 37 | 74 | 74 |
| **Instrumentation Response/ Total** | NA | NA | 40% | 40% | 40% |

* For the **Equipment Sample**, the overall response rate assumes that 40% of the Establishment Sample would agree to instrumentation. We obtain the overall Equipment Sample response rate by multiplying the overall Establishment Sample response rate by 40%. Thus, **64% x 40% = 26%.**

Table OV-6 shows the actual performance rates for the EOI portion of the study. From the onset of the study, it is clear that actual dispositions were with few exceptions lower than originally expected. A significant reason for this was the lower-than-expected eligibility rate. In response to this, in subsequent phases of the study (Phase 2, integrated sample, and Phase 3), the eligibility requirements were revised to increase the eligibility rate. Tables ES-6 and ES-7 illustrate the impact of this.

**Table OV-6 Actual Performance Rates for EOI, All Phases of Integrated Sample**

| | EOI PHASE 1 | EOI PHASE 2 | | EOI PHASE 3 |
|---|---|---|---|---|
| | PSU 1 | PSU 1 | PSU 2+3 | PSU 4+5 |
| **Screening Response** | 58% | 50% | 60% | 28% |
| **Interview Response** | 94% | 70% | 87% | 100% |
| **Overall Response** | 54% | 35% | 53% | 28% |
| **Eligibility*** | 38% | 15% | 14% | 31% |
| **Total Sample** | 304 | 2015 | 1453 | 2048 |
| **Total Interviewed** | 162 | 101 | 107 | 179 |
| * Eligibility criteria were revised for each 'column' of data collection shown above. | | | | |

The overall performance rates for Equipment Sample recruiting are presented in Table OV-7 below.

**Table OV-7 Actual Performance Rates for ESI, All Phases of Integrated Sample**

| | EOI PHASE 1/2 | EOI PHASE 2 | EOI PHASE 3 |
|---|---|---|---|
| | PSU 1 | PSU 2+3 | PSU 4+5 |
| **Screening Response** | 36% | 60% | 28% |
| **Interview Response** | 28% | 37% | 35% |
| **Overall Response** | 10% | 23% | 8% |
| **Eligibility** | 9% | 14% | 31% |
| **Total Sample** | 2319 | 1453 | 2048 |
| **Total Agreed to Inventory** | 22 | 43 | 54 |
| **Estabs Inventoried** | **11** | **30** | **38** |
| **Estabs Instrumented** | **7** | **9** | **13** |

## Summary of PEMS and PAMS Data Collected Throughout Study

Table OV-8 provides counts of the numbers of establishments that were originally recruited for inventories, establishments which were inventoried, establishments which were recruited but then refused inventories, and establishments which were not inventoried for reasons other than establishment refusal, such as all sites being outside the study area or the establishment would have no active sites until after the end of the phase.

**Table OV- 8 Summary Counts of Establishments Inventoried**

| ES Phase | Establishments Recruited for Inventories | Establishments Inventoried | Establishments Refusing Inventories | Establishments Not Inventoried for Other Reasons |
|---|---|---|---|---|
| **1** | 22 | 11 | 7 (32%) | 4 |
| **2** | 43 | 30 | 11 (26%) | 2 |
| **3** | 54 | 38 | 12 (22%) | 4 |
| **Totals** | **119** | **79** | **30 (25%)** | **10** |

As can be seen in Table OV-8, approximately 25% of the establishments who originally agreed to participate in the inventory and measurement phase of the study later reversed their decision and declined to participate any further in the study. Some of these were categorized as "passive" refusals, i.e., field inventory teams were never able to reach a contact, or were given extraordinarily unusual reasons that participation was not possible at that time.

Table OV-9 provides counts of equipment inventoried and instrumented throughout the study.

**Table OV-9 Summary Counts of Equipment Inventoried and Instrumented**

| | Overall | ES Phase 1 | ES Phase 2 | ES Phase 3 |
|---|---|---|---|---|
| **Count of equipment inventoried** | 292 | 56 | 110 | 126 |
| **Count of PEMS-eligible equipment** | 179 | 41 | 65 | 73 |
| **Count of PAMS installations** | 30 | 7 | 11 | 12 |
| **Count of PEMS installations** | 40 | 6 | 13 | 21 |

Thirty-five of the 119 establishments that were inventoried were also asked to participate in instrumentation (PAMS, PEMS, or both). It is interesting that only 6 of those 35 establishments refused to participate in the instrumentation process after the inventory. In Table OV-9, PEMS eligibility was generally based on whether sufficient room was available for securing the PEMS rack, as approximately 4 ft by 3 ft (footprint) was required to mount the rack. In addition, the PEMS rack could not be mounted on equipment where it would hinder work or pose a visibility or safety hazard.

Table OV-10 provides a summary of PEMS and PAMS data that was collected throughout all three phases of study fieldwork. As previously noted, Phase 3 PEMS tests were enhanced with several additional weeks of CRC-funded testing.

**Table OV-10 Summary of data collected throughout the Nonroad PEMS Study**

| | PEMS | | PEMS Successful | | | PAMS | | |
|---|---|---|---|---|---|---|---|---|
| **ES Phase / PSU** | **Target PEMS** | **PEMS Attempts** | **Gaseous** | **PM** | **RPM** | **Target** | **Install Attempts** | **Data Collected** |
| ES Ph 1, Summer 07 Jackson, MO (PSU 1) | 5 | 6 | 3 | 2 | 1 | 5 | 7 | 7 |
| Es Ph 2, Fall 07 Linn, IA (PSU 2) & Scott, IA (PSU 3) | 10 | 13 | 10 | 10 | 9 | 10 | 11 | 10 |
| ES Ph3, Summer&Fall 08 Clay, MO (PSU 4) & Shawnee, KS (PSU 5) | 16 | 21 | 16 | 15 | 15 | 10 | 12 | 12 |
| **Totals** | **31** | **40** | **29** | **27** | **25** | **25** | **30** | **29** |

As shown in Table OV-10, a higher number of PEMS and PAMS "attempts" were made than "target" test counts, in order to account for loss of data to equipment malfunctions and other problems.

### Data Processing and QC

At the completion of EOI/ESI data collection, NuStats processed the establishment interview and recruiting database, conducting quality control and edit checks, using specifications established for this study. Study data was analyzed regarding sample performance. Final data files were prepared and transferred to ERG according to the protocols required in the statement of work.

All PEMS and PAMS data was monitored during collection followed by extensive QC and processing performed after data collection was completed. For PEMS data, QC and analysis included time-alignment, RPM scaling, estimation of brake-specific emissions based on engine RPM and fuel rate, review of analyzer gaseous drift, review of exhaust mass flow rates, review of MPS proportionality to exhaust flow, and a detailed second-by-second review of all recorded parameters by way of analysis of plots and raw data. This second-by-second review entailed evaluation of all gaseous pollutants, review of RPM quality, reviewing sampling system pressures such as the MPS inlet pressure and SEMTECH pressures, evaluating all system flows including the exhaust mass flow rates, review of the calculated fuel flow rate, MPS sampling flowrates and gravimetric filter flowrates, and evaluating all system and sampling temperatures such as exhaust temperatures, external heated line, chiller, cyclone, manifold and gravimetric filter temperatures and ambient and internal PEMS rack temperatures. Corrections were applied to the data as needed and uncorrectable or erroneous data has been excluded from reporting summaries. In addition, a number of sources of uncertainty in the emissions results are described in Section 6.2.2 of this report and have been quantified in Appendix AO. These uncertainty estimates are shown in the emission results presented in this overview.

PAMS data processing varied from test to test depending on the type of installation, PAMS equipment used and equipment being tested. In general, review and correction of PAMS data involved reviewing and correcting date / time stamp assignments (including on dataloggers with sub-second acquisition), performing RPM calibration corrections, flagging observations that could be associated with ERG team activities (installation, removal and revisit dates), assigning equipment activity and key-position flags, assigning RPM validity flags and defining a "correct" RPM for each test.

**Study Results**

***Phase 1 EOI and Recruiting Results***

Analysis of Phase 1 EOIs showed that the distribution of construction establishments was highly skewed with respect to number of employees much in the way that most business productivity and revenue distributions are distributed in the U.S. -- a relatively small subset of establishments account for the majority of productivity or revenue. Such was the case with the employee distribution across construction establishments in PSU 1: the distribution pattern approximately followed a Pareto distribution (i.e., about 20% of establishments accounted for roughly 80% of employees). If the correlation assumption between employees and equipment held up, then the observed distribution of establishments in the sampling frame would support the use of PPS sampling.

For PSU 1, we encountered a large number of self-representing/certainty establishments.[5] Table OV-11 shows the frequency and percentage distributions of establishments and number of employees in our PSU 1 frame by self-representing status.

[5] Self-representing establishments in PSU1 were those for whom SSI reported 15 or more employees; non self-representing establishments had 1-14 employees.

### Table OV-11  Frame Characteristics of PSU 1

| | NUMBER OF ESTABLISHMENTS | PERCENT OF ESTABLISHMENTS | NUMBER OF EMPLOYEES | PERCENT OF EMPLOYEES |
|---|---|---|---|---|
| **Self-representing SSUs** | 267 | 11% | 18,248 | 74% |
| **Nonself-representing SSUs** | 2,052 | 86% | 6,317 | 26% |
| **Excluded establishments (0 employees)** | 77 | 3.2% | 0 | 0 |
| ***TOTAL*** | ***2,396*** | ***100%*** | ***24,565*** | ***100%*** |

The need for self-representing units in the PSU 1 sample design precipitated a major modification in the overall design.  This was because a large number of establishments (i.e., the self-representing units) belonged to *both* the Establishment and Equipment Samples by virtue of their large measures of size.  This meant that all self-representing SSUs needed to be taken through the both the EOI and ESI survey protocols (e.g., EOI, recruitment for inventory and instrumentation, incentive experiment, etc.).

Table OV-12 lists the various response rates by stratum for EOI (interviews) in Phase 1. The net effect is seen as the last row of Table OV-12 – Net Yield.  Net Yield refers to the bottom line percentage of the sample that will yield a completed interview.  Using our design parameters a net yield of 41% was expected. The actual yield for EOI Phase 1 Establishment Sample was 21%, or about half of what we planned.  Net yield varied twofold by PSU status – 33% for self-representing units and 16% for non-self-representing units.  Both figures fell well below the expected/planned value of 41%.

### Table OV-12  PSU 1 Expected vs. Actual Design Parameters

| DESIGN PARAMETER: | ACTUAL SELF REP | ACTUAL NONSELF-REP | OVERALL ACTUAL | OVERALL EXPECTED |
|---|---|---|---|---|
| eligibility rate | 51% | 32% | 40% | 65% |
| screen rate | 72% | 51% | 58% | 75% |
| interview rate | 89% | 97% | 93% | 85% |
| **overall response rate** | **64%** | **49%** | **54%** | **64%** |
| Net Yield | 33% | 16% | 21% | 41% |

The EOI Phase 1Interviews were successful in that they achieved the primary goal of preparing for the remainder of the Study.  The results are summarized as follows:

- The distribution of construction establishments in the sampling frame was highly skewed with respect to number of employees (generally following a Pareto distribution -- 20% of establishments acct for 80% of employees), and the sample and data collection designs were adapted accordingly;

- If the number of employees is to be used as a measure of size for sampling establishments, then within-PSU sampling of establishments requires a two-step approach. First, identify a set of "self-representing" establishments; second, subsample the non-self-rep establishments;

- The overall response rates were generally favorable; however there was considerable variation by self-representing and non-self representing response rates;

- Eligibility was considerably lower than planned in our design parameters, and this was differential by PSU; this suggested that higher levels (than planned/budgeted) of screening and calling would be required per completed EOI; under a model of fixed level of resources, the target number of completed interviews would need to be reduced;

- There is no efficient way (short of calling) to identify ineligible sample; however, the screening response rate can be increased by adopting a protocol that requires a nominal amount of research of the disconnected numbers. This would verify that there are no other listings for that establishment and/or that all additional listings are disconnected or 'wrong numbers' and a conclusion could be drawn that the establishment is no longer in business (which in turn helps the screening response rate).

***Phase 2 EOI and Recruiting Results***

Analysis of the remainder of the PSU 2-5 Frame data for the combined Establishment and Equipment samples indicated that even performing a census of all establishments in PSUs 2-5 might fail to yield the recruitment goals for the Equipment Sample. This potential shortfall, along with the need for self-representing establishments to be taken through both the EOI and ESI survey protocols, led to a full integration of the EOI Phase 2 Establishment and Equipment Samples into a single, unified design.

Table OV-13 compares the PSU 2 and 3 recruiting rates with the expected values used for planning. The last row shows that the actual net yield was under that anticipated by a factor of 7. The rightmost column shows the ratios of actual-to-expected rates and most are relatively near an ideal value of 1.0. However the biggest departure is due to the discrepancy in eligibility rates. The actual eligibility rate was 14% while the planned value was 75 percent. This factor alone represented a lower-than-expected net yield by a factor of 5.4.

### Table OV-13 PSU 2 and 3 Actual Versus Expected Design Parameters

| | COMBINED PSU 2 & 3 ACTUAL | EXPECTED | RATIO (EXPECTED/ACTUAL) |
|---|---|---|---|
| Screening Rate | 60% | 75% | 1.3 |
| Eligibility Rate | 14% | 75% | 5.4 |
| Recruitment Rate | 37% | 34% | 0.9 |
| Overall Response rate | 23% | 26% | 1.1 |
| | | Actual increase relative to Expected | 7 |

***Phase 3 EOI and Recruiting Results***

Table OV-14 presents actual and expected screening response rates and eligibility rates; also, interview response rates are provided separately for EOI and ESI. All rates are reported by PSU (Columns A and B) and for the overall sample (Column C), along with the corresponding expected values that were used in planning (Column D).

### Table OV-14 PSU 4 and 5 Actual Versus Expected Design Parameters

| EOI PHASE 3 | A | B | C | D |
|---|---|---|---|---|
| | PSU 4 | PSU 5 | Total Actual | Expected |
| Screening response | 27% | 29% | 28% | 75% |
| Eligibility Rate | 33% | 29% | 31% | 75% |
| EOI Interview Response | 100% | 100% | 100% | 85% |
| ESI Interview Response | 31% | 29% | 30% | 40% |
| Overall Response -- EOI | 27% | 29% | 28% | 64% |
| Overall Response -- ESI | 8% | 8% | 8% | 26% |
| ESI Net Yield (1 in N) | 35.4 | 41.0 | 37.9 | 5.2 |

The values in columns A-C of Table OV-14 indicate that the screening, eligibility and response rates were consistent across PSUs 4 and 5. Columns C and D can be used to compare actual and expected response and eligibility rates for EOI Phase 3. Actual screening response rates were substantially below the expected/planned value (28% actual vs. 75% expected). This was due to a number of reasons including the quality of the business contact data, the need to conduct additional searches to obtain business information and the need for multiple call backs to businesses to reach a knowledgeable contact.

Even among the successfully screened establishments, the actual eligibility rate was less than half of the expected rate (31% actual vs. 75% expected). This was disappointing in that the eligibility criteria had been loosened (e.g., companies with 0 employees were eligible provided they met other criteria, removing the restriction that establishments be prime contractors). The lower-than-expected eligibility rate led to higher screening burden to identify eligible establishments (requiring 2.4 times the expected amount of screening than what was planned).

***Incentive Test Analysis Results***

The incentive tests for each of EOI Phases 1 and 2 were not definitive and a decision was made to continue the testing in EOI Phase 3. The design of the test involved a random assignment to an incentive offering to establishments just before commencing the ESI portion of the survey. The incentive was an offer of a $100 check sent to the establishment regardless of their participation in the ESI (recruitment). The experimental design called for a random half of respondents to receive the incentive.

The results of the incentive experiment are presented in Table OV-15. The results combine PSUs 4 and 5 for the sake of parsimony (since the separate tables show the same result). A total of 171 establishments participated in the incentive test. To "participate" in the incentive test, the introduction must be read to the respondent. The results show that the incentive had no observed impact on accepting the invitation to participate in the inventory and instrumentation. With one degree of freedom, a chi-square statistic whose value is 2.71 or greater would have been needed to establish a 10% level of significance; the observed value was 1.98.

**Table OV-15 Combined PSU 4 and 5 Incentive Test on Instrumentation**

| | OUTCOME | | |
|---|---|---|---|
| **Experimental Group:** | **Recruited** | **Declined** | **Total** |
| **Incentive** | 33 | 58 | 91 |
| **No incentive** | 21 | 59 | 80 |
| **Total** | 54 | 117 | 171 |
| **Chi-Squared** | 1.98 | **NOT Signif. at 10%** | |

The possibility that the incentive offer might impact *actual participation* in the inventory/instrumentation even if we failed to detect a treatment effect at the recruitment stage was explored. That is, *follow-through to instrumentation* as the outcome instead of *agreement to participate* was explored because some establishments agreed during the CATI interview but then later declined when the reality of inventory/instrumentation was at hand.

Table OV-16 presents the results of the incentive test where the outcome is the *actual follow-through to instrumentation*. Unfortunately, the incentive did not show a significant impact on instrumentation follow-through. The results here are striking contrast to the incentive test results for PSUs 2 and 3 (EOI Phase 2). In EOI Phase 2 there was a highly significant incentive effect detected for follow-though to instrumentation.

### Table OV-16 Combined PSU 4 and 5 Incentive Test on Instrumentation Follow-Through

| | OUTCOME | | |
|---|---|---|---|
| **Experimental Group:** | **Instrumented** | **Declined** | **Total** |
| **Incentive** | 14 | 77 | 91 |
| **No incentive** | 10 | 70 | 80 |
| **Total** | 24 | 147 | 171 |
| **Chi-Squared** | 0.29 | **NOT Signif. At 10%** | |

To explore the EOI Phase 2 and 3 results we combined the EOI Phase 2 and 3 incentive tests to see if the incentive effect remained. Table OV-17 shows the results of that analysis. We see that the incentive effect remains highly significant when the outcome measure is *follow-through to instrumentation*.

### Table OV-17 Combined PSUs 2-5 Incentive Tests on Instrumentation Follow-Through

| | OUTCOME | | |
|---|---|---|---|
| Experimental Group: | Instrumented | Declined | Total |
| Incentive | 34 | 116 | 150 |
| No incentive | 17 | 122 | 139 |
| Total | 51 | 238 | 289 |
| Chi-Squared | 5.41 | **Signif. At 2.5% level** | |

These findings are insightful. First, it is clearly more important to generate *follow-through* to instrumentation rather than *assent* at the recruitment stage. As such, we recommend that future research focus on this as the outcome of interest/treatment effect. Secondly, the findings from Tables ES-16 and ES-17 are decidedly mixed. There is a very strong incentive effect from EOI Phase 2 when combining the data from EOI Phases 2 and 3. However, the absence of a treatment effect in EOI Phase 3 is troubling and therefore the EOI Phase 2-3 incentive experience begs further analysis and investigation. Clear, significant incentive effects would have conclusively led to a recommendation to adopt incentives in all future studies of this type.

These mixed results give pause to a wholehearted acceptance of incentives. What could lead to such outcomes? The following are some possible explanations:

- Site effects: it could be that PSUs 2-3 contain fundamentally different establishments than those of PSUs 4-5, although it is hard to believe that the effect is due to the peculiarities of establishments within PSUs.

- Interviewer effects: there may have been a difference in the composition of the field interviewer staff between EOI Phases; this could occur if, say, in EOI Phase 2 a highly experienced interviewer staff was used but less experienced interviewers were used in EOI Phase 3.

- Incongruent samples: EOI Phase 3 sampling involved a census of construction establishments regardless of employee size; even establishments showing zero employees (according to SSI) were fielded; this was not the case for EOI Phase 2, where zero-employee establishments were not sampled and if identified in the EOI were terminated; differences in sample universe make-up might explain the incentive results.

The conclusion we reach from these findings is that incentives are cautiously recommended. If at all possible incentive testing should be continued in a way that helps inform our understanding of what factors are associated with differential instrumentation.

**PEMS Results**

Figures ES-1 through ES-14 present PM and gaseous emissions on a "brake specific" or mass / work basis (in units of grams or kg per kW-hr), by equipment category. PM emissions are based on the first three filters collected, and gaseous emissions are based on the overall test average (including times when filters were and were not sampled). When reviewing these results, it should be noted that these emission results were collected during real-world operation and may be biased due to extensive idle or low engine speed operation. Due to differences in work cycles, direct comparisons should not be made between emission standards and the emission results presented here.

**Figure OV-1 PM Emissions from Backhoe Loaders, Work Basis, Filters 1 - 3**

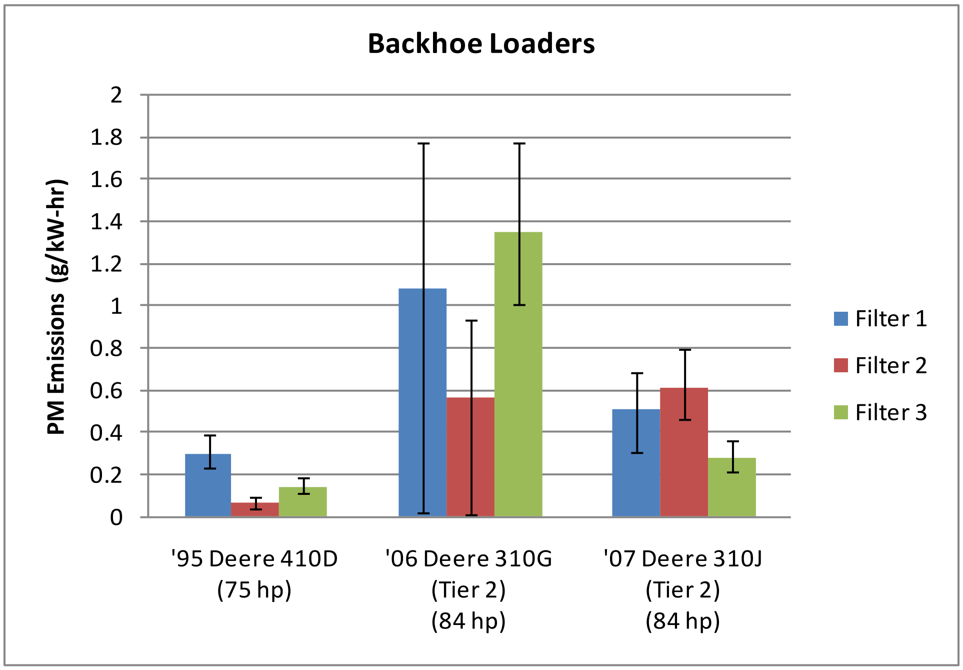



**Figure OV-2 Gaseous Emissions from Backhoe Loaders, Work Basis, Overall test**

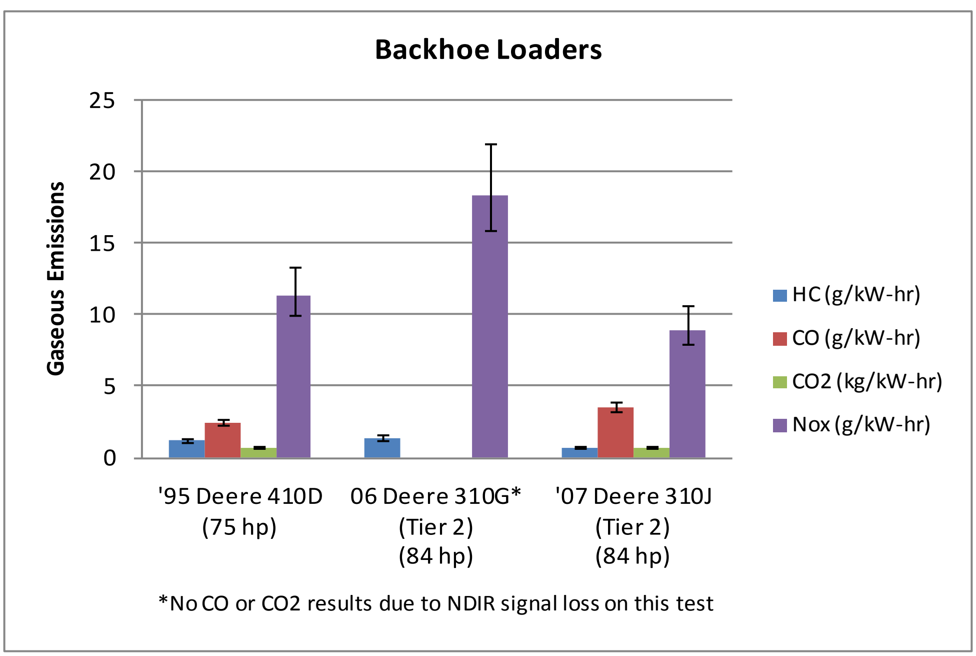


**Figure OV-3  PM Emissions from Dozers, 50-99 hp, Work Basis, Filters 1 – 3**

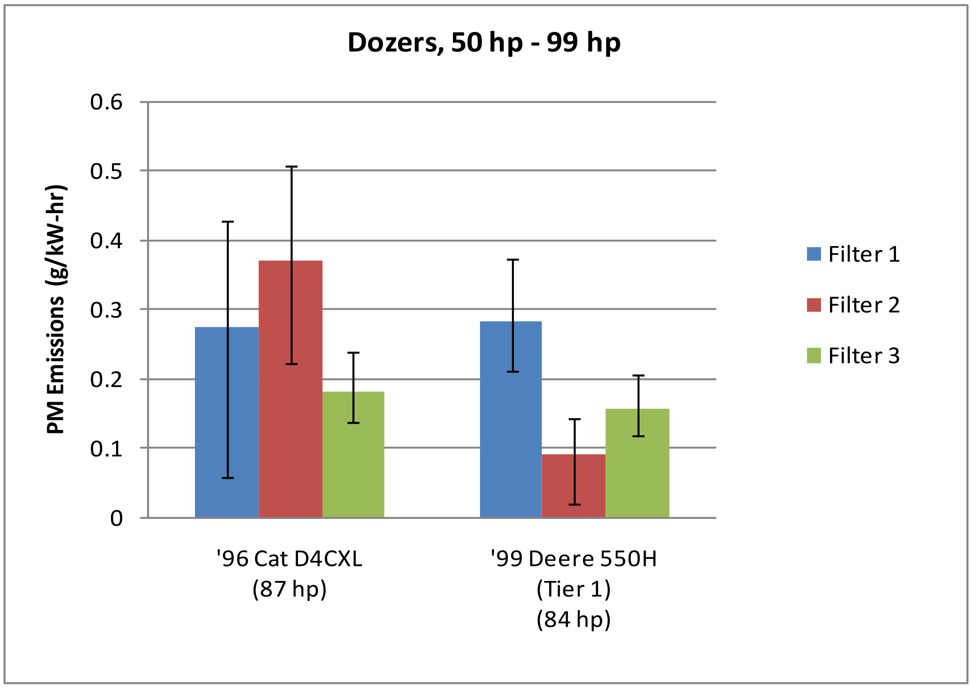



**Figure OV-4  PM Emissions from Dozers, ≥ 100 hp, Work Basis, Filters 1 - 3**

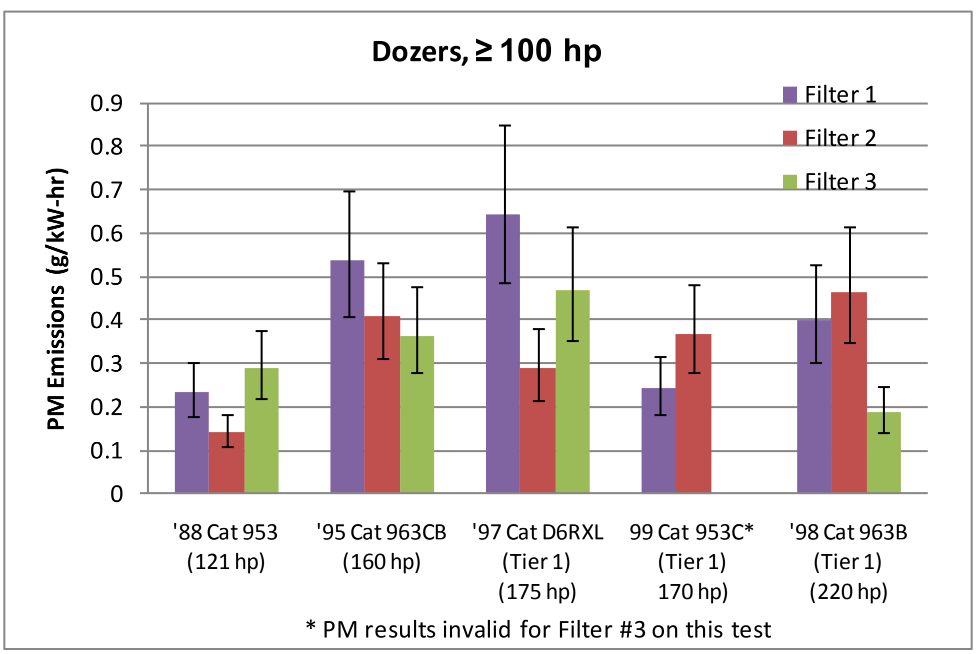


**Figure OV-5 Gaseous Emissions from Dozers, 50-99 hp, Work Basis, Overall test**

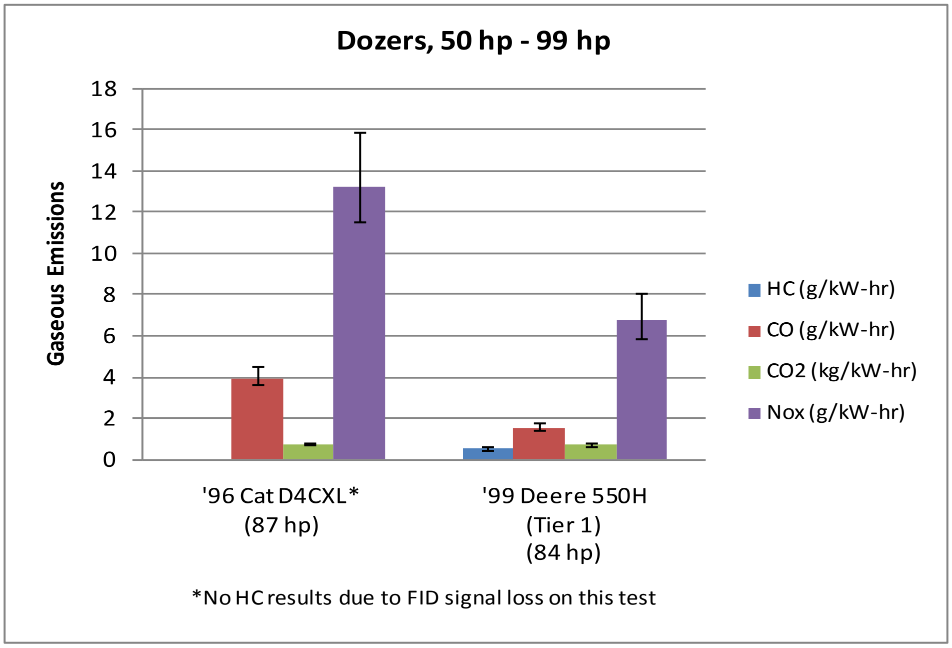



**Figure OV-6 Gaseous Emissions from Dozers, ≥ 100 hp, Work Basis, Overall test**

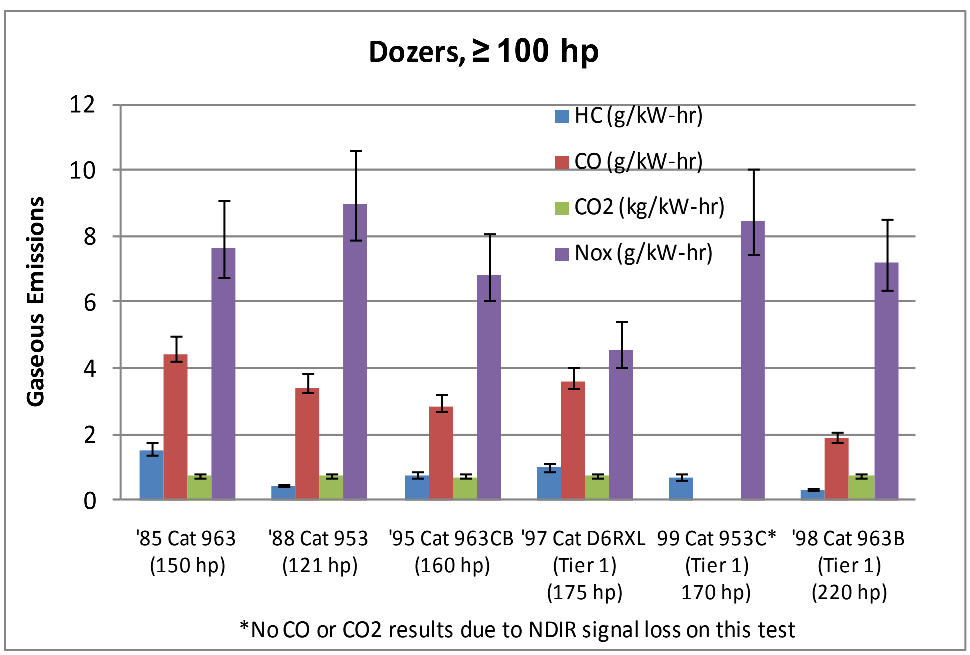


**Figure OV-7 PM Emissions from Excavators, < 300 hp, Work Basis, Filters 1 - 3**

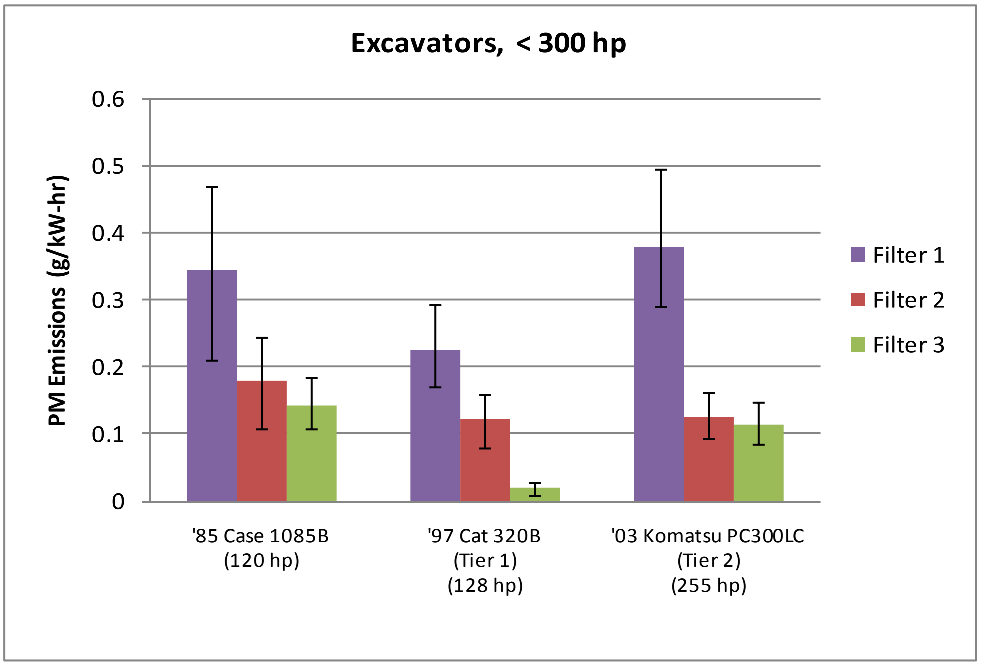



**Figure OV-8 PM Emissions from Excavators, ≥ 300 hp, Work Basis, Filters 1 - 3**

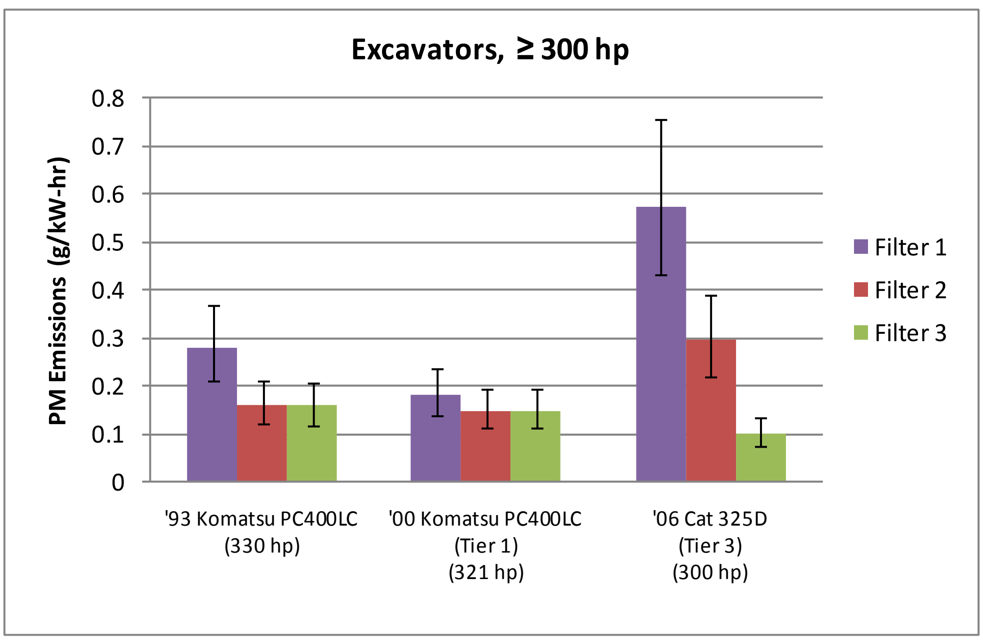


**Figure OV-9 Gaseous Emissions from Excavators, < 300 hp, Work Basis, Overall Test**

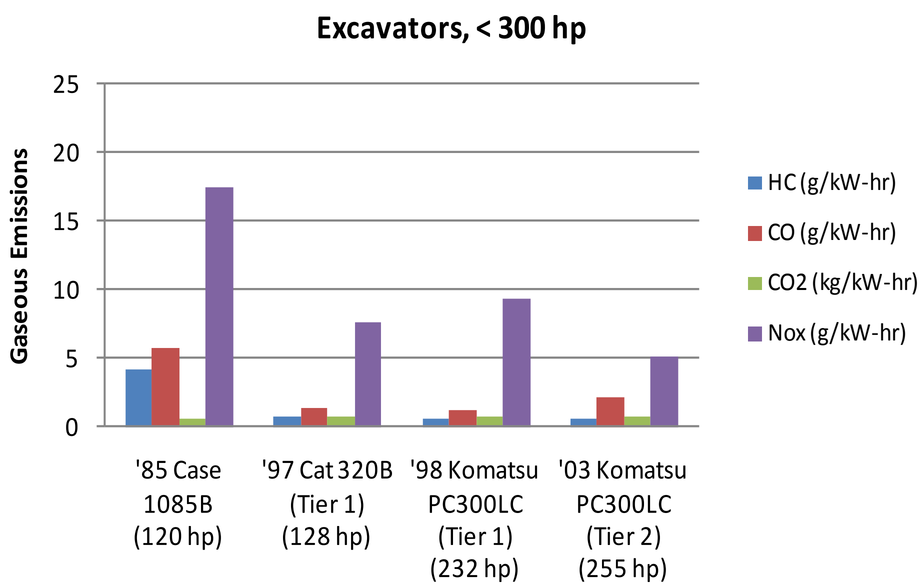
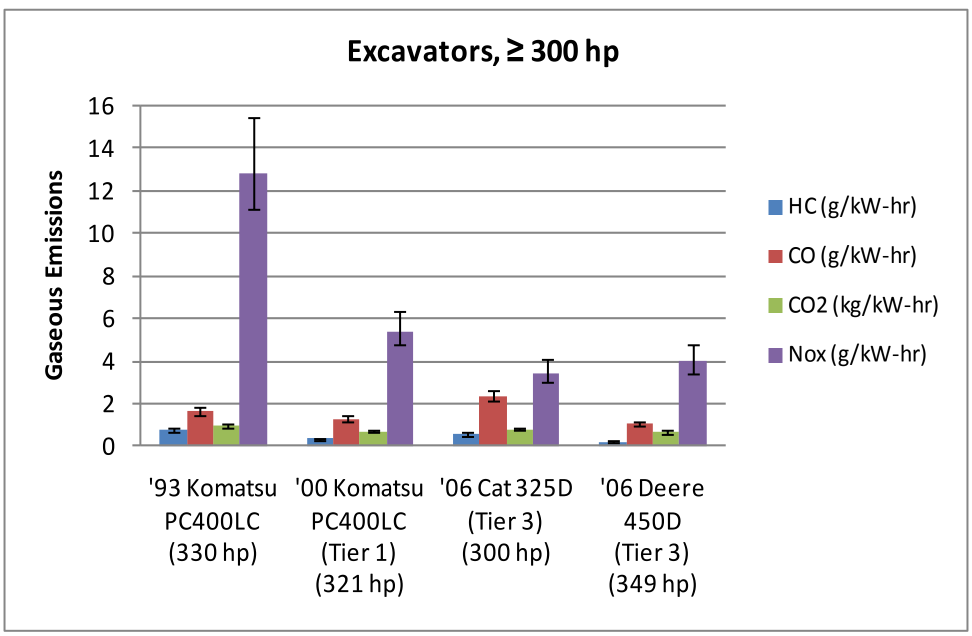
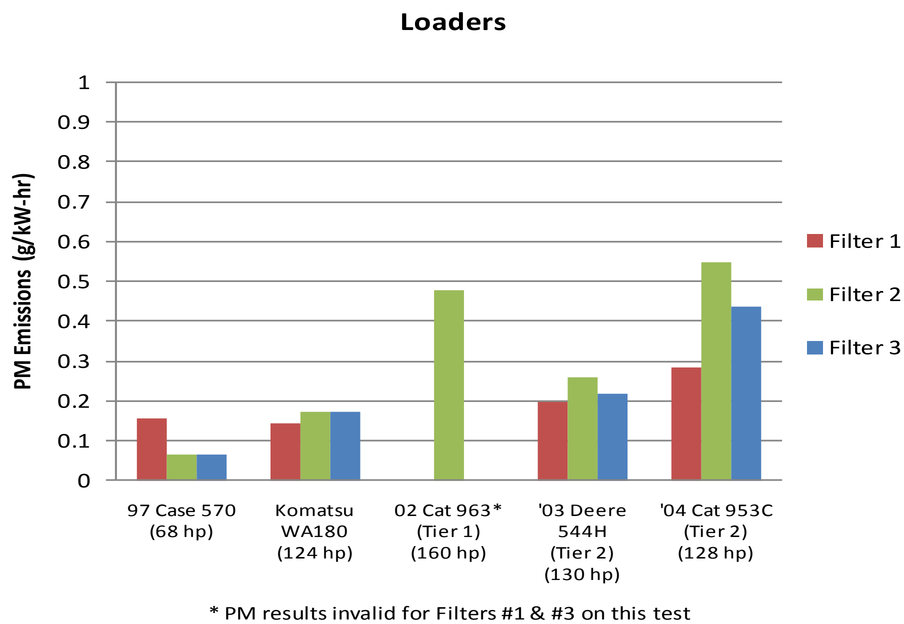


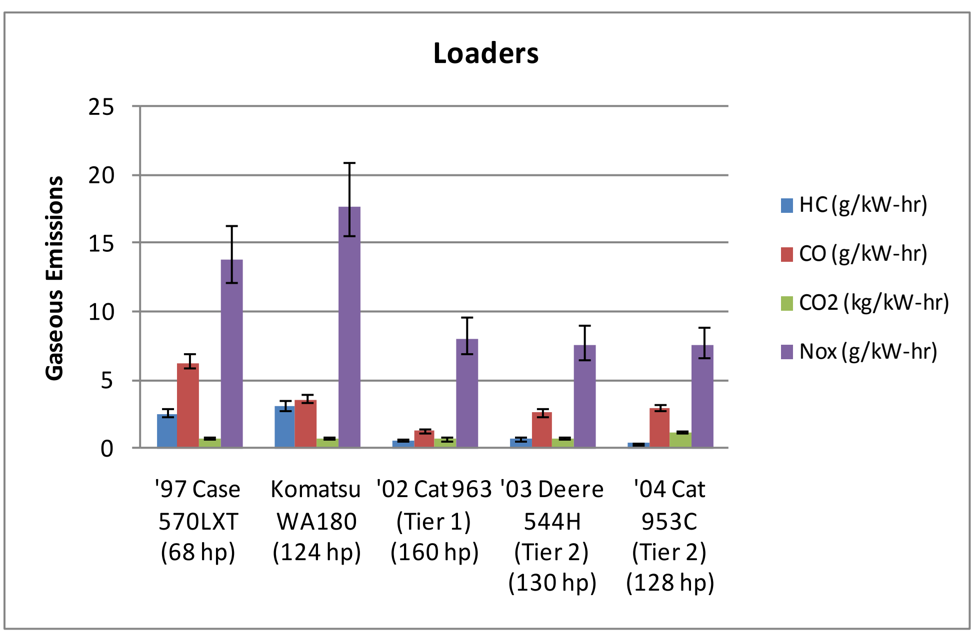

**Figure OV-10 Gaseous Emissions from Excavators, ≥ 300 hp, Work Basis, Overall Test**



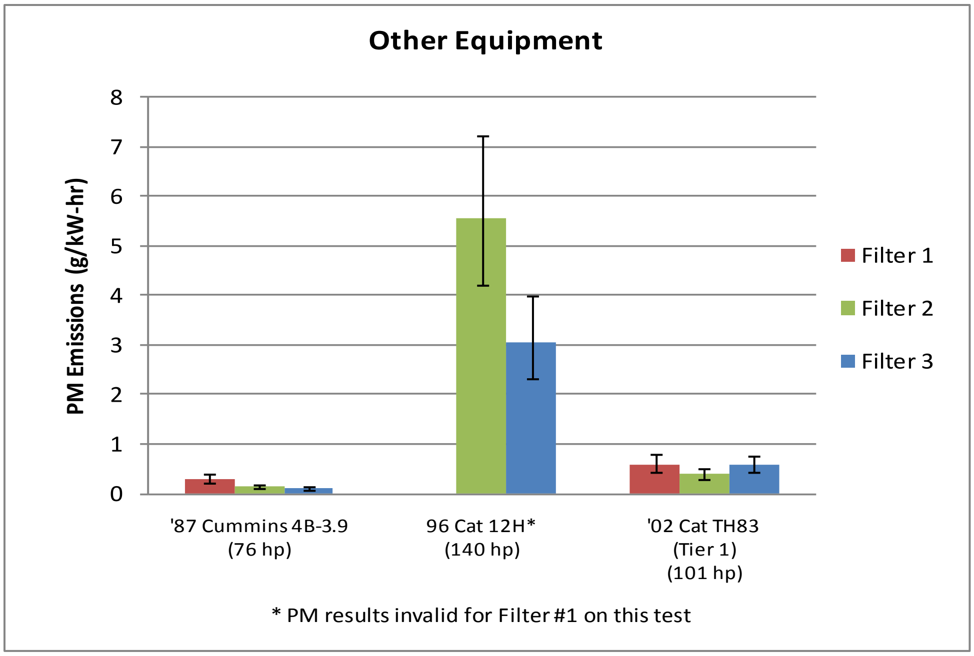
## Figure OV-11 PM Emissions From Loaders, Work Basis, Filters 1 - 3



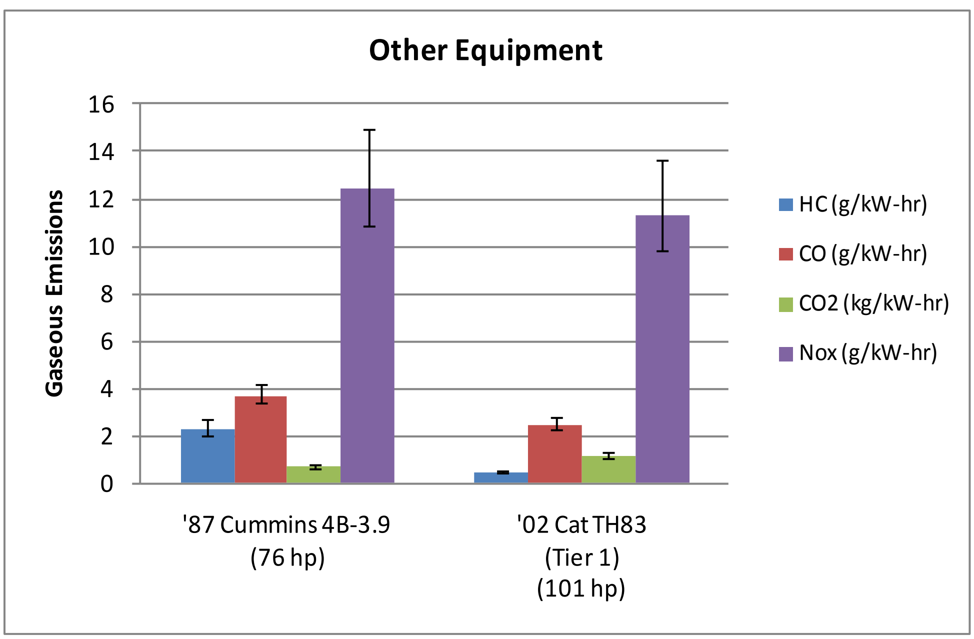

## Figure OV-12 Gaseous Emissions From Loaders, Work Basis, Overall test



## Figure OV-13  PM Emissions From Other Equipment, Work Basis, Filters 1 - 3




## Figure OV-14  Gaseous Emissions From Other Equipment, Work Basis, Overall Test



Figures OV-15 through OV-28 present PM and gaseous emissions on a fuel basis (grams or kg of emissions per gallon of fuel consumed), rather than a work basis, again grouped by equipment category. PM emissions are based on the first three filters collected, and gaseous emissions are based on the overall test average (including times when filters were and were not sampled).

Using a fuel basis to evaluate emissions eliminates several of the points of uncertainty inherent in work basis estimates. However, as with the work basis emissions, extensive idle periods can have an influence on the fuel-based emissions, and the accuracy of the PM measurements are still dependent on the performance of the micro-proportional sampler throughout the range of operation (including outside of the NTE zone). In addition, any errors associated with the SEMTECH-DS' determination of the second-by-second (and hence cumulative) fuel consumption rate will affect the accuracy of the fuel-based emissions estimates. These errors have been estimated in Appendix AO, Nonroad Error Estimates, and are shown in Figures OV-15 through OV-28.

**Figure OV-15  PM Emissions From Backhoe Loaders, Fuel Basis, Filters 1 - 3**

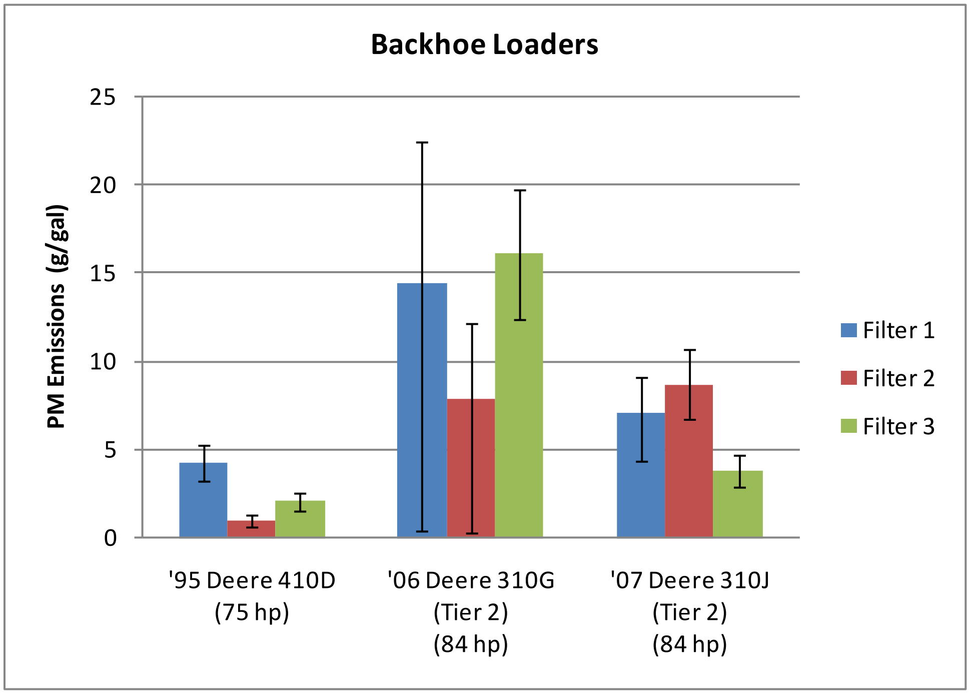


**Figure OV-16  Gaseous Emissions From Backhoe Loaders, Fuel Basis, Overall Test**

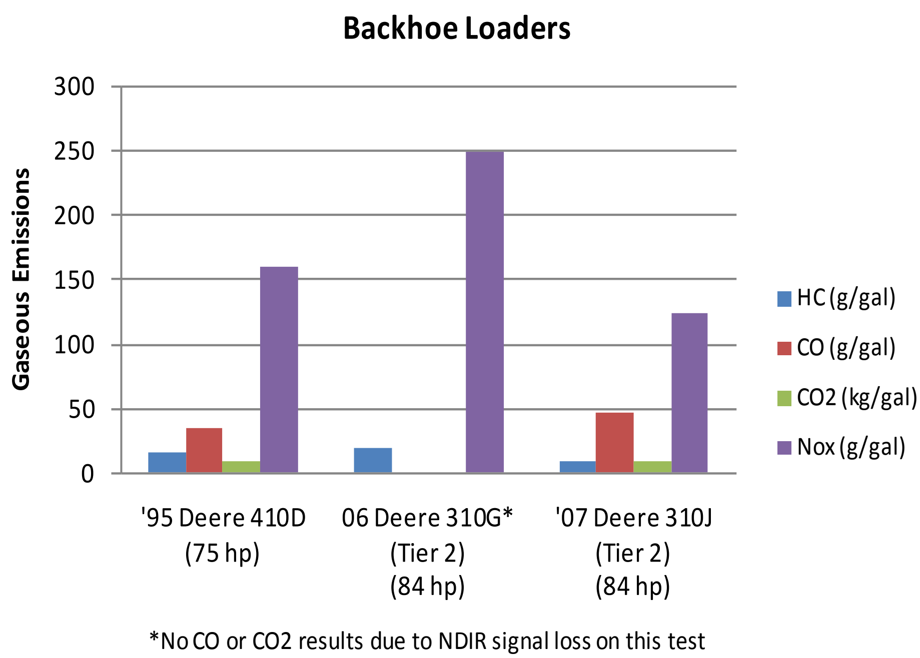



**Figure OV-17  PM Emissions From Dozers, 50-99hp, Fuel Basis, Filters 1 – 3**

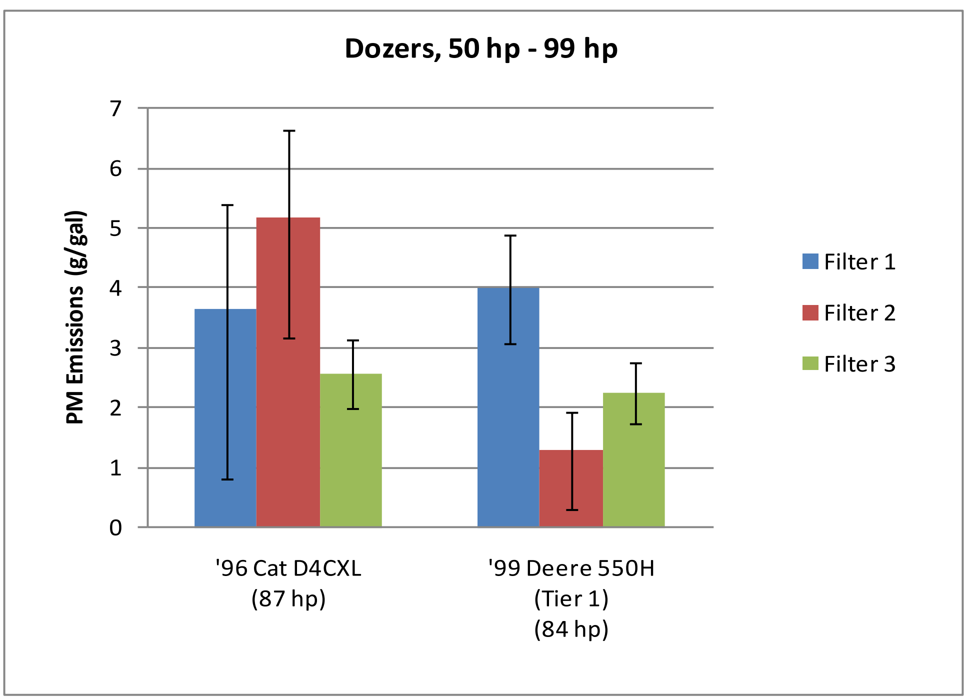


**Figure OV-18 PM Emissions From Dozers, ≥ 100 hp, Fuel Basis, Filters 1 - 3**

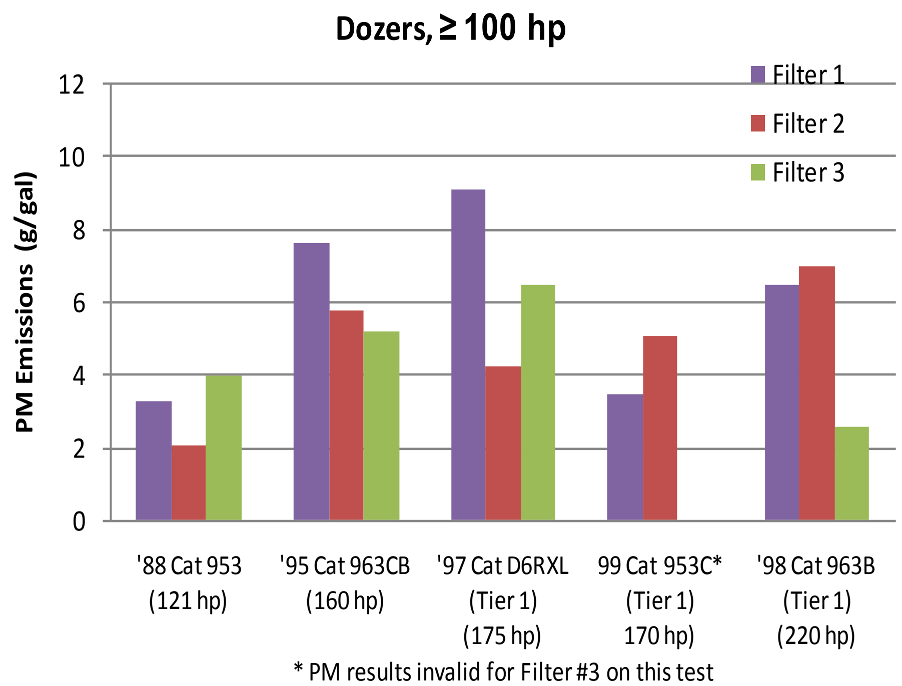



**Figure OV-19 Gaseous Emissions From Dozers, 50-99 hp, Fuel Basis, Overall Test**

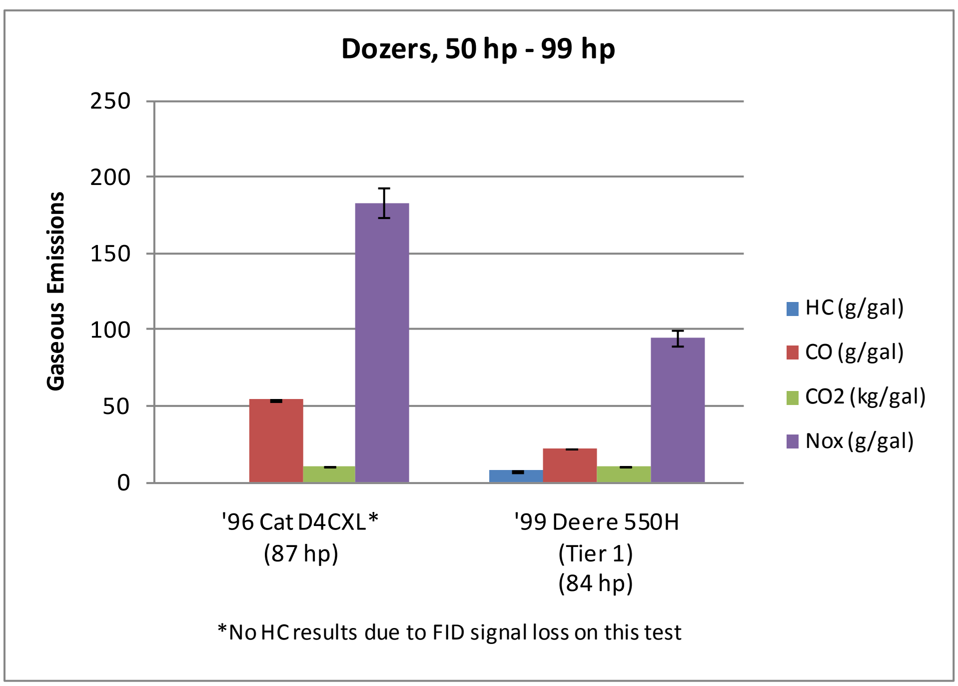


**Figure OV-20 Gaseous Emissions From Dozers, ≥ 100 hp, Fuel Basis, Overall Test**

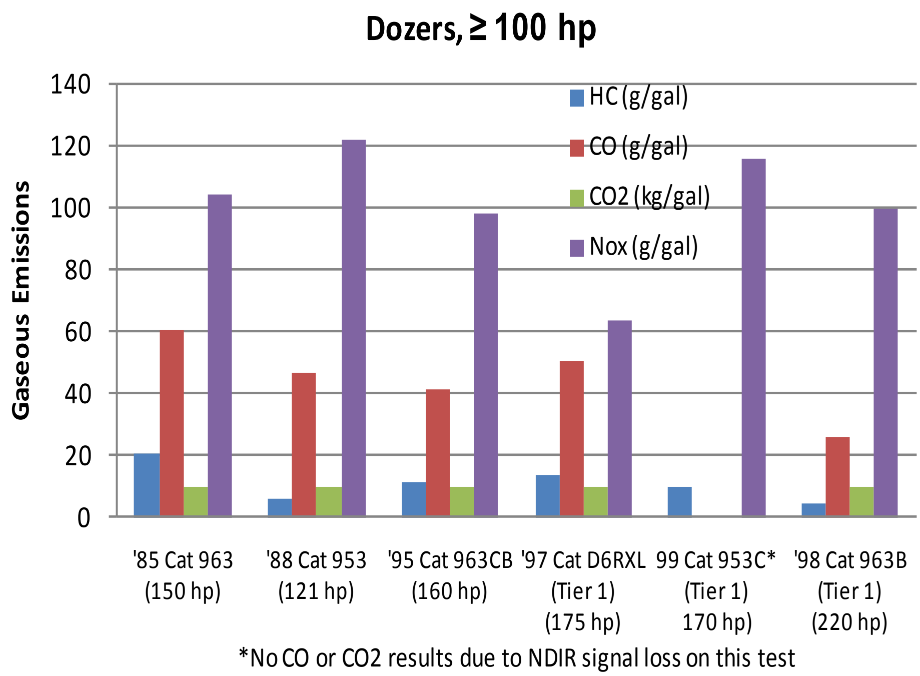



**Figure OV-21 PM Emissions From Excavators, < 300 hp, Fuel Basis, Filters 1 - 3**

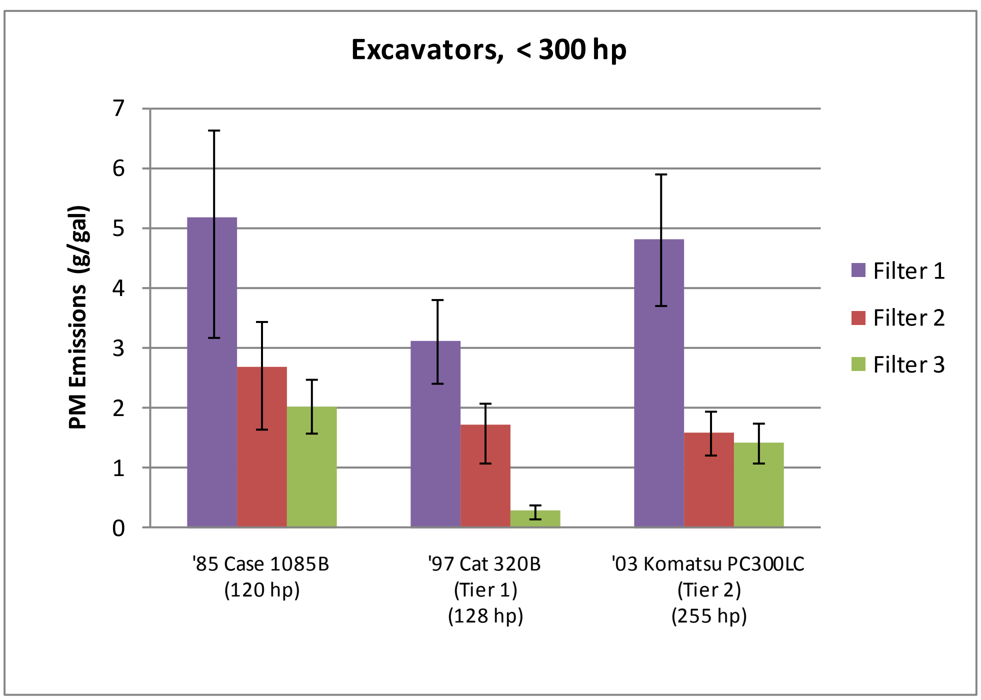


**Figure OV-22  PM Emissions From Excavators, ≥ 300 hp, Fuel Basis, Filters 1 - 3**

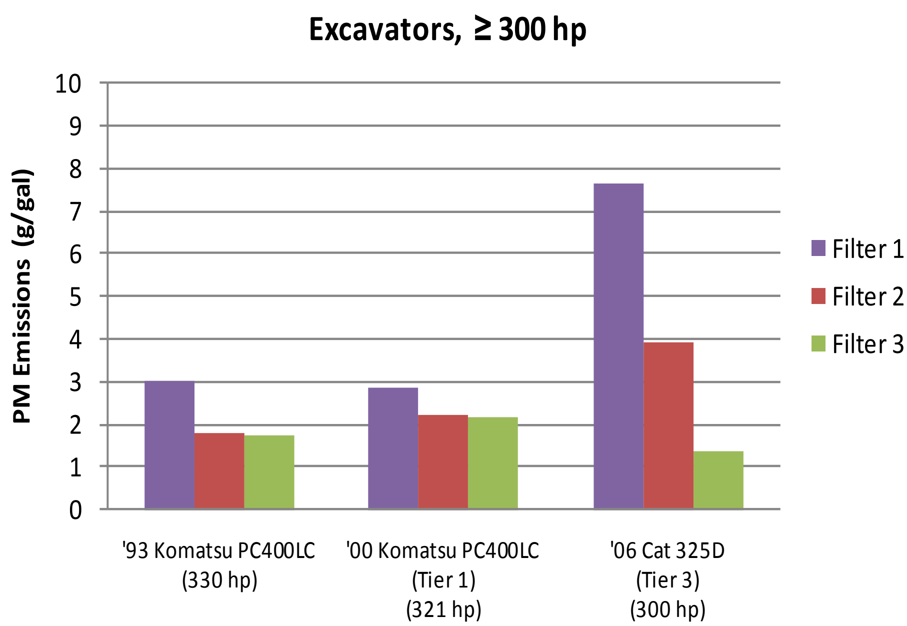



**Figure OV-23  Gaseous Emissions From Excavators, < 300 hp, Fuel Basis, Overall Test**

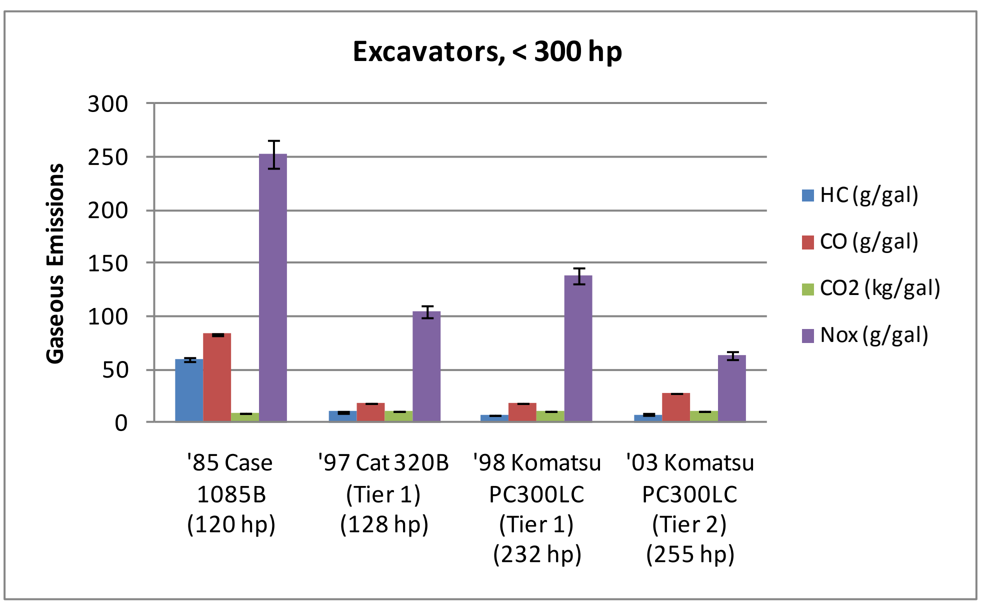


**Figure OV-24 Gaseous Emissions From Excavators, ≥ 300 hp, Fuel Basis, Overall Test**

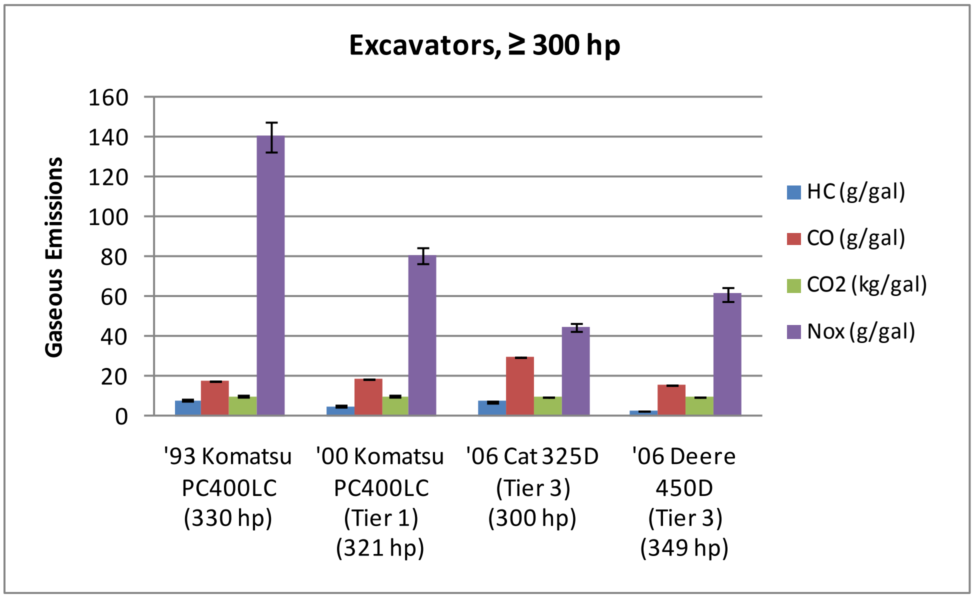



**Figure OV-25 PM Emissions From Loaders, Fuel Basis, Filters 1 - 3**

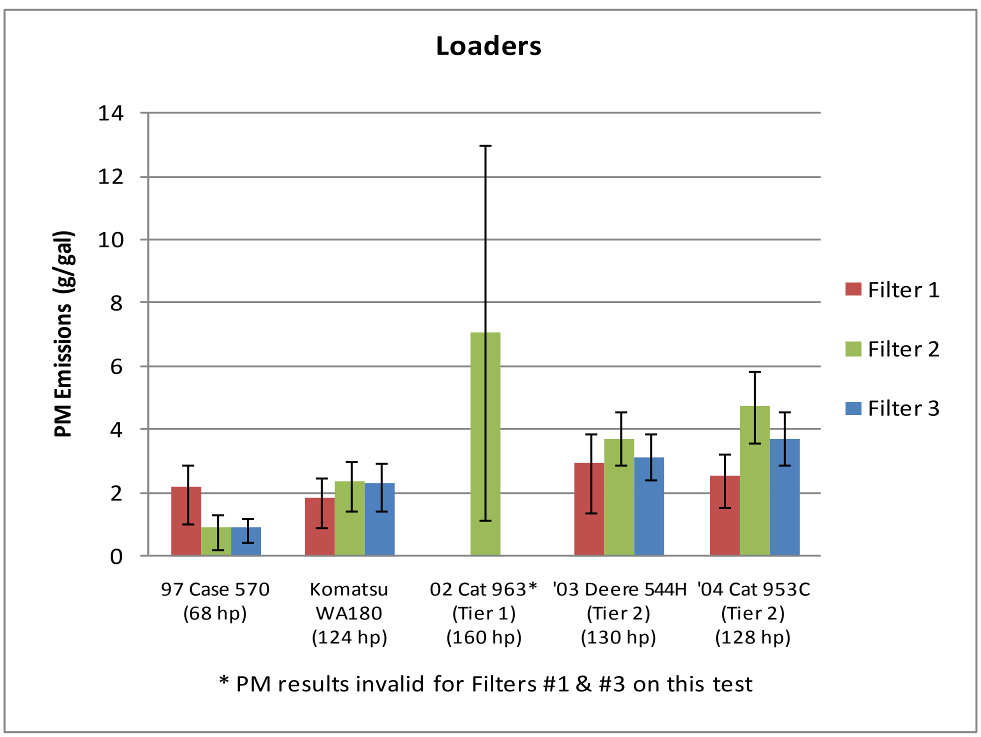


**Figure OV-26  Gaseous Emissions From Loaders, Fuel Basis, Overall Test**

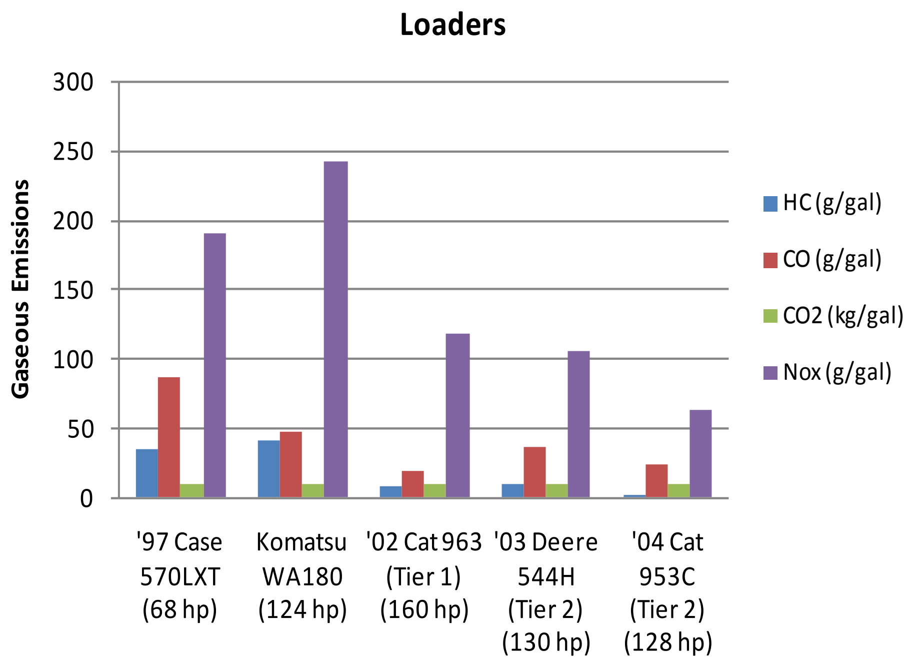



**Figure OV-27  PM Emissions From Other Equipment, Fuel Basis, Filters 1 - 3**

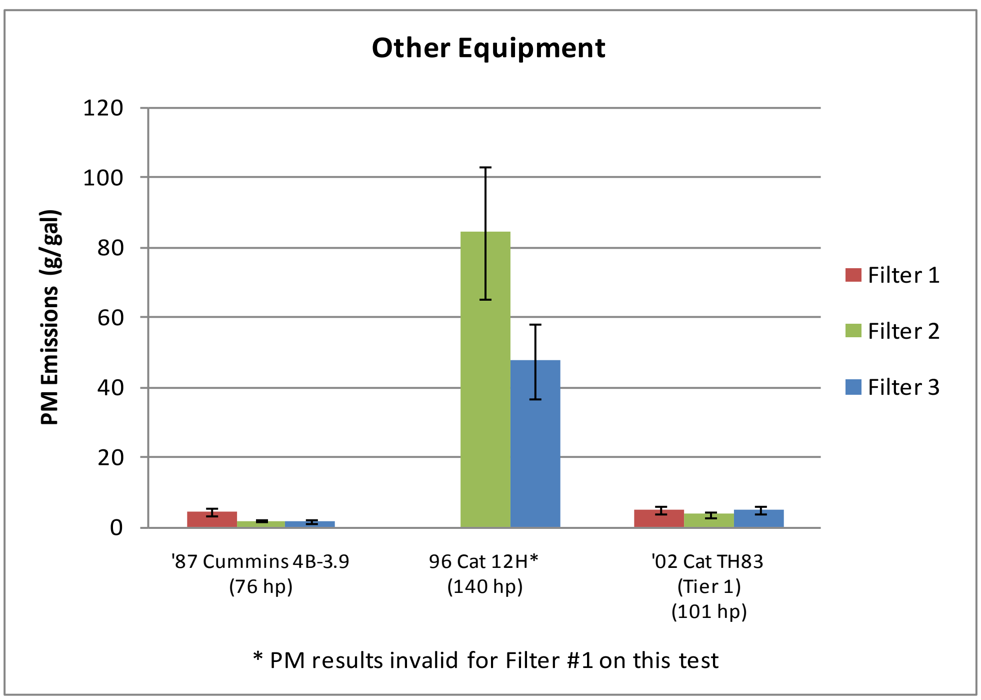
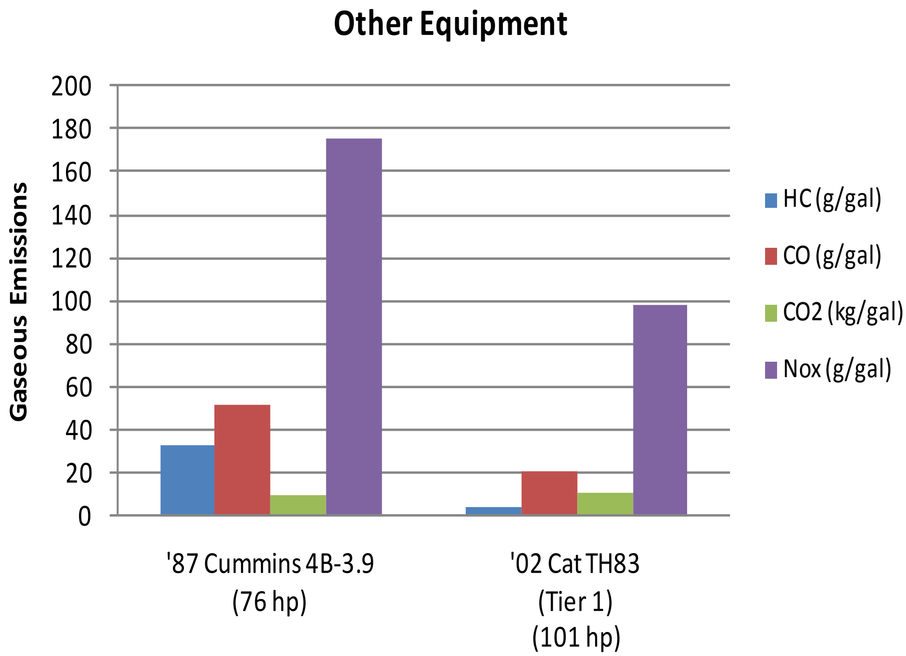


**Figure OV-28 Gaseous Emissions From Other Equipment, Fuel Basis, Overall Test**




## PAMS Results

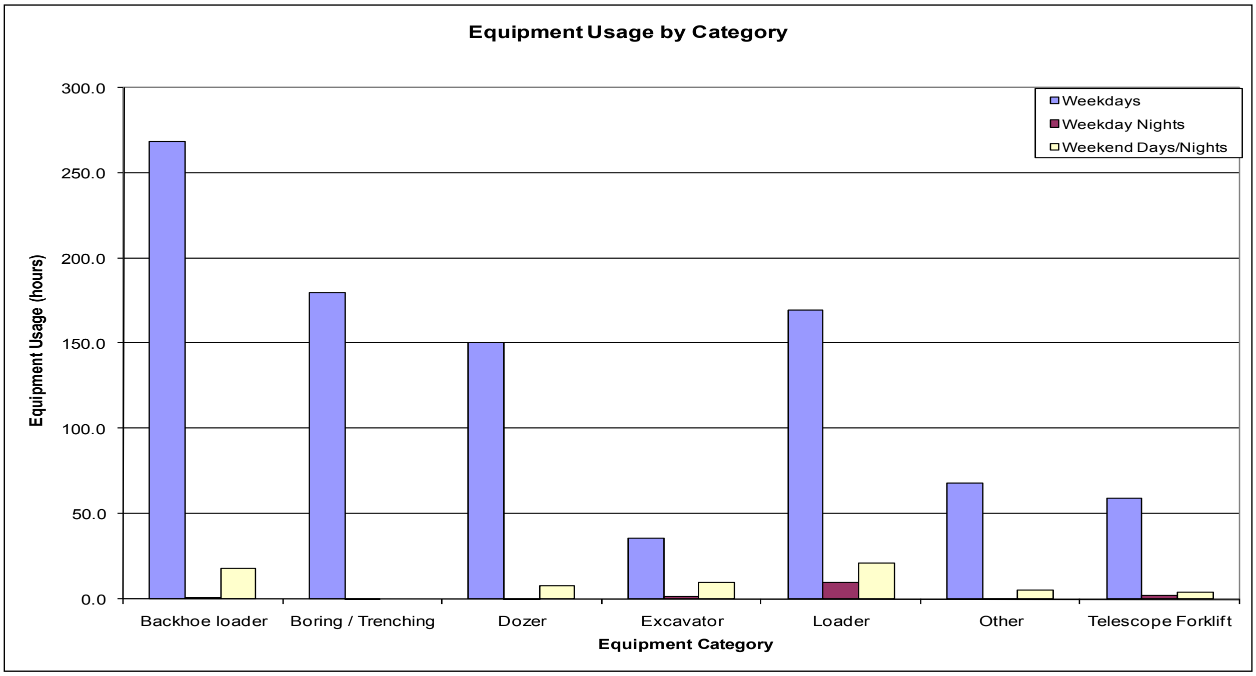
Table OV-18 lists total usage of the PAMS-instrumented equipment in hours, summed by equipment category. In this table, "weekday days" refers to operation on Mondays through Fridays, 7 am – 7:59 pm. "Weekday nights" operation is defined as operation on Mondays thru Fridays, beginning at 8 pm each evening (Monday through Friday) and ending at 6:59 am the following morning (Tuesday through Saturday). Weekend operation is defined as operation beginning Saturday at 7 am and ending Monday at 6:59 am. These summed categories are shown graphically in Figure OV-29. Figure OV-30 shows these same categories normalized to percentages.

**Table OV-18 Activity Summary by Equipment Category (in Hours)**

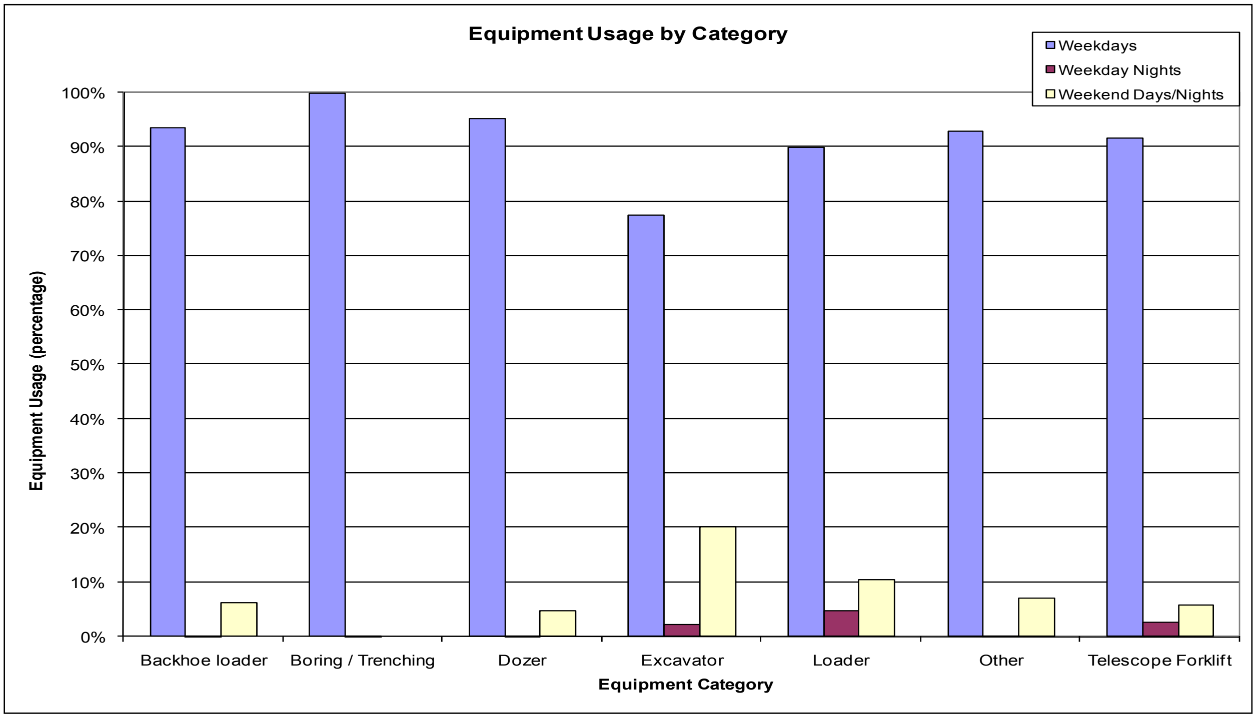
| Equipment Category | Overall | Weekday days | Weekday Nights | Weekend Days/Nights |
|---|---|---|---|---|
| Backhoe loader | 286.5 | 268.1 | 0.5 | 17.9 |
| Boring / Trenching | 179.7 | 179.6 | 0.0 | 0.0 |
| Dozer | 157.6 | 150.0 | 0.2 | 7.4 |
| Excavator | 45.7 | 35.5 | 1.0 | 9.2 |
| Loader | 199.9 | 169.3 | 9.6 | 21.0 |

| | | | | |
|---|---|---|---|---|
| Other | 72.7 | 67.6 | 0.1 | 5.1 |
| Telescope Forklift | 107.6 | 58.9 | 1.7 | 3.7 |

## Figure OV-29 Activity Summary by Equipment Category (in Hours)



### Figure OV-30  Activity Summary by Equipment Category (in Percentages)




## Study Conclusions and Recommendations

### *Sample Design and Recruitment*

**Sample frames**:   This study utilized Survey Sampling International (SSI) as the primary sampling frame and tested the use of Equipment Data Associates (EDA) as a replacement or supplemental frame.  SSI remains a viable and productive sampling frame; however, as discussed in Section 4.4, we recommend future considerations of the EDA frame as a supplemental fame in a dual-frame design to increase coverage.  The relative costs of processing EDA and SSI sample need to be considered and analyzed before implementing this recommendation.

**Two stage sampling**: Given the unexpected low prevalence of eligible establishments in the pilot study, combined with the absence of correlation between data items on the SSI sampling frame and the actual number of eligible equipment pieces for an establishment, we now believe that in most if not all situations a census of establishments will be needed even to instrument a small number of equipment pieces. If censuses are used, then issues of sample design within PSUs become moot.

However, there may be large metropolitan area such as New York City, Chicago or Los Angeles where the number of establishments for sampling would far exceed that needed for this type of study. In these cases we would resist the use of PPS sampling of establishments based on our findings in this pilot. Instead, we would encourage the creation of a few strata based on number of employees as follows: first exploit the skewed Pareto distribution of establishments to create a “large stratum” (say all establishments in the top 20th percentile according to number of employees), a “zero employee” stratum and a residual stratum. Based on our pilot study we expect that the eligibility rates to be highest among the “large stratum” and lowest among the “zero employee” stratum. This could lead to either a proportional allocation sample of establishments, or a mild optimum (Neyman) allocation stratified sample that employs ‘best estimates’ of eligibility rates across strata. But we would not recommend a PPS sample using number of employees as a measure of size.

**Use of incentives:** While the incentive tests conducted during this study were inconclusive, we cautiously recommend their use in future studies. Section 4.5 discusses a number of explanations for this including possible site or interviewer effects and differences among establishments. Clearly, it is more important to generate follow-through to instrumentation rather than assent at the recruitment stage. As such, we recommend that future research focus on this as the outcome of interest/treatment effect.

**Establishment eligibility:** Clearly, the number of eligibility requirements included in a survey impacts eligibility and ultimately response rates and sample design. Revisions were made to the questionnaire throughout the study to clarify issues such as fuel type (i.e., diesel versus gasoline-fueled equipment) or prime versus subcontractor status (the requirement of being a prime contractor was relaxed following Phase 1). Future studies with other industry sectors or other geographic locations within the construction sector should incorporate modifications made during this study. Appendix AK contains the survey questionnaires used throughout the study, by EOI phase of study.

**Survey instrument introduction:** A number of enhancements were made to the survey instrument introduction over the course of the study to reduce the likelihood that an establishment would refuse to participate in the study at the onset of the interview. The introduction should mention the Environmental Protection Agency and provide a very concise one-sentence description of the study that does not allude to eligibility (allowing prospective establishment to self-determine eligibility at the onset and giving them an easy way to opt out of the survey). For example, rather than, “…we are conducting a study with construction companies about the diesel equipment and machinery used in their daily operations” the following is preferable, "…we are conducting a study with companies about the equipment used in their daily operations."

**Advance letter:** We recommend continuing the use of an advance letter with FAQ brochure and endorsement from trade associations in future work, as these serves a critical function of pre-notifying establishments about the study.

**Fraction of establishments using diesel nonroad equipment**: About 49 percent of the establishments participating in the EOI Phases 2 and 3 survey use diesel non-road equipment. Specifically, out of 1,099 establishments, 544 reported they have (1) at least one rented or leased item of equipment or machinery that runs on diesel fuel or (2) at least 1% of equipment that run on diesel.

**Proportion of establishments employing at least one person on a part-time or full-time basis**: Data collected in the EOI Phases 2 and 3 suggest that approximately 82% of the establishments in the targeted sectors employed at least one person on a part-time or full-time basis during the previous twelve months. EOI Phase 1 data is excluded from this analysis because zero-employee establishments were excluded from the sample drawn for EOI Phase 1.

**Correlation of number of persons employed in a company and the amount of eligible equipment**: A regression analysis was employed to explore the correlation between the number of employees in a company and the amount of eligible equipment. The findings indicate that there was ***no significant correlation*** between these variables. As a result we decided to field the 0-employee establishments for EOI Phases 2 and 3.

**Variances in key variables (to inform sample size estimation for subsequent data collection efforts):** The descriptive statistics for the key variables are provided in Table OV-19. However, we recommend caution in the use of these parameters for sample size estimation. For instance, the number of paid employees is not related to equipment usage, so its use in the design of a study on nonroad equipment has limited or no value. The number of equipment pieces is useful but only available *after data collection.* It is not available prior to data collection. Nonetheless, it could be useful in determining sample size for statistics where the *establishment is the unit of analysis*. If the desired unit of analysis is nonroad diesel equipment, then the clustered nature of our sample must be addressed, since equipment pieces are clustered within establishments (as well as within work sites).

**Table OV-19 Descriptive Statistics for Key Study Variables**

| | VALID NO. OF ESTABLISHMENTS | MIN. | MAX. | MEAN | STD. DEVIATION | VARIANCE |
|---|---|---|---|---|---|---|
| No. of paid employees | 409 | 0 | 2300 | 42.07 | 175.40 | 30765.32 |
| No. of diesel equipment pieces | 454 | 1 | 3200 | 24.39 | 173.44 | 30082.61 |

***Emissions and Activity Data***

Reviewing data and emissions plots from this study suggests engine size and regulatory tier may not be meaningful stratification variables for estimating emissions rates of diesel engines, as emission rate variations seemed to be influenced less by these observational parameters as by other parameters such as engine speed range and engine load. The type of work being done (power-take off, equipment transport, or both) might be a good indicator of both engine speed ranges and loads used and may be a good operational parameter to consider when selecting stratification variables for future work. Although potentially hindered by the small sample size, data collected during this study could be evaluated in order to identify appropriate stratification variables for future studies, considering both observational and operational parameters in a regression analysis. Such an analysis was beyond the scope of work in this study.

With consideration of the small sample set of data collected, reviewing the PAMS usage data does suggest the majority of equipment usage occurs during typical weekday hours. Some types of equipment did appear to have higher night / weekend usage rates, although this could be attributed in part to rain, mud and other conditions which prevented operations during typical hours. Throughout the three ES phases of fieldwork, our experience does indicate that the type of industry in which each establishment worked did have an effect on what days and times equipment was operated. Type of work (and hence equipment type) may therefore be a good indicator of hours of operation (days / nights / weekends). Work hours did appear to be fairly consistent within establishments.

# 1.0 Introduction

The Nonroad PEMS and PAMS study was a multi-year pilot study funded and supported by the U.S. Environmental Protection Agency (EPA) and the Coordinating Research Council (CRC) which was intended to refine methods of developing larger-scale estimations of populations, usage and emissions of heavy-duty non-road diesel equipment in various economic sectors. During this pilot study, the ERG team, consisting of ERG, Sensors, Inc., NuStats, the Urban Institute, Southern Research Institute and the Desert Research Institute worked with the United States Environmental Protection Agency (EPA) to integrate statistical sampling techniques, the latest activity and emissions measurement technology and rigorous quality assurance and quality control methods to characterize in-use, real-world emissions from nonroad diesel engines within the commercial construction sector in EPA Region 7 (work was performed in the states of Iowa, Kansas and Missouri).

The study focused on commercial establishments within the construction sector (defined by NAICS code 23), with the objective of developing recruitment and data collection protocols for ultimately expanding the study to other commercial sectors that operate fleets of nonroad diesel engines (owned or leased) in their daily operations such as agriculture, mining, and utility sectors. These protocols included:

- Sample Frame – the list from which a sample of commercial establishments is drawn.
- Sample Design – the approach for randomly selecting commercial establishments within the sample frame to meet a specified sampling target.
- Recruitment Protocols – the process and materials used to (1) provide advance notice to prospective participants about the study, (2) screen establishments for eligibility as a study participant, and (3) recruit qualified establishments to participate in the study (this later process includes the use of monetary incentives). See Section 5, Fieldwork Operations, for details on these protocols.
- Data Processing and Statistical Analysis– procedures for processing and analyzing the dispositions or outcomes of sampling and recruitment stages for the purposes of data weighting and analysis.

While these protocols and data collection processes were developed, tested and modified within the construction sector, it is reasonable to expect that they will generally apply to other commercial sectors with some modifications needed to address nuances with sample frames and fleet operations that may be specific to a particular commercial sector.

In total, 549 establishments were interviewed regarding their equipment ownership and usage. From those establishments, 119 volunteered to allow project team members to conduct onsite inventories and emissions and activity measurements on their eligible nonroad equipment. Inventories were conducted at sites of 79 of those establishments, and emissions and/or activity measurements were performed at sites of 29 establishments. Emissions tests were ultimately conducted on 58 different pieces of nonroad equipment, and activity information was collected from 30 pieces of nonroad equipment. Statistical sampling was applied prior to and during fieldwork in order to randomize the recruitment and screening of participants and the selection of equipment to be instrumented, and various ways of establishing a rapport with and minimizing our testing burden on participants were explored throughout the study.

For the emissions measurements, portable on-board emission measurement systems (PEMS) were used to perform 40 CFR 1065-compliant onboard measurements of gaseous and aggregate particulate matter (PM) exhaust emissions on 50 horsepower or greater diesel engines in nonroad construction equipment. In order to withstand the rigors of testing in a nonroad environment, equipment had to be "ruggedized", and equipment modifications and enhancements were made throughout the course of the study to achieve test goals.

For the activity measurements, various commercially-available portable activity measurement systems (PAMS) were evaluated, three different types of systems purchased, and these systems were used during the work assignment to collect activity (date / time / engine speed) over a period of approximately one month. This activity testing provided information on long-term equipment usage patterns of this equipment and also provided an opportunity to test and evaluate the performance of PAMS equipment and data quality during the work assignment.

Study data was analyzed, quality assured and processed for input into the EPA Office of Transportation and Air Quality's (OTAQ's) Mobile Source Observation Database (MSOD), where it may be used to help expand and improve the data currently supporting emission inventory modeling for nonroad engines. Information regarding the sample design and field team approach is presented in this report, and study results, including sampling / recruiting results and also emissions and activity results, are provided herein. Lessons learned from this study and recommendations for future work based on what was learned during this study are also provided.

## 2.0 Background

As described in the EPA's statement of work for this work assignment, nonroad equipment contributes substantially to mobile-source emissions, with their contribution in relative terms expected to increase as emissions from highway vehicles are controlled (Kean, Sawyer & Harley 2000). Based on estimates derived from diesel fuel sales published by the Energy Information Administration (EIA 2001) and estimates from the NONROAD model, fuel consumption in nonroad equipment accounts for 15-18% of all diesel fuel supplied to the U.S. market in 2000 (57.2 billion gallons), where "diesel" includes No. 1 and No. 2 distillates (excluding kerosene, jet fuel and fuel oils). In addition, the sector selected for inclusion in this survey (construction) is important in terms of diesel fuel consumption and emissions. In the same year, this sector accounted for approximately 20% of nonroad diesel fuel consumption, which corresponds to approximately 4% of all diesel fuel consumed by mobile sources (44.9 billion gallons) where mobile sources include highway vehicles, locomotives, marine vessels and nonroad equipment (EPA, 2006).

Generally, nonroad equipment includes vehicles powered by combustion engines, designed to perform a wide variety of tasks other than street or highway transportation. Thus, the term "nonroad equipment" covers a broad variety of machines including forklifts, graders, crawler dozers, backhoe loaders, excavators and other equipment.

At the request of Congress, the National Academy of Sciences published a report on EPA's emissions inventory modeling for mobile sources (NRC 2000). A committee of technical experts was given the primary charge of conducting a detailed review of the MOBILE model, which estimates fleet average emission factors for motor vehicles. Nonetheless, the report bears mention in the context of nonroad equipment inventories because the committee also took the opportunity to make comments concerning EPA's inventory modeling for nonroad equipment. Under the heading of "Technical Issues Associated with the MOBILE Model," the committee remarked that

> *As future Tier 2 vehicle standards and corresponding sulfur-reduction regulations reduce on-road mobile-source emissions, non-road emissions will become a larger fraction of the total emissions. The NONROAD model is extremely data driven, and there are many gaps in the available data. EPA should place more emphasis on improving both the emissions factors and activity data in this model. (p. 74)*

In the executive summary, the committee emphasized the need for EPA to design and implement programs to expand and improve the data used to support emissions inventory estimation for nonroad equipment, and added that:

*The plan should include the population and activity data and real-world emissions factors for gasoline and diesel engines (p. 13).*

The recommendations in the NRC report have influenced the concept and design of EPA's new inventory model for highway vehicles, the Motor Vehicle Emissions Simulator (MOVES). Similarly, this work assignment is intended as the first step in a program to respond to recommendations concerning the quantity and representativeness of the data supporting inventory modeling for nonroad engines.

# 3.0 Study Design Overview

## 3.1 Workplan and Survey Design Development

With the goal of characterizing emissions from nonroad diesel engines, EPA and the ERG team developed a workplan that outlined the study design to characterize emissions from 50 nonroad diesel engines operated in specified counties within EPA Region 7 (in the states of Iowa, Kansas, and Missouri) by establishments in the construction sector, NAICS 23.

This section describes the key elements of the study design including the definition of the target population and coverage, a discussion of the sample frame, sample sizes and the sampling method.

### 3.1.1 Target Population

The **population of inference** for the pilot study was composed of:

> *all nonroad equipment powered by nonroad diesel engines from commercial establishments within the construction sector (defined by NAICS code 23) that are located within the geographic area of study*.

Unlike motor vehicles, for which registration databases exist, it is not practical to construct sample frames listing individual equipment pieces. To compensate for this difficulty, coverage was expressed in terms of the owners or users of equipment within the construction sector.

Thus, for this pilot study, coverage of the target population included engines owned, rented or leased by commercial establishments in the construction sector (NAICS 23) that employed at least one person on a full-time or part-time basis during the previous twelve months. Elements of the target population were identified and selected through the constituent establishments that operated this equipment.[6]

### 3.1.2 Sample Frame

The term *sampling frame* denotes the list from which a sample is drawn. Ideally, the list is all-inclusive of the target population. At the onset of this study, the ERG team employed the Comprehensive Business Samples (CBS) supplied by Survey Sampling International (SSI) of Fairfield, Connecticut as the sampling frame. SSI compiles listings from telephone directories

[6] Government and other non-commercial establishments were excluded from the target population.

and additional industry-specific sources including government listings, bank records, trade directories, city directories and proprietary sources. Listings are verified and updated on a continuous basis. Because it was the most recent sample available at the time the task was initiated, it was used (and not updated) throughout the duration of the study. [7]

### 3.1.3 Study Objectives and Sample Sizes

The study objectives called for the collection of emissions and activity data from 50 nonroad diesel engines operated within the study area. To achieve this, it was necessary to collect a total of 550 observations from two independent samples:

- Establishment sample – a sample of 500 establishments for a telephone survey, referred to as the Equipment Ownership Interview (EOI), involving the administration of an equipment ownership survey to screen and qualify establishments for the study.

- Equipment sample – a sample of establishments from which 50 equipment measurements consisting of 25 emissions measurements and 25 activity measurements would be drawn. These were establishments qualified in the Establishment sample who agreed to participate in an inventory and emissions and activity testing of their equipment fleet.[8]

The administration of the EOI was intended as a predecessor to the administration of the Equipment Sample Interview (ESI) to recruit participants for an equipment inventory and random selection of equipment for instrumentation.

Specific targets were provided for the numbers of establishments and pieces of equipment for which data were collected. Table 3.1-1 presents the targeted distribution of observations by measurement type.

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[7] As is presented later in this section, this original design was modified based on the performance of Phase 1 and subsequent data collection efforts of the study.

[8] For the 50 observations involving equipment measurements, an experiment was embedded to test for response rate effects associated with incentives. The incentive was offered to a random half of the eligible Equipment Sample subjects upon completion of the EOI (telephone) portion of the survey (and as part of the recruitment process into the inventory and measurement components of data collection).

**Table 3.1-1 Targeted Distribution of Observations by Measurement Type**

| | MEASUREMENT TYPE | ESTABLISHMENT SAMPLE | EQUIPMENT SAMPLE | |
|---|---|---|---|---|
| Economic Sector | Total—EOI and Instrumentations | Equipment Ownership Interview | Emissions Measurement | Activity Measurement |
| Construction | 550 | 500 | 25 | 25 |

The numbers of establishments recruited into the Equipment Sample via the EOI were purposely larger than the number that actually completed the emissions and/or the activity measurements. This was because the study team anticipated (1) inevitable non-cooperation post-EOI (i.e., agreed on the telephone but declined at the time of the on-site visit); and (2) recognition that a certain fraction of completed measurements would nonetheless result in unusable measurement data due to a variety of reasons (i.e., equipment ineligible, equipment failure, equipment not operated as planned or moved to another construction site). The data collection plan reflected these factors.

This pilot study was planned to be implemented in two phases for the Establishment Sample and three phases for the Equipment Samples, depending on funding levels and observed performance of the sample. The Pilot would commence with the first phase of the Establishment Sample (involving conduct of only the EOI). EOI data collection would start slowly in one of the five study areas: PSU 1. EOI Phase 2 of the Establishment Sample would follow the completion of EOI Phase 1, and a similar roll out of the Equipment sample was planned following completion of the Establishment Sample. Tables 3.1-2 and 3.1-3 provide the original plan for sample sizes by phase for the Establishment and Equipment Samples, respectively. These tables show that the Establishment Sample was to be limited to two phases of activity, while the Equipment Sample would involve three sequenced phases of activity.

**Table 3.1-2 Original Plan for Conducting Establishment Sample Surveys**

| ESTABLISHMENT SURVEY PHASE | # PSUS | TARGET # COMPLETES |
|---|---|---|
| EOIs, Phase 1 | 1 | 100 |
| EOIs, Phase 2 | 2-5 | 400 |
| TOTAL Establishment Sample | 5 | 500 |

**Table 3.1-3 Original Plan for Conducting Equipment Sample Measurements**

| MEASUREMENT TYPE (INCLUDING EOI) | ES PHASE 1 | ES PHASE 2 | ES PHASE 3 | TOTAL |
|---|---|---|---|---|
| # of PSUs | 1 | 2 | 2 | 5 |
| Activity Measurements (with oversampling) | 6 | 12 | 12 | 30 |
| Emissions Measurements (with oversampling) | 6 | 12 | 12 | 30 |

The Equipment Sample called for the conduct of an EOI (via centralized CATI), after which the incentive experiment for recruitment was given, followed by preliminary "onsite equipment inventory" interview, then followed by a face-to-face visit to the establishment to conduct a site inventory (or inventory of more than one site), and finally selection of equipment and the emissions and activity measurements. Moreover, because the EOI was the precursor to the onsite equipment inventory and instrumentation phase, the study team expected that a number of establishments in the Equipment Sample would participate in the EOI interview, then agree to a face-to-face visit but then decline to participate in the inventory and/or the emissions and/or activity testing (despite earlier indications of cooperation). As such, the EOI sample sizes for the Equipment Sample were planned larger than the final targeted number of equipment measurements in order to allow for this inevitable attrition.

The impact of this on the number of EOIs conducted in the Equipment Sample is shown in the second data row of Table 3.1-4. A total of 185 EOI interviews were expected to be needed in order to secure 60 total inventories and equipment measurements. This table also presents the by-phase distribution of inventories and instrumentations which were expected (similar to that shown in Table 3.1-3). Summaries of the actual outcomes of onsite inventories and instrumentations are provided in Section 5.6.

**Table 3.1-4 Expected Completions by Sample and Measurement Type**

| COMPLETES BY TYPE | EOI PHASE 1 | EOI PHASE 2 | ES PHASE 1 | ES PHASE 2 | ES PHASE 3 | TOTAL |
|---|---|---|---|---|---|---|
| EOI - Establishment Sample | 100 | 400 | | | | 500 |
| EOI - Equipment Sample | | | 37 | 74 | 74 | 185 |
| Inventory | 0 | 0 | 12 | 24 | 24 | 60 |
| Emissions measurements | 0 | 0 | 6 | 12 | 12 | 30 |
| Activity measurements | 0 | 0 | 6 | 12 | 12 | 30 |

The sample sizes by study phases that would be needed to achieve the target number of completions for the pilot were estimated. As shown in Table 3.1-5, a total of 2,803 selections would be needed, including the reserve sample to complete the EOIs for the Establishment Sample and the EOI portion of the Equipment Sample. It was estimated that more than 185 EOIs would need to be conducted in order to get 185 establishments agreeing to be instrumented; under these design a total of 1,588 EOIs would be necessary. However, these were conservative estimates and assumed that only ***one*** instrumentation would occur per piece of equipment (i.e., either an activity measurement or an emissions measurement, but not both).

**Table 3.1-5 Anticipated Sample Needed to Achieve Sample Targets**

| TYPE OF DATA COLLECTION | ESTABLISHMENT SAMPLE (EOI) | | EQUIPMENT SAMPLE | | | TOTAL |
|---|---|---|---|---|---|---|
| | PHASE 1 | PHASE 2 | PHASE 1 | PHASE 2 | PHASE 3 | |
| EOIs | 243 | 971 | 318 | 635 | 635 | 2803 |
| Inventory & Instrumentations | 0 | 0 | 37 | 74 | 74 | 185 |

### 3.1.4 Sampling Methods

The sample design for this pilot study employed stratified multi-stage probability sampling with probabilities proportional to size. The number of selection stages varied by the type of data collection (i.e., establishment vs. equipment samples). The survey of establishments employed two-stages of selection, while the equipment samples involved a three-stage design.

To reduce travel time and associated expense for field technicians installing and maintaining instrumentation on site, the equipment sample was drawn in three stages as follows:

- First Stage (Primary) County level
- Second Stage (Secondary) Establishment level (within county)
- Third Stage (Tertiary) Equipment piece (within establishment)

Because the first- and second-stage sampling units were different sizes, in terms of the numbers of equipment expected within each unit, the second-stage samples were drawn with probability proportional to size (PPS). This technique is commonly employed in combination with state sampling to reduce differences in the final sampling weights among individual sample units. In PPS, the first and second-state selection probabilities would then be managed to compensate for the fact that third-stage probabilities cannot be managed.

The measure of size (MOS) is ideally a measure of the units in the target population (equipment pieces—or diesel engines—in this case), or alternatively, another measure of influence that is assumed to correlate fairly strongly with the target population in each sampling unit. Lacking direct estimates of equipment populations by county or establishment, the number of employees per establishment was selected because it was assumed to be correlated to equipment population.

In the third stage, one or more eligible equipment pieces would be drawn from each selected establishment using simple random sampling (SRS). Specifics of the design at each stage are discussed below.

**First Stage.** The first stage of selection was utilized by all samples in the study and involved a sample of 5 counties (primary sampling units or PSUs) with probabilities proportional to size (pps) from the collection of counties selected within EPA Region 7. EPA designed the sample and selected these counties, which are shown in Table 3.1-6.

**Table 3.1-6 Primary Sampling Units for the Pilot Study**

| PSU | FIPS | STATE | COUNTY | EST. NO. EMPLOYEES | SAMPLING PROBABILITY |
|---|---|---|---|---|---|
| 1 | 29095 | MO | Jackson | 63,800 | 0.3063 |
| 2 | 19113 | IA | Linn | 25,400 | 0.1216 |
| 3 | 19163 | IA | Scott | 18,500 | 0.4277 |
| 4 | 29047 | MO | Clay | 16,500 | 0.3813 |
| 5 | 20177 | KS | Shawnee | 13,000 | 0.3006 |

**Second Stage.** Within each PSU, commercial establishments were the secondary sampling unit (SSU), drawn with selection probabilities based on the same measure of size used to draw the first-stage sample. For construction establishments, the establishment MOS was the estimated number of employees, as derived for use in the first stage (Table 3.1-6). After compiling the establishment frame for each PSU, an estimated number of employees was assigned to each establishment (MOS), based on its assigned size class.

EPA required that the universe of establishments be obtained from SSI with the expectation the data would contain sufficient information (i.e., number of employees) so that the same calculations can be implemented to create the MOS.

It was likely that the initial measure of size estimate ***MOS*(ij),*** when summed over the relevant establishments in county ***j,*** would not match the specific county-level total ***MOS(jg)*** used by EPA to select the first phase sample. The size measure could be adjusted accordingly so the adjusted ***MOS*(ij)*** in county ***j*** would match the corresponding MOS from the stage one sampling. Such an adjustment would have no impact on the Phase 2 selection probabilities. Nevertheless, *the distribution of adjustment factors might provide some insights regarding the performance of the proposed MOS*. For instance, if the adjustment factors were roughly equal across the sampled counties, this would suggest a robust formulation for MOS.

At stage two of sampling it would be necessary to draw independent samples by PSU. Table 3.1-5 in the preceding subsection showed the required sample sizes by sample type and phase to achieve the targeted number of completed interviews and instrumentations.

To illustrate the stage two approach, let ***m*** be the number of construction establishments selected per PSU. Furthermore, let ***MOS*(ij)*** denote the measure of size for establishment ***i*** and PSU ***j***. (In practice constructed the MOS* from the universe file obtained from SSI.)

The second stage conditional selection probability of establishment ***i*** and PSU ***j*** would be:

$$Prob(establishment\ i \mid PSU\ j) = m \times MOS^*(ij) / Sum\ i|j\{ MOS^*(ij)\}$$

The denominator sum of ***MOS*(ij)*** occurs over all establishments ***i*** in PSU ***j.*** Depending on the prevalence and sizes of construction establishments in a given PSU, the second stage selection probabilities were expected to vary significantly. Another consequence is that it was expected to be difficult or impossible to achieve the desired PSU sample size targets. That is, there was no guarantee that a nominal number of construction establishments would be available for selection from each PSU.

Considering the overall selection probability of an establishment was relevant for the equipment ownership survey in Phases I and II, letting ***MOS(j)*** denote the stage one measure of size of PSU ***j***, the overall (unconditional) probability of selecting establishment ***i*** in PSU ***j*** would be:

$$\mathbf{Prob(establishment}\ i\mathbf{)} = Prob(establishment\ i \mid PSU\ j) \times Prob(PSU\ j)$$

$$= m \times MOS^*(ij) \times 5 \times MOS(j) / \{ Sum\ j[ MOS\ (j)] \times Sum\ i|j\ [ MOS^*(ij)] \}$$

$$= c(ij) \times \{ MOS(j) / Sum\ i|j\ [ MOS^*(ij)] \}$$

$$= c(ij) \times r(j)$$

where $\mathbf{c(ij) = m \times MOS^*(ij) \times 5\ /\ Sum\ j[MOS\ (j)]}$ **and**

$r(j) = MOS(j)\ /\ Sum_{i|j}\ [\ MOS^*(ij)]$

Thus, ***c(ij)*** is proportional to ***MOS*(ij),*** and ***r(j)*** depends only on PSU ***j***.

The overall probability of an establishment would be proportional to its second stage measure of size ***MOS*(ij)*** when the ratio ***r(j)*** is a constant**.** But ***r(j)*** is the ratio of the first stage PSU measure of size ***MOS(j)*** to the summed measures of size ***Sum i|j [ MOS*(ij)]*** used in the second stage of selection. The first stage measure of size ***MOS(j)*** is summed over all establishments used in the selection of the PSUs (*the nature of the establishments used for developing the MOS was not clear*), while the second stage denominator term ***Sum i|j [ MOS*(ij)]*** is summed only over a subset of establishments—only those in PSU ***j*** for the construction sector**.**

**Third Stage.** The third stage of selection was relevant to the sampling of equipment from the equipment inventory performed prior to instrumentation. The conditional probability of selection at this last stage of sampling was simply ***1/t(i),*** where ***t(i)*** denotes the total number of equipment pieces for establishment ***i.***

Assuming the selection of one piece of equipment from each establishment, the overall selection probability of equipment piece ***h*** in establishment ***i,*** and PSU ***j*** is simply the product of the second stage overall selection probability and the conditional equipment probability ***1/t(i).*** Thus, the overall probability is written as:

$$\mathbf{Prob(equipment\ h)} = Prob(equipment\ h\ |\ establishment\ i) \times Prob(establishment\ i\ |\ PSU\ j) \times Prob(PSU\ j)$$

$$= 1/t(i) \times c(ij) \times r(j)$$

$$= 1/t(i) \times m \times MOS^*(ij) \times 5\ /\ Sum\ j[\ MOS\ (j)] \times r(j)$$

$$= \{m \times 5\ /\ Sum\ j[MOS\ (j)]\} \times \{MOS^*(ij)\ /\ t(i)\} \times r(j)$$

$$= c^* \times s(i) \times r(j)$$

Where ***r(j)*** is defined as before,

$c^* = m \times 5\ /\ Sum\ j[\ MOS\ (j)]$ = a constant, and

$s(i) = MOS^*(ij)\ /\ t(i)$

To the extent that the number of pieces of equipment in establishment ***i*** is correlated to the second stage measure of size used in selecting establishments, ***MOS*(ij),*** the factor ***s(i)*** will be constant. And if both ***s(i)*** and ***r(j)*** are constant, then the three stage design produces an equal probability of selection (epsem) sample for equipment**.** We have discussed reasons why ***r(j)*** would likely not be constant, but if the measure of size proposed by EPA was correlated with equipment pieces, then the factors ***s(i)*** would be relatively stable within the construction sector.

## 3.2 Development of the Draft Quality Assurance Project Plan (QAPP)

As part of the proposal effort, the ERG Team tailored the corporate Quality Management Plan (QMP) into a guidance document which provides corporate quality guidelines for work under this contract. In addition, a Quality Assurance Project Plan (QAPP) was developed as part of this study to provide project-specific guidelines that cover all facets of the study. This QAPP was drafted prior to the commencement of project activities, and underwent multiple revisions at different times during the project. As specified in the work assignment, the QAPP was based on the following two guidance documents:

- Requirements for Quality Assurance Project Plans. EPA QA/R-5. EPA/240/B-01/003. USEPA Office of Environmental Information. Washington, D.C. (Available at http://www.epa.gov/quality/qs-docs/r5-final.pdf ).
- Guidance for Quality Assurance Project Plans. EPA QA/G-5. EPA/240/R-02/009. USEPA Office of Environmental Information. Washington, D.C. (Available at http://www.epa.gov/quality/qs-docs/g5-final.pdf ).

The QAPP conforms to requirements specified in Section 2.1 of the work assignment, and describes the following measures:

- standard procedures for calibration of all portable measurement instruments
- standard schedules for regular calibration of portable measurement instruments, and the maintenance of permanent and retrievable records of all calibrations
- procedures or decision rules for verifying proper operation of a portable measurement system when reviewing records of calibrations, spans, or zeroes
- maintenance of operating logs for all portable measurement systems
- standard operating procedures for equipment used to perform calibrations
- standard operating procedures for portable measurement instruments (PEMS/PAMS)
- procedures for sampling and recruitment of respondents

- procedures for data transfer, entry and management
- procedures for regular transfer of all data generated within this project to the Work Assignment Manager for review and audit, and
- procedures for the protection of respondent confidentiality
- data tracking and chain of custody procedures

A copy of the QAPP, and its associated appendices, is provided in Appendix N of this report.

### 3.3 Conducting Equipment Ownership Surveys, Revising QAPP

An Equipment Ownership Interview (EOI) was administered to Phase 1 (PSU 1) survey participants during a field period running April 20, 2007 through June 20, 2007. While the protocols developed for the study administration are presented in Section 5 of this report, this section describes the general approach followed in conducting the EOI.

Prior to the administering the EOI survey, the study team conducted a number of activities with the purpose of improving response and participation rates. This included (1) securing study support from area trade associations; (2) conducting an advance mailing to prospective respondents that contains a letter and brochure informing them about the survey and assuring study confidentiality; and, (3) cognitive testing / structured interviews following Phase 1 of the establishment ownership questionnaire. Each is briefly discussed below.

- Obtain Trade industry support. Obtaining support from industry trade associations can positively influence prospective respondents decision to participate in the study (e.g., complete an Equipment Ownership Interview or agree to instrumentation during the Equipment Ownership Interview). Early in the study, contact was made with trade associations to enlist their support in the study. Specifically, the following associations agreed to and provided their logos for use in the advance letter: American Road & Transportation Builders Association, Associated Equipment Distributors, Associated General Contractors of Iowa, Associate General Contractors of Missouri, Associated General Contractors of Kansas, and the Kansas Contractors Association. Additional details on trade organization recruitment are provided in Section 5.2.

- Conduct advanced mailing. Administration of the study began with an advance letter to inform business owners of the purpose of the survey, to reassure the business owners of study participation confidentiality as described below, and to enlist their participation in the study. The advance letter also provided prospective respondents with a fact sheet containing more detailed information about the study and demonstrating industry support. The letter was printed on EPA letterhead to increase the perceived legitimacy of the survey. Prior to conducting the survey, each sample record was sent an advance mail packet containing the advance letter and information brochure, as shown in Appendices AI and AJ.

- Conduct cognitive interviews. Cognitive testing[9] of the Establishment Sample Equipment Ownership Interview was conducted after Phase 1 of the Establishment Sample Equipment Ownership Interviews in order to have the benefit of initial analysis of data and response rates. The cognitive interviews were conducted with persons who participated in the Phase 1 EOI interview. Minor adjustments to question wording and flow were made based on the cognitive test results. In addition, the cognitive interviews also assessed the effectiveness of the advance mail materials (e.g., whether the use of EPA letterhead and sponsorship of trade associations influenced their decision to participate in the study).

For the Establishment Sample, the EOI was to be conducted by telephone over two phases. In Phase 1, only the first PSU was sampled with the goal of completing 100 interviews. As previously described, within a week following receipt of the advance letter, a phone call was made to a knowledgeable respondent and the EOI was completed. Data was collected under a pledge of confidentiality that responses would be used for statistical purposes only. During collection, storage, and reporting, steps were taken to protect the identity of respondents or establishments with the information collected, as required by the workplan and the QAPP.

During data collection, NuStats monitored call attempts, dispositions and progress in completing interviews. At the completion of Phase 1 interviews, the study team processed and analyzed the data collected, revised the Equipment Ownership Questionnaire and the QAPP based upon the performance of Phase 1 data collection efforts

As part of this assessment, seven cognitive interviews were conducted as described above. The study team prepared a report that analyzed the questionnaire's performance with the final standard call dispositions, provided recommendations on revisions to the questionnaire and on the study design based on the analysis of Phase 1 data collection results.

[9] A cognitive interview provides an assessment of the mental processes (e.g., question comprehension, memory retrieval, response formation and editing) associated with the questions in a survey instrument using persons that possess similar characteristics to the survey's intended audience, involving in-person interviewing. These interviews were also used to assess the adequacy of the questionnaire flow (structure and design), and to test advance mailing materials and other aspects of the study.

### 3.4 Acquiring and Preparing EAM Equipment

The acquisition and preparation of emissions and activity measurement (EAM) equipment began in February 2007, several months before establishments were first contacted for EOIs (and participation in the study). The following sections describe the equipment used during the study and the steps taken to prepare equipment for use in the study.

#### 3.4.1 Overview of Emissions and Activity Test Equipment

The ERG team used SEMTECH-DS PEMS manufactured by Sensors, Inc. and provided by the EPA for collection of emissions data for this work assignment, and researched and acquired from commercial vendors the PAMS used for collection of activity measurements. A description of the research for and procurement of the PAMS equipment is provided in Section 3.4.3.

Under this contract, the ERG team leased a trailer from Sensors, Inc. which was used to house, transport and maintain the PEMS and all associated support equipment. Sensors personnel transported this trailer to and from EPA Region 7 and the various work locations within the region using a flatbed truck with a boom lift, which was also part of the lease agreement. This boom lift allowed the PEMS installation team members to place the approximately 400-pound PEMS rack onto each piece of equipment being tested. Figure 3.4-1 shows the PEMS rack on a rolling cart, prior to installation on a backhoe loader, with the leased SEMTECH support trailer in the background. Figure 3.4-2 shows the leased four-wheel drive truck with flatbed-mounted boom lift being used for installation of the PEMS rack on the backhoe loader.

Figure 3.4-1  PEMS Rack and Trailer


Figure 3.4-2  Installation of PEMS Rack Using Truck-Mounted Boom

For emissions measurements, the PEMS rack collected the following information in one-second intervals, as specified in the work assignment:

- engine speed (revolutions per minute, rpm),
- oxygen concentration in the exhaust stream ([$O_2$], percent by weight, wt%),
- carbon-dioxide concentration in the exhaust stream ([CO2], percent by weight, wt%),
- oxides of nitrogen concentration in the exhaust stream ([$NO_x$], parts per million, ppm),
- carbon monoxide concentration in the exhaust stream ([CO], percent by weight, wt%)
- total hydrocarbon concentration in the exhaust stream, ([THC] parts per million, ppm)
- aggregate particulate matter by gravimetric methods (g),
- ambient temperature (°C),
- exhaust temperature (°C),
- exhaust mass flow rate (via the Sensors EFM)
- relative humidity (%), and
- barometric pressure (kilo-Pascals, kPa).
- date/time stamp.

The following derived measurements, also specified in the work assignment, were provided for all emissions measurements:

- exhaust flow volume (adjusted to standard temperature and pressure, cu. ft/min (scfm)),
- fuel flow volume (g/sec, gal/sec),
- carbon dioxide emission rate (g/sec, g/kg fuel),
- pollutant emission rates for NOx, CO, THC, and PM, (g/sec, g/gal).

The PEMS rack consisted of the EPA-provided SEMTECH-DS PEMS (as well as a backup SEMTECH-DS PEMS), a Sensors micro-proportional Sampler (MPS), a Sensors Gravimetric Filter Sampler and 2", 3", 4" and 5" diameter exhaust flowmeters (EFMs). Flowmeter diameter selection was based on each particular installation. A small air compressor and filtration unit was used to operate the MPS, and to automatically back-purge the EFM pressure lines at specified intervals. This air compressor operated using A/C power provided by a Honda portable generator. Automated zero calibrations of the SEMTECH-DS analyzers were performed throughout the sampling period using ambient air which was scrubbed with a carbon filter and a particulate filter.

All emissions measurements throughout the study included gravimetric filter sampling using a micro-proportional sampling system (MPS) and Sensors' 3-chamber gravimetric filter sampler provided by EPA . The SEMTECH MPS is a two-stage dilute proportional sampler in which a proportional sample flow is extracted from the exhaust flow. This sample flow is controlled to be a constant fraction of the varying exhaust flow by way of a two-stage dilution system. The first stage performs a fine "valving" function and the second stage is a venturi which adds the major part of the dilution flow and forces the sample plus the primary dilution flow to exit the MPS (Fulper, Giannelli, et al., 2010). The MPS total flow (sample flow plus primary and secondary dilution) was held to a constant rate of approximately 12.5 liters per minute in this study. Maximum exhaust flowrates and major and minor dilution ratios were tailored for each installation based on engine size and anticipated workload according to guidelines in the PEMS installation SOPs (Appendix F). Additional information regarding flowrates and system settings are available in Appendix F (PEMS Installation SOPS) and Appendix I (PEMS Data QC Criteria).

Gravimetric PM samples were collected on 47mm Teflon filters housed in the gravimetric filter sampling unit which was heated to 1065 specifications. Filter flow was maintained at a rate of approximately 18 liters per minute. The filter sampler automatically switched between the three gravimetric filters, based on an integral timer, input voltage signal indicating engine start, or the filter could also be switched by a wireless remote electrical signal. One filter was used to capture the first start at the beginning of the day or shift (generally a 10-minute cold-start), and the second and third filters captured continued warm operation or hot start emissions (20-minutes sampling for the second filter and 30-minutes sampling for the third filter). Each "start" episode was defined as the first ten (10) minutes of operation after the engine was turned on.

For testing during PSU1, Desert Research Institute (DRI) supplied pre-weighed 47 mm Teflon filters to the PEMS installation team in pre-loaded URG-2000-30FL filter cassettes provided by EPA. DRI provided all gravimetric laboratory analysis for PSU 1 (and EPA subsequently provided the filters and gravimetric laboratory analysis in ES Phases 2 and 3 of the study). After PM collection, filter samples were kept cold and returned to the DRI or EPA laboratories in the URG filter cassettes for post-test gravimetric measurements. Resultant data was provided to ERG on a total mass per filter basis (i.e., mg/filter).

Dynamic and field gravimetric filter blanks were collected during the study in order to identify and quantify any transport and handing contamination on the gravimetric filters. Field blanks were treated as actual samples, including all shipping, handling and transport to the field during testing, although they were never removed from their shipping cassettes or placed in the gravimetric sample system holder. Dynamic blanks were also treated as actual samples but in addition to field handling they were placed in the gravimetric sample system holder rack during emissions testing. However, no exhaust sample (or air) was routed through the dynamic blanks (the flow-control solenoid on the gravimetric sampler which held the dynamic blank remained closed during testing). Comparison of the measurement results for dynamic blanks and field blanks can help provide information regarding potential contamination in the filter holder as well as any leaks in the flow-control solenoids used to isolate that specific filter holder in which the dynamic blank was placed. Five percent of all filters were designated as field blanks and five percent as dynamic blanks, as defined in Appendix K (Onsite Installation Manager SOPs).

Initial study design included the use of a carousel-equipped quartz crystal microbalance (cQCM) to allow up to 8-hours of continuous PM measurement. However, since cQCM availability was limited due to EPA's concurrent Heavy-Duty In-use Verification Program and the double-dilution which would be required to operate the cQCM would require extensive PEMS rack modifications beyond the project's budget and schedule constraints, PM emissions measurements were limited to gravimetric filter sampling and no continuous sampling was performed.

ERG acquired "core" portable activity measurement systems (PAMS) conforming to the PAMS specifications outlined in the work assignment. These systems measured and recorded engine on and off times, engine speed and associated date and time stamps over approximately one month for each activity instrumentation. Section 3.4.3 describes the PAMS research and purchase performed in support of this work assignment.

### 3.4.2 Fabrication of the PEMS Equipment Rack

Prior to the start of fieldwork, Sensors Inc., under subcontract to ERG, fabricated an enclosed rack to house all PEMS sampling equipment, including the SEMTECH-DS PEMS, exhaust flow meter and heated sample line, external weather station, the micro-proportional sampler (MPS), air compressor and flow control unit to provide filtered dilution air, the three-stage 47mm gravimetric sampling system, a rotary vane vacuum pump for filter sampling, power supply and backup battery, nitrogen bottle for switching gravimetric filter solenoids and Carousel Quartz Crystal Microbalance (cQCM) continuous PM sampling system (although the cQCM was not used during this study). Figures 3.4-3 and 3.4-4 show the PEMS rack during construction, before the side covers were installed. In these images, the gravimetric sampling system is not yet housed in the PM filter box, and several components (such as the air compressor and nitrogen bottle) are not included or cannot be seen. This rack was used throughout the work assignment.

**Figure 3.4-3 PEMS Rack During Construction (open sides), Front**

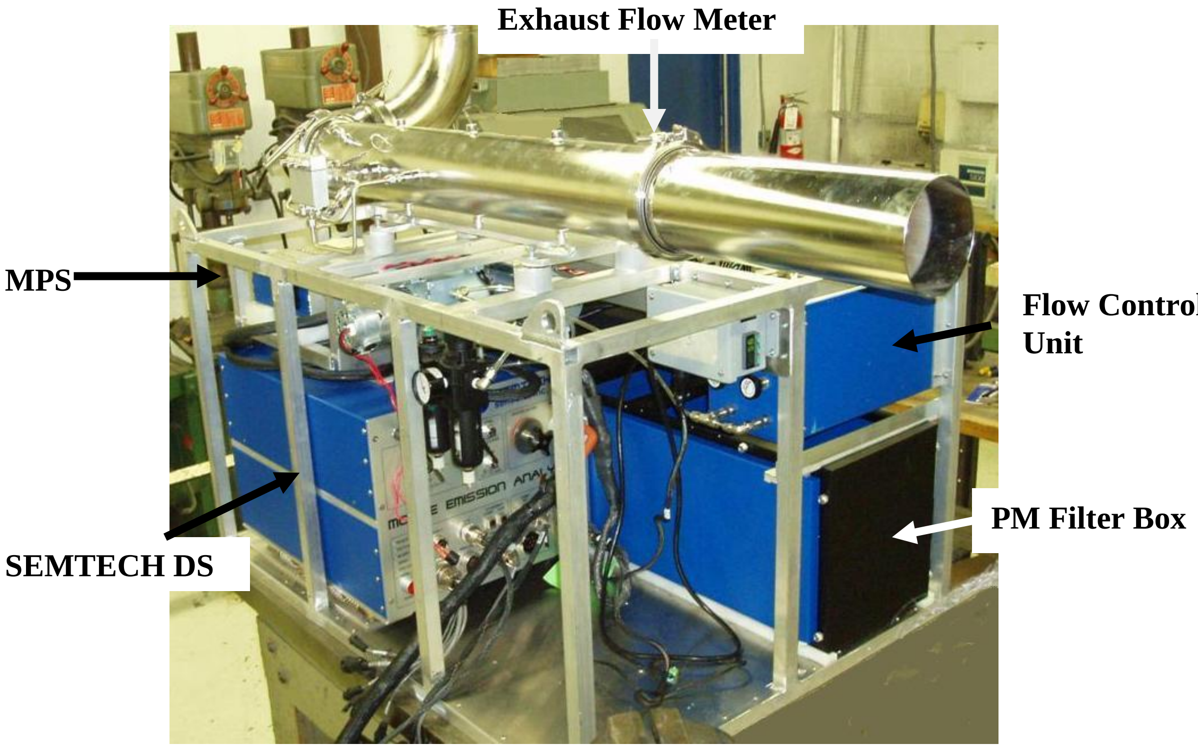
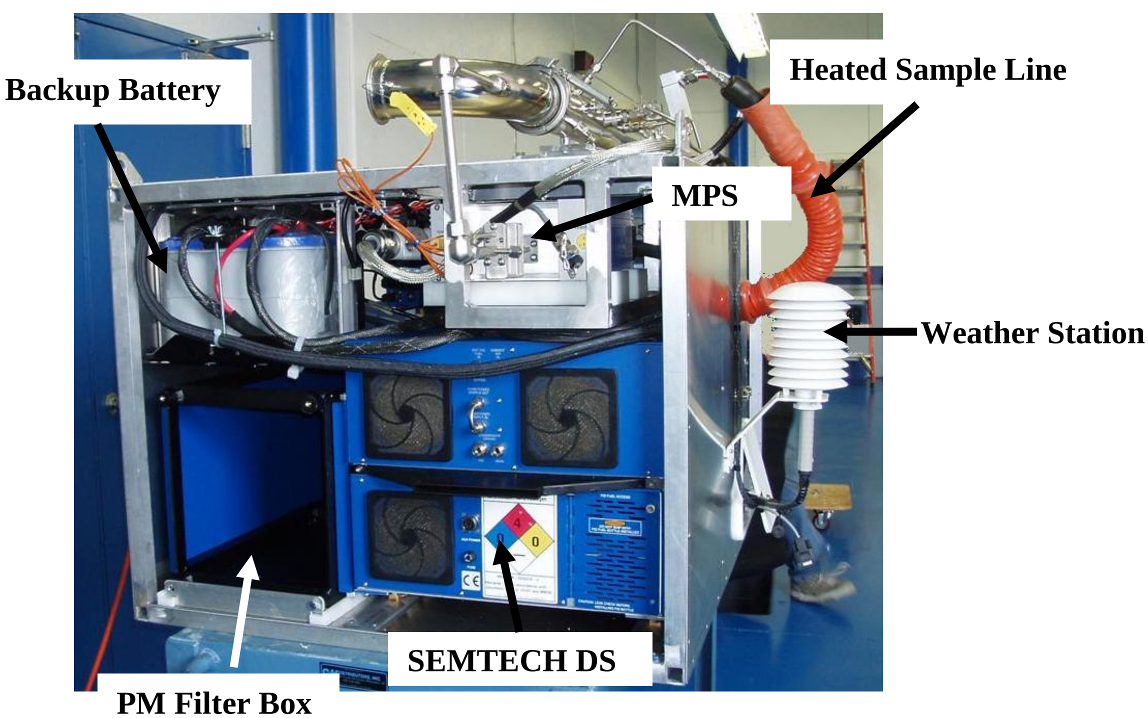



**Figure 3.4-4 PEMS Rack During Construction (open sides), Rear**



### 3.4.3 Acquisition and Preparation of PAMS Equipment

Prior to the start of fieldwork, ERG was tasked with identifying portable activity measurement systems (PAMS) that could be used to collect activity measurements. Cost and conformance with work assignment specifications (as listed in Appendix C, PAMS Specifications, of the work assignment) were used as the primary basis for evaluation, with additional consideration given to factors such as a qualitative assessment of overall product design and anticipated responsiveness and support of the PAMS supplier.

Market research was conducted in order to identify the universe of candidates from which the most suitable units could be selected. Although no PAMS were identified which conformed entirely to the PAMS Specification, several candidates were identified which did satisfy a number of the requirements, especially with respect to "core" units. Once these units were identified, primary consideration was given to factors such as unit cost, ability to automatically shift into "sleep" mode and auto-initiate, ability to operate from the vehicle or equipment's power source with minimal electrical current drain, OBD/CAN datastream communication capabilities, availability of additional analog and digital input channels for auxiliary sensor inputs, and ability to be placed into service without the need to independently develop acquisition and configuration software (i.e., units are provided with suitable configuration and processing software). Although units meeting only the "core" specification requirements were considered during our search, emphasis was placed on those units that could be modularly expanded into "comprehensive" units. In this way, the PAMS selected for this study could also be used in future studies with different system requirements.

Nine systems were identified which appeared to meet a number of the critical PAMS Specification requirements. Each of these units was investigated to assess overall conformance with the specification. Manufacturers and distributors were contacted in order to obtain technical information, cost information and demonstrations of interfaces and capabilities. Ratings were assigned based on how well each unit satisfied the PAMS Specification requirements. Eventually, ERG recommended purchasing dataloggers from three manufacturers, and in coordination with EPA, ERG then purchased only enough units in order to perform testing in the first phase of the study (6 activity tests, plus possible concurrent testing during emissions testing, and a backup unit). The initial purchase was limited to only enough units for the first phase in order to allow additional evaluation of these systems to be made regarding during ES Phase 1 testing, prior to a second purchase order being placed for the following two phases of the study (in which 12 activity tests plus backups would be necessary). For ES Phase 1, five Corsa EZII

Dataloggers, one Isaac V8 Sealed Datalogger and one Hemdata DAWN-LOG16 datalogger were purchased. Figure 3.4-5 shows a Corsa datalogger, an Isaac datalogger, and the Hemdata DAWN-LOG16 datalogger which were part of our initial purchase for this study.

**Figure 3.4-5 Corsa EZII, Isaac V8, and HEMDATA Dawn Dataloggers**

Appendix O contains three memos, the first two describe results of the market review of dataloggers and recommendations for purchasing dataloggers for ES Phase 1 of the study, and the third memo provides recommendations for purchasing five additional Isaac dataloggers to be used for the remainder of the study (ES Phases 2 and 3). In all, five Corsa dataloggers, six Isaac dataloggers and one Hemdata datalogger were purchased for support of this study. EPA provided an additional two Corsa dataloggers which were also used during field testing.

### 3.4.4 Preliminary Installation and Testing of EAM Equipment

Prior to the commencement of field activities, EPA, Sensors, ERG and SRI assembled a "mock-up" of the emissions and activity measurement systems on a piece of diesel equipment at Sensors' facility in Saline, Michigan. At this time, Sensors also provided training on the installation, operation and maintenance of the gaseous and particulate sampling systems, and ERG provided training on installation and operation of the PAMS systems. This "mock-up" served several purposes, including:

- Installation team members were able to increase their familiarity with equipment and procedures to be used in the field
- Team members were able to identify and acquire (or develop) remaining equipment, tools, materials and procedures that were lacking prior to the start of field activities
- Previously unforeseen technical or logistical challenges were identified and resolved prior to field activities
- Equipment operation was confirmed and systematic performance was evaluated and optimized
- A gravimetric filter "blind" comparison study between DRI and EPA was performed, and
- All consumables required for field testing were sourced and acquired

### 3.4.5 Gravimetric Particulate Matter Blind Study

The ERG team coordinated a round of interlaboratory gravimetric mass measurement comparisons between EPA and DRI prior to ES Phase 1 emission testing. This "blind study" was conducted in the following sequence:

1) DRI pre-weighed and sent 12 Teflon filters with unique identification numbers to EPA in EPA-provided filter holders (URG-2000-30FL filter cassettes). DRI provided these pre-weights, along with filter ID, to ERG.

2) EPA weighed these filters (pre-weights) and collected samples on 8 of these filters. Four of these filters were treated as field/transport blanks. EPA provided these pre-weights, along with filter ID, to ERG.

3) After collecting samples on 8 of these filters, EPA re-weighed the filters and provided these post-weights, along with Filter ID, to ERG.

3) All twelve filters (including the four blanks) were then returned to DRI. DRI weighed all twelve filters, then removed a tiny portion from the filter ring on one of the blank filters. DRI then re-weighed the one altered blank, and provided all weights, along with filter ID, to ERG. DRI then sent these twelve filters to EPA.

4) EPA then weighed all twelve filters and provided these post-weights, along with filter IDs, to ERG

Results of the blind study are provided in Section 6.2.1.

## 3.5 Overview of Fieldwork Activities

The fieldwork for this study was conducted in three phases (ES Phases 1, 2 and 3), encompassing testing throughout 5 counties, or Primary Sampling Units (PSUs). Only one county (PSU 1) was sampled in ES Phase 1, while two counties each were sampled in ES Phases 2 and 3 (PSUs 2 and 3 were sampled in ES Phase 2, and PSUs 4 and 5 were sampled in ES Phase 3). The work assignment specified a total of 25 emissions and 25 activity measurements to be conducted over the course of the five-county study (five emission and five activity measurements in each county). However, more tests were attempted than were specified in the work assignment to account for loss of sample due to equipment or data issues. In addition, several weeks of PEMS testing were added to the scope of work during ES Phase 3, so a total of 40 emissions and 30 activity measurements were ultimately conducted during the study. Table 3.5-1 provides a summary of emissions testing conducted throughout the three phases of the study.

**Table 3.5-1 Summary of data collected throughout the Nonroad PEMS Study**

| | PEMS | | PEMS Successful | | | PAMS | | |
|---|---|---|---|---|---|---|---|---|
| **ES Phase / PSU** | **Target PEMS** | **PEMS Attempts** | **Gaseous** | **PM** | **RPM** | **Target** | **Install Attempts** | **Data Collected** |
| ES Ph 1, Summer 07<br>Jackson, MO (PSU 1) | 5 | 6 | 3 | 2 | 1 | 5 | 7 | 7 |
| ES Ph 2, Fall 07<br>Linn, IA (PSU 2) &<br>Scott, IA (PSU 3) | 10 | 13 | 10 | 10 | 9 | 10 | 11 | 10 |
| ES Ph3, Summer&Fall 08<br>Clay, MO (PSU 4) &<br>Shawnee, KS (PSU 5) | 16 | 21 | 16 | 15 | 15 | 10 | 12 | 12 |
| **Totals** | **31** | **40** | **29** | **27** | **25** | **25** | **30** | **29** |

At the outset of fieldwork, the sampling plan permitted up to four pieces of equipment (two emissions measurements and two activity measurements) to be sampled per establishment. However, EPA and the ERG team decided to allow some of the sampled pieces of equipment to be measured for *both* activity and emissions (which would reduce the total number of pieces of equipment sampled per site). In addition, during the course of the work assignment, the teams discovered that fewer establishments used PEMS-eligible equipment than originally anticipated. Because of this, PEMS sampling requirements were relaxed to allow up to five pieces of equipment to be sampled per establishment (three emissions and two activity measurements). Again, some of these sampled pieces could receive both emissions and activity measurements.

The following subsections describe the inventory and equipment selection process used throughout the study.

### 3.5.1 Conducting the Onsite Inventory and Selecting Equipment to Test

As previously described, initial contact with each establishment was made by NuStats' call center, Datasource. A subset of establishments contacted by Datasource were solicited for and agreed to participate in onsite inventories and emissions and activity measurements (field testing). For those establishments who agreed to participate, NuStats transferred to ERG (via a secure FTP site) all relevant establishment information, including equipment counts and contact information. Updated information was generally posted at least twice per week, or more frequently if needed.

Personnel in ERG's Kansas City office retrieved the establishment information from the secure FTP site and attempted to call each establishment. Inventory appointments were scheduled for each participating establishment and details regarding locations, times and contact information for the onsite inventories were established. Inventory appointment information was then transmitted to the ERG onsite manager and the ERG inventory team leader.

Inventories were either scheduled to occur at a specific work site or instead to be initiated at a general location, usually the establishment office. If the meeting took place at the establishment office and a choice was provided regarding sites which could be inventoried, the ERG inventory team leader selected one or two sites at which to conduct inventories. When more than one site was available for inventory, the ERG inventory team leader had the discretion to decide whether one or two sites would be inventoried. Once a decision was made regarding the number of sites to be inventoried, the inventory team was then required to inventory all sites selected (even if an abundant amount of equipment suitable for instrumentation was identified at the first site inventoried). If more than two sites were available to inventory, the inventory team leader randomly selected which one or two sites would be inventoried. This was only necessary if more sites were available for inventory than were actually to be inventoried.

For each site inventoried, information regarding all equipment belonging to, leased by, or used by a particular establishment was collected on a site inventory form, as shown in Appendix C. Sufficient information was gathered for each piece of equipment in order to allow determination of equipment model year and engine power using supplemental information, such as EquipmentWatch or other commercially available equipment specification resources. Equipment serial number and cumulative hours of use (from the equipment's hour meter) were recorded and each piece of equipment's PEMS and PAMS testability was also assessed. In order to help inventory personnel locate serial numbers and ensure accurate data collection, guidelines were made available to field personnel describing common serial number locations and formats for various types of nonroad equipment, such as the "Serial Number Location Index" provided in the Equipment Watch Serial Number Guide.

Digital photographs of equipment, serial numbers and equipment specification tags were taken whenever possible, to help clarify or correct any ambiguous or inaccurate information recorded during on-site inventories. Photographs were also taken of engine tags, when possible, in order to help confirm horsepower ratings. Maintenance hours written on or near the equipment's oil filter were also recorded in order to help confirm hour meter information.

Inventory information collected in the field was entered into a master spreadsheet posted on a project-specific secure server. Hardcopy inventory forms were also sent to ERG's Austin office to allow independent confirmation of data which had been entered. Also in Austin, equipment horsepower and model year information was determined using equipment specification literature. Information pertaining to the equipment's age, engine size, and cumulative usage was used to assign each piece of equipment to a specific weighted bin for PEMS or PAMS selection, as described in more detail in Section 5.1.3, Equipment Sampling in The Field.

After equipment was classified in the weighted stratification bins, individual pieces of equipment were selected for PEMS and PAMS instrumentation by ERG's Austin staff. Each eligible piece of equipment was selected either as a primary, or "first choice" piece of equipment, or as "backup" equipment in case one or more of the primary pieces of equipment could not be tested. After the equipment information entry was verified and PEMS and PAMS instrumentation selections were made, all information was updated in the master equipment inventory spreadsheet, and the spreadsheet was posted back to the project secure server for onsite field staff. The process for selecting equipment is described in more detail in Section 5.1.3.

A complete list of equipment inventoried for each establishment in each phase of the study, including equipment selection results, is provided in Appendix W. Establishment-specific identifiers (names, addresses and ID numbers) have been removed from this list but will be provided as part of the final deliverable to EPA for this study. Additional details regarding onsite inventory tasks are provided in Appendix J.

### 3.5.2 Performing PEMS and PAMS Testing

After equipment selection for PEMS and PAMS instrumentation, the ERG onsite installation manager scheduled instrumentations with the appropriate establishment contact, sought permission to instrument the specific pieces of equipment, and asked the site contact about each selected piece of equipment's general usage and anticipated usage during the measurement period (as specified in questions 8-11 of Appendix B, Onsite Equipment Questions). If the site contact indicated the equipment was not to be used or not available for testing during the anticipated measurement period, an alternate piece of equipment was selected for instrumentation from the list of backup equipment. Backup equipment selections were made according to numerical rankings, as shown in Appendix W. PAMS installation and PEMS testing appointments were scheduled and conducted independently.

#### *3.5.2.1 PAMS Installations*

PAMS installations were performed at the outset of each phase of testing, prior to the start of PEMS testing. PAMS units were then revisited, monitored and maintained throughout the PEMS test period for each phase of the study. Teams of two to three people performed the PAMS installations, and on average installed two PAMS per day (typically at the same site or establishment). Both Corsa and Isaac PAMS units were used during each phase, and engine speed (revolutions per minute, or RPM) was collected in several different ways, including via a Capelec voltage processor connected to the equipment's battery, an optical sensor directed at a rotating object to which reflective tape was applied, a magnetic pickup mounted near a rotating object to which a magnet was affixed, or by non-destructively tapping into the equipment's electronic tachometer signal. Non-destructive taps were accomplished using supplemental connectors with harnesses which connected inline with the equipment's original harness.

In ES Phase 1, an attempt was made to acquire ***two*** independent RPM signals for each PAMS installation, usually via a Capelec RPM device and an optical or magnetic RPM device or the equipment's own RPM signal (using the non-destructive tap). Although it was recognized that collecting two RPM signals would pose additional complications during data processing (i.e., trying to determine the "correct" RPM), this was done to in order to increase the likelihood of obtaining a valid RPM signal in the event one of the signals was lost or incorrect. Dual RPM collection (and the use of Capelec devices) was largely abandoned in the second and third phases of the fieldwork (ES Phases 2 and 3).

In ES Phase 1, PAMS were either left "active" or configured to switch into "active" mode (or into "standby" mode) based on RPM, equipment battery voltage changes, or a switched power signal. For Corsa dataloggers, standby mode was found to be problematic for equipment that was inactive for several or more days, as this could drain batteries that were already weak (the standby current drain for Corsa dataloggers was approximately 175 mA). Therefore, in ES Phases 2 and 3, Corsa dataloggers were installed to be "dead" (draw no "standby" power) when the equipment was turned off. This was accomplished by using switched power as the main power source for the logger. For the Isaac dataloggers, installation teams typically attempted to provide constant input voltage to the unit, with a supplemental switched 12V signal to indicate key on / key off condition. Occasionally, it was not possible to use this configuration, and either switched power was used for the main power, or a constant (non-switched) power source powered the PAMS unit.

For units that went into "standby" mode or were switched entirely dead, some delay was experienced when the equipment was first turned on. Testing showed that on average, Corsa dataloggers required approximately four seconds to awaken from "dead" mode after switched power was provided, and Isaac dataloggers required about 2 seconds to awaken from "dead" mode. Once a Corsa or Isaac unit was "active" (recording data), engine RPM data had an approximately 2 to 3 second delay. Results of data acquisition delay testing are provided in Appendix AE, PAMS Acquisition Delay Test Results. Details regarding configurations, equipment used, calibrations performed and other details on all PAMS installations are provided in Appendix U, PEMS and PAMS Testing Details.

#### *3.5.2.2 PEMS Testing*

Emissions measurements were usually performed by three person teams, with a fourth field technician providing fieldwork management, PEMS rack mounting support, testing oversight and other fieldwork logistic support. Emission measurements were typically gathered over a one-day period in an effort to collect emissions information throughout the equipment's entire work day. PEMS installation, operation and maintenance was scheduled and performed in such a way as to minimize interruption of equipment use. PEMS instrumentation teams generally performed installations during each site's non-working hours (after the equipment was no longer needed for that working day). Hence, PEMS installations usually took place the evening prior to the day of testing, and the instrumentation team would then arrive the next morning at least two hours prior to site operations to warm-up, calibrate and verify the equipment's operation prior to emissions testing. This schedule usually allowed the PEMS instrumentation team to obtain cold-start emissions data for both gaseous pollutants and PM. However, occasionally it was not possible to obtain cold start data because of inaccessibility of equipment during facility off-hours. Whenever possible, installations were scheduled and performed at times when equipment was to be dormant for 12 or more hours (in order to get true "cold-start" results).

For every PEMS and PAMS instrumentation, detailed information pertaining to the equipment being instrumented as well as calibration, filter sampling and other PEMS and PAMs test details were collected on PEMS and PAMS instrumentation forms, shown in Appendix E. A compilation of all this information collected for all PEMS and PAMS instrumentations throughout the study is provided in Appendix U. The information in Appendix U will also be provided as part of the MSOD data submission for this project. In Appendix U (and elsewhere), the primary key field for each test is an eight digit test ID number. The first four digits of the test ID correspond to the last four digits of the unique establishment ID (assigned by NuStats) and the last four digits of the test ID correspond to the last four digits of the chassis serial number of the equipment being tested.

For both PEMS and PAMS testing, field staff followed the methodology provided in the project QAPP and associated standard operating procedures (SOPs). Significant detail was associated with PEMS and PAMS instrumentations, and procedural training was provided to all team members prior to fieldwork. PEMS and PAMS SOPs are provided in Appendices F and G, respectively. Training and SOPs were also provided for other facets of PEMS and PAMS testing, including gravimetric filter handing (Appendix L), oil and diesel fuel sampling (Appendix M), onsite manager responsibilities (Appendices J and K) and QA checks of PEMS results (Appendix I). Quality control steps were integrated into all fieldwork processes in an effort to identify and correct any problems as soon as possible.

Daily calibrations of PEMS equipment were performed and results are provided in Appendices Q, R and S. In addition, laboratory calibration and verification of flowmeter measurements and SEMTECH gaseous measurement linearity results were performed by Sensors, Inc. prior to and following each phase of fieldwork and are being compiled by EPA. Laboratory results which have been made available are provided in Appendices AB and AC.

PEMS installation teams attempted to collect diesel fuel and crankcase lubricating oil samples on all pieces of equipment that received emissions measurements. Occasionally, it was not possible to collect a sample because of a locked or inaccessible filler neck, anti-siphon equipment, or an inability to access the engine crankcase oil through the oil dipstick or fill tube. All fuel and oil samples which were collected were stored and shipped in appropriate containers provided by EPA, according to guidelines listed in Appendix M, Oil and Diesel Sampling SOPs. Fuels samples were gathered so that adjustments can be made to the emission measurements based on fuel properties (i.e density, C/H ratios, etc). Oil samples were taked because they might be able to determine the engine status or wear. All fuel and oil samples which were collected were stored and shipped in appropriate containers provided by EPA.

All samples were stored in the Sensors support trailer and returned to EPA at the end of each phase of testing.

Gravimetric filters were loaded into the filter sampling equipment prior to each test and switched during breaks in equipment operation. Gravimetric filters were transported and handled in plastic holders sealed in Ziploc plastic bags and carried/stored in small ice-chest coolers. However, since these filters were loaded in the field, they were briefly exposed to ambient contamination as they were removed from their bags and holders and placed in the sampling equipment. An effort was made to shelter filters from wind during loading (to prevent filter contamination). Although wind speed was not recorded during the study, dynamic and field blanks were collected to help quantify the extent of ambient contamination on the PM results. Dynamic and field blank results are presented in Section 6.2.1 (PM Filter Weights).

As described in Section 3.4.1, an attempt was made to capture PM emissions from the first 10 minutes of cold-start operation with the first filter used each day. The second and third filters captured continued warm operation or hot start emissions (generally 20-minutes sampling for the second filter and 30-minutes sampling for the third filter). If testing permitted, filters were switched during the day's operations to obtain additional PM data. The fourth and subsequent filters captured continued warm operation or hot start emissions. Filters were not dedicated to a specific type of operation, and operations (and work load) varied from test to test and filter to filter. Appendix V (PEMS Filter Log) lists mass weights and sampling information for each sampled filter, including sample type such as cold start, warm operation, hot start, blank, etc. Appendix AH (PEMS Measurement Results) lists sample times and by-filter emissions for all sampled filters.

Significant differences were seen in equipment operation and workloads from job site to job site and from test to test. For instance, at one job site a backhoe was used to gently move piles of loose, fine aggregate soil, while at another job site an excavator was heavily loaded while excavating deep, rocky compacted soil. In addition to job demands and soil conditions, the overall operation of the equipment varied widely from site to site (and person to person). For example, in one test, a backhoe was gently used move light soil and dig a residential trench, while at another jobsite a backhoe was operated so aggressively that violent shaking and vibrations broke several mounts and flipped breakers in the test equipment, rendering the test equipment inoperable for several days. As another example, at one job site (a commercial waste collection facility), an excavator with an inoperable transmission was "permanently" outriggered onto railroad ties and used only to compact trash in a roll-away dumpster, while at another jobsite where a commercial excavation was taking place, excavators were very heavily loaded while removing rock and compacted, damp soil and also used with jackhammer attachments to assist with rock excavation. Even soil moisture content varied greatly throughout the study, and work at jobsites was frequently suspended during our study due to heavy rains. It was beyond the scope of this pilot study to attempt to assign and classify the types of workloads based on worker operation, soil types, moisture content or types of operation. However, as described in Section 6.2, emission results are presented in a work-basis and in a fuel-basis in an attempt to normalize emissions based on work output. Some limitations to this methodology are also presented and described in Section 6.2 (PEMS Measurement Results).

Operation of all PEMS test equipment was continuously monitored by PEMS instrumentation teams throughout the test day. During breaks in usage of the construction equipment, team members would attempt to access the PEMS to refill the generator, replace the gravimetric filters and calibrate the SEMTECH-DS, as necessary. Real-time monitoring of test parameters was performed using remote laptops connected to the PEMS rack wirelessly in order to identify and correct any data or equipment issues. In addition, test files were extracted during and immediately after each test, processed and reviewed for data quality issues or problems.

At the completion of ES Phase 1 fieldwork, the team revised the Emissions and Activity Measurement sections of the QAPP (as well as the associated SOPS) based on field-testing experience. SOPs were continually revised and redistributed throughout each phase of testing as procedural and equipment refinements were made.

#### *3.5.2.3 Testing Challenges*

Significant challenges were encountered throughout the study which reduced the overall productivity of the field teams. These challengers were not unexpected, since the team was attempting to perform gaseous and PM testing on in-use equipment in the field without interfering with everyday construction site operations. In addition, the PEMS rack described in Section 3.4.2 was designed and built specifically for this study, so this study was essentially an initial field validation of the PM and gaseous sampling equipment integrated in the rack. Previous testing with these systems has primarily been in on-road and laboratory environments. Non-road testing subjected the equipment to extreme conditions not typically encountered in other test environments. Highlights of some of the challenges encountered are provided in the following sections:

**Logistical Issues** This was an “in-use” study in which it was imperative to not interfere with the operations of the participating facility (construction company). Consequently, test scheduling had to be extremely flexible and tailored to each company’s operations (and downtime). Frequently, it was difficult to obtain access to job sites and equipment during off-hours (nights/weekends), and many times on-site contacts did not know upcoming work schedules for equipment to be tested, which made staffing and test scheduling very challenging. Heavy rain and mud though much of the fieldwork prevented site operations and equipment testing and hampered test planning, since PEMS installations were not performed if no site operations were planned or if the chance of appreciable rain over the test period was significant.

Occasionally, equipment used during the day was transported to and domiciled nightly at the establishment’s headquarters. The equipment would then be transported back to a job site the following day. This usage pattern generally prevented instrumentations from taking place on these pieces of equipment, since the equipment usually could not be transported with the PEMS rack installed (due to height concerns) and insufficient time was available for instrumentation in the mornings after the equipment had been transported to the site but before it was used.

Often, after a test was initiated and the equipment was placed into service, the equipment was not available again to field team members until much later in the day or the evening. Any equipment problems which arose during these periods of inaccessibility could not be addressed, including maintenance issues such as filter changes and generator refueling. As safety and onsite operations permitted, team members did maintain and calibrate equipment, change filters and refuel generators whenever equipment use was paused.

Variability in onsite operations occasionally resulted in equipment being needed before the PEMS installation had been completed. In these instances, the PEMS hardware (generally the complete rack, less generator) was secured and the equipment was released for service with an incomplete installation. The installation was then completed later in the day or evening (once the equipment was no longer in use) for testing over the next usage cycle.

Finally, variability in usage made it difficult to predict which installations would be "safe" installations. Some equipment was used so aggressively that the PEMS rack and PEMS and PM equipment was significantly damaged during the work day. Typical damage included broken welds, dislodged electrical boards, broken electrical connections, internal SEMTECH and PPMD damage, etc.

**Equipment Issues** – Since the PEMS rack had been specifically constructed for this study, the durability of the system integration had not been field-verified prior to the study. As a result, some failures were encountered during testing, and a significant portion of the fieldwork effort was dedicated to repairing and maintaining the equipment. Highlights of the equipment problems encountered are provided below, and additional details of PEMS equipment issues encountered during testing are provided in Appendix Y, PEMS Data QC Results.

- Electrical problems were encountered throughout the study due to circuit boards and wiring becoming dislodged and disconnected during testing, excessive electrical loads, and faulty ground and electrical leads. The impact of these electrical problems ranged from loss of flows necessary for gaseous or PM sampling to loss of an entire test (i.e., after a power supply failure or system shut down). Circuit breakers used in the PEMS rack would also occasionally shut off, apparently due to extreme shaking and vibration.
- Excessive vibration and rough equipment usage resulted not only in electrical problems but also problems such as occasional loss of MPS calibration and loss of various bench signals during the study. In addition, the NDIR bench signal would intermittently fail during a test, resulting in a loss of CO, $CO_2$, oxygen and RPM data for the remainder of that test.
- MPS flow control and gravimetric sampling system malfunctions prevented PM filter collection for some tests, and gaseous sampling system leaks were also

encountered. This was likely due in part to vibrations and moisture encountered during testing, MPS controller board failure (vibration), and also disconnection and kinking of tubing connecting the various systems in the integrated PEMS rack.

- Since the PEMS team had to maintain distance from the in-use equipment, remote control (via wireless antenna) of the PEMS rack and filter switching system was occasionally lost, depending on the distance from the equipment and the PEMS monitoring team.

All issues were identified and corrected when they occurred, and tests were redone as necessary. Throughout the study, the team continued to enhance the equipment to withstand the rigors of this type of testing, and the experience gained in this study can be used to refine the integrated package for future non-road studies.

**Installation Issues**

As described in Sections 7.2 and 7.3 (Lessons Learned), installing and operating the PEMS rack and associated equipment was a challenging learning process. One obstacle simply involved installing the equipment. Because the PEMS rack contained the SEMTECH DS, MPS, gravimetric sampler, compressor and all other equipment needed for PM and gaseous sampling, a crane was required for all installations. This was particularly challenging at some locations where truck access was limited. The mounting location for each installation varied depending on the equipment to be tested, and all installations required mounting points for rack tie downs. Four people were typically required to mount the rack onto the nonroad equipment. Even finding a location with suitable room and strength to support the rack was not always possible, and occasionally wooden platforms were fabricated in order to support the PEMS rack on the nonroad equipment to be tested. Sufficient space was not always available to install the PEMS in a safe and secure manner, in which case that piece of equipment was deemed untestable. It is possible that some of the equipment not testable with the PEMS rack would be testable if the individual PEMS system components (SEMTECH DS, MPS, gravimetric sampler, etc) were individually mounted in separate locations.

Once installed, hooking up the exhaust collection system, sample lines, nitrogen and FID fuel lines, power supply lines, RPM sensor and calibration lines and securing the tie-downs was typically challenging since the PEMS rack was mounted on top of the nonroad equipment. Access to the rack required the use of ladders and climbing/standing on various areas of the equipment to reach the rack (see Figure 3.4-2). If a system malfunctioned while on the nonroad equipment, disassembly of the PEMS rack while installed or removal of the rack was required, generally adding several or more hours to the installation process.

Also described in Section 7.3, high exhaust flow rates and temperatures frequently resulted in the high-temperature silicon exhaust connections melting and/or blowing off the equipment's tailpipe. These melting exhaust connections resulted in contamination of the PM sampling system, including internal MPS contamination which could result in loss of proportional sampling and would require full disassembly for cleaning and recalibration.

Due to the effort and time required for test equipment installation and preparation, in-use test monitoring and post-test equipment maintenance, daily back-to-back testing was not possible during this study. However, daily (back-to-back) testing would be possible with additional staff beyond the 4-person teams described in Section 3.5.2.2. In addition, multiple complete PEMS test systems would be required so equipment could be prepared and installations could be initiated while existing testing was still underway (i.e., two teams working independently with complete equipment sets).

Significant time was spent during each installation connecting the exhaust system, securing the PEMS rack, installing the RPM pickup device, gas bottles, generator and power lines, calibrating the gaseous sampling system and MPS system, and ensuring all systems were functioning prior to the start of the test. Maintaining, calibrating and operating the PM and gaseous PEMS system is complex and requires equipment expertise and a significant amount of attention to detail. While certainly a manageable task, staff with adequate training and experience are required, and testing expectations should include the above challenges, in particular when performing this work in "real world" settings. Sufficient staff with dedicated duties should be provided for testing support, with heavy use of SOPs, guidelines, and checklists to ensure safety and proper test preparation and procedures.

## 3.6 EOI Phase 1 Initial EOI / EAM Interview

This effort involved the recruitment of construction businesses from PSU 1 for the purpose of PEMS and PAMS instrumentation. To accomplish this, a sample of businesses was drawn and called by a centralized telephone facility. For most of the sample,[10] the EOI was administered (questions 1 through 13 of Appendix A), followed by the administration of the incentive experiment, and finally the administration of the Equipment Sample Interview (ESI) with the objective of recruiting qualified establishments to participate in the inventory and instrumentation phase of the study (questions 14 through 22 of Appendix A). During the ESI, data on the qualified businesses (e.g., business name, site selected for the inventory and address,

[10] A small portion of the sample involved re-calling the businesses that participated in the Phase 1 Pilot. The Pilot only involved the administration of the EOI and was conducted in early 2007.

contact name and phone number, etc.) that completed the EOI and agreed to be inventoried were electronically transferred to ERG by NuStats for scheduling.

It is important to note that the eligibility requirements for the EOI in Phase 1 differed from those of the ESI in Phase 2. Both required confirmation of the business name, operating in the construction sector, having more than one employee, and owning or leasing diesel powered nonroad equipment. But the Phase 2 ESI employed an additional eligibility criterion:

*The establishment had to be a prime contractor.*

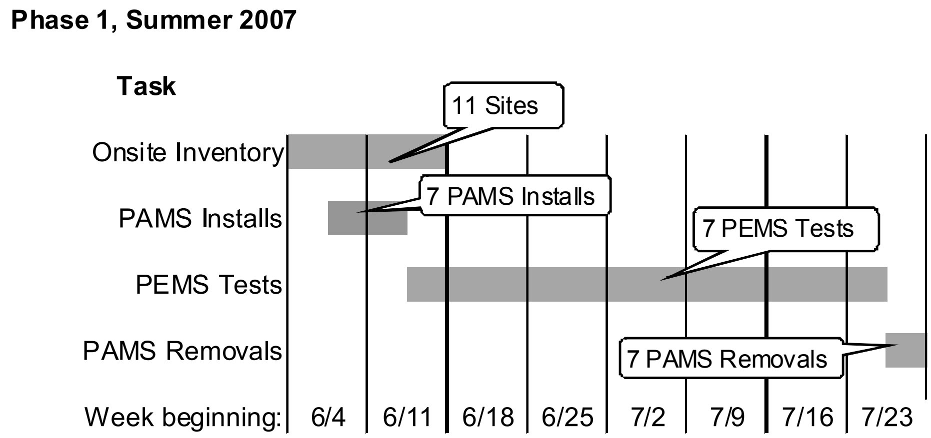
The reason for this restriction (which in Phase 3 was lifted in order to increase eligibility rates) lies in the selection probabilities of equipment. We were trying to control the paths by which a piece of equipment could fall into the sample for instrumentation. For those establishments that served as both a prime and subcontractor, the establishment would have multiple chances of selection – one as a prime contractor, plus multiple chances as a subcontractor (one per subcontract for each distinct prime). By limiting the ESI to prime contractors, we would effectively limit the selection probability of an establishment (and its equipment) to a known value.[11]

## 3.7 ES Phase 1 Emission and Activity Measurements

Figure 3.7-1 shows the sequence of events in ES Phase 1 of fieldwork, performed in the county of Jackson, Missouri. Phase 1 fieldwork was initiated with on-site inventories (conducted June 4th through 14th, 2007) and PAMS installations began shortly after the start of on-site inventories (PAMS installations were initiated June 6th and were completed June 11th). Inventory information regarding equipment test eligibility was transmitted from the inventory team to the PAMS installation team on a daily basis. To maximize the amount of activity data collected, all PAMS installations were performed by ERG and Southern Research Institute (SRI) personnel prior to the commencement of PEMS testing. PEMS testing, involving staff from ERG, Sensors, Inc., Southern Research Institute and EPA began after the completion of PAMS installations. PEMS testing in Phase 1 was conducted from June 15th through July 24th, 2007. PAMS revisits and downloads were performed periodically during PEMS testing, as schedules permitted. Hence, PAMS revisits were generally performed on weekends (and on days when a PEMS test was not being conducted).

[11] Unfortunately, due to the extremely low eligibility rates we encountered using the prime contractor criterion, we were forced to drop this restriction for the sake of being able to implement the instrumentation to attain our desired sample size.

**Figure 3.7-1 Emissions and Activity Measurements in ES Phase 1**




## 3.8 Integrated Sample Surveys, Phase 2 EAMS

According to our study design, Phase 2 was to proceed with conducting the establishment sample EOI with PSUs 2 through 5. However, analysis of EOI Phase 1 demonstrated that a full integration of the Phase 2 Establishment and Equipment Samples (i.e., the EOI & ESI) into a single, unified design would lead to cost efficiencies and produce more accurate reporting.

The reason for integrating the EOI-ESI sample design was partly due to the skewed nature of the establishments according to the measure of size (MOS) which led to a large number of self-representing units needing to be shared by the Establishment and Equipment Samples. Another factor was the finding of lower net yield rates relative to what we had planned and expected[12]. The Phase 1 Establishment Sample yield rates were half that of the expected rates, and meant that *twice* the sample than was originally planned would be needed for the Phase 2 Establishment and Equipment Samples. Taken together, these factors suggested that even a census of all establishments in PSUs 2-5 would fail to produce the targeted number of EOIs in order to achieve the study's Equipment Sample targets.

Based on these findings, the study design was modified to integrate the establishment and equipment sample into a single, integrated interview process. Table 3.8-1 presents the revised sample size goals by study phase and sample type that would be needed to achieve the target number of completions for the pilot. It reflects our integrated design and Phase 1 Establishment Sample experience by showing censuses conducted for Inventory and Instrumentation for Phases

[12] The net yield rate is the 'bottom line' number of sampled establishments required to secure a single completed EOI survey; it combines sample losses from ineligibility, screening nonresponse and interview nonresponse.

II (PSUs 2&3) and III (PSUs 4&5). A second stage sample was estimated to be needed to be drawn only within PSU 1 for the Inventories and Instrumentations in order to achieve the targeted sample size specified in the survey objectives. For the other PSUs, the revised plan involved conducting censuses of all establishments in order to maximize the possibility of achieving the targeted numbers of EOIs and instrumentations. As shown in Table 3.8-1, a total of 3541 selections were expected to be needed to complete the EOIs for the Establishment Sample and the EOI portion of the Equipment Sample.

**Table 3.8-1 Revised Total Sample Needed to Achieve Sample Targets**

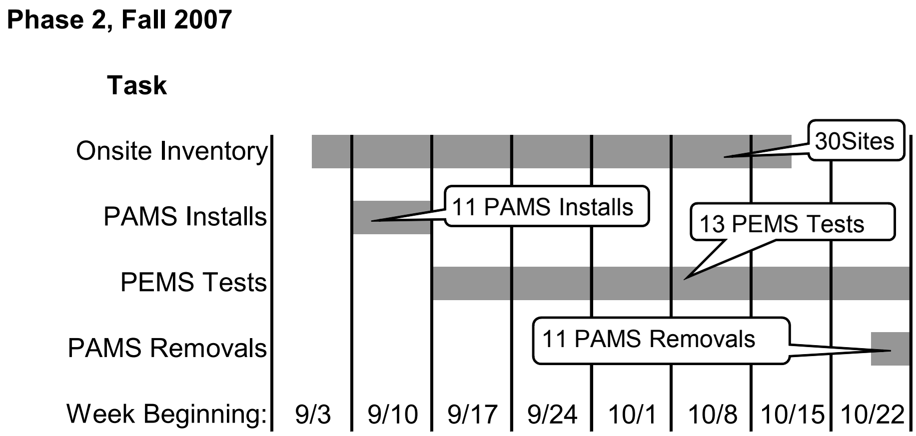
| TYPE OF DATA COLLECTION | ESTABLISHMENT SAMPLE | | EQUIPMENT SAMPLE | | | TOTAL |
|---|---|---|---|---|---|---|
| | PHASE 1 | PHASE 2 | PHASE 1 | PHASE 2 | PHASE 3 | |
| EOIs | 243 | n/a | 404 | 1522 | 1372 | 3541 |
| Inventory & Instrumentations | 0 | 0 | 37 | 74 | 74 | 185 |

The process for the integrated sample mirrored the establishment sample process for the first PSU with the exception of an extended interview to select a site at which an in-field equipment inventory would be conducted and equipment selected for instrumentation. All prospective respondents received an advance letter to alert them about the study and encourage their participation. This step of data collection began on June 15, 2008 and continued through August 2, 2008.

Figure 3.8-1 shows the sequence of field events in ES Phase 2, which targeted establishments located in the counties of Linn and Scott, Iowa. ES Phase 2 inventories began September 5, 2007, and PAMS installations began September 10$^{th}$. ES Phase 2 PEMS testing was conducted from September 17$^{th}$ through October 27$^{th}$, 2007.

Although geographic considerations were taken into account when scheduling inventories, PAMS installations and PEMS testing, these counties were contiguous and activities were not segregated based on county. As can be seen in Figure 3.8-1, inventories continued for a much longer duration than in ES Phase 1, primarily due to the larger number of establishments participating in Phase 2, a result of a 2-county census being performed. Later during the phase, as the rate of inventory appointments decreased, the inventories were scheduled in “groups”, which allowed inventory personnel to assist with PAMS monitoring support and PEMS testing tasks.

**Figure 3.8-1 Field Schedule for ES Phase 2**




## 3.9 Enhancements Prior to Phase 3

As a pilot project, the design strategy was to capitalize on experience with previous phases of the project and build upon that experience before proceeding with the subsequent phase. Previous enhancements to the study design, based on the earlier study phases included revising eligibility criteria[13] and integrating the establishment sample EOI and equipment sample ESI into a single survey application. As a result of the EOI Phase 2 effort, in order to meet data collection goals, a decision was made to explore the viability and utility of drawing a supplemental sample from a file provided by Equipment Data Associates, Inc. (EDA).[14]

The focus of this section is on the design enhancements that were made in acquiring and processing this supplemental database into the PSU 4 and PSU 5 sampling of establishments. This includes a review of the process for obtaining and processing the EDA data and assessment of the EDA data for PSU 4 and PSU 5 sampling.

### 3.9.1 EDA Data Acquisition and Processing for Sampling

EDA data was purchased for PSUs 1-5 using the same specifications employed by EPA in its earlier acquisition of EDA data for PSU 1 (Jackson, MO). Data for PSU 1 was purchased as an update from the previous purchase date (July 31, 2003). For the remaining PSUs, data was purchased anew, as there was no previous EDA acquisition for those areas.

[13] Certain eligibility criteria were revised, including establishments that (according to the SSI sample frame) reported having zero employees were no longer excluded from the study as a result of Phase 1 and establishments that were non-prime contractors were considered eligible during Phase 2.

[14] The EDA data provide a list of establishments that have financed construction equipment purchases. The data set contains identifying company information, equipment pieces financed (by equipment type) and date of transaction.

Once the data were obtained, they were reviewed for integrity and completeness. This was accomplished through quality checks (e.g., running summary reports by PSU and verifying against existing EDA-produced reports). The data set structure was then organized to match against the SSI data set. This was done by merging the EDA data with the SSI sampling frame data sets. In doing so, the SSI and EDA data were treated as two collections of records aggregated across PSUs 1 through 5 (rather than 10 distinct data sets requiring pair-wise merging). This step reduced processing time and guaranteed a standardized approach for all PSUs.

This merging process resulted in three distinct sets of establishment records:

- Records that appear in the SSI frame only.
- Records that appear in the EDA frame only.
- Records that appear in both SSI and EDA lists.

The result of this assessment was a merged data set of 2,209 records, comprising the sample frame for EOI Phase 3. Accordingly, all 2,209 records in the combined SSI-EDA frame were loaded into the sample management system for the issuance of advance letters and subsequent calling by the telephone facility.

### 3.9.2 Improvements to Sampling Protocols

Merging the EDA-SSI data onto the ESI and EOI survey data for PSUs 1-3 provided a unique opportunity to explore important survey design and survey quality issues. The analysis involved two steps with one related to sampling frame development, design parameter assessment and weighting, and the other focusing on response error and coverage.

For the first analysis we focused on the use of EDA data to improve understanding of eligibility and nonresponse, as described below:

- Eligibility. To begin, the EDA data would aid in determining the eligibility status of a portion if not all of the establishments that were not able to be screened using the conventional CATI calling protocols. This would allow the development of enhanced estimates of eligibility by PSU. Secondly, the correlates of eligibility status could also be explored. A key component of this analysis would be the ability of the EDA equipment list to identify establishments that are eligible for ESI/EOI prior to mailing and calling. Such "*pre-screening*" via EDA could potentially lead to a high level of efficiency. Analysis would also explore opportunities to more efficiently partition the sampling frame into groups of establishments that exhibit highly differential eligibility rates across strata. This will be important for developing *optimal allocation* designs that take into account the high cost of screening.

- Response Rate Analysis. The EDA data was anticipated to also provide new extant data on most of the establishments appearing in the SSI sampling frame. This would allow an additional avenue for exploring correlates of nonresponse at the screening and interviewing stages of data collection. The extent to which nonresponse for EOI and ESI is related to establishments with certain patterns of equipment purchases (i.e., by equipment type), and/or certain equipment inventories (by amount and configuration of equipment) would also be explored. The results could provide insight into the risks of nonresponse bias.

- Weighting adjustments. The nonresponse analysis was expected to yield specific recommendations for enhanced nonresponse weight adjustments that rely on the use of the EDA data (which was previously unavailable and therefore not an option for such adjustments).

To explore coverage, an analysis was conducted on three principal subgroups that comprise the EDA-SSI merged data set: (1) matched records; (2) records in SSI but not in EDA; and (3) records in EDA but not in SSI. Results of this analysis are presented in Section 4.

### 3.9.3 ES Phase 3 Data Collection Enhancements

A delay between ES Phase 2 and ES Phase 3 of this work assignment provided the team an opportunity to refine data collection equipment and procedures prior to ES Phase 3 fieldwork, based on information learned during ES Phase 1 and II testing. The team considered several changes, but eventually focused on enhancing PEMS RPM collection and PEMS ECU data collection. These two enhancements are described in the following subsections.

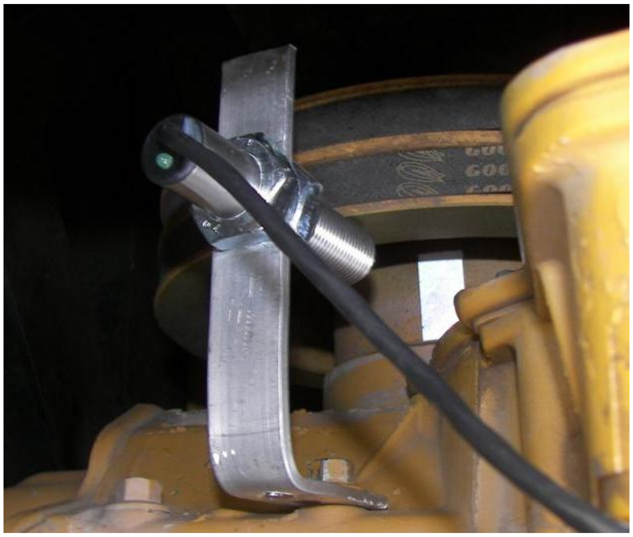
#### *3.9.3.1 RPM Collection Enhancement*

"Capelec" RPM measurement devices were the primary RPM measurement device used during PEMS tests in ES Phases 1 and 2 of this work assignment. These devices, which were specifically purchased for use in this study, determine an engine's RPM by processing voltage fluctuations measured at the terminals of the nonroad equipment's battery (these fluctuations result from alternator output fluctuations during equipment operation). Although these units are very simple to install and operate, only limited success was achieved obtaining an accurate and reliable RPM signal. Specifically, RPM signals were often erroneous and erratic (would drop out) during equipment operation, and they would jump to a high level when the equipment was turned off. It appears much of the Capelec's unusual behavior was likely due to the unit picking up signals from the PEMS test equipment, rather than true RPM information from the equipment being tested.

Conversely, optical and magnetic RPM collection equipment were the primary RPM collection devices used during ES Phase 1 and 2 PAMS testing and were shown to provide a fairly accurate and reliable signal, although installation procedures were somewhat more time consuming. However, because of the reliability and universal applicability of optical sensors for RPM collection, the ERG team and EPA decided to use optical sensors for PEMS RPM acquisition during ES Phase 3 testing. The ERG team and EPA worked together to identify dedicated optical sensor holders which could be attached to high-powered rare-earth magnets (acquired separately). These high-powered mounts proved to be capable of securely attaching the optical sensors for both day-long PEMS testing and month-long PAMS testing. Figure 3.9-1 shows an optical sensor mounted using a magnetic base, with an extension allowing the sensor to point at a rotating pulley (not shown). Although a long extension was used in this particular installation, in general an effort was made to minimize the distance from the optical sensor to the sensor's mounting base, in order to minimize vibration and mis-alignment potential of the optical sensor. Figure 3.9-2 shows an optical sensor mounted using an aluminum bracket, as was done when equipment configurations permitted.

**Figure 3.9-1 Optical Sensor on a Bracket With a Magnetic Base**

**Figure 3.9-2 Optical Sensor on an Aluminum Bracket**



***3.9.3.2 Enhancement of Collection of Electronic Control Unit Operation Data (ECU data) for Electronically-Controlled Equipment***

The majority of equipment tested in ES Phases 1 and 2 was mechanically-controlled, rather than electronically controlled by way of an electronic control unit, or ECU. However, for equipment which was electronically-controlled, attempts to collect ECU data during ES Phase 1 and 2 PEMS testing were not successful. The intent of this task, therefore, was to supplement PEMS test procedures and equipment in order to allow the team to successfully collect ECU data from electronically-controlled equipment that would be PEMS-tested throughout the remainder of this work assignment.

Initial research suggested that although SAE J1939 is intended by SAE to be the standard protocol for 2004 and later heavy-duty on-road vehicles (superseding the use of J1587/1708), the J1939 standard thus far has seen limited penetration into the heavy-duty (on-road) vehicle market and non-standardization appeared to be even greater in the non-road heavy-duty equipment sector.

Because of the prevalence of Caterpillar equipment inventoried and tested during the first two phases of this study, the ERG team decided to focus efforts on only Caterpillar ECU data acquisition, in hopes that the information learned could then be applied to other equipment manufacturers in future studies. Therefore, ERG, EPA and Sensors worked with Caterpillar in acquiring "CAT ET" (Caterpillar Electronic Technician) equipment and software necessary for ECU data collection on nonroad equipment. The project team established training sessions with

Caterpillar for use of this equipment and software. These training sessions were also used as an opportunity to explore alternative manufacturer-specific RPM-collection devices (such as inductive flywheel signal pickups), although ultimately the decision was made to focus efforts on use of optical RPM pickups, as this is universally applicable in the field.

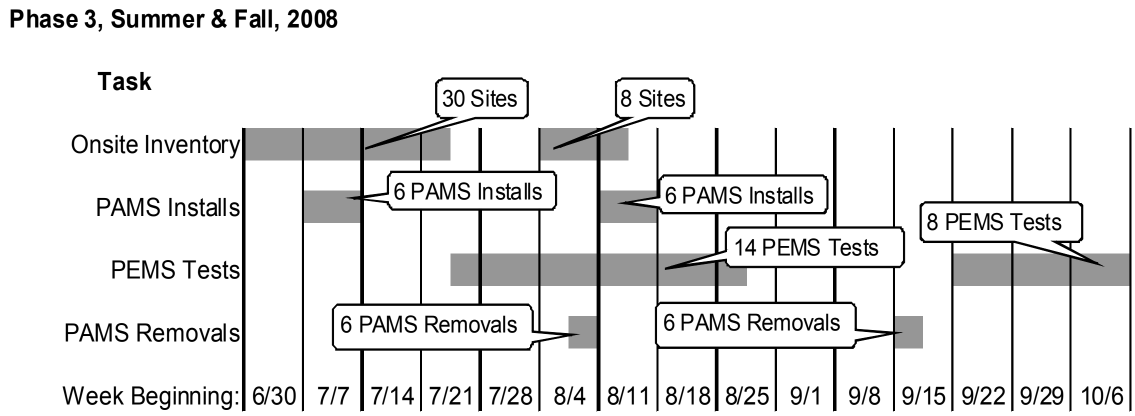
After hardware and software for Caterpillar ECU data collection were acquired, new procedures were developed to allow this data to be collected in the field during emissions testing (rather than collection of data during engine diagnosis or repairs, the typical application for this equipment). Due to time and budget constraints, it was not feasible to log the data directly into the SEMTECH-DS. Instead, the CAT ET software was installed on a remote laptop for which the “sleep” power mode was disabled (allowing the laptop to operate with the lid closed). This laptop was placed in the cab of the equipment being tested, connected directly to the ECU CAN port (via the Cat ET communication module) and to a power supply (taken from the PEMS onboard generator). Since acquisition could not start until after the equipment was turned on, remote control of the acquisition laptop was necessary and was achieved by way of a standard Wi-Fi computer transmitter/receiver. Preliminary testing showed this configuration adequate for remotely collecting ECU data from electronically-controlled Caterpillar equipment. This data could then later be merged and time-aligned with the PEMS data for the same test.

## 3.10 ES Phase 3 EAMS

Figure 3.10-1 shows the sequence of fieldwork events in ES Phase 3 testing, which was conducted with establishments located in the counties of Clay, Missouri and Shawnee, Kansas. Because of the distance which separated these two counties, inventories, emissions and activity measurements were conducted independently in each county (work for each task was completed in Clay, Missouri before moving on to Shawnee, Kansas). This reduced the amount field teams needed to commute long distances between the two non-adjacent counties.

Inventories in Clay County were conducted from June 30$^{th}$ through July 24$^{th}$, 2008 and in Shawnee County from August 4$^{th}$ through August 14$^{th}$, 2008. PAMS were installed in Clay County from July 7$^{th}$ through July 11$^{th}$, 2008 and in Shawnee County from August 11$^{th}$ through August 14$^{th}$ 2008. PEMS testing began in Clay County on July 23$^{rd}$, and ended on Aug 26$^{th}$, 2008 and in Shawnee County PEMS testing began on September 23$^{rd}$ and continued through October 10$^{th}$, 2008. The quality of RPM data collected during ES Phase 3 was higher than that in ES Phases 1 and 2, and although only one piece of electronically-controlled Caterpillar equipment was tested, ECU data collection was successful for this test.

## Figure 3.10-1 Field Schedule for ES Phase 3




## 3.11 Data Processing, Analysis and Submission

At the completion of EOI/ESI data collection, NuStats processed the database, conducting quality control and edit checks, using specifications established for this study and analyzed the data regarding sample performance. Final data files were prepared and transferred to ERG according to the protocols required in the statement of work.

All PEMS and PAMS data was monitored during collection followed by extensive QC and processing performed after data collection was completed. Data processing, QC and analysis steps are described for PEMS and PAMS data in the following sections.

### 3.11.1 PEMS Data Processing and QC

As mentioned in Section 3, the operation of PEMS test equipment was continuously monitored by PEMS instrumentation teams throughout the test. Real-time monitoring of test parameters was performed using remote laptops communicating wirelessly with the PEMS rack in order to identify and correct any data or equipment issues. In addition, test files were extracted during and immediately after each test, processed and reviewed for data quality issues or problems. This real-time and "in-field" QC was intended to identify issues with exhaust and MPS flows and gravimetric filter system flowrates, system temperatures and pressures, pollutant concentrations and other measured and recorded parameters. An overview of the work done with the data after fieldwork was completed follows.

#### *3.11.1.1 Summary of PEMS Data Processing and Analysis*

After testing was completed, all PEMS data was read into Statistical Analysis Software (SAS) and thorough processing and quality control (QC) steps were performed in order to identify and flag any suspect data. QC involved SAS screening, a review of information recorded in field logs and data processing logs and a detailed second-by-second review of all recorded parameters by way of analysis of plots. Second-by-second review involved evaluation of all gaseous pollutants, reviewing sampling system pressures such as the MPS inlet pressure and SEMTECH pressures, evaluating all system flows including the exhaust mass flow rates, calculated fuel flow rate, all MPS sampling flowrates and gravimetric filter flowrates, and evaluating all system and sampling temperatures such as exhaust temperatures, external heated line, chiller, cyclone, manifold and gravimetric filter temperatures, and ambient and internal PEMS rack temperatures. Data identified as suspect has been eliminated from emissions summaries reported in Section 6.2, PEMS Data. A detailed list of criteria used during review of the second-by-second data is provided in Appendix I, and Appendix Y contains notes on the review performed for each of the datafiles collected during PEMS testing.

In addition to the second-by-second review of PEMS data, the following analysis steps were performed and corrections applied to the PEMS data collected during this study:

**Time alignment** - Time alignment was applied by Sensors during the initial processing of the xml files into CSV files. All measured parameters such as gaseous pollutants, MPS system flows, exhaust flow and RPM and GPS signals were aligned to within one second. Uncertainty associated with time-alignment errors is included in the emission estimates provided in Section 6.2.2 and in Appendix AO, Nonroad Error Estimates.

**RPM scaling** - RPM scaling was applied by Sensors during the initial processing of the xml files into CSV files. Scale factors were based on the known RPM ranges for the equipment being tested as well as the RPM verification and calibration information collected prior to and after each PEMS test.

**Estimation of brake-specific emissions based on engine RPM and fuel rate** – ERG, Sensors and EPA worked together to develop protocols to calculate cumulative brake-specific fuel consumption (BSFC) mass-based gaseous and PM emissions using existing PEMS test data (including exhaust flow, calculated fuel flow rate, RPM and MPS data), gaseous measurement results and gravimetric filter results. Using this methodology, in SAS, ERG calculated brake-specific emissions using the SEMTECH-DS' fuel consumption rate and the manufacturer-specific BSFC vs. RPM curves (lug curves) for equipment that had been tested. The engine power output for each observation was based on maximum power output at that RPM scaled by the ratio of "measured" fuel consumption (via PEMS) to maximum fuel consumption (from lug curves) . BSFC vs. RPM curves were acquired by EPA and provided to ERG. Although some of these curves were provided by the engine manufacturers for the specific engine models, curves for other tests were “generic” curves for similar or multiple models of engines. These “generic” curves likely provide a reasonable estimation of brake-specific emissions, although a more accurate estimate could be obtained using curves specific to each engine model. These “generic” curves likely add approximately 5% variability, mainly at low and high engine speeds.

The methodology used for calculating BSFC emissions is provided in Appendix AD, BSFC Calculation Methodology. Use of the methodology developed for this work assignment is based on the assumption that brake-specific fuel consumption is constant across varying engine loads at any given RPM. Comparing results from this methodology to BSFC emission estimates using in-house EPA laboratory results, EPA has shown this “constant fuel consumption” assumption to be reasonable. A list of sources lug curves used for estimating BSFC emissions is provided in Appendix Y. However, because some of these lug curves are confidential business information, they are not included as an appendix to this report. Uncertainties associated with estimating brake-specific emissions based on engine RPM and fuel rate and from the use of generic lug curves are included in the emission estimates provided in Section 6.2.2. These uncertainty estimates are derived and presented in detail in Appendix AO, Nonroad Error Estimates.

**By-test analyzer drift check (test record review)** – PEMS gaseous span calibrations were generally performed prior to and following each day’s testing (and mid-day spans were performed as field testing conditions permitted). However, occasionally a post-test span was not performed (such as when testing or equipment failures occurred). For this task, ERG and Sensors compiled all span results conducted throughout the study, in order to quantify the amount of system drift occurring during the test on a percentage basis, through review of the post-test span results. A summary of drift results (on a percentage basis) is provided in Appendices Q, R and S for all three phases of the fieldwork. These drift checks were not applied to the test data during post-processing of the data.

**Comparison of known exhaust mass flowrates vs. measured flowrates:** For engines for which displacements were known, ERG compared both the idle flowrates and maximum flowrates for each test with empirical data from engines with similar displacements operating at similar speeds. Scale factors were used to correct for differences in displacement and engine speed between measured and empirical data. This comparison of known versus measured flowrates helped confirm the proper flowmeter diameters were used and entered into the test setup screen and data processing calculations. However, in general, for the equipment tested during the study, the idle flowrates were high enough that even the largest diameter flowmeter used in the study (5”) would provide acceptable resolution at low (idle) flows, but conversely the measured flows would not reach the maximum flow limits if a smaller than optimum diameter flowmeter was used for a test. Guidelines for expected flowrates based on displacement and engine speed are provided in Appendix F, PEMS Installation SOPS, and results of the comparison of measured flowrates with expected parameters, for engines for which displacement is known is provided in Appendix Y, PEMS Data QC Results.

**MPS proportionality to flow review:** In SAS, ERG plotted the MPS average sample flow rate (iMPS_Average_Q, SCCM) against the exhaust mass flow rate (icMASS_FLOW, kg/hr) and calculated the best fit line slope, intercept, coefficient of determination ($r^2$) and root mean square error (RMSE) in order to assess the quality of proportionality. Results are provided in Appendix Z, MPS to Exhaust Flow Proportionality Plots. These proportionality plots only pertain to time periods when filter sampling was being performed.

**Review of flowmeter usage during each phase of the fieldwork:** In order to provide information regarding the reliability and durability of flowmeters used during the study, ERG summarized the usage time of each flowmeter tube during each study phase, provided in Table 3.11-1 below. Only one of each diameter flowmeter was used during each of the three phases of the fieldwork. For example, only 3 flowmeters were used in ES Phase 1, one 3” flowmeter, only one 4” flowmeter, and one 5” flowmeter. Any results of pre and post-fieldwork MPS and flowmeter testing which has been made available is provided in Appendix AB.

**Table 3.11-1 Flowmeter Usage During Each Phase of Fieldwork**

| ES Phase | 2” usage (mins) | 3” usage (mins) | 4” usage (mins) | 5” usage (mins) |
|---|---|---|---|---|
| **1** | 208 | 784 | – | 24 |
| **2** | – | 3959 | – | |
| **3** | – | – | 3522 | 696 |

#### *3.11.1.2 Issues Identified during PEMS Data Analysis*

In this section we discuss issues that were encountered during PEMS data processing and analysis, and steps taken to resolve each issue.

**Post-fieldwork laboratory verification of PEMS equipment showed a bias in the 5" flowmeter used during ES Phase 3:** The 5" flowmeter used during Phase 3 of the fieldwork failed the subsequent February 2009 calibration, apparently due to an incorrectly installed Torbar exhaust flow measurement pitot tube in the exhaust flow meter. The incorrect installation of the pitot tube would bias exhaust flow readings from this flowmeter low by approximately 8%. However, review of ES Phase 3 testing shows the Torbar pitot tube was incorrectly installed after test 8418_0961, which was conducted on August 25$^{th}$, 2008 (the Torbar had been removed for cleaning after an exhaust boot melted and contaminated the sampling system). However, it was determined that this was the last test in which this 5" flowmeter had been used, so no subsequent tests were affected and no data corrections were necessary.

**Post-fieldwork laboratory verification of the PEMS equipment showed a bias in the mass flow controller used during ES Phase 3:** The mass-flow controller used for proportional exhaust sampling in ES Phase 3 was removed from service August 26$^{th}$, 2008 and sent to the manufacturer for repairs. During this repair process, different coefficients were entered into the firmware which resulted in a small (approximately 10%) bias in the gravimetric filter mass controller flow rate. However, investigation of this issue revealed that no correction to the PM data was necessary, since this bias in the gravimetric filter flow rate only affected the amount of dilution added to the sample ***after*** it was collected, and hence the entire PM sample was still passed through the PM filter. The total PM collection rate and the overall dilution ratios used for determining tailpipe PM emission rates were unaffected.

**Invalid time stamps were identified for several of the tests:** – PEMS second-by-second timestamps for some tests in ES Phases 2 and 3 were found to be erroneous, most likely due to a weak or dead battery in the SEMTECH-DS' internal clock. In order to correct for this, in SAS ERG corrected all second-by-second times using the GPS timestamp's Greenwich Mean Time (GMT) value corrected to central daylight time (CDT).

**RPM data issues**: As described in Section 3.9.3, RPM acquisition was problematic during the first two phases of the study, when the team used a device which calculated an RPM signal based on slight changes in voltage readings measured at the battery. These problems prompted the team to use an optical RPM collection device during ES Phase 3 of the study. Although using the optical RPM sensor during ES Phase 3 greatly increased the reliability and accuracy of the RPM signal, RPM data corrections were necessary for all three phases of the study, to correct the following problems:

- *Erroneous or spiked RPM* – RPM spikes (unreasonably high transient values) and suspect RPM values (RPM higher or lower than expected based on measured data such as exhaust flow rate) were seen in the data, both during engine-off periods and during engine operation. Erroneous data during engine-off periods were most common with the Capelec RPM device (ES Phases 1 and 2), likely due to the processor misidentifying signals from the PEMS hardware or portable generator as engine RPM. All erroneous and spiked RPM data was corrected as described below.

- *RPM scale* – RPM calibration checks were performed prior to and following each PEMS test, whenever possible (equipment failures or other factors sometimes prevented pre or post-test calibrations). Using this calibration check information collected in the field along with knowledge of engine operating ranges and manufacturer specifications, RPM scale factors were applied during post-processing and verified during data analysis. Final RPM scale corrections were applied in SAS, as needed.

- *Missing RPM* – RPM data is missing during certain segments of some data files. This missing data was caused by loss of signal from the RPM collection device (due to a malfunctioning processor or misaligned sensor) or due to equipment failures such loss of the AMBII board signal in the SEMTECH-DS, through which the RPM signal was routed. Segments of test data where RPM was missing were identified by manual review of plots and second-by-second data, and when RPM data was missing, a new RPM field was provided as described below.

RPM issues such as spikes and missing or erroneous values were identified during review of plots and data such as pollutants and exhaust flow rates from each test file. All original RPM data was kept intact, but a new "corrected RPM" field was added to each test file where RPM corrections were made. If possible, spikes and other transient RPM problems were corrected using interpolation between valid points (verifying operating range using exhaust mass flow rate). If a significant portion of the PEMS RPM appeared invalid and PAMS or ECU data was available (i.e., PAMS or ECU data was collected concurrently with the PEMS test), the PAMS or ECU RPM data was merged (in SAS) and time-aligned with the PEMS data to obtain a new "corrected" RPM. If no concurrent PAMS or ECU data was available but the test had large segments of missing or invalid data, ERG developed the new "corrected RPM" field by multiplying the measured exhaust mass flow rate by constants which were calculated based on the ratio of RPM and exhaust mass flow rates during periods of "valid" RPM collection. These test-specific RPM to exhaust "scale factors" were developed for low-range and high-range exhaust mass flow rates. ERG attempted to model RPM from exhaust mass flow rate using non-linear relationships (such as polynomials), but it was seen that when flow was segregated into high/low ranges, linear relationships defined flow versus rpm in each individual range as well as non-linear relationships. This is likely due to the large variability in the relationship between engine volumetric throughput and RPM due to variations in throttle position and demand (i.e., varying loads at constant RPM). Therefore, simple constant multipliers were used, one for the low-flow region and one for the high-flow region, where the low and high flow ranges and constants were specifically defined for each test.

After the factors were developed, this newly calculated RPM was compared with data from a segment of the test where "valid" RPM had been collected. Comparing plots of this new RPM with actual, recorded RPM provided an indication of validity of the new RPM field, and when necessary, an upper bound was applied to limit the newly-developed RPM's maximum values. These limits were based on actual RPM values seen during periods of valid data collection (maximum or governed engine speed). This correlation was then applied to those segments of test data where RPM was erroneous or missing.

Occasionally, no "reasonable" operating RPM was available in the data, in which case a new RPM field was developed based entirely on RPM to exhaust scale factors seen during field comparisons between RPM and exhaust mass flow rates for that piece of equipment (i.e., factors seen during test setup were used instead of collected test data). Unfortunately, when using factors based only on RPM to exhaust ratios seen during setup and not on test data during which valid RPM was collected, no assessment of the quality of this newly-derived RPM could be made, and upper bounds (based on measured data) could not be applied.

Details of the all RPM corrections, including the RPM scale factors and upper bounds used for this study, are provided in Appendix Y, PEMS Data QC Results. A summary of the analysis used for RPM factor development is provided in Appendix AA. Appendix AA shows time-series comparisons of the "calculated" to "measured" RPM values (during time periods when the "measured" RPM appears reasonable) and it also shows scatter plots between "measured" and "calculated" RPM (again during these "valid" regions). As can be seen from reviewing these plots, some tests have a much better correlation than others, most likely due to fluctuations in load at maximum (or governed) RPM and also due to the influence of turbochargers (each of these influences affect exhaust mass flow rate at certain RPMs, based on load). ERG has performed a preliminary assessment of improving this relationship by modeling a second independent variable in the relationship, thereby improving the accuracy of the "calculated" RPM. Completion and application of this new methodology was not possible within the schedule and budget of the current project, but is described in Section 3.11.1.3 as possible follow-on work. However, estimates of error associated with use of this "derived" RPM are included with the emission estimates in Section 6.2.2. Details regarding uncertainty estimates are presented in Appendix AO, Nonroad Error Estimates.

**Autozeros were performed during gaseous sampling:** Since engine RPM and exhaust emission rates weren't set to zero during autozeros, autozeros performed during gaseous sampling could produce a slight bias in cumulative gaseous emission results (since pollutants are artificially low during autozeros). This bias could be more problematic for those time periods when PM filter sampling was being performed (as occurred during ES Phases 1 and 2), as these were relatively short sampling durations (so the relative bias would be greater) and also because this would bias the cumulative gaseous results low relative to the unbiased PM results for the filter that was being sampled during the autozero. The PEMS firmware was updated in the enhancement stage between ES Phase 2 and 3 sampling so that autozeros would not be performed during filter sampling in ES Phase 3.

The US EPA has reviewed all test files and identified all instances where autozeros were performed during filter sampling in ES Phases 1 and 2, and they have confirmed autozeros were not performed during filter sampling in ES Phase 3. All filters that were affected by gaseous autozeros are identified in Appendix Y, PEMS Data QC Results. In order to correct for gaseous autozeros, all observations (seconds of data collection) during which an autozero was being performed are excluded from the cumulative gaseous emission results (gaseous emissions and the work performed during each second of data are not included in the cumulative total). However, if a PM filter was being collected during an autozero, the PM total flow and total work basis are left intact for the PM results (only the gaseous data is adjusted).

In order to exclude gaseous observations where autozeros took place, in SAS, ERG screened $CO_2$, CO, $NO_x$ and $O_2$ records on a second-by-second basis. For each second of data during which $CO_2$ was under one percent, CO and $NO_x$ were under 50 PPM and $O_2$ was greater than 19 percent (these conditions indicated an autozero was underway), RPM and exhaust mass flow rate were set to zero, thereby eliminating that observation from cumulative reporting (both gaseous and work). This adjustment was made only for the gaseous reporting summaries which accompany this report. The MSOD submission will contain the complete original data prior to the application of these adjustments.

**Incorrect NOx correction was applied to some PEMS data:** EPA has requested that the methodology outlined in 40 CFR 1065.670 be applied to all data collected during the study. However, the NOx emission results in ES Phase 2 data was corrected using the methodology outlined in 40 CFR 86.1370-2007NTE, because the PEMS data processor did not offer 1065.670

methodology at the time ES Phase 2 data was processed. In addition, some ES Phase 1 and 3 data was also inadvertently processed using 40 CFR 86.1370-2007NTE methodology. In SAS, ERG has applied 1065 corrections to all data processed using NTE methodology, so 40 CFR 1065.670 humidity and temperature-corrected NOx values are applied consistently to all data.

**Some gaseous data was null during filter sampling:** Occasionally, equipment issues resulted in gaseous emission data not being collected during filter sampling. Similar to the autozero situation previously described, if gaseous pollutants are invalid or zero for a portion of time during which a filter was being sampled, the cumulative gaseous results will be biased low relative to the PM results for that filter. The column entitled "Some gaseous null during filters" in Appendix Y, PEMS Data QC Results, identifies filters affected by this, and these gaseous results are excluded from the PEMS gaseous result reporting in Section 6.2. The column entitled "Observations to Exclude From reporting" in Appendix Y lists all invalid data contained in the final dataset which will be excluded from reporting, whether or not during filter sampling. This data will be included but flagged in the final data submission for this project.

**Some post-test span calibrations are missing:** Pre and post-test span calibrations may be used to quantify instrument drift during each testing episode, per 40 CFR 1065 guidelines. Occasionally, equipment failures or other scenarios would prevent post-test spans from being performed. In these situations, it is not possible to quantify the instrument drift during the test. However, post-test spans are missing for other tests conducted during the study which could have received a post-test span, typically when other testing problems, such as PM data collection problems, occurred. For these tests, as well as for tests with equipment failures, post-test span data is not available. All available audit and span results are compiled in Appendices Q, R and S.

**Other issues identified during second-by-second review of the PEMS data:**

A summary of some of the more common issued identified during the second-by-second review of PEMS data is provided below. These issues are listed under "General Review Comments" in Appendix Y, PEMS Data QC Results, and criteria applied during the review are listed in Appendix I, PEMS data QC Criteria.

- Some variations and out of range temperatures were seen in various gravimetric sampling components, including the cyclone, filter holders, and manifold. Many of the temperature anomalies appear to have been due to switched or malfunctioning thermocouples.

- Some pulsations were seen in some of the measured values (mostly sampling system parameters such as the SEMTECH-DS' sampling pumps). Sensors reports that these pulsations result from electrical current fluctuations, as power was taken directly from the 12V rail in the PEMS rack. However, constant current control in these components is not necessary, and regulated power was used for current needs for any component which required constant control.

- For a select few tests, some MPS total flowrates were lower than optimal – Sensors reports that additional flow control under our testing conditions was not feasible and these MPS flowrate variations are inherent in this type of test system. Although the impact of this will be quantified in the PM measurement allowance study being conducted by EPA, flow proportionality is the critical parameter for MPS sampling. Appendix Z provides plots of MPS flow proportionality during periods of filter sampling, and estimates of error associated with MPS flow proportionality issues are included with the emission results in Section 6.2.2 and are derived in Appendix AO, Nonroad Error Estimates.

- Engine-off flowrates for some tests (such as 0062-0748 in ES Phase 3) are higher than expected (around 14 SCFM). Since the flowmeter has four pitot tube systems, each one measuring flows in different ranges, this bias only affects the low/zero flows, and not higher flows, and consequently this zero-flow bias will have a negligible effect on overall flow measurements. In addition, the zero flow measurement is also more susceptible to drift than the other 3 systems, so this bias is limited to the zero flow and low flow regimes.

Details regarding other issues identified for each test are provided in the "General Review Comments" in Appendix Y, PEMS Data QC Results.

#### *3.11.1.3 Possible Future Work*

Below is a summary of additional analysis which could be performed as resources permit.

**Apply drift corrections to test data:** The amount of drift for each PEMS test for which a post-test span is available has been calculated on a percentage basis. Using this drift percentage, drift corrections could be applied to the final PEMS gaseous data on a work (or other) basis.

**Apply corrections to emissions data using results of laboratory fuel analysis:** PEMS gaseous data was processed using default diesel fuel properties (such as a 0.85 specific gravity and a 1.8 hydrogen to carbon ratio). However, after fieldwork was completed, the EPA's NVFEL fuel laboratory performed analysis on all fuel samples collected during the study, and samples were also sent to an outside laboratory for additional analysis, so results from the fuels analysis could be used in place of the default fuel properties used during initial processing in order to improve the accuracy of the reported emissions estimates. Use of these "actual" properties would either require reprocessing the xml data files using the SEMTECH-DS's post processor or applying corrections to the data already in SAS. For changes to the fuel hydrogen to carbon ratio, reprocessing would probably be the most efficient method, although it is likely the laboratory-determined hydrogen to carbon ratio is already so close to the default ratio of 1.8 used for processing that the small influence on emissions changes would not warrant reprocessing. A comparison of data from one or two files processed with different values might be helpful in determining the impact of the change. Specific gravity changes could easily be made to the existing data in SAS, by ratioing the specific gravity used with the "actual" specific gravity (divide by the default specific gravity and multiply by the actual).

**Collection of MPS / Flowmeter calibration verification data** – Laboratory calibration checks of the exhaust flowmeters and microproportional samplers (EFM / MPS) used in the study were performed by Sensors prior to and following each phase of the Nonroad PEMS study. EPA is currently working with Sensors to acquire and compile results of the EFM / MPS calibration verifications performed in support of this study. Review of this data can be used to confirm accuracy of exhaust flow measurements or develop correction factors for any bias in the exhaust flow measurements. EFM / MPS laboratory verification data received thus far is provided in Appendix AB.

**Collection of SEMTECH multipoint linearity verification data** – Laboratory linearity verification of the SEMTECH-DS PEMS used in the study was performed by Sensors prior to and following each phase of the Nonroad PEMS study. EPA is currently working with Sensors to acquire and compile results of the SEMTECH-DS' multipoint linearity verification results performed in support of this study. Review of this data can be used to confirm accuracy of the gaseous measurements or develop correction factors for any non-linearity in the data. SEMTECH-DS multipoint linearity verification data received thus far is provided in Appendix AC.

**Test alternate corrections for SEMTECH gaseous autozeros performed during filter sampling** – Although data has been corrected for autozeros performed during filter sampling (by way of exclusion), it is likely one or more additional methodologies could be developed which would allow correction of cumulative emission results during which autozeros were performed without altering the cumulative work basis used for reporting. One simple methodology might be to calculate an average one-second emission rate for each pollutant, based on the overall test average emission rate, then use that average for each pollutant during all seconds an autozero was being performed. Another more refined methodology would be to classify emissions for the test being analyzed based on engine speed (RPM) and load (as indicated by exhaust mass flow rate). These power-based emission rates could then be used in appropriate power regimes in order to estimate instantaneous emission rates during periods of autozero. Obviously, some uncertainty would be associated with either of these methodologies, as emissions variability and transient emission rates have not been captured and would not be known for these time periods.

**Improve accuracy of estimated RPM for tests where RPM was invalid or missing** – As described in Section 3.11.1.2, an engine's exhaust mass flow rate was occasionally used to estimate the engine's RPM during a portion of a test collected when the measured RPM signal was lost or erroneous. As shown in Appendix AA, some tests had a less than ideal correlation between exhaust and RPM, which is most likely due to changes in engine load at maximum (or governed) RPM and also due to the influence of turbochargers on the exhaust to RPM relationship. ERG has performed a preliminary analysis which suggests using a second variable, such as the exhaust's oxygen content, air / fuel ratio or pollutant concentration such as carbon dioxide content, along with exhaust mass flow rate, might be helpful in calculating a more accurate estimate of "true" RPM. This second variable could help correct for engine load, in particular at higher RPMs. Currently, this correction for load is done by "capping" the maximum RPM based on data trends seen during periods of valid RPM collection. Estimates of error associated with use of this "derived" RPM are included with the emission estimates in Section 6.2.2.

**Obtain revised lug curves used for BSFC emissions estimates** – As previously described, EPA provided lug curves for all engines tested during the study, but many of these were "generic" lug curves. Use of engine model/family specific lug curves could improve the accuracy of the work-based emission estimates. A list of the types of curves (i.e., generic from a website or engine specific from the manufacturer) used for estimating BSFC emissions is provided in Appendix Y. For those tests for which only generic curves are available, engine manufacturers could be contacted in order to obtain engine-model "specific" lug curves. The engine model and serial number information listed in Appendix U could be used to specify engines for which curves are needed. Once obtained, equations could be developed which represent the curves over the full operating range, and these equations could replace the "generic" curve equations currently used in SAS to calculate work-based emissions. In SAS, caps should be placed on the maximum brake-specific fuel consumption for engine speeds above the maximum RPM listed in the lug curve, in order to avoid overestimating emissions during times when the RPM value exceeds the range provided in the lug curve. An assessment has been made with the existing curves and data to ensure the majority of engine operation occurs within the limits of the applied lug curve equations. Limits have been applied to BSFC values outside of valid RPM ranges, and estimates of error associated with the use of "generic" lug curves are included with the emission estimates in Section 6.2.2.

**Reprocessing data files (if necessary) -** In the event any reprocessing of the SEMTECH-DS xml files is required, all test-specific input settings, processing parameters or any other test inputs originally used for file processing is included in the "Summary Information" section of the processed file (this information follows the second-by-second data in each test's *.csv file). For example, starting at the "Vehicle Description" section, fuel specific gravity, H/C molar ratio of fuel, and AMBII RPM multiplier are all given. The time delays (time alignment) are all provided in the "delays" section ("NDIR Delay(s)", "NDUV Delay(s)", "THC FID Delay(s)", "Methane FID Delay(s)"). If the flow was scaled for any reason, this would be listed in the "Overrides" section.

### 3.11.2 PAMS Data Processing and QC

Several different configurations of PAMS installations were used throughout the study. These configurations were dependent both upon equipment used for the PAMS installation as well as how the PAMS and accessories were connected to the equipment being tested. PAMS data processing varied from test to test depending on the type of installation, PAMS equipment used, and equipment being tested. A summary of the PAMS data processing and QC steps is provided below.

**Process, export, consolidate, read into SAS** - All PAMS datalogger files were processed and exported to comma-separated variable (CSV) files. Duplicate records resulting from interim PAMS data downloads during site revisits were identified and extracted, and all remaining unique CSV files were read into Statistical Analysis Software (SAS) and compiled into a single, chronological dataset for each piece of equipment (i.e., each installation).

**Perform date and time assignments and corrections** - All date and times were reviewed and corrected, as necessary. Occasionally, PAMS installers experienced some problems setting PAMS units to the current time zone, so some date / time corrections involved adjusting the times to the proper time zone (CDT). Initially, the Isaac software only provided a date and time at the start of each monitoring episode, but did not provide second-by-second dates and times, so date and time stamps were assigned to each Isaac second-by-second record (observation) based on the starting date/time provided for the sampling episode. Note that updated Isaac processing software now allows dates/times to be included with each second-by-second observation.

Although the Corsa data was collected on a 1-second basis, the Corsa datalogger timestamps were in a sub-second format, so in SAS the timestamps were truncated to the nearest second. As a result, after truncation, two records were sometimes obtained for any individual second. In these instances, the second observation was flagged and not used in reporting summaries. All original and "corrected" data will be provided as part of the MSOD data submission for this work assignment.

**Perform engine speed calibration corrections** - Based on the installation, revisit or removal records, in SAS, RPM calibration corrections were applied to the data as needed.

**Flag observations on installation, revisit and removal dates –** Provided in Appendix U (PEMS and PAMS Testing Details), records were kept regarding when the PAMS were installed, revisited, and removed. Based on these installation, revisit and removal records, all second-by-second records which were collected on days when the PAMS was installed, revisited or removed were flagged, since any engine activity on these days could be the result of the ERG PAMS team, rather than actual equipment use by the establishment.

**Assign equipment activity flags** - Depending on the type of installation, new variables were assigned to each dataset in order to indicate whether each second-by-second record was collected when the equipment was active (equipment active), the engine was on (engine on) or the key was on (key on).

For some installations, the datalogger was always active (always collecting data, even if the key and engine were off). In other installations, voltage was used as an indicator of engine on/off status, resulting in a number of observations collected after the equipment had been shut off (as the equipment's battery voltage slowly decayed below the shutoff limit). For these two situations, RPM was not always a reliable indicator of engine activity, because the PAMS would sometimes record an RPM signal when the equipment was off (erroneous RPM signal), and also because RPM was sometimes lost during actual engine usage (these two problems were generally only an issue in ES Phase 1, when the Capelec RPM signal device was used). Because of these two issues (data being collected in inactive equipment and unreliable RPM signals), new fields were defined which indicated whether or not the equipment was being used. These assignments were made based both on RPM readings and voltage readings (which fluctuated predictably based on equipment activity). "Equipment active" was used in ES Phase 1 to indicate whether the equipment was in operation (engine running) at the time each observation was recorded by the datalogger. "Engine on" was used for ES Phase 2 and 3 installations for which switched power wasn't recorded. "Key on" was used for ES Phase 2 and 3 installations for which switched power was recorded. Additional details regarding assignment of these three parameters are provided in the PAMS Data Dictionary in Appendix X.

**Assign RPM validity flags** - Erroneous RPM signals were sometimes recorded by the PAMS, primarily during ES Phase 1 when the Capelec RPM signal devices were used. ERG assigned "RPM valid" flags to the ES Phase 1 second-by-second data to indicate when RPM was being collected but the equipment was not active (hence the RPM signal was invalid noise), or if the RPM was too high (RPM greater than 6000). In ES Phases 2 and 3, unrealistic RPM values (RPM greater than 6000) were flagged as "too high".

**Assignment of "Correct" RPM** – For all PAMS data in all three phases, the "ERG RPM" field was used to indicate, for each observation, the "true" RPM. The ERG RPM is "null" for observations where the RPM is invalid (zero when the engine was on or values above 6000 RPM). For installations where two RPM signals were collected, the "ERG RPM" is the value felt to be correct. Again, if neither of the two values were felt to be correct, this field was left null. Non-destructive taps into engine harnesses to obtain RPM values appeared to provide the most reliable signal, followed by optical and then magnetic pickups, and lastly Capelec RPM signal devices. Initial defaults for "ERG RPM" were based on this hierarchy, then comparison of RPM with validity flags and manual review of data was used to further refine the "ERG" RPM values assigned in SAS.

**Assignment of trips and trip counts** – In SAS, counts of trips (and number of observations for each trip) were assigned for each test file. Trips were defined as episodes of engine operation. Trip counts were the total number of "trips", separated by engine off periods.

Details regarding review of each PAMS datafile are provided in Appendix AF, PAMS Data Review Notes. All original and processed data will be provided as part of this work assignment.

# 4.0 Sample Design Performance

At the onset of any study, it is important to develop estimates of how many sampling elements must be selected to meet the specified sampling targets for the study. Key design parameters must be predefined and expected dispositions of the sample from selection through actual interview completion and instrumentation must be estimated. These estimates are used for planning the survey operation and estimating the level of effort that will be required to screen businesses for eligibility in the study and then to recruit sufficient number of businesses to participate in the instrumentation of their nonroad equipment.

The sample design for this study, described in Section 3 of this report, employed a multi-stage probability sample with probabilities proportional to size. The EOI Phase 1 sample of the study involved four-stages of selection (county, establishment, site, equipment) while the integrated sample (EOI Phases II and III) involved a three-stage design (since a census of all establishments was taken). The expected performance of the sample used in this pilot study was based upon several basic design parameters. These included:

- Establishing the sample number called is a business and verifying a correct address
- Verifying the business conducts construction activity
- Calculating an overall screening response
- Confirming business eligibility to participate in the study (e.g., owns or leases one or more pieces of diesel nonroad equipment, the business is a prime contractor, etc.)
- Completing the interview questions (agreeing to or not agreeing to participate in the inventory/instrumentation)

Following each phase of the study, the sample design and data collection performance was analyzed using these parameters. Based on the findings of this analysis, modifications were made to the study design based on the outcome of the sample performance. For example, while it was initially assumed that a single sample frame would be sufficient to achieve the study goals (e.g., obtain the requisite number of completed equipment measurements), an additional sample frame was obtained in EOI Phase 3 of the study to augment the initial sample obtained from SSI.

This section presents the results of the study design performance using the above parameters and design elements for each Phase of the study. The findings of each study phase are presented by first reviewing the sample design / sample performance findings, followed by data collection findings. Implications of these findings on the sample or data collection design of the subsequent phase are also presented.

## 4.1 EOI Phase 1 Results

### 4.1.1 Sample Analysis

EOI Phase 1 represented our first opportunity to assess the performance of the SSI sampling frame. Within PSU 1, construction establishments (the secondary sampling unit or SSU) were drawn with selection probabilities proportional to the estimated number of employees (pps). Our decision to use a pps sampling and in particular to choose the *number of employees* as our measure of size was driven by a desire to increase efficiency. We plausibly expected that employees in establishments operated nonroad equipment and that the number employees in the establishment would be positively correlated with the number of pieces of eligible equipment. Conversely, we expected that establishments with no/zero employees would not be operating equipment and could therefore be eliminated from the frame prior to selection. To get a feel for the implications of these assumptions on the second stage sampling process, we ran a frequency distribution on the number of employees in our PSU 1 frame.

Our analysis showed that the distribution of construction establishments was highly skewed with respect to number of employees much in the way that most business productivity and revenue distributions are distributed in the U.S. -- a relatively small subset of establishments account for the majority of productivity or revenue. Such was the case with the employee distribution across construction establishments in PSU 1: the distribution pattern approximately followed a Pareto distribution (i.e., about 20% of establishments accounted for roughly 80% of employees). If the correlation assumption between employees and equipment held up, then the observed distribution of establishments in the sampling frame would support the use of pps sampling.

An important concomitant to the use of number of employees as a measure of size is the likelihood of encountering ‘self-representing’/‘certainty’ establishments. This happens when one or more establishments feature such large measures of size that they must be selected with certainty into a given sample. For PSU 1, we encountered a large number of self-representing/certainty establishments.[15] Table 4.1-1 shows the frequency and percentage

[15] Self-representing establishments in PSU1 were those for whom SSI reported 15 or more employees; non self-representing establishments had 1-14 employees.

distributions of establishments and number of employees in our PSU 1 frame by self-representing status.

**Table 4.1-1 Frame Characteristics of PSU 1**

| | NUMBER OF ESTABLISHMENTS | PERCENT OF ESTABLISHMENTS | NUMBER OF EMPLOYEES | PERCENT OF EMPLOYEES |
|---|---|---|---|---|
| **Self-representing SSUs** | 267 | 11% | 18,248 | 74% |
| **Non self-representing SSUs** | 2,052 | 86% | 6,317 | 26% |
| **Excluded establishments (0 employees)** | 77 | 3.2% | 0 | 0 |
| ***TOTAL*** | ***2,396*** | ***100%*** | ***24,565*** | ***100%*** |

The need for self-representing units in the PSU 1 sample design precipitated a major modification in the overall design. This was because a large number of establishments (i.e., the self-representing units) belonged to *both* the Establishment and Equipment Samples by virtue of their large measures of size. This meant that all self-representing SSUs needed to taken through the both the EOI and ESI survey protocols (e.g., EOI, recruitment for inventory and instrumentation, incentive experiment, etc.). In consequence, the Equipment and Establishment sample designs were integrated to allow the same self-representing units to be included in both samples. Field protocols were needed to incorporate this design change, as well.

A significant complication to the field protocol integration involved the sequential timing of the data collection for the Establishment and Equipment Samples. In terms of field schedule, the two samples had been planned to be fielded several months apart. However, we wanted to avoid a significant gap in time between the conduct of the EOI survey and the recruitment of the establishment and conduct of instrumentation. Conventional survey practice suggested that the EOIs for the self-representing units be conducted during the latter Equipment Sample data collection. To address the timing issue, we decided to draw a small equal probability sample from the collection of self-representing establishments for fielding in the Establishment Sample. This would leave the bulk of the largest establishments in the Equipment Sample yet permit some learning from self-representing units through the EOI interviews in the Establishment Sample. Accordingly, a subsample of n = 100 (out of 267 total) self-representing units was used in the PSU 1 Establishment Sample, and the balance was allocated to the Equipment Sample.

### 4.1.2 Data Collection Analysis

Before presenting the results of data collection we must first describe the ***eligibility criteria*** used for EOI Phase 1 PSU 1 (namely, for conducting the EOI). Establishments were eligible[16] for the EOI if they had the following attributes (each of which is tied to an EOI survey question):

- the establishment verified that it was the establishment that had been selected into the sample;
- the establishment operated in the construction sector;
- the establishment used diesel powered nonroad equipment; and
- the establishment employed one or more persons.

The EOI Phase 1 Establishment sample consisted of a total of 304 establishments: 100 Self-representing establishments, and 204 non-self-representing establishments. Table 4.1-2 shows the performance of the Establishment Sample. An overall response rate of 54% was achieved even though we planned for a 64% overall response rate. The screening rate was principally responsible for the response rate shortfall – 58% actual versus 75% expected. Once an establishment provided screening information and was found eligible, it appeared that cooperation for conducting the EOI was very high (93% actual versus 85% planned).

**Table 4.1-2 Expected Vs. Actual Design Parameters by Stratum for EOI Phase 1**

| DESIGN PARAMETER: | ACTUAL SELF REP | ACTUAL NONSELF-REP | OVERALL ACTUAL | OVERALL EXPECTED |
|---|---|---|---|---|
| eligibility rate | 51% | 32% | 40% | 65% |
| screen rate | 72% | 51% | 58% | 75% |
| interview rate | 89% | 97% | 93% | 85% |
| **overall response rate** | **64%** | **49%** | **54%** | **64%** |
| Net Yield | 33% | 16% | 21% | 41% |

Table 4.1-2 also demonstrates the substantial differential response rates by PSU type. In particular, the screening response rate for self-representing units (72%) is over 20 percentage points higher than the screening rate of the non-self-representing units (51%). Moreover, the eligibility rates[17] between self- and non-self-representing units show striking differences: 51% eligibility for self-representing units versus only 32% for non-self-representing units. In

[16] We note that for Phase 2 PSU1, the ESI which is used to recruit establishments for instrumentation used an additional criterion to establish eligibility prior to administering the recruitment questions. We will describe the additional criteria in the next subsection.

[17] It is important to remind the reader that Phase 1 EOI and subsequent ESI (recruitment) employed different eligibility criteria, with ESI being more restrictive for PSUs 1-3. With regard to PSU 1, the subsequent ESI (in Phase 2) added a restriction that establishments must be prime contractors. We will see later in the report that the eligibility rates for ESI are significantly lower than what we see above in Table 5.2-1, and the reason lies with the additional ESI eligibility requirements that were imposed.

addition, both of these figures fell substantially below our expectation of 65% that we used to plan the data collection.

The net effect is seen as the last row of Table 4.1-2 – Net Yield. Net Yield refers to the bottom line percentage of the sample that will yield a completed interview. Using our design parameters a net yield of 41% was expected. The actual yield for EOI Phase 1 Establishment Sample was 21%, or about half of what we planned. Net yield varied twofold by PSU status – 33% for self-representing units and 16% for non-self-representing units. Both figures fell well below the expected/planned value of 41%.

### 4.1.3 Implications of Findings on Study Design

The EOI Phase 1 Establishment Sample was successful in that it achieved its primary goal of preparing for the remainder of the Pilot Study. The results of the EOI Phase 1 Establishment Sample are summarized as follows:

- The distribution of construction establishments in the sampling frame was highly skewed with respect to number of employees (generally following a Pareto distribution -- 20% of establishments acct for 80% of employees), and the sample and data collection designs were adapted accordingly;

- If the number of employees is to be used as a measure of size for sampling establishments, then within-PSU sampling of establishments requires a two-step approach. First, identify a set of "self-representing" establishments; second, subsample the non-self-rep establishments

- The overall response rates were generally favorable; however there was considerable variation by self-rep and non-self rep response and this should be incorporated into the EOI Phase 2 sample design;

- Eligibility was considerably lower than planned in our design parameters, and this was differential by PSU Status; this suggested that higher levels (than planned/budgeted) of screening and calling would be required per completed EOI; under a model of fixed level of resources, the target number of completed interviews would need to be reduced;

- There is no efficient way (short of calling) to identify ineligible sample; however, the screening response rate can be increased by adopting a protocol that requires a nominal amount of research of the disconnected numbers. This would verify that there are no other listings for that establishment and/or that all additional listings are disconnected or ‘wrong numbers’, and a conclusion could be drawn that the establishment is no longer in business (which in turn helps the screening response rate).

To develop recommendations for Establishment Samples in EOI Phase 2 and Equipment Sampling, we reviewed the sampling frame data for our remaining PSUs 2-5. Table 4.1-3 presents a expected data collection outcome distributions using Establishment Sample PSU 1 empirical data applied to PSUs 2-5. Column A presents the number of establishments that appear in the sampling frame (including ineligible establishments with only one employee). Note the relatively small number of establishments available for sampling in these PSUS, ranging from the mid-600s to the mid-800s. Column B provides the expected number of self-representing units for PSUs 2-5. These estimates are obtained by applying the proportion of self-representing establishments (about 11%) that were found in PSU 1 to the remaining PSUs. Column C exhibits the remaining non-self-representing establishments after the self-representing are taken into account. Column D provides the total number of completed EOIs for the combined Establishment and Equipment samples. Column E is a projection of the number of completed EOIs from the self-representing units (for the combined Establishment and Equipment Samples) using the effective yield that was attained from EOI Phase 1 Establishment Sample PSU 1. More importantly, Column F applies the effective yield (16%) from non-self-representing units in the EOI Phase 1 Establishment Sample to create a projection of the number of completed EOIs if a census of all establishments were taken. Thus, Column G presents the total expected number of EOIs combining the Establishment and Equipment Samples under a census design. Note that all projections of completed EOIs are well under the targeted value of 192. The shortfalls appear in Column H.

### Table 4.1-3 PSU 2-5 Projections for the *Combined* Establishment and Equipment Samples

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| | **Number of establishments in Sampling Frame** | **Expected Number of Self Rep SSUs*** | **Expected Number of NSR SSUs** | **TARGET EOIs for Both Phases** | **Expected EOIs from Self-Rep @33% yield** | **Expected EOIs with census of NSRs** | **Total EOIs for both Phases with Census** | **Expected SHORTFALL in EOIs** |
| **PSU 1** | 2396 | 266 | 2130 | *192* | 88 | 341 | n/a | *n/a* |
| **PSU 2** | 833 | 92 | 741 | *192* | 31 | 118 | 149 | ***43*** |
| **PSU 3** | 689 | 76 | 613 | *192* | 25 | 98 | 123 | ***69*** |
| **PSU 4** | 709 | 79 | 630 | *192* | 26 | 101 | 127 | ***65*** |
| **PSU 5** | 663 | 74 | 589 | *192* | 24 | 94 | 119 | ***73*** |

The analysis results shown in Table 4.1-3 demonstrated that based on the EOI Phase 1 Establishment sample experience, even a census of all establishments in PSUs 2-5 would fail to produce the targeted number of EOIs in order to achieve the Establishment and Equipment sample targets. This is irrespective of budgetary issues.

The significance of the Table 4.1-3 analysis was profound. Under the initial study design, the Equipment Sample was scheduled for fielding after the Establishment Sample. But instrumentations were to be based primarily on recruitment that occurs during the latter (Equipment Sample) data collection. Table 4.1-3 indicated that there was insufficient sample for both an 'earlier' Establishment Sample (EOI only) and a 'later' Equipment Sample (EOI, inventory, instrumentation).

Moreover, a crucial design parameter in the Equipment Sample had not yet been verified – the percentage of establishments that complete the EOI then agree to instrumentation. The study design had planned for 40% cooperation rate (among those completing the EOI), but EOI Phase 1 showed that other design parameters were off by as much as 50% (e.g., effective yield). This was a significant area of risk and suggested that a robust approach needed to be adopted for the Equipment Sample to ensure adequate sample for instrumentation recruiting.

To address this issue, a full integration of the EOI Phase 2 Establishment and Equipment Samples into a single, unified design was adopted. Under this design, a single data collection effort was conducted in which the only difference between the "Establishment" and "Equipment" samples would be the recruitment of establishments for instrumentation at the end of the EOI. The transition from one to the other was seamless, represented by the asking of a few additional questions at the end of the EOI. All self-representing units were included in the Equipment Sample. Then non-self-representing establishments would be partitioned into random replicates and fielded sequentially, beginning with the "Equipment Sample". If the target number of instrumentation recruitments in a given PSU was achieved (i.e., 92 x .040 = 37), then all remaining non-self-representing replicates would be designated "Establishment Sample," yielding only EOIs.

## 4.2 EOI Phase 2 Results (Integrated EOI & ESI in PSU1)

EOI Phase 2 involved the recruitment of construction businesses from PSU 1 for the purpose of PEMS and PAMS instrumentations. To accomplish this, a sample of businesses (from SSI) was drawn and called by a centralized telephone facility. For most of the sample[18], the EOI was administered, followed by the administration of the incentive experiment, and finally the administration of the recruitment protocol. Businesses that completed the EOI and

[18] A small portion of the sample involved re-calling the businesses that participated in the Phase 1 Pilot. The Pilot involved only the administration of the EOI and was conducted early in 2007.

agreed to be instrumented were then sent to the field for site visits to conduct an inventory of eligible off-road equipment, and instrumentation on a sample of that equipment.

### 4.2.1 Sample Analysis

The sample involved businesses that were in the construction industry (according to SIC codes) according to the SSI sampling frame. Because the eligibility of businesses was sufficiently low, a census of all construction establishments in PSU 2 was conducted. Thus, the sample was composed of two parts:

- *The Pilot Sample*; a small portion of the sample included all businesses that participated in the EOI Phase 1 Pilot and thus had conducted an EOI; these businesses were re-called at EOI Phase 2 because of the need for additional sample.

- *Fresh sample*; this represents the residual, random sample of establishments in the PSU 1 sampling frame that were being contacted for the first time at EOI Phase 2; they were asked to complete the EOI prior to being recruited for instrumentation;

Table 4.2-1 shows the distribution of Pilot and Fresh Sample by SSU type[19] (self-representing versus non-self-representing) used in the EOI Phase 2 data collection effort. Column E shows that a total sample of 2,319 was used. It should be noted that only 62 of the 304 total establishments in Column A were called because there were 62 completed EOIs as a result of the EOI Phase 1 Pilot calling effort.

**Table 4.2-1 Distribution of Pilot and Fresh Samples by SSU Type for PSU 1**

| | PILOT SAMPLE | | FRESH SAMPLE | | TOTAL | |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | F |
| SSU Type: | N | % | N | % | N | % |
| Self-rep | 100 | 33% | 167 | 8% | 267 | 12% |
| Non-self rep | 204 | 67% | 1848 | 92% | 2052 | 88% |
| Total | *304* | *100%* | *2015* | *100%* | *2319* | *100%* |

Prior to recruiting an establishment for site inventory and instrumentation, a series of 13 questions was administered, five of which were designed to establish eligibility to participate in instrumentation. Thus, to determine whether or not an establishment was screened, the responses to five questions were assessed:

[19] Self-representing establishments in PSU1 were those for whom SSI reported 15 or more employees; non-self-representing establishments were reported by SSI to have 1-14 employees.

- **Q1:** whether the business on the telephone line is actually the establishment drawn into the sample;
- **Q2:** whether or not the business is in the construction industry;
- **Q3:** the use of diesel powered off-road equipment;
- **Q4:** whether the business has one or more number of employees; and
- **Q13:** whether the business operates as a prime contractor[20] (**note:** *this requirement was removed during the ESI field period in order to increase eligibility*)

An establishment that adhered to these criteria was eligible to participate (and be recruited) into instrumentation was established by this set of responses. And the provision of responses (regardless of eligibility) amounted to a "successful screening." Note that any point in the question sequence, if an establishment failed an eligibility criterion, the screening was immediately terminated (to reduce respondent burden) and the case was declared "screened, ineligible." Only those cases whose responses indicated eligibility to all criteria were advanced to the incentive experiment and subsequent recruitment.

Once the screening status of an establishment was determined, the calling history for that establishment was reviewed to obtain the proper final disposition for reporting, as shown in Table 4.2-2. It was necessary to prioritize the dispositions in order to gain full insight into the nature of the non-responding cases. For instance, a "not-screened" establishment that was coded as a 'first refusal' at the first call (meaning that a later call would be made to convert the refusal to full cooperation) may have had a busy signal on its last call before data collection ceased. We would want the disposition of this case to be "not screened – first refusal". This determination can only be made using a hierarchical disposition protocol for assigning final dispositions. Table 4.2-2 provides the hierarchical structure we used to assign the final dispositions.

[20] Note that the last criterion (Q 13) transcends the Phase 1 eligibility criteria used for the EOI (even though it was subsequently removed during data collection).

## Table 4.2-2 EOI Phase 2 Screening and Recruitment Response Disposition Hierarchies

| SCREENED: | | | HIERARCHY |
|---|---|---|---|
| **Eligible** | | | |
| | **Completed Recruitment** | | |
| | | Complete | **1** |
| | **Recruitment Not Completed** | | |
| | | Partial Complete | **3** |
| | | Final Refusal | **3** |
| | | Over Quota | **3** |
| | | Partial Refusal | **4** |
| | | Short Completes | **4** |
| | | Specific Callback, Respondent | **5** |
| | | First Refusal | **5** |
| | | Privacy Manager (Caller ID) | **5** |
| | | Language Barrier/Deaf | **5** |
| | | Hang Up | **6** |
| | | Disconnect | **6** |
| | | General Callback | **6** |
| | | Fax/Modem | **6** |
| | | Wrong Number | **6** |
| | | Answering Machine | **6** |
| | | Busy | **6** |
| | | No Answer | **6** |
| | | Household Number | **6** |
| **Ineligible** | | | |
| | | Q2: No Construction Services | **2** |
| | | Q3: No Diesel Equipment | **2** |
| | | Q4: No Paid Employees | **2** |
| | | Q13: Sub Contractor | **2** |
| | | Out-Of-Area Completes | **2** |
| **NOT SCREENED:** | | | **Hierarchy** |
| | Final Refusal | | **3** |
| | First Refusal | | **5** |
| | Privacy Manager (Caller ID) | | **5** |
| | Language Barrier/Deaf | | **5** |
| | Hang Up | | **6** |
| | Disconnect | | **6** |
| | General Callback | | **6** |
| | Fax/Modem | | **6** |
| | Wrong Number | | **6** |
| | Answering Machine | | **6** |
| | Busy | | **6** |
| | No Answer | | **6** |
| | Household Number | | **6** |
| | Not dialed | | **7** |

### 4.2.2 Screening Results

Table 4.2-3 presents the screening rates for EOI Phase 2 by sample source (fresh versus pilot). Columns A and B show that the pilot EOI Phase 1 screening effort was more successful than that of the EOI Phase 2 calling. This was likely due to the higher mix of self representing (i.e., larger) establishments in the pilot EOI Phase 1 sample. Column C exhibits the combined screening rate for Phase 2 – 36%. The screening rate was about half of what was expected in the initial study design (as shown by columns C and D of Table 4.2-3).

**Table 4.2-3 Screening Rates for Phase 2 by Sample Frame**

| PSU 1 | PH II SAMPLE SOURCE | | PHASE 2 | |
|---|---|---|---|---|
| | Fresh | Ph I Pilot | COMBINED | EXPECTED |
| | A | B | C | D |
| SCREENING RATE | 35% | 44% | 36% | 75% |
| Sample size | 2015 | 304 | 2319 | n/a |

The eligibility rates for instrumentation recruitment were calculated from the 844 establishments that were actually screened. Table 4.2-4 presents the eligibility rates experienced in the EOI Phase 2 recruitment calling. The pilot sample achieved an eligibility rate that was over twice that of the fresh EOI Phase 1 sample. This also reflects the higher proportion of large (self-representing) establishments in the pilot sample. Column C shows the overall eligibility rate of all establishments among those screened (recall that for EOI Phase 1 a census of all establishments in PSU 1 was taken). The actual eligibility rate was lower than planned by a factor of (75/8.6) = 8.5. This represents a major departure from expectation. Such a huge reduction factor begs the question as to whether the eligibility criteria are conceptually relevant/coherent (i.e., worthy of a major 'reality check'). The restriction to prime-contractor-only establishments had been lifted during data collection, but that did not seem to appreciably increase the overall rate compared to what was encountered in the Phase 1 EOIs (i.e., 40%).

One possible explanation was that the reduction was due to response error. Both the survey introduction and some of the question wording announced or hinted at the eligibility requirements. It was possible that the respondents were responding negatively in an effort to quickly terminate the call and thereby reduce their own burden. To address this possibility we reviewed and revised the survey protocols (i.e., introduction and question wordings) to remove any hint regarding eligibility. The impact of these changes are seen in later in this report when presenting the findings of EOI Phase 3 activity.

**Table 4.2-4 EOI Phase 2 Eligibility Rates by Sample Source for PSU 1**

| PSU 1 | PH 2 SAMPLE FRAME | | PHASE 2 | |
|---|---|---|---|---|
| | Fresh | Ph 1 Pilot | COMBINED | EXPECTED |
| | A | B | C | D |
| Eligibility RATE | 7.5% | 15.7% | 8.6% | 75% |
| Total Screened | 710 | 134 | 844 | n/a |

### 4.2.3 Data Collection Analysis

The screening effort yielded a total of 74 establishments that were eligible to be recruited for instrumentation. Of these, 21 were recruited by telephone and sent to the field for site inventories, representing an overall recruitment rate of 28%. Table 4.2-5 presents the EOI Phase 2 recruitment rates for eligible establishments by sample type. The recruitment rates among the fresh and pilot samples were fairly consistent. However, compared to our expectations, recruitments were down by (1 – 28.4/34) = 17 percent. This was not viewed as substantial in the larger picture (compared to, say, the discrepancy in expected versus actual eligibility rates that lead us to re-think the concept of eligibility).

**Table 4.2-5 EOI Phase 2 Recruitment Rates by Sample Type for PSU 1**

| PSU 1 | PH 2 SAMPLE FRAME | | PHASE 2 | |
|---|---|---|---|---|
| | Fresh | Ph 1 Pilot | COMBINED | EXPECTED |
| Recruitment RATE | 28.3% | 28.6% | 28.4% | 34% |
| Total Eligible | 53 | 21 | 74 | n/a |
| Total Recruited | 15 | 6 | 21 | n/a |

The overall response rate for the EOI Phase 2 recruitment process was calculated by taking the product of the screening and recruitment rates (see Table 4.2-6). This yielded an overall response rate of (35% x 28.4%) = 10.2%, which was lower than we expected by a factor of 2.6.

**Table 4.2-6 EOI Phase 2 Overall Response Rates by Sample Source for PSU 1**

| PSU 1 | PH 2 SAMPLE FRAME | | PHASE 2 | |
|---|---|---|---|---|
| | Fresh | Ph 1 Pilot | COMBINED | EXPECTED |
| | A | B | C | D |
| Overall Response | 9.9% | 12.6% | 10.2% | 26% |
| Total Recruited | 15 | 6 | 21 | n/a |

### 4.2.4 Implications of Findings on Sample Design

Table 4.2-7 summarizes the EOI Phase 2 recruitment effort and compares the actual design parameters that were encountered to those that were used for planning. The ratios of the expected to actual rates show the increased effort factors for each component of the design. The biggest contributor of additional effort was the unexpected 7.8 factor increase in screening to identify eligible establishments. That is followed by the twofold increase in sample size needed to compensate for a lower-than-expected screening response. The bottom row of Table 4.2-7 shows the cumulative effect: roughly 55 times more sample would be needed than expected to achieve the original target number of recruits from telephone recruiting.

EOI Phase 2 sample and data collection analysis showed that higher than expected effort was needed to recruit establishments due to significantly lower than expected eligibility rates, compounded by lower screening and recruitment rates relative to what was expected. Similar performance was expected and planned for EOI Phase 3.

**Table 4.2-7 EOI Phase 2 Actual Versus Expected Design Parameters for PSU 1**

| PSU 1 | PHASE 2 ACTUAL | EXPECTED | RATIO (EXP/ACT) |
|---|---|---|---|
| Screening Rate | 36% | 75% | 2.1 |
| Eligibility Rate | 8.8% | 75% | 8.5 |
| Recruitment Rate | 28% | 34% | 1.2 |
| Overall Response rate | 10% | 26% | 2.6 |
| | Actual increase relative to Expected | | 55 |

## 4.3 EOI Phase 2 Results (Integrated EOI & ESI, PSUs 2 and 3)

EOI Phase 2 also included the data collection component for PSUs 2 and 3 that were launched after the PSU 1 fieldwork. The results for PSUs 2 and 3 are reported in this subsection. The objective for this portion of EOI Phase 2 was to test and refine our survey field protocols which featured a fully integrated EOI-ESI instrument as well as an incentive test to establish the utility of cash incentive for equipment participation.

### 4.3.1 Sample Analysis

The sample consisted of a census of all establishments appearing in the SSI frame for PSUs 2 and 3. There were 1,522 total listings in the two PSUs, with PSU 2 accounting for 55 percent of the total. After deleting 69 listings which were not reachable (e.g., no name, telephone number or address), the remaining 1,453 establishments were fielded for the EOI and

ESI. We note that in reality there was a single survey protocol which concatenated the EOI and ESI in a seamless fashion. The separation between the "EOI" and "ESI" simply represented the transition from one section of a survey instrument to the next. Essentially, the EOI was composed of a series of screening questions to establish eligibility, while the ESI was the recruitment (to instrumentation) section that was administered only to those establishments for which eligibility was established.

Because of the relatively small sizes of the PSU 2 and 3 samples and the fact that they were counties in eastern Iowa that were similar socio-demographically, we combined the samples for the presentation of these analyses.[21] More important is a change to eligibility criteria that was implemented midway into the screening operation, which is discussed in the next section.

### 4.3.2 Screening Results

Screening results for this data collection require separate reporting by two important time periods – (1) prior to September 27, 2007; and (2) September 27 and afterwards. September 27 marks the date that two criteria that restricted eligibility were removed. Prior to September 27, eligibility criteria included a requirement that the establishment have at least one employee. On September 27 that criterion was removed, thus allowing establishments with zero employees to be eligible for instrumentation if they used nonroad diesel equipment. (All other eligibility criteria remained in place.)

**Table 4.3-1 Comparing Two Sets of ESI Eligibility Criteria Used for PSUs 2 and 3**

| EOI PHASE 2 (PSUS 2-3) ESI ELIGIBILITY CRITERIA | |
|---|---|
| **prior to 9/27** | **9/27 and after** |
| **Q1** verify Company name | **Q1** verify Company name |
| **Q2** type of business = construction | **Q2** type of business = construction |
| **Q3B** % diesel equipment < 1% | **Q3B** % diesel equipment < 1% |
| **Q4** paid employees > 0 | |

Table 4.3-2 presents the screening rates for PSUs 2 and 3 by criteria period. Unfortunately, the screening rates in Columns A and B cannot be substantively compared because the entire sample was fielded at the beginning of data collection. Because of that, the 'easy', more cooperative establishments tended to be screened prior to September 27 under the

[21] There is little if any insight that would be gained by examining results separately PSU because of the PSUs' similarities.

more stringent criteria. The rate in column B reflects the screening rate for the harder-to-reach establishments. A more appropriate statistic is the combined rate in column C. This shows that the overall screening rate (regardless of the criteria used) was 60 percent. This is fairly close to the expected rate of 71 percent. This suggests that the field protocols were roughly performing as expected, based on our PSU 1 experience.

**Table 4.3-2 Screening Rates for Combined PSUs 2 and 3 by Criteria Period**

| | CRITERIA PERIOD | | | |
|---|---|---|---|---|
| | Prior to 9/27 (1+ employees) | 9/27 and after (0+ employees) | COMBINED | EXPECTED |
| | A | B | C | D |
| SCREENING RATE | 78% | 28% | 60% | 75% |
| Sample size | 935 | 518 | 1453 | n/a |

Eligibility rates for instrumentation recruitment were calculated using the 878 establishments that were screened. Table 4.3-3 presents the eligibility rates experienced in the EOI Phase 2 recruitment calling. The effect of removing the 0 employee restriction on eligibility is clearly seen. The eligibility rate after 9/27 (0+ employee criterion) is more than twice that of the rate prior to 9/27 (1+ employee criterion). And this does not take into account the fact that the rates in Column B are based on harder-to-reach establishments. In this table Column C is less informative because it provides the overall average eligibility rate. The important statistic lies in Column B because we would now expect a 26 percent eligibility rate under the criteria used in Column B. This value could now be used for planning the implementation of PSUs 4 and 5.

**Table 4.3-3 Eligibility Rates for Combined PSUs 2 and 3 by Criteria Period**

| | PRIOR TO 9/27 (1+ EMPLOYEES) | 9/27 AND AFTER (0+ EMPLOYEES) | COMBINED | EXPECTED |
|---|---|---|---|---|
| | A | B | C | D |
| Eligibility RATE | 12% | 26% | 14% | 75% |
| Total Screened | 733 | 145 | 878 | n/a |

### 4.3.3 Data Collection Analysis

The data collection process produced the expected rate of recruitment: 37% actual versus 34% expected. The total of 123 eligible screened establishments yielded 46 agreeing to be instrumented. There was a 7 percentage point higher rate of recruitment among the "0+

employee group". This may be associated with the less constrained eligibility criterion, but ultimately the difference is not so great to have substantive value in terms of findings or design recommendations. The bottom line result is that the expected rate of cooperation with instrumentation recruitment can be reasonably planned at 35 to 37 percent.

**Table 4.3-4 PSU 2 and 3 Eligible Establishment Recruitment Rates by Criterion Period**

| | PRIOR TO 9/27 (1+ EMPLOYEES) | 9/27 AND AFTER (0+ EMPLOYEES) | COMBINED | EXPECTED |
|---|---|---|---|---|
| **Recruitment RATE** | 35% | 42% | 37% | 34% |
| **Total Eligible** | 85 | 38 | 123 | n/a |
| **Total Recruited** | 30 | 16 | 46 | n/a |

Table 4.3-5 presents the overall response rates for combined PSUs 2 and 3 by criterion period. As expected, the initial group (i.e., prior to 9/27) displays a substantially higher response rate than its later counterpart. This is simply a reflection of fact that easier, more cooperative establishments were more likely to be encountered at the beginning of data collection (i.e., in the prior to 9/27 group) than in the latter group. The overall response rate for the "prior to 9/27 group" is over twice that of the post-9/27 group (i.e., 28% vs. 12%).

It is more meaningful to review the overall response rate for the *combined groups*. This is seen in the third column (23%). This value is close to the expected value of 26 percent.

**Table 4.3-5 Overall Response Rates for Combined PSUs 2 and 3 by Criterion Period**

| | PRIOR TO 9/27 (1+ EMPLOYEES) | 9/27 AND AFTER (0+ EMPLOYEES) | COMBINED | EXPECTED |
|---|---|---|---|---|
| **Overall Response** | 28% | 12% | 23% | 26% |
| **Total Recruited** | **30** | **16** | **46** | n/a |

### 4.3.4 Implications of Findings on Study Design

Table 4.3-6 compares the empirical design parameters that resulted from our computer assisted telephone interviewing (CATI) field experience with combined PSU 2 and 3 to the expected values used for planning. Each row of the table offers a comparison and the bottom row shows the overall impact in terms of a factor representing net increase. The last row shows that the actual net yield was under that anticipated by a factor of 7. The rightmost column shows the ratios of actual-to-expected rates and most are relatively near an ideal value of 1.0. However the biggest departure is due to the discrepancy in eligibility rates. The actual eligibility rate was 14% while the planned value was 75 percent. This factor alone represents a lower-than-expected net yield by a factor of 5.4.

The good news from the data collection is that the screening and recruitment rates appear to be predictable. This can help in planning as well as set the stage for exploring methods to increase response rates.

**Table 4.3-6 Combined PSU 2 and 3 Actual Versus Expected Design Parameters**

| | COMBINED PSU 2 & 3 ACTUAL | EXPECTED | RATIO (EXPECTED/ACTUAL) |
|---|---|---|---|
| Screening Rate | 60% | 75% | 1.3 |
| Eligibility Rate | 14% | 75% | 5.4 |
| Recruitment Rate | 37% | 34% | 0.9 |
| Overall Response rate | 23% | 26% | 1.1 |
| | | Actual increase relative to Expected | 7 |

## 4.4 EOI Phase 3 Results (SSI/EDA Combined Sample, PSUs 4 and 5)

### 4.4.1 Sample Analysis

The sample design for EOI Phase 3 was unique from the other Phases in that it employed a *dual frame* sample design. Instead of using only the Survey Sampling International (SSI) for selecting establishments, we drew a supplemental sample from a file provided by a vendor -- Equipment Data Associates (EDA). EDA furnished a complete listing of companies who leased or purchased heavy construction equipment and whose transactions occurred over an 18 year period spanning January, 1990 and February, 2008.

Because companies can purchase or lease equipment repeatedly over time, change names and/or merge or move their offices, considerable processing was needed to prepare the EDA file for fielding. Moreover, since we were combining samples from two sources, extensive processing was required to identify and remove duplicate and other ineligible companies. This process resulted in 2,209 total listings – 1,155 from PSU 4 and 1,054 from PSU 5.

Figure 4.4-1 presents visually the decomposition of PSU 4 and 5 according to three states of nature:

- The records appear in the SSI frame only.
- The records appear in the EDA frame only.

- The records appear in both SSI and EDA lists.

This information is also given in tabular form in Table 4.4-1.

**Figure 4.4-1: Composition of PSU 4 and 5 Establishments by Sampling Frame Status**

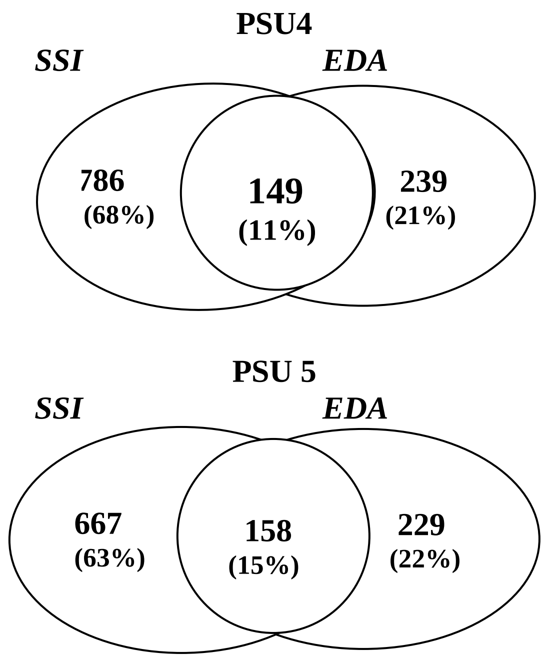



**Table 4.4-1 Distribution of Establishments by Frame Status and PSU**

| | PSU 4 | PSU 5 | Total |
|---|---|---|---|
| **SSI only** | 68% | 63% | 66% |
| **Both SSI & EDA** | 11% | 15% | 13% |
| **EDA only** | 21% | 22% | 21% |
| **Total** | **100%** | **100%** | **100%** |
| **Total Establishments** | **1,155** | **1,054** | **2,209** |

Both Figure 4.4-1 and Table 4.4-1 relay a consistent pattern showing that a relatively small percentage of establishments appeared in both SSI and EDA frames (roughly 1 in eight establishments appear in both frames). Moreover, the coverage value that was added by EDA represented a 27% increase in numbers of listings (since 21/(66+13)) = 0.27 in Column C of Table 4.4-1). Finally, the SSI contributed distinct frame-specific establishments to the overall sample by a ratio of more than a 3:1 (since 66/21 = 3.1).

As in previous study Phases, a census of all establishments was undertaken in EOI Phase 3. Accordingly, all 2,209 records in the combined SSI-EDA frame were loaded into the sample management system for the issuance of advance letters and subsequent calling by the telephone facility.

### 4.4.2 Survey Disposition Documentation

In this section the calling outcomes of the EOI-ESI data collection effort are presented. Before discussing the disposition of the sample, a further refinement of the sample is noted: The list of 2,209 establishments to be fielded included 161 *unusable listings* that could not be fielded. Unusable listings represent seeming valid establishments but were missing key contact information such as telephone number and/or address, and for which pre-field research efforts failed to gather sufficient information necessary in order to make contact. Such listings included establishments that no longer existed, moved out of the area, or were bought, merged or renamed. There was no benefit from fielding a listing that could not be contacted. Only those listings that contained at least a company name and telephone number were retained in the sample.

Table 4.4-2 shows the distribution of the 2,209 establishments by usability status and PSU. As discussed earlier, 161 listings were deemed unusable, representing about 7 percent of the sample. This percentage of unusable listings was consistent across PSUs 4 and 5.

**Table 4.4-2 Combined SSI-EDA EOI Phase 3 Sample by Usability Status and PSU**

| | PSU 4 | PSU 5 | TOTAL |
|---|---|---|---|
| **Listing Unusable** | 8% | 7% | 7% |
| **Fielded sample** | 92% | 93% | 93% |
| **Total** | **100%** | **100%** | **100%** |
| ***Fielded Sample*** | ***1,063*** | ***985*** | ***2,048*** |

**Table 4.4-2a SSI-Only EOI Phase 3 Sample by Usability Status and PSU**

| | PSU 4 | PSU 5 | TOTAL |
|---|---|---|---|
| **Listing Unusable** | <1% | <1% | <1% |
| **Fielded sample** | 100% | 100% | 100% |
| **Total** | **100%** | **100%** | **100%** |
| ***Fielded Sample*** | ***785*** | ***665*** | ***1,450*** |

### Table 4.4-2b EDA-Only EOI Phase 3 Sample by Usability Status and PSU

| | PSU 4 | PSU 5 | TOTAL |
|---|---|---|---|
| **Listing Unusable** | 38% | 29% | 34% |
| **Fielded sample** | 62% | 71% | 66% |
| **Total** | **100%** | **100%** | **100%** |
| ***Fielded Sample*** | ***146*** | ***162*** | ***308*** |

### Table 4.4-2c Both SSI & EDA EOI Phase 3 Sample by Usability Status and PSU

| | PSU 4 | PSU 5 | TOTAL |
|---|---|---|---|
| **Listing Unusable** | 0% | 0% | 0% |
| **Fielded sample** | 100% | 100% | 100% |
| **Total** | **100%** | **100%** | **100%** |
| ***Fielded Sample*** | ***132*** | ***158*** | ***290*** |

The recommendations from our EOI Phase 1 experience included the full integration of the EOI and ESI process, meaning that the transition from "EOI" survey questions to the series of "ESI" questions was seamless and completely transparent to the respondent. Essentially, the first thirteen questions of the integrated survey gather information about the eligibility and other characteristics of the establishment and represent the **EOI**. The last nine questions involve recruitment into the equipment inventory and instrumentation; they comprise the **ESI**. Questionnaires, by phase, are provided in Appendix AK.

## 4.4.3 Screening

The final disposition of the sample of 2,048 fielded establishments was based on the pattern of survey responses to the questionnaire. In order for either an EOI or ESI to be completed, the establishment needed to *screened* in order to determine its eligibility status. The screening process comprised the first three questions in the survey:

- Q1: verification that the telephone number was associated with the intended establishment;
- Q2: verification that the establishment operated in the construction industry; and
- Q3: verification that at least 1 percent of the equipment used by the establishment was diesel powered.

An *eligible establishment* needed to be contacted (Q1), had to operate in the construction industry (Q2) and had to employ diesel powered equipment in its operations for at least 1 percent of its fleet (Q3B). The screening process failed when insufficient information from QQ1-3 was obtained to establish eligibility; the disposition of such establishments was "*not screened*." *Screened establishments* were those for which a pattern of survey responses to QQ1-3 allowed a definitive determination of eligibility status.

It should be noted that unlike earlier Phases of the pilot, EOI Phase 2 employed a singular eligibility standard for both the EOI and ESI (as detailed above). In EOI Phase 2 PSU 1, for instance, ESI 'eligibility' required the establishment to be a prime contractor (with no similar restriction for EOI eligibility).

- The disposition of an establishment was deemed an "*EOI-complete*" if (1) the establishment was screened eligible and (2) valid survey responses were obtained through the QQ 12-13 series (which asked about purchasing equipment and financing such purchases, respectively).
- The disposition of an establishment was deemed an "*ESI-complete*" if (1) the establishment was screened eligible and (2) valid survey responses were obtained through Q19 (soliciting the best time to contact a specific establishment representative to arrange for the agreed site visit and instrumentation).

Table 4.4-3 represents the final disposition of the sample by PSU and for the combined overall sample. Note that among eligible establishments, there are two possible interview dispositions (see the two "screened eligible" rows of Table 4.4-3):

- Establishments where the EOI was conducted but the ESI was not completed (e.g., refusal to be recruited for instrumentation); and
- Establishments where both the EOI and ESI were completed.

Also note the absence of the scenario where a screened eligible establishment did not complete an EOI. This is due to the integration of the screening and "EOI" interview survey questions. Once respondents began answering questions, those from eligible establishments continued to answer questions up to the point of being asked to participate in inventory and instrumentation (i.e., at Q 14 or at the incentive offering if it was triggered). This point in the questionnaire was where break-offs first commenced (although they could occur later in the questioning as well). Consequently, in this Phase of the study, once a respondent commences the interview, they uniformly continued to participate until the "stakes were raised" in the ESI recruitment process.

### Table 4.4-3 Final Disposition of EOI Phase 3 Fielded Sample by PSU

| | A | B | C |
|---|---|---|---|
| **Final Disposition -- Counts** | **PSU 4** | **PSU 5** | **Total** |
| **NOT screened** | 772 | 701 | 1,473 |
| **Screened -- INELIGIBLE** | 194 | 202 | 396 |
| **Screened eligible -- EOI *ONLY* Completed** | 67 | 58 | 125 |
| **Screened eligible -- EOI & ESI Completed** | 30 | 24 | 54 |
| ***Total*** | ***1,063*** | ***985*** | ***2,048*** |

The EOI Phase 3 expected and actual design parameters were next examined. The term *design parameter* refers to the factors that determine sample outcomes for a given sample survey. Four design parameters can be reported from the EOI Phase 3 work:

- *screening response*, representing the ability of field calling to gather enough information to determine the eligibility of an establishment;
- *eligibility*, which reflects the rate at which screened establishments meet the criterion for inclusion in the study (i.e., are in the construction industry and use diesel powered equipment);
- *EOI interview response rate,* reflecting the rate at which screened/known eligible establishments participate in the EOI interview; and
- *ESI interview response rate,* which is the rate at which screened/known eligible establishments participate in the ESI recruitment question series.

The *net yield* was also examined – the number of sample listings needed to be processed (based on the design parameters) in order to produce a single recruitment.

Table 4.4-4 presents actual and expected screening response rates and eligibility rates; also, interview response rates are provided separately for EOI and ESI. All rates are reported by PSU (Columns A and B) and for the overall sample (Column C), along with the corresponding expected values that were used in planning (Column D).

**Table 4.4-4 Actual and Expected Design Parameters for EOI Phase 3 Sample by PSU**

| EOI PHASE 3 | A<br>PSU 4 | B<br>PSU 5 | C<br>Total Actual | D<br>Expected |
|---|---|---|---|---|
| **Screening response** | 27% | 29% | 28% | 75% |
| **Eligibility Rate** | 33% | 29% | 31% | 75% |
| **EOI Interview Response** | 100% | 100% | 100% | 85% |
| **ESI Interview Response** | 31% | 29% | 30% | 40% |
| **Overall Response -- EOI** | 27% | 29% | 28% | 64% |
| **Overall Response -- ESI** | 8% | 8% | 8% | 26% |
| **ESI Net Yield (1 in N)** | 35.4 | 41.0 | 37.9 | 5.2 |

The values in columns A-C of Table 4.4-4 indicate that the screening, eligibility and response rates were consistent across PSUs 4 and 5. Columns C and D can be used to compare actual and expected response and eligibility rates for EOI Phase 3. Actual screening response rates were substantially below the expected/planned value (28% actual vs. 75% expected). This was due to a number of reasons including the quality of the business contact data, the need to conduct additional searches to obtain business information and the need for multiple call backs to businesses to reach a knowledgeable contact. This experience with EOI Phase 3 is consistent with that from earlier Phases of data collection. It is difficult to secure initial cooperation with the establishment personnel who are willing or able to provide the needed information.

Even among the successfully screened establishments, the actual eligibility rate was less than half of the expected rate (31% actual vs. 75% expected). This was disappointing in that the eligibility criteria had been loosened (e.g., companies with 0 employees were eligible provided they met other criteria, removing the restriction that establishments be prime contractors). The lower-than-expected eligibility rate led to higher screening burden to identify eligible establishments (requiring 2.4 times the expected amount of screening than what was planned).

However, the actual EOI interview rates were consistently 100%, which simply reflected the integrated nature of the screening questions and the EOI survey questions. The transition was seamless and the respondent never realized the transition (as there was no need to demarcate it).

The actual ESI interview response rate was about a quarter lower than expected (30% actual vs. 40% expected). It was anticipated that the EOI experience would allow a rapport between the interviewer and respondent to take hold and 'power' a successful transition from the process of asking survey questions to being recruited into instrumentation. But this did not happen. In part this may be to the relatively short duration of the EOI (only 13 questions); such a short duration may not allow much if any rapport to be nurtured. Another issue is certainly the magnitude of the recruitment request. The higher than expected recalcitrance for recruitment led to larger samples required to secure a single instrumentation.

All design parameters can be combined into the ESI *net yield* which estimated the total number of sample establishments fielded and processed in order to produce a single recruitment (i.e., an ESI complete). *Net yield* accounts for both the overall nonresponse rate and the eligibility rate – two chief factors that determine how much sample is fielded to achieve a targeted sample size. The last row of Table 4.4-4 shows that fielding roughly 5 establishments per completed ESI was planned, but fewer than 38 actual fielded establishments were needed to secure a completed ESI/recruitment. This represents an over sevenfold increase in fielding effort compared to what was originally anticipated.

### 4.4.4 EDA-SSI Performance

A principal objective of EOI Phase 3 was to explore the utility of acquiring EDA lists of establishments that purchase or lease diesel off-road equipment. To explore this issue, we compiled the disposition performance measures for samples associated with each frame.

Table 4.4-5 presents the full set of sample performance measures for the SSI frame and the EDA frame. Note that 13% of the sample appeared in both frames; for the purpose of this analysis the overlap cases in each frame were used in the calculations for both Columns A and B and are included. The data is presented this way because each frame should be assessed on its own merits as a stand-alone frame.

A comparison of Table 4.4-5 Columns A and B suggest that both frames demonstrate similar performance with regard to screening and interview response rates (as one might expect given that a standardized field protocol was employed for both samples). Table 4.4-5 Column C reveals one striking difference between frames: the EDA sample exhibited over twice the *eligibility rate* as that of SSI (62% vs. 30%). The net effect is a 56 percent reduction needed to produce an ESI recruit for EDA relative to that needed for SSI.

### Table 4.4-5 Comparison of SSI and EDA Sample Performance Rates

| | A | B | C = B/A |
|---|---|---|---|
| **Response & Eligibility** | **SSI** | **EDA** | **Ratio** |
| **Screening response** | 30% | 28% | **0.94** |
| **Eligibility Rate** | 30% | 62% | **2.10** |
| **EOI Interview Response** | 100% | 100% | **1.00** |
| **ESI Interview Response** | 30% | 35% | **1.15** |
| **Overall Response -- EOI** | 30% | 28% | **0.94** |
| **Overall Response -- ESI** | 9% | 10% | **1.08** |
| **ESI Net Yield (1 in N)** | 37.8 | 16.6 | **0.44** |
| **% of original sample**** | 79% | 34% | **0.43** |
| * % is based on original sample of 2,209; each Frame includes overlaps | | | |

## 4.4.5 Analysis of the EDA as a replacement frame or a screening tool

All else being equal, the increased eligibility of the EDA frame appears very attractive because of its high eligibility rates. The EDA data set is extremely expensive, costing $10,139 compared to the SSI frame which costs $2,262 (for all PSUs). SSI provides over 2.3 times as many listings as EDA. And over 38% of the EDA listings (290/756) appeared in the SSI frame. On the other hand a clear comparison of the two frames should be made on the basis of 'eligible establishments' rather than listings, especially when the eligibility of the EDA frame is over twice that of the SSI. To explore the distribution of expected "eligible listings" in each frame, the expected number of eligible establishments was calculated using the differential eligibility rates in Table 4.4-5 and applying them to the initial frame distributions in Table 4.4-1 (showing sample listings by frame status). The results appear in Table 4.4-6.

### Table 4.4-6 Expected Eligible Establishments by Frame Using Phase 3 Eligibility Rates

| | A | B | C = A X B | D | E | F |
|---|---|---|---|---|---|---|
| | **Sample** | **% Exp Eligible** | **Exp # Eligible** | **Combined Frames** | **SSI Frame** | **EDA Frame** |
| **SSI only** | **1,453** | 24% | 343 | 42% | 66% | -- |
| **Both SSI & EDA** | **290** | 62% | 180 | 22% | 34% | 38% |
| **EDA only** | **466** | 62% | 289 | 36% | -- | 62% |
| **Total** | **2,209** | **37%** | **812** | **100%** | **100%** | **100%** |

Table 4.4-6 reveals that the distribution of expected eligible establishments is more equally distributed between SSI and EDA frames than one might think based on the raw (unscreened) sample shown in Column A. As separate frames, SSI and EDA overlap with the

other by a little over a third of their listings (ranging 34% and 38%, respectively, as shown in Columns E and F).

The SSI frame contributes more ‘eligible’ sample (343+180 = 523) than the EDA frame (180+289 = 469), as shown in Column C. Finally, in terms of assessing the EDA as a supplemental sampling frame (to increase coverage), the EDA adds 289/523 = 55 percent more expected eligible sample than would otherwise not be available from the SSI. This is considerable, especially since the eligibility rate from the EDA frame is twice as high as that of the SSI.

These findings are sufficient to conclude that EDA would be inappropriate as a *replacement* frame. The findings also contraindicate the use of EDA as *a pre-screening tool* to help reduce screening costs: the high cost of the EDA frame outweigh the screening benefits. However, the EDA holds promise as a *supplemental frame* in a dual frame design to increase coverage. The principal driver is cost – is the EDA purchase expense offset by its accompanying decrease in screening costs due to a twofold increase in eligibility rates (relative to SSI)?

The relative costs of processing EDA and SSI sample require further analysis (which is outside the scope of this report). This future analysis is encouraged.

### 4.5 Incentive Test Analysis

The incentive tests for each of EOI Phases 1 and 2 were not definitive and a decision was made to continue the testing in EOI Phase 3. The design of the test involved a random assignment to an incentive offering to establishments just before commencing the ESI portion of the CATI survey (at Question 14). The incentive was an offer of a $100 check sent to the establishment regardless of their participation in the ESI (recruitment). The experimental design called for a random half of respondents to receive the incentive.

The results of the incentive experiment are presented in Table 4.5-1. The results combine PSUs 4 and 5 for the sake of parsimony (since the separate tables show the same result). A total of 171 establishments participated in the incentive test. To “participate” in the incentive test, the introduction must be read to the respondent. The results show that the incentive had no observed impact on accepting the invitation to participate in the inventory and instrumentation. With one degree of freedom, a chi-square statistic whose value is 2.71 or greater would have been needed to establish a 10% level of significance; the observed value was 1.98.

### Table 4.5-1 Combined PSU 4 and 5 Incentive Test on the Invitation to Instrumentation

| | OUTCOME | | |
|---|---|---|---|
| **Experimental Group:** | **Recruited** | **Declined** | **Total** |
| **Incentive** | 33 | 58 | 91 |
| **No incentive** | 21 | 59 | 80 |
| **Total** | 54 | 117 | 171 |
| **Chi-Squared** | 1.98 | **NOT Signif. at 10%** | |

The possibility that the incentive offer might impact *actual participation* in the inventory/instrumentation even if we failed to detect a treatment effect at the recruitment stage was explored. That is, *follow-through to instrumentation* as the outcome instead of *agreement to participate* was explored because some establishments agreed during the CATI interview but then later declined when the reality of inventory/instrumentation was at hand.

Table 4.5-2 presents the results of the incentive test where the outcome is the *actual follow-through to instrumentation*. Unfortunately, the incentive did not show a significant impact on instrumentation follow-through. The results here are striking contrast to the incentive test results for PSUs 2 and 3 (EOI Phase 2). In EOI Phase 2 there was a highly significant incentive effect detected for follow-though to instrumentation.

### Table 4.5-2 Combined PSU 4 and 5 Incentive Test on Instrumentation Follow-Through

| | OUTCOME | | |
|---|---|---|---|
| **Experimental Group:** | **Instrumented** | **Declined** | **Total** |
| **Incentive** | 14 | 77 | 91 |
| **No incentive** | 10 | 70 | 80 |
| **Total** | 24 | 147 | 171 |
| **Chi-Squared** | 0.29 | **NOT Signif. At 10%** | |

To explore the EOI Phase 2 and 3 results we combined the EOI Phase 2 and 3 incentive tests to see if the incentive effect remained. Table 4.5-3 shows the results of that analysis. We see that the incentive effect remains highly significant when the outcome measure is *follow-through to instrumentation*.

**Table 4.5-3 Combined PSUs 2-5 Incentive Tests on Instrumentation Follow-Through**

| | OUTCOME | | |
|---|---|---|---|
| Experimental Group: | Instrumented | Declined | Total |
| Incentive | 34 | 116 | 150 |
| No incentive | 17 | 122 | 139 |
| Total | 51 | 238 | 289 |
| Chi-Squared | 5.41 | **Signif. At 2.5% level** | |

These findings are insightful. First, it is clearly more important to generate *follow-through* to instrumentation rather than *assent* at the recruitment stage. As such, we recommend that future research focus on this as the outcome of interest/treatment effect. Secondly, the findings from Tables 4.5-2 and 4.5-3 are decidedly mixed. There is a very strong incentive effect from EOI Phase 2 when combining the data from EOI Phases 2 and 3. However, the absence of a treatment effect in EOI Phase 3 is troubling and therefore the EOI Phase 2-3 incentive experience begs further analysis and investigation. Clear, significant incentive effects would have conclusively led to a recommendation to adopt incentives in all future studies of this type.

These mixed results give pause to a wholehearted acceptance of incentives. What could lead to such outcomes? The following are some possible explanations:

- Site effects: it could be that PSUs 2-3 contain fundamentally different establishments than those of PSUs 4-5, although it is hard to believe that the effect is due to the peculiarities of establishments within PSUs.
- Interviewer effects: there may have been a difference in the composition of the field interviewer staff between EOI Phases; this could occur if, say, in EOI Phase 2 a highly experienced interviewer staff was used but less experienced interviewers were used in EOI Phase 3.
- Incongruent samples: EOI Phase 3 sampling involved a census of construction establishments regardless of employee size; even establishments showing zero employees (according to SSI) were fielded; this was not the case for EOI Phase 2, where zero-employee establishments were not sampled and if identified in the EOI were terminated; differences in sample universe make-up might explain the incentive results.

The conclusion we reach from these findings is that incentives are cautiously recommended. If at all possible incentive testing should be continued in a way that helps inform our understanding of what factors are associated with differential instrumentation.

# 5.0 Fieldwork Operations

## 5.1 Overview of field protocols

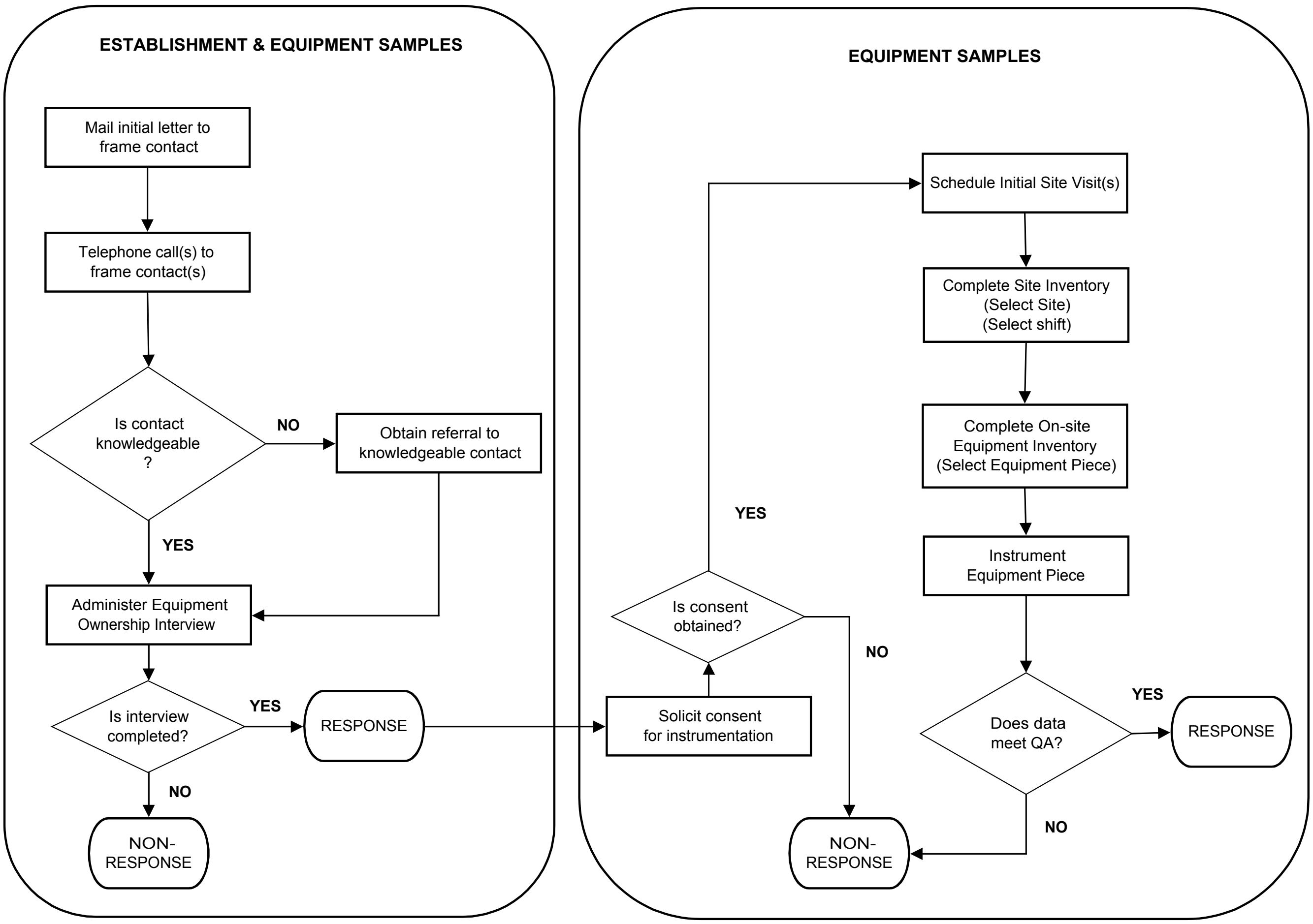
### 5.1.1 Initial protocols

The study objectives called for the collection of emissions data from nonroad diesel engines operated within the study area. The protocols to achieve this were initially based on a plan to collect data using computer assisted telephone interviewing (CATI) from two distinct samples, establishment sample and equipment sample, for equally distinct purposes. An overview of the protocol for the study as originally intended is illustrated in the figure below.

Data collection for the first sample, the establishment sample, was designed to estimate the prevalence of equipment ownership in the study area through an equipment ownership interview (EOI) survey. This sample would be administered in two phases in which EOI Phase 1 would serve as a pilot in which the first PSU would be included. Analysis on the EOI Phase 1 would lead to revisions to the questionnaire that would be used in EOI Phase 2 with the remaining PSUs. The data collected in the EOI was intended to (1) evaluate the sample frames in relations to the target study populations; (2) Obtain direct estimates of proposed measure of establishment size; and (3) estimate proportions of eligible establishments.

For the second sample, the equipment sample, a new sample would be drawn in which participants would participate in an EOI interview followed by an Equipment Sample Interview (ESI) in which qualified establishments would next be invited to participate in an inventory of their nonroad diesel construction equipment (with the goal of achieving their consent to allow one randomly selected piece of equipment be instrumented for activity or emissions monitoring immediately following the inventory). Prior to the telephone interview, participants in this sample would receive an advanced letter containing a fact sheet about the study. Furthermore, as part of the study design for this sample, incentives would be offered to establishments with the intended effect of increasing likeliness of participation.

**Figure 5.1-1 Original Field Protocol**




### 5.1.2 Revision for Phase 2 (complete integration of EOI & ESI (EAM))

The study protocol was modified following ES Phase 1 of the establishment sample due to low instrumentation yield rates of the sample frame which demonstrated that there was not sufficient sample in the study region (within all five PSUs, in fact) to conduct the study as originally intended. Rather, to achieve the study goals it was determined that a census of establishments would be necessary. As such, the field protocols were modified through an integration of the establishment and equipment sample and administration of their respective surveys. The administration of the EOI remained the predecessor to the recruitment for an equipment inventory and random selection of equipment for instrumentation.

### 5.1.3 Equipment Sampling in The Field

As described in Section 3.5.1, weighted equipment selection for each site was performed in Austin after the site inventory was completed. Equipment selection was based on stratified sampling by size and usage, to provide a semi-random sample weighted toward large, heavily-used equipment. This process was similar to picking every nth vehicle from a weighted distribution of randomly arranged vehicles. The weightings were used to increase the likelihood for the selection of vehicles based on size and usage. Equipment "size" categories were based on maximum power output, with small equipment having engine with 100 hp or less and large equipment having engines over 100 hp. Heavily-used equipment was classified as equipment which had a lifetime average of at least 500 hours/year, as determined using hour meter readings and the equipment's age (model year). Relative weights to various classification categories are shown Figure 5.1-2.

**Figure 5.1-2 Sampling Selection Weighting Criteria**

| Equipment Usage Classification | | Equipment Size Classification: Large | Small | Unk |
|---|---|---|---|---|
| | High | 3 | 2 | 1 |
| | Low | 2 | 1 | 1 |
| | Unk | 1 | 1 | 1 |

As described in Section 3.5.1, equipment model year (hence age) and engine power were determined after each site inventory was completed. Using the above weighting scheme, equipment selection took place for sites inventoried for each establishment using the equipment selection workbook developed by EPA and included in Appendix D. Equipment for which model year, power, or cumulative hours used could not be determined were classified as "unknown" as shown in the above figure. After equipment selections were made, this workbook was archived for each establishment, and the equipment selection results were then imported into the master equipment inventory sheet and transmitted back to field personnel. A complete copy of the equipment inventory sheet with all equipment selections made during the study is provided in Appendix W.

## 5.2 Trade organization recruitment

In order to increase establishment participation in the study, national and local trade organizations to which construction establishments within the study area likely belonged or dealt with were initially recruited by ERG to seek their support in the study. Specifically, trade organization representatives were asked if they would review our stakeholder contact list to ensure all relevant stakeholders were included, provide input regarding how to improve participation in the study, and they were asked to notify their membership of this study and encourage participation through newsletters and or faxes. Additionally, the logos of trade organizations who agreed to participate in the study were included in the footer of the program introduction letter initially mailed out to establishments.

Eighteen trade organizations in EPA's region 7 were contacted for support. A call script was developed briefly explaining the program and seeking support, and ERG contacted all organizations to explain the program and request participation. A follow-up letter was also developed to thank the trade organization contact person for their time and to provide additional information regarding the study and type of support that was being requested. Ultimately, seven trade organizations agreed to participate, as shown in the footer of the establishment program introduction letter provided in Appendix AI.

## 5.3 Mail out and FAQ

NuStats sent an advanced letter describing the study to candidate establishments. The advance letter served multiple purposes. First, it informed business owners about the study and about an upcoming telephone call to complete the survey. Second, it asked them to inform NuStats if they are not the most knowledgeable person about their non-road equipment fleet. Finally, it informed prospective respondents they were under no obligation to participate in the survey and, if they did, their responses would remain confidential.

To lend credibility to the study, EPA letterhead was used (rather than NuStats or another study team member) and seven trade associations allowed the use of their logo on the letter to demonstrate their support of the study. A copy of this letter is provided in Appendix AI.

In addition to the advance letters, a "frequently asked questions" (FAQ) brochure was also included with a focus on the process for conducting the equipment inventory and selection of equipment for instrumentation. The advance letter and FAQ brochure and were not originally intended to be administered in the establishment sample portion of the study, but once the samples were integrated, beginning with EOI Phase 2, the letter and brochure were sent to all establishments. A copy of the FAQ brochure is provided in Appendix AJ.

## 5.4 EOI/EAM Script Development

The Equipment Ownership Interview and Equipment Sample Interview were administered to a person with knowledge of the establishment's operation, and were purposefully designed to not require company records or consultation with other employees.

Draft versions of the Establishment Ownership Interview (EOI) and the Equipment Sample Interview (ESI) questionnaire were included in the work assignment. Using these draft questionnaires, NuStats reviewed the EOI survey for minor editing in preparation for Computer Assisted Telephone Interviewing (CATI) programming. A number of revisions were made in consultation with EPA. The following summarizes those modifications:

The sequence of questions was changed so that all qualifying items (those that could potentially deem a respondent as being eligible) were at the beginning of the survey instrument. This was done from a productivity perspective so that resources are not spent interviewing a prospective respondent that does not qualify for the study.

In lieu of asking a business to confirm their NAICS code, respondents were asked to verify that their organization's primary function was construction-related. The list of potential activities was broad and representative of the types of activities as possible.

Once EPA reviewed and approved the survey, it was programmed into CATI and internal tests were conducted to check for correct skip patterns and overall functioning of the program.

However, as a result of the findings of the EOI Phase 1 effort with PSU 1, a decision was made to change the study design into an integrated sample. This necessitated combining the two survey instruments (EOI and ESI) into a single survey instrument for EOI Phase 2 of the study. During subsequent survey administrations, the instrument was modified prior to each study phase to account for low eligibility rates necessitating the removal of certain qualifying screening questions or streamlining the interview flow to improve response rates. The survey instruments for each phase are contained in Appendix AK, and a summary of the eligibility criteria, by EOI Phase, is provided in Table 5.4-1.

**Table 5.4-1 Eligibility Criteria by PSU**

| | | EOI Phase 1 | EOI Phase 2 | | | EOI Phase 3 |
|---|---|---|---|---|---|---|
| | PSU | PSU 1 | PSU 1 | PSUs 2 & 3 BEFORE 9/27 | PSUs 2 & 3 9/27 & AFTER | PSUs 4 & 5 |
| | Survey | EOI | Integrated EOI/ESI | | | |
| **Eligibility Criteria by Question Number** | Q1 Verify establishment | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Q2 Primary function as construction | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Q3 Rent/own diesel fuel equipment | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Q4 One or more paid employees | ✓ | ✓ | ✓ | NA | NA |
| | Q13 Prime contractor | NA | ✓ | NA | NA | NA |

### 5.4.1 Incentive Tests

Incentive tests were conducted in Phases 2 and 3 to test the extent (if any) that a cash incentive would facilitate recruitment into instrumentation. The experiment called for half of the screened eligible establishments to be offered an 'advance incentive' prior to being recruited into instrumentation (which constitutes participation in ESI). The incentive test was offered following question 13 of the survey instrument (see Appendix AK). Among those respondents who were eligible for recruitment for the instrumentation phase of the study, half were flagged via CATI programming for the incentive test. This was done via a "coin toss" programmed into the CATI script in which a sample item received a 50/50 chance of being offered an incentive. Those that were flagged as an incentive were read a script designed to offer the incentive. This script emphasized that the offer of the incentive was not for their guaranteed participation in the instrumentation part of the study. All respondents who were offered an incentive received the incentive regardless of their ultimate consent to participate in the study. Those that were not flagged as an incentive skipped the incentive script altogether. Results of the incentive test were presented in Section 4.5.

### 5.4.2 Cognitive Test

Cognitive or one-on-one interviews were conducted with construction business owners in the Kansas City, MO, region to test reactions to the materials designed to mail to business owners to invite and encourage their participation in the study. These materials included an advance letter and Frequently Asked Questions Fact Sheet. As part of the testing process, NuStats conducted a probe into a number of study design issues, primarily the incentive process.

Using a list of the 64 respondents who previously participated in EOI Phase 1 (PSU1) of the project, seven Kansas City area business owners or managers were recruited to be part of the interviews. Two trained cognitive interviewers from NuStats conducted the research in one-on-one interviews. Four interviews took place at Delve, a professional focus group facility in Kansas City, MO. For the other three interviews, a member of the NuStats research team visited the business and conducted the interview on site. Interviews lasted approximately one hour and participants received compensation for their time.

Table 5.4-2 summarizes the profiles of the seven participants based on their responses provided in the Phase 1 Equipment Ownership Interviews.

**Table 5.4-2 Profile of Participants in Cognitive Interviews**

| No. | Sample Type* | Services Performed | Number of Employees | Number of Equipment |
|---|---|---|---|---|
| 1 | NSR | Building & general contracting<br>Special trade contractor<br>Excavation | 7 | 3 |
| 2 | NSR | Building and general contracting | 3 | 4 |
| 3 | SR | Building & general contracting<br>Heavy construction<br>Excavation<br>Wrecking or demolition | 50 | 50 |
| 4 | SR | Other: Roofing contractor | 35 | 7 |
| 5 | SR | Other: Plumbing contractor | 5 | 8 |
| 6 | NSR | Other: Paving contractor | 8 | 10 |
| 7 | NSR | Building & general contracting<br>Heavy construction<br>Excavation<br>Wrecking or demolition | 13 | 7 |

*NSR=Non Self Representing and SR = Self Representing

NuStats designed the interview to capture insight and reactions to the letter and FAQ sheet and to guide research design issues. A copy of the cognitive interview script is provided in Appendix AM. Overall, the study materials were well received. Participants seemed to understand the reason for the study and why their company would receive information in the mail. The letter and fact sheet were generally clear, easy to read and communicated the appropriate information. Knowing the letter was from EPA played a strong role in the willingness of participants to take the survey. Most participants indicated the materials would provide enough information about the study, and in particular, the inventory and instrumentation stages.

Discussions and in-depth probing about the letter and FAQ sheet generated positive reaction to the materials, their questions and statements were telling in terms of what additional detail we should consider for inclusion as well as recommendations for the study design as it relates to enlisting participation in the equipment inventory/instrumentation portion of this pilot study. All but two of the participants expressed willingness to participate in this later portion of the study after reading the study materials. When asked whether or not compensation would increase willingness to participate, they felt it would; however, it did not alter the decision of the two who had previously said they would still not agree to participate. Regardless, monetary compensation in the amount of one hundred dollars or more was recommended. Because the general contractor agreeing to the equipment inventory/instrumentation at a project site may also have subcontractors with equipment on the site, participants also recommended that compensation be offered to the subcontractors if they are asked to participate in the equipment instrumentation.

Finally, participants generally felt that the study's sample design assumption that business size—number of employees—was correlated to the number of the equipment in their fleet was **not** always valid. For instance, if the company was a general contractor, and primarily subcontracted much of the work requiring owned or leased equipment, it may have many employees but few pieces of equipment.

The following summarizes the recommendations that resulted from the cognitive interviews and guided the revisions to the study materials and design.

*Letter*

- Keep EPA logo, have a local EPA official sign the letter; also contact information for a local EPA employee as well as a key NuStats person.
- Reword the beginning of the letter to immediately state why we need to talk to these business owners and why they are in a unique position to help with this study. The immediate "hook" should be as soon as possible in that first paragraph.
- Incorporate more language about the bottom line reason for the study: cleaner air.
- Use 'off-road' instead of 'nonroad' diesel equipment.

- Keep trade association logos.

- Consider switching the two sections on participation so the confidentiality comes before the steps involved.

*FAQ Sheet*

- Consider removing the word “trouble” from last question.

- Consider adding a photo of the instrument, and include dimensions (i.e., 5” by 8”) and size approximations such as “about the size of a pallet” or “similar in size to a lunchbox.”

- Remove the words “pilot” and “population” throughout.

- Bold the instrumentation web site URL.

- Appeal to protecting the air we all breathe, and consider not focusing so heavily on the equipment and technical terminology. Explain that leased/rented/subcontracted equipment will be treated identical to equipment owned by the prime contractor during the study.

*Equipment Inventory / Instrumentation Recruitment Design*

- Training of interviewers for inventory / instrumentation recruitment (immediately following the EOI) should include the findings from these interviews, especially those related to hesitancy among prospective participants. Training should include the FAQ’s and / or a script to address these types of concerns.

- Fieldwork protocols (field manuals) for the technical specialists performing the equipment inventory / instrumentation should account for the following:

- If equipment on a site is operated by subcontractors, it may be necessary to obtain permission from subcontractors to inventory and /or instrument equipment. Field protocols will instruct specialists to approach a site as if they have “blanket approval” from the prime contractor to inventory and instrument equipment operated at the construction site.

- The process for randomly selecting equipment for instrumentation should incorporate steps to identify up to 3 equipment items in case a subcontractor will not allow instrumentation of their equipment. If agreement for all four items is not obtained, then consider that instrumentation attempt an “incomplete.”

- Equipment owners may want to be present with their equipment is being instrumented. This may require addition time to accommodate their schedules.

- Include script to prepare specialists for responding to potential concerns (e.g., details on the instrumentation of PEMS or PAMS units such as size of units, length of instrumentation, liability for damaged units and compensation if their equipment is damaged.

## 5.5 EOI Performance

### 5.5.1 Outcomes

At the onset of the study, specified targets were developed for sampling and simulated the expected dispositions of the sample frame selection through actual interview completion and recruitment for instrumentation for each of the study phases and for each of the sample frames. These were used to estimate how many sampling elements must be purchased and selected to achieve specific sampling and data collection goals and were also used for planning the survey operation and developing the level of effort for the survey interviewing effort. Appendix AL contains the expected disposition assumptions for the study.

At the completion of each study phase survey data collection effort and following data processing, we conducted analysis of the sample and data collection outcomes. This analysis consisted primarily of a hierarchical analysis of the call history dispositions to determine screening status, eligibility status (among screened establishments) and recruitment status (among 'eligibles'). This analysis entailed determining final call history for each survey question encompassing the screening for eligibility process.

Screening status of an establishment was determined first using the call history for that establishment to obtain the proper final disposition for reporting. The dispositions were prioritized in order to gain full insight into the nature of the non-responding cases. For instance, a "not-screened" establishment that was coded as a 'first refusal' at the first call (meaning that a later call will be made to covert the refusal to full cooperation) may have had a busy signal on its last call before data collection ceased. We would want the disposition of this case to be "not screened – first refusal". This determination can only be made using a hierarchical disposition protocol for assigning final dispositions, as shown in Table 5.2-2.

The hierarchical disposition analysis ultimately provided the data necessary for a full analysis of the sample and data collection performance in conducting the EOI and ESI (instrumentation recruitment). Specifically, it provided documentation of the screening rate, eligibility rates, interview rates, and overall response rates for each of the study phases.

### 5.5.2 Discussion

The table below shows the expected dispositions of the study over each of the study phases and for each of the sample frames.

**Table 5.5-1 *Expected* Dispositions for each Sample Frame and Study Phase**

| | ESTABLISHMENT SAMPLE | | EQUIPMENT SAMPLE | | |
|---|---|---|---|---|---|
| | PHASE 1 | PHASE 2 | PHASE1 | PHASE 2 | PHASE 3 |
| | PSU1 | PSU 2-5 | PSU1 | PSU 2+3 | PSU 4+5 |
| **Screening Response** | 75% | 75% | 75% | 75% | 75% |
| **Interview Response** | 85% | 85% | 85% | 85% | 85% |
| **Overall Response*** | 64% | 64% | 26% | 26% | 26% |
| **Eligibility Rate** | 85% | 85% | 75% | 75% | 75% |
| **Total Sample** | 304 | 1214 | 318 | 635 | 635 |
| **Total Interviewed (EOI)** | 100 | 400 | 93 | 185 | 185 |
| **Total Agreeing to Instrumentation** | NA | NA | 37 | 74 | 74 |
| **Instrumentation Response/ Total** | NA | NA | 40% | 40% | 40% |

* For the **Equipment Sample**, the overall response rate assumes that 40% of the Establishment Sample would agree to instrumentation. We obtain the overall Equipment Sample response rate by multiplying the overall Establishment Sample response rate by 40%. Thus, **64% x 40% = 26%.**

Table 5.5-2 shows the actual performance rates for the EOI portion of the study. From the onset of the study, it is clear that actual dispositions were with few exceptions lower than originally indicated. A significant reason for this was the lower-than-expected eligibility rate. In response to this, in subsequent phases of the study (Phase 2, integrated sample, and Phase 3), the eligibility requirements were revised to increase the eligibility rate. Tables 5.5-2 and 5.5-3 illustrate the impact of this.

**Table 5.5-2 Actual Performance Rates for EOI, All Phases of Integrated Sample**

| | EOI PHASE 1 | EOI PHASE 2 | | EOI PHASE 3 |
|---|---|---|---|---|
| | PSU 1 | PSU 1 | PSU 2+3 | PSU 4+5 |
| **Screening Response** | 58% | 50% | 60% | 28% |
| **Interview Response** | 94% | 70% | 87% | 100% |
| **Overall Response** | 54% | 35% | 53% | 28% |
| **Eligibility*** | 38% | 15% | 14% | 31% |
| **Total Sample** | 304 | 2015 | 1453 | 2048 |
| **Total Interviewed** | 162 | 101 | 107 | 179 |
| * Eligibility criteria were revised for each 'column' of data collection shown above. | | | | |

The overall performance rates for ESI are presented in Table 5.5-3 below.

**Table 5.5-3 Actual Performance Rates for ESI, All Phases of Integrated Sample**

| | EOI PHASE 1/2 | EOI PHASE 2 | EOI PHASE 3 |
|---|---|---|---|
| | PSU 1 | PSU 2+3 | PSU 4+5 |
| **Screening Response** | 36% | 60% | 28% |
| **Interview Response** | 28% | 37% | 35% |
| **Overall Response** | 10% | 23% | 8% |
| **Eligibility** | 9% | 14% | 31% |
| **Total Sample** | 2319 | 1453 | 2048 |
| **Total Agreed to Inventory** | 22 | 43 | 54 |
| **Estabs Inventoried** | **11** | **30** | **38** |
| **Estabs Instrumented** | **7** | **9** | **13** |

## 5.6 Summary of Onsite Inventories and Instrumentation

The process of conducting the onsite inventories and selecting equipment to test is discussed in Section 3.5.1, and a description of PEMS and PAMS testing is provided in Section 3.5.2. Section 5.1.3 outlines the process used for selecting inventoried pieces of equipment for instrumentation. This section provides counts of establishments and pieces of equipment which were inventoried and instrumented, and also provides an overview of the types of equipment on which instrumentations took place.

### 5.6.1 Establishments and Equipment Inventoried

Table 5.6-1 provides counts of the numbers of establishments that were originally recruited for inventories, establishments which were inventoried, establishments which were recruited but then refused inventories, and establishments which were not inventoried for reasons other than establishment refusal, such as all sites being outside the study area or the establishment would have no active sites until after the end of the phase.

**Table 5.6-1 Summary Counts of Establishments Inventoried**

| ES Phase | Establishments Recruited for Inventories | Establishments Inventoried | Establishments Refusing Inventories | Establishments Not Inventoried for Other Reasons |
|---|---|---|---|---|
| **1** | 22 | 11 | 7 (32%) | 4 |
| **2** | 43 | 30 | 11 (26%) | 2 |
| **3** | 54 | 38 | 12 (22%) | 4 |
| **Totals** | **119** | **79** | **30 (25%)** | **10** |

As can be seen in Table 5.6-1, approximately 25% of the establishments who originally agreed to participate in the inventory and measurement phase of the study later reversed their decision and declined to participate any further in the study. Some of these were categorized as “passive” refusals, i.e., field inventory teams were never able to reach a contact, or were given extraordinarily unusual reasons that participation was not possible at that time.

Table 5.6-2 provides counts of equipment inventoried and instrumented throughout the study.

**Table 5.6-2 Summary Counts of Equipment Inventoried and Instrumented**

| | Overall | ES Phase 1 | ES Phase 2 | ES Phase 3 |
|---|---|---|---|---|
| **Count of equipment inventoried** | 292 | 56 | 110 | 126 |
| **Count of PEMS-eligible equipment** | 179 | 41 | 65 | 73 |
| **Count of PAMS installations** | 30 | 7 | 11 | 12 |
| **Count of PEMS installations** | 40 | 6 | 13 | 21 |

Thirty-five of the 79 establishments that were inventoried were also asked to participate in instrumentation (either PAMS, PEMS, or both). It is interesting that only 6 of those 35 establishments refused to participate in the instrumentation process after the inventory. In Table 5.6-2, PEMS eligibility was generally based on whether sufficient room was available for securing the PEMS rack, as approximately 4 ft by 3 ft (footprint) was required to mount the rack. In addition, the PEMS rack could not be mounted on equipment where it would hinder work or pose a visibility or safety hazard.

A more detailed breakdown of the above counts of establishments and equipment, including by-establishment counts of equipment and counts of installations per establishment, is provided in Appendix AG. A complete list of all equipment inventoried is provided in Appendix W.

### 5.6.2 PEMS and PAMS Testing Summary

As shown in Table 5.6-3, 40 PEMS installations were attempted throughout the duration of the study. If more than one installation attempt was made on any individual piece of equipment, both dates are listed in Table 5.6-3. The status of gaseous (gas), particulate matter (PM) and engine speed (RPM) acquisition for each test are also shown in Table 5.6-3. Additional information pertaining to each PEMS test, including details on the piece of equipment that was instrumented and PEMS operating and setup parameters for that test, is provided in Appendix U. Appendix Y contains detailed information regarding results of QC and analysis performed on each PEMS test.

Table 5.6-4 provides a summary of the 30 PAMS installations throughout the duration of the study. Activity data was successfully collected for all installations except as noted in the "notes" column. Additional information pertaining to each PAMS installation, including details regarding the piece of equipment that was instrumented and PAMS setup parameters and revisits for each installation, is provided in Appendix U. Appendix AF provides additional information pertaining to QC analysis of data from each PAMS installation.

An overall and "by-phase" summary of the counts of PEMS and PAMS tests conducted throughout the study is also provided in Table 3.5-1.

### Table 5.6-3 PEMS Testing Summary

| ES Phase | Test ID | Equip Type | Mfr | Model | Model Year | Test Date | Gas | PM | RPM |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| 1 | 2208 - 1918 | Backhoe loader | John Deere | 410B Turbo | 1983 | 6/15/07 | Yes | No | No |
| 1 | 0685 - 2214 | Track/Crawler Loader | Caterpillar | 963C | 2002 | 6/21/07 | No | Yes | No |
| 1 | 0685 - 1214 | Grader | Komatsu | GD655 | 2005 | 6/26/07 | No | No | No |
| 1 | 0008 - 1644 | Backhoe loader | JC Bamford Excavators | 210S Series 2 | 1977 | 6/29/07 | Yes | No | No |
| 1 | 1688 – 1462 | Horizontal Boring Machine | Vermeer | Navigator D16x20A | 2006 | 7/2/07 | No | No | No |
| 1 | 0619 - 0968 | Track/Crawler Loader | Caterpillar | 953C | 2004 | 7/24/07 | Yes | Yes | Yes |
| | | | | | | | | | |
| 2 | 3858 - 1482 | Crawler Dozer | Caterpillar | D4CXL | 1996 | 9/18, 9/20 | Yes | Yes | Yes |
| 2 | 3858 - 5754 | Wheel Loader | Case | 480FLL | 1992 | 9/21/07 | Yes | Yes | Yes |
| 2 | 2523 - 0713 | Track dozer | Caterpillar | D6RXL | 1997 | 9/27/07 | Yes | Yes | Yes |
| 2 | 2523 - 6087 | Articulated Loader | John Deere | 544H | 2003 | 9/28/07 | Yes | Yes | Yes |
| 2 | 2523 – 0210 | Track Excavator | Caterpillar | 325D | 2006 | 10/2/07 | Yes | Yes | No |
| 2 | 3597 - 095K | Roller Compactor | Hyster | C340C | 1997 | 10/4/07 | No | Yes | Yes |
| 2 | 3597 - 0726 | Grader | Caterpillar | 12H | 1996 | 10/9/07 | No | Yes | Yes |
| 2 | 2745 - 1190 | Well Driller | Cummins / James W Bell Co | 4B-3.9 | 1987 | 10/11/07 | Yes | Yes | Yes |
| 2 | 3858 - 4862 | Telescopic Lift Truck | Caterpillar | TH83 | 2002 | 10/13, 10/15 | Yes | Yes | Yes |

| ES Phase | Test ID | Equip Type | Mfr | Model | Model Year | Test Date | Gas | PM | RPM |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 3597 - 4734 | Tractor Loader | Case | 570 LXT | 1997 | 10/24/07 | Yes | Yes | Yes |
| 2 | 3597 - 9706 | Crawler Dozer | John Deere | 550H | 1999 | 10/27/07 | Yes | Yes | Yes |
| | | | | | | | | | |
| 3 | 8925 - 2466 | Track Dozer | Caterpillar | 953C | 1999 | 7/23/08 | Yes | Yes | Yes |
| 3 | 9960 - 6086 | Articulated Loader | Komatsu | WA180 | Unk | 7/28, 8/5 | Yes | Yes | Yes |
| 3 | 0229 - 3781 | Excavator | Case | 1085B | 1985 | 7/31/08 | Yes | Yes | Yes |
| 3 | 0229 - 0045 | Backhoe | John Deere | 410D Turbo | 1995 | 8/1/08 | Yes | Yes | Yes |
| 3 | 9960 - 5674 | Excavator | Komatsu | PC300LC | Unk | 8/6/08 | Yes | Yes | Yes |
| 3 | 8391 - 3333 | Excavator | John Deere | 450D | Unk | 8/12, 8/13 | Yes | No | Yes |
| 3 | 8418 - 0997 | Track Dozer | Caterpillar | 963CB | 1995 | 8/18, 8/19 | Yes | Yes | Yes |
| 3 | 8418 - 0377 | Track Dozer | Caterpillar | 963 | 1985 | 8/22, 8/26 | Yes | Yes | Yes |
| 3 | 8418 - 0961 | Excavator | Komatsu | PC300LC-6LC | 1998 | 8/25/08 | Yes | Yes | No |
| 3 | 0349 - 1836 | Track Dozer | Caterpillar | 953 | 1988 | 9/23/08 | Yes | Yes | Yes |
| 3 | 0349 - 2422 | Excavator | Caterpillar | 320B | 1997 | 9/24/08 | Yes | Yes | Yes |
| 3 | 9272 - 3481 | Excavator | Komatsu | PC400LC | 2000 | 9/30/08 | Yes | Yes | Yes |
| 3 | 9272 - 2494 | Track Dozer | Caterpillar | 963B | 1998 | 10/1, 10/2 | Yes | Yes | Yes |
| 3 | 9272 - 0853 | Excavator | Komatsu | PC400LC | 1993 | 10/6/08 | Yes | Yes | Yes |

| ES Phase | Test ID | Equip Type | Mfr | Model | Model Year | Test Date | Gas | PM | RPM |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 0062 - 0748 | Backhoe Loader | John Deere | 310J | 2007 | 10/9/08 | Yes | Yes | Yes |
| 3 | 0062 - 6092 | Backhoe Loader | John Deere | 310G | 2006 | 10/10/08 | Yes | Yes | Yes |

## Table 5.6-4  PAMS Testing Summary

| ES Phase | Test ID | Equip Type | Mfr | Model | Model Yr | Install Date | Removal Date | Notes |
|---|---|---|---|---|---|---|---|---|
| 1 | 1437 - 0399 | Compact Skid Steer Loader | IR Bobcat | 873 Turbo | 1999 | 6/7/07 | 7/25/07 | |
| 1 | 1688 - 0216 | Horizontal Boring Machine | Vermeer | D20 x 22 | 2007 | 6/8/07 | 7/26/07 | |
| 1 | 1688 - 1462 | Horizontal Boring Machine | Vermeer | D16 x 20A | 2006 | 6/8/07 | 7/26/07 | |
| 1 | 1437 - 1396 | Skidsteer loader | IR Bobcat | S300 Turbo | 2004 | 6/9/07 | 7/25/07 | |
| 1 | 2208 - 1918 | Backhoe loader | John Deere | 410B Turbo | 1983 | 6/10/07 | 7/25/07 | |
| 1 | 1911 - 1916 | Tracked Loader | IR Bobcat | T300 Turbo | 2003 | 6/11/07 | 7/3/07 | |
| 1 | 1911 - 9540 | Concrete Saw | Core Cut | CC6560 XLS | 2006 | 6/19/07 | 7/3/07 | |
| 2 | 3597 - 095K | Roller Compactor | Hyster | C340C | 1997 | 9/10/07 | 10/24/07 | |
| 2 | 3597 - 0265 | Wheel Loader | Caterpillar | 962G | 1999 | 9/14/07 | 9/20/07 | No data collected |
| 2 | 3928 - 1649 | Telescopic Lift Truck | Lull | 644B-42 | 1998 | 9/11/07 | 10/29/07 | |
| 2 | 3854 - 9162 | Straight-Mast Lift Truck | Case | 586D | 1985 | 9/12/07 | 10/25/07 | |
| 2 | 3868 - 0304 | Wheeled Crane | Grove | RT640C | 1999 | 9/13/07 | 10/12/07 | |
| 2 | 3868 - 8720 | Telescopic Lift Truck | Ingersoll Rand | VR-90B | 1997 | 9/19/07 | 10/26/07 | No date / time stamps |
| 2 | 3702 - 9726 | Telescopic Lift Truck | Skytrak | 6042 | 2005 | 9/15/07 | 10/29/07 | |
| 2 | 3858 - 1482 | Crawler Dozer | Caterpillar | D4CXL | 1996 | 9/16/07 | 10/25/07 | |
| 2 | 3858 - 5754 | Backhoe loader | Case | 480FLL | 1992 | 9/16/07 | 10/25/07 | |
| 2 | 2535 - 9216 | Backhoe loader | Case | 580 Super L | 1999 | 9/17/07 | 10/29/07 | |
| 2 | 2535 - 2754 | Backhoe loader | Case | 580 Super M | 2002 | 9/17/07 | 10/29/07 | |
| 3 | 8555 - 2757 | Compact Skid Steer Loader | IR Bobcat | S185 Turbo | 2002 | 7/7/08 | 8/7/08 | |
| 3 | 0229 - 3781 | Wheeled Excavator | Case | 1085B | 1985 | 7/8/08 | 8/8/08 | |
| 3 | 8597 - 1096 | Compact Track Loader | IR Bobcat | T190 | 2008 | 7/9/08 | 8/9/08 | No RPM, "activity" via voltage |
| 3 | 8597 - 0194 | Compact Track Loader | IR Bobcat | T250 | 2008 | 7/10/08 | 8/9/08 | |
| 3 | 8542 - 1271 | Mini Track Excavator | IR Bobcat | 329G | 2007 | 7/10/08 | 8/9/08 | |
| 3 | 0229 - 0045 | Backhoe loader | John Deere | 410D Turbo | 1995 | 7/11/08 | 8/8/08 | |
| 3 | 0062 - 0934 | Tracked Dozer | Caterpillar | D4C | 2001 | 8/11/08 | 9/16/08 | |
| 3 | 0062 - 6976 | Backhoe loader | John Deere | 310G | 2006 | 8/11/08 | 9/16/08 | |
| 3 | 9429 - 7232 | Backhoe loader | Caterpillar | 420E | 2008 | 8/12/08 | 9/16/08 | |
| 3 | 9429 - 0323 | Directional Boring Machine | Ditch Witch | JT2020 | 2006 | 8/12/08 | 9/18/08 | |
| 3 | 9679 - 6459 | Skid Steer Loader | New Holland | LX665 Turbo | 1995 | 8/13/08 | 9/17/08 | |
| 3 | 0349 - 0567 | Track Excavator | Caterpillar | 330D | 2006 | 8/14/08 | 9/16/08 | |

### 5.6.4 Sample management system development

This study required a system for tracking establishments which had agreed to participate in an equipment inventory through to instrumentation for PEMS and PAMS. The original scope was an electronic (real-time) reporting tool, with overall establishment tracking, but not equipment-inventory-level tracking. However, after PSU1, ERG provided to NuStats a list of all data requirements for conducting fieldwork (including all inventoried equipment, equipment selection, equipment backup, etc.). NuStats had worked on developing a system intended to accommodate these needs. However, with the inventory and equipment selection facets of this project, several requirements were difficult to accommodate with an online system:

- Site locations were subjected to change following initial field contact
- All pieces of equipment (including details) for all sites for an establishment needed to be documented and editable on one page (including instrumentation selections and backup selections).
- In addition to canned reports, being able to parse/sort/manipulate the equipment data in other ways (i.e., sort by engine HP, sort by Mfr, extract all the backhoes, etc.) was necessary
- Lists need to be available offline
- Import of data and rapid editing and review of large amounts of data was needed.

For these reasons, the focus shifted to preparing a system as an overall tracking/reporting tool, but not as a comprehensive field-management tool. The system was designed to have the ability to pull in all Equipment Sample establishments (info on those establishments which agree to participate) from CATI.

The system contained the following information:

- Establishment Level

  1) ES Phase of Study (Phase 1, Phase 2, Phase 3) (entered by NuStats/CATI import)
  2) Establishment ID # (entered by NuStats/CATI import)
  3) Establishment Type (Self-Rep vs. non Self-Rep) (entered by NuStats/CATI import)
  4) Incentive Offered? (Yes / No) (entered by NuStats/CATI import)

- Date Inventoried (ERG enter thru web-based system)

    1) Number of pieces of equipment for each establishment (ERG enter thru web-based system)
    2) Number of PEMS eligible pieces of equipment (ERG enter thru web-based system)
    3) Number of pieces of equipment on which a PAMS was installed (ERG enter thru web-based system)
    4) Number of pieces which received a PEMS test (ERG enter thru web-based system)
    5) Number of pieces of equipment on which a PAMS was installed **and** which received a PEMS test (ERG enter thru web-based system)
    6) Establishment Status (Options are "Active" and "Closed", Default to "Active", and changed to "Closed" when completed at all the establishment's sites) (ERG enter thru web-based system)

- Equipment Level

    1) Establishment ID # (where the equipment is located) (ERG enter thru web-based system)
    2) ES Phase (this would be linked by Establishment ID)
    3) Equipment ID (this is the serial #) (ERG enter thru web-based system)
    4) Type of equipment (open field for text entry, ERG enter thru web-based system)
    5) Instrumentation type (PAMS, PEMS, or both) (ERG enter thru web-based system)
    6) If "Instrumentation Type" is "PAMS" or "both"
    7) PAMS Install date (ERG enter thru web-based system)
    8) PAMS Removal date (ERG enter thru web-based system)
    9) If "Instrumentation Type" is PEMS or both
    10) PEMS Test date (ERG enter thru web-based system)
    11) PEMS Removal date (ERG enter thru web-based system)

- Reporting by ES Phase (Phase 1, Phase 2, Phase 3) and total

    1) # of establishments recruited (Representing vs. non self-representing/ Incentive vs. non-incentive
    2) # of establishments inventoried
    3) # of establishments where PAMS have been installed (but no PEMS tests)
    4) # of establishments where PEMS tests have been conducted (but no PAMS installs)
    5) # of establishments where both PEMS tests have been conducted and where PAMS have been installed
    6) Total # of PAMS installations (here, PAMS installations is defined by PAMS install date)
    7) Total # of PEMS tests

# 6.0 Study Results and Conclusions

## 6.1 Recruiting and EOI Findings

### 6.1.1 Recruiting Database

Since this was a pilot study, our design strategy capitalized on learning, revising, implementing and assessing from one phase to the next. Our EOI Phase 1 experience suggested that we eliminate specific eligibility criteria in order to generate sufficient numbers of establishments so that the instrumentation could be fielded. It also suggested that the EOI and ESI data collection vehicles be integrated into a single, seamless survey application. The sample design was also modified when it was realized that a census of establishments would be needed in order to even approach the objectives of the pilot. The need for a census also rendered moot the need to explore the merits of alternative measures of size for establishment sampling within PSUs (since there is no need for MOS when all establishments are being taken into the sample). Another insight came from finding a lower net yield rate relative to what we had expected, *i.e.*, a much larger number of sampled establishments was actually required to recruit a single establishment.

Our EOI Phase 2 experience suggested that we no longer exclude establishments that (according to the SSI sampling frame) reported having zero employees. This was because the measure of size (MOS), *i.e.,* number of employees per establishment used for sampling did not correlate strongly with the equipment population. In addition, EOI Phase 2 suggested that we further loosened our eligibility criteria (to include establishments that are non-prime contractors. For EOI Phase 2 we continued the incentive experiment, where half of EOI respondents were offered an 'advance incentive' prior to being recruited into instrumentation (which constitutes participation in ESI). The EOI Phase 2 recruitment process for instrumentation showed that a higher than expected effort was needed per recruit due to significantly lower than expected eligibility rates, compounded by lower screening and recruitment rates relative to our original expectations.

Our experience with PSUs 2 and 3 was insightful, as well. We demonstrated that the full integration into a seamless EOI/ESI instrument was both feasible and efficient. Our 'institutional learning' from EOI Phase 1 allowed us to realize/achieve our expected response rate targets. And the continued striking gap between expected versus actual (much lower) eligibility rate confirmed our suspicion that reality means low prevalence of eligible construction establishments in the SSI frame (despite our focus on the construction sector listings). On the other hand, the lower than expected eligibility rates also spurred our thinking that there may be response error to our screening questions and introductory scripts. In this spirit, our PSU 2-3 experience led us to refine our scripts (e.g., no longer announcing the eligibility criteria before asking a respondent about the nature of their business) and questions (e.g., asking about the nature of their business in open-ended fashion rather than a yes/no question about construction). The merit of these enhancements would be seen in EOI Phase 3, where the eligibility rate *more than doubled* from 15% to 31%.

We also decided to explore the utility of the EDA database which comprises a list of purchasers of eligible off-road equipment for EOI Phase 3. We purchased EDA data – at considerably greater expense in order to explore its utility as (1) a separate or supplemental sampling frame, (2) as a method of pre-screening establishments to determine eligibility, and (c) as a potential method of exploring response error (i.e., situations where an establishment reports in the EOI to not having any eligible equipment when in fact they have purchased such equipment according to EDA). The findings suggested that while the EDA database is promising as a supplemental frame in a dual-frame design to increase coverage, it is inappropriate as a replacement frame due to lower contribution towards 'eligible' sample (in comparison to the SSI database) and high cost that outweighs the screening benefits.

### 6.1.2 Construction Sector Findings

The following summarizes the general findings regarding the study as applied to the targeted construction sector:

- <u>Fraction of establishments using diesel nonroad equipment</u>. About 49 percent of the establishments participating in the EOI Phases 2 and 3 survey use diesel non-road equipment. Specifically, out of 1,099 establishments, 544 reported they have (1) at least one rented or leased item of equipment or machinery that runs on diesel fuel or (2) at least 1% of equipment that run on diesel.
- <u>Proportion of establishments employing at least one person on a part-time or full-time basis.</u> Data collected in the EOI Phases 2 and 3 suggest that approximately 82% of the establishments in the targeted sectors employed at least one person on a part-time or full-time basis during the previous twelve months. EOI Phase 1 data is excluded from this analysis because zero-employee establishments were excluded from the sample drawn for EOI Phase 1.
- <u>Correlation of number of persons employed in a company and the amount of eligible equipment.</u> A regression analysis was employed to explore the correlation between the number of employees in a company and the amount of eligible equipment. The findings indicate that there was ***no significant correlation*** between these variables. As a result we decided to field the 0-employee establishments for EOI Phases 2 and 3.

Variances in key variables (to inform sample size estimation for subsequent data collection efforts). The descriptive statistics for the key variables are provided in Table 6.2-1. However, we recommend caution in the use of these parameters for sample size estimation. For instance, the number of paid employees is not related to equipment usage, so its use in the design of a study on nonroad equipment has limited or no value. The number of equipment pieces is useful but only available *after data collection.* It is not available prior to data collection. Nonetheless, it could be useful in determining sample size for statistics where the *establishment is the unit of analysis*. If the desired unit of analysis is nonroad diesel equipment, then the clustered nature of our sample must be addressed, since equipment pieces are clustered within establishments (as well as within work sites).

**Table 6.2-1 Descriptive Statistics for Key Study Variables**

| | VALID NO. OF ESTABLISHMENTS | MIN. | MAX. | MEAN | STD. DEVIATION | VARIANCE |
|---|---|---|---|---|---|---|
| No. of paid employees | 409 | 0 | 2300 | 42.07 | 175.40 | 30765.32 |
| No. of diesel equipment pieces | 454 | 1 | 3200 | 24.39 | 173.44 | 30082.61 |

## 6.2 PEMS Measurement Results

The following subsections provide results of PEMS particulate matter and gaseous emissions measurements collected throughout the study. Emission results are provided in units of emissions per work performed, emissions per fuel used, and emissions per time. Results of a PM blind study conducted prior to fieldwork in order to compare DRI and EPA laboratory measurement results (this blind study is described in Section 3.4.5) and results of gravimetric measurements of dynamic and field blanks collected during the field study are also presented. Summaries listed here include gaseous results for the overall test as well as gaseous and PM results for the first three filters collected. Additional emissions information from filters 4 through 9 (if available), as well as test and filter sampling durations, fuel used during each test and filter, and a summary of data “flags” (potentially invalid data) overall and by filter are provided in Appendix AH.

### 6.2.1 PM Filter Weights

All gravimetric sample particulate measurements were collected in accordance with guidelines provided in Appendix L (Gravimetric Filter Handling SOPs) and Appendix F (PEMS Installation SOPs). Weights of all gravimetric filters collected throughout the study are provided in Appendix V (PEMS Filter Log).

### *6.2.1.1 PM Blind Study*

As described in Section 3.4.5, the ERG team coordinated a round of interlaboratory gravimetric mass measurement comparisons between EPA and DRI prior to ES Phase 1 emissions testing. Results from this "blind study" are provided in Table 6.2-2. All EPA measurements are buoyancy corrected. Copies of the complete EPA and DRI laboratory results from the PM blind study are provided in Appendix P.

**Table 6.2-2 PM Blind Study Results**

| DRI Filter ID | DRI Pre-test Mass (mg) (5/9/07) | EPA Pre-test Mass (mg) (5/14/07) | First EPA post-test Mass (mg) (5/24/07) | DRI Post-test Mass (mg) (6/4/07) | Final EPA post-test Mass (mg) (6/7/09) |
|---|---|---|---|---|---|
| PEMGT001 | 143.140 | 143.2874 | 143.7841 | 143.645 | 143.8029 |
| PEMGT002 | 145.650 | 145.8060 | 146.3091 | 146.168 | 146.3238 |
| PEMGT003 | 143.573 | 143.7601 | 145.2798 | 145.153 | 145.3145 |
| PEMGT004 | 142.391 | 142.5794 | 144.1330 | 144.004 | 144.1666 |
| PEMGT005 | 144.709 | 144.8656 | 147.8169 | 147.677 | 147.8481 |
| PEMGT006 | 145.072 | 145.2474 | 148.2430 | 148.113 | 148.2890 |
| PEMGT007 | 144.561 | 144.7396 | 149.0786 | 148.945 | 149.1243 |
| PEMGT008 | 143.043 | 143.2262 | 147.6319 | 147.505 | 147.6890 |
| PEMGT009 | 141.756 | 141.9189 | 141.9310 | 141.786 | N/A |
| PEMGT009 - With Ring Cut | N/A | N/A | N/A | 141.327 | 141.4719 |
| PEMGT010 | 139.224 | 139.4020 | 139.4219 | 139.280 | 139.4238 |
| PEMGT011 | 144.181 | 144.3591 | 144.3708 | 144.227 | 144.3727 |
| PEMGT012 | 140.774 | 140.9449 | 140.9602 | 140.818 | 140.9612 |

### *6.2.1.2 Dynamic and Field Blanks*

As described in Section 3.4 1, dynamic and field blanks were collected throughout the study to quantify the effect of handling and system contamination on the gravimetric filters collected during the study. Table 6.2-3 provides the laboratory measurement results from all dynamic and field blanks collected during the study. These results (and additional information pertaining to associated tests, etc.) are included in the PEMS Filter Log, Appendix V.

**Table 6.2-3 Dynamic and Field Blank Measurement Results**

| Field Tracking # | EPA Filter ID | Est ID | Equip ID | ES Phase | Date Collected | Blank Type | Mass Collected (mg) |
|---|---|---|---|---|---|---|---|
| PEMGT037 | N/A | 0619 | N/A | 1 | 7/24/07 | Field | -0.005 |
| PEMGT072 | 6075325 | 2523 | 6087 | 2 | 9/28/07 | Dynamic | 0.0010 |
| PEMGT073 | 6075326 | 2523 | 6087 | 2 | 9/28/07 | Field | 0.0064 |
| 5070730 | 5070730 | 3858 | 4862 | 2 | 10/13/07 | Dynamic | 0.0273 |
| PEMGT116 | 5070707 | 3597 | 4734 | 2 | 10/24/07 | Field | 0.0099 |
| PEMGT121 | 6075346 | 3597 | 9706 | 2 | 10/27/07 | Dynamic | 0.0020 |
| PEMGT123 | 7049845 | 3597 | 9706 | 2 | 10/27/07 | Field | 0.0097 |
| 8004436 | 8004436 | N/A | N/A | 3 | 7/30/08 | Dynamic | 0.0075 |
| 8004437 | 8004437 | N/A | N/A | 3 | 7/30/08 | Dynamic | 0.0079 |
| 8004439 | 8004439 | N/A | N/A | 3 | 7/30/08 | Field | 0.0048 |
| 8001550 | 8001550 | 8418 | 0097 | 3 | 8/18/08 | Dynamic | 0.0000 |
| 8000039 | 8000039 | 9272 | 0853 | 3 | 10/6/08 | Dynamic | 0.0233 |
| 8000042 | 8000042 | 9272 | 0853 | 3 | 10/6/08 | Dynamic | 0.0708 |
| 8000044 | 8000044 | 9272 | 0853 | 3 | 10/6/08 | Dynamic | 0.0179 |
| 7078362 | 7078362 | 9272 | 2494 | 3 | 10/1/08 | Dynamic | 0.0085 |

### 6.2.2 Summary of Gaseous and PM Emission Results

Tables 6.2-4, 6.2-5 and 6.2-6 list gaseous pollutant emissions for each PEMS test conducted during the study. Results are cumulative for the overall test. Results in Table 6.2-4 are provided on a work basis (grams per kilowatt-hour, or g/kW-hr), calculated as outlined in Section 3.11.1 (with a more detailed derivation in Appendix AD). Emissions in Tables 6.2-5 and 6.2-6 are provided in a fuel basis (grams/gallon) and a time basis (grams/second), respectively. Potentially invalid or "suspect" results are excluded from Tables 6.2-4, 6.2-5 or 6.2-6.

Additional details regarding these results, including notes regarding data corrections and potentially invalid data that has been excluded from these summaries, are provided in Appendix AH, PEMS Measurement Results, and additional details regarding PEMS data quality checks are provided in Appendix Y, PEMS Data QC Results.

When reviewing Tables 6.2-4, 6.2-5 and 6.2-6, it can be seen that work-based results are not listed for some tests which do have fuel-based and time-based results listed. For these tests, either RPM was not available and could not be developed, or no lug curve was available (both RPM and lug curves are necessary to develop work-based emissions estimates but not fuel or time-based emissions estimates). Appendix Y provides details regarding lug curve and RPM availability for each test. As can be seen in Appendix Y, lug curves were provided for all equipment except four pieces, and test results for these four pieces were either suspect, missing gaseous data, or very short (under 15 minutes).

NOx in all emissions results refers to the total exhaust nitrogen oxides, corrected for humidity using methodology defined in 40CFR 1065.670. THC refers to the total hydrocarbon content of the exhaust, and CO and $CO_2$ refer to carbon monoxide and carbon dioxide exhaust content, respectively. PM refers to the total exhaust particulate matter, determined using dilution-corrected weight measurement results of heated 47mm gravimetric filters collected during testing.

Several points should be kept in mind when reviewing all emission results from this study, in particular when comparing these results with emission standards:

- The calculation methodology used to estimate the work basis for each test assumes no change in engine efficiency across varying loads at any given RPM. That is, we assume

$$\begin{aligned} bsfc\ (N) &= fc\ (N) / work(N) \\ &= fc\ (N) / P(N) \cdot \Delta t \\ &\approx fc_{max}\ (N) / P_{max}\ (N) \cdot \Delta t = bsfc_{max}\ (N) \end{aligned}$$

  Engine efficiencies are engine load and speed dependent. For a more detailed discussion of the assumptions used in these calculations, please see Appendix AD.

- The calculated brake specific emissions for many of these tests are calculated using "generic" engine lug curves, in particular the brake specific fuel consumption, bsfc, as a function of engine speed, N. Any variation between the "generic" bsfc curve used and the true bsfc curve for each engine will result in error in the calculated brake specific emissions for the test (or filter).

- PM and gaseous results were collected during real-world operation, including extensive idle periods for some tests. Extensive idle (or low engine speed / load) operation may result in a higher estimate of brake specific emissions than higher speed/load operation. This is due to the ratio of bsfc(N) emissions to small values of fuel consumption in the denominator, i.e., the ratio of emissions to actual work output..

- The bsfc(N) for many of these tests are based in part on an estimated engine speed that is calculated using exhaust mass flow rate, as described in Section 3.11.1.2. The amount of error between this engine speed estimation and the "actual" engine speed will vary from test to test. This engine speed error will be propagated to the bsfc(N) calculation which is used to calculate the gaseous (or PM) brake specific emissions estimations for the test (or filter).

- Although measured and estimated engine speeds have been range checked and corrected for any unreasonableness, any engine speed in an individual test outside of the range defined for any bsfc curve could result in a bias in the brake specific emissions calculated for each test (or filter). However, BSFC values have been limited at max BSFC for work-based emission estimates with out-of-range (high) RPM.

- As mentioned above, engine loads were determined using the ratio of the "measured" fuel rate (calculated by the SEMTECH-DS) to the maximum fuel rate (determined using each engine's lug curve). Some variation between this calculated load and the true load of the engine is possible depending on the engine's efficiency, the accuracy of the bsfc curve and the accuracy of the SEMTECH-DS' estimate of fuel usage on a second-by-second basis.

- Because of differences in soil conditions and types of work performed at each jobsite, workloads varied widely among the different tests performed in this study. Some equipment was used very heavily under great loads, and some equipment use was very light. The way a piece of equipment is used (heavy load and high RPM vs. light load) can have an influence on the emissions from one test (or piece of equipment) to another. Time-based emission estimates are most susceptible to these differences in workloads, since the emission estimates are not normalized by the work produced (or energy consumed) as with work-based and fuel-based emission estimates. Work-based estimates do account for this as emissions are presented on a work-output basis.

- Accuracy of the PM measurements are based on the ability of the micro-proportional sampling system to collect a partial sample proportional to total exhaust mass flow rate at any point in time. The system used for sampling was designed for performing micro-proportional sampling during operation in the "Not To Exceed Zone" (NTE Zone), hence the proportionality varied from test to test. Accuracy of proportionality will have an influence on total PM emission results reported for each test. Plots of proportionality for each test during filter sampling are provided in Appendix Z.

Any PEMS / PM system measurement error including exhaust and sample flow measurement error, instrument drift, time alignment errors, temperature measurement errors, bench errors (errors in measuring specific pollutants), and errors associated with PM collection and measurement, including filter contamination and lab procedures, proportionality and sample flow control, sample loss and collection efficiency, etc. will affect overall emission results. These errors, as well as the other errors discussed in this section have been estimated as shown in Appendix AO, Nonroad Error Estimates, and are summarized in Tables 6.2-4 through 6.2-7 and shown in Figures 6.2-1 through 6.2-28. Uncertainty associated with test-to-test emissions variability (changes in an engine's "true" emissions from one test to the next) and changes in fuel properties (specific gravity and hydrogen to carbon ratio) were not quantified in this study.

## Table 6.2-4 PEMS Gaseous Results, Overall Average Work-Based Emissions

| Test ID | Equipment Type | Manufacturer | Model | Model Year | Rated HP | Test Time (mins) | Fuel Used (gals) | THC (g/kW-hr) | CO (g/kW-hr) | $CO_2$ (kg/kW-hr) | $NO_x$ (g/kW-hr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2208 - 1918 | Backhoe loader | John Deere | 410B Turbo | 1983 | 75 | 206.33 | 4.365 | – | – | – | – |
| 0685 - 2214 | Track Loader | Caterpillar | 963C | 2002 | 160 | 161.38 | 11.558 | 0.586 | 1.278 | 0.679 | 7.97 |
| 0685 - 1214 | Grader | Komatsu | GD655 | 2005 | 197 | 7.17 | 0.276 | – | – | – | – |
| 0008 - 1644 | Backhoe loader | JC Bamford Excavators | 210S Series 2 | 1977 | 64 | – | – | – | – | – | – |
| 1688 – 1462 | Boring Machine | Vermeer | Navigator D16x20A | 2006 | 64 | – | – | – | – | – | – |
| 0619 - 0968 | Track Loader | Caterpillar | 953C | 2004 | 128 | 305.13 | 15.854 | 0.351 | 2.869 | 1.211 | 7.50 |
| 3858 - 1482 | Crawler Dozer | Caterpillar | D4CXL | 1996 | 87 | 99.82 | 3.366 | – | 3.857 | 0.752 | 13.68 |
| 3858 - 1482-1 | Crawler Dozer | Caterpillar | D4CXL | 1996 | 87 | 469.65 | 13.058 | – | 3.925 | 0.736 | 13.26 |
| 3858 - 5754 | Wheel Loader | Case | 480FLL | 1992 | 63 | 275.42 | 2.803 | – | – | – | – |
| 2523 - 0713 | Track dozer | Caterpillar | D6RXL | 1997 | 175 | 86.42 | 5.767 | 0.976 | 3.613 | 0.730 | 4.57 |
| 2523 - 6087 | Articulated Loader | John Deere | 544H | 2003 | 130 | 263.42 | 8.987 | 0.677 | 2.585 | 0.721 | 7.49 |
| 2523 – 0210 | Track Excavator | Caterpillar | 325D | 2006 | 300 | 327.07 | 26.589 | 0.575 | 2.313 | 0.787 | 3.44 |
| 3597 - 095K | Roller Compactor | Hyster | C340C | 1997 | 83 | 185.85 | – | – | – | – | – |
| 3597 - 0726 | Grader | Caterpillar | 12H | 1996 | 140 | 482.97 | – | – | – | – | – |
| 2745 - 1190 | Well Driller | Cummins / JW Bell | 4B-3.9 | 1987 | 76 | 399.72 | 8.690 | 2.297 | 3.678 | 0.709 | 12.46 |

| Test ID | Equipment Type | Manufacturer | Model | Model Year | Rated HP | Test Time (mins) | Fuel Used (gals) | THC (g/kW-hr) | CO (g/kW-hr) | $CO_2$ (kg/kW-hr) | $NO_x$ (g/kW-hr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3858 - 4862-1 | Telescopic Lift | Caterpillar | TH83 | 2002 | 101 | 56.98 | 1.146 | 0.591 | 2.249 | 1.035 | 10.46 |
| 3858 - 4862-2 | Telescopic Lift | Caterpillar | TH83 | 2002 | 101 | 188.47 | 3.441 | 0.497 | 2.437 | 1.182 | 11.35 |
| 3597 - 4734 | Tractor Loader | Case | 570 LXT | 1997 | 68 | 215.13 | 2.053 | 2.561 | 6.242 | 0.725 | 13.72 |
| 3597 - 9706 | Crawler Dozer | John Deere | 550H | 1999 | 84 | 244.27 | 8.726 | 0.520 | 1.539 | 0.726 | 6.71 |
| 8925 - 2466 | Track Dozer | Caterpillar | 953C | 1999 | 170 | 136.13 | 9.327 | 0.717 | – | – | 8.470 |
| 9960 - 6086 | Articulated Loader | Komatsu | WA180 | Unk | 124 | 424.37 | 8.280 | 3.045 | 3.527 | 0.725 | 17.654 |
| 0229 - 3781 | Excavator | Case | 1085B | 1985 | 120 | 60.52 | 0.794 | 4.132 | 5.757 | 0.682 | 17.443 |
| 0229 - 0045 | Backhoe loader | John Deere | 410D Turbo | 1995 | 75 | 68.08 | 1.457 | 1.174 | 2.441 | 0.712 | 11.292 |
| 9960 - 5674 | Excavator | Komatsu | PC300LC | 2003 | 255 | 482.65 | 33.323 | 0.648 | 2.197 | 0.805 | 5.061 |
| 8391 - 3333_1 | Excavator | John Deere | 450D | 2006 | 349 | 344.38 | 36.937 | 0.202 | 1.024 | 0.659 | 3.971 |
| 8391 - 3333_2 | Excavator | John Deere | 450D | 2006 | 349 | 82.33 | 0.641 | – | – | – | – |
| 8418 - 0097_1 | Track Dozer | Caterpillar | 963CB | 1995 | 160 | 14.88 | 0.694 | 0.702 | 3.222 | 0.722 | 7.345 |
| 8418 - 0097_2 | Track Dozer | Caterpillar | 963CB | 1995 | 160 | 111.32 | 10.093 | 0.782 | 2.865 | 0.705 | 6.826 |
| 8418 - 0377_1 | Track Dozer | Caterpillar | 963 | 1985 | 150 | 8.70 | 1.071 | 1.517 | 4.436 | 0.739 | 7.653 |
| 8418 - 0961 | Excavator | Komatsu | PC300LC-6LC | 1998 | 232 | 265.35 | 20.820 | 0.529 | 1.249 | 0.690 | 9.420 |
| 8418 - 0377_2 | Track Dozer | Caterpillar | 963 | 1985 | 150 | – | – | – | – | – | – |

| Test ID | Equipment Type | Manufacturer | Model | Model Year | Rated HP | Test Time (mins) | Fuel Used (gals) | THC (g/kW-hr) | CO (g/kW-hr) | $CO_2$ (kg/kW-hr) | $NO_x$ (g/kW-hr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0349 - 1836 | Track Dozer | Caterpillar | 953 | 1988 | 121 | 94.98 | 5.455 | 0.445 | 3.428 | 0.745 | 8.959 |
| 0349 - 2422 | Excavator | Caterpillar | 320B | 1997 | 128 | 113.97 | 9.030 | 0.738 | 1.328 | 0.736 | 7.596 |
| 9272 - 3481 | Excavator | Komatsu | PC400LC | 2000 | 321 | 605.68 | 77.240 | 0.352 | 1.274 | 0.685 | 5.394 |
| 9272 - 2494_1 | Track Dozer | Caterpillar | 963B | 1998 | 220 | 17.03 | 1.160 | 0.474 | 2.277 | 0.717 | 6.838 |
| 9272 - 2494_2 | Track Dozer | Caterpillar | 963B | 1998 | 220 | 186.43 | 14.929 | 0.317 | 1.876 | 0.735 | 7.184 |
| 9272 - 0853 | Excavator | Komatsu | PC400LC | 1993 | 330 | 268.55 | 30.592 | 0.752 | 1.631 | 0.936 | 12.859 |
| 0062 - 0748 | Backhoe Loader | John Deere | 310J | 2007 | 84 | 365.42 | 8.362 | 0.710 | 3.474 | 0.735 | 8.963 |
| 0062 - 6092 | Backhoe Loader | John Deere | 310G | 2006 | 84 | 167.55 | 2.068 | 1.395 | – | – | 18.269 |

**Note: Various sources of bias and uncertainty exist in the emission estimates provided in this table, and reported work-based gaseous emissions could vary by as much as 20% from "true" emission values, as listed in Appendix AO. In addition, these "in-use" estimates may differ from certification standards due to differences between the certification test cycles and this study's "in-use" work cycles.**

## Table 6.2-5 PEMS Gaseous Results, Overall Average Fuel-Based Emissions

| Test ID | Equipment Type | Manufacturer | Model | Model Year | Rated HP | HC (g/gal) | CO (g/gal) | $CO_2$ (kg/gal) | $NO_x$ (g/gal) |
|---|---|---|---|---|---|---|---|---|---|
| 2208 - 1918 | Backhoe loader | John Deere | 410B Turbo | 1983 | 75 | 22.141 | 43.839 | 10.142 | 165.1 |
| 0685 - 2214 | Track Loader | Caterpillar | 963C | 2002 | 160 | 8.699 | 18.960 | 10.078 | 118.2 |
| 0685 - 1214 | Grader | Komatsu | GD655 | 2005 | 197 | 10.151 | 83.365 | 10.098 | 65.9 |
| 0008 - 1644 | Backhoe loader | JC Bamford Excavators | 210S Series 2 | 1977 | 64 | – | – | – | – |
| 1688 – 1462 | Boring Machine | Vermeer | Navigator D16x20A | 2006 | 64 | – | – | – | – |
| 0619 - 0968 | Track Loader | Caterpillar | 953C | 2004 | 128 | 2.967 | 24.235 | 10.231 | 63.4 |
| 3858 - 1482 | Crawler Dozer | Caterpillar | D4CXL | 1996 | 87 | – | 52.203 | 10.181 | 185.1 |
| 3858 - 1482-1 | Crawler Dozer | Caterpillar | D4CXL | 1996 | 87 | – | 54.138 | 10.154 | 183.0 |
| 3858 - 5754 | Wheel Loader | Case | 480FLL | 1992 | 63 | 56.102 | 62.055 | 9.623 | 136.7 |
| 2523 - 0713 | Track dozer | Caterpillar | D6RXL | 1997 | 175 | 13.610 | 50.394 | 10.181 | 63.8 |
| 2523 - 6087 | Articulated Loader | John Deere | 544H | 2003 | 130 | 9.595 | 36.655 | 10.221 | 106.2 |
| 2523 – 0210 | Track Excavator | Caterpillar | 325D | 2006 | 300 | 7.474 | 30.045 | 10.219 | 44.7 |
| 3597 - 095K | Roller Compactor | Hyster | C340C | 1997 | 83 | – | – | – | – |
| 3597 - 0726 | Grader | Caterpillar | 12H | 1996 | 140 | – | – | – | – |
| 2745 - 1190 | Well Driller | Cummins / JW Bell | 4B-3.9 | 1987 | 76 | 32.264 | 51.661 | 9.952 | 175.0 |
| 3858 - 4862-1 | Telescopic Lift | Caterpillar | TH83 | 2002 | 101 | 5.852 | 22.259 | 10.245 | 103.6 |
| 3858 - 4862-2 | Telescopic Lift | Caterpillar | TH83 | 2002 | 101 | 4.302 | 21.086 | 10.229 | 98.2 |
| 3597 - 4734 | Tractor Loader | Case | 570 LXT | 1997 | 68 | 35.491 | 86.495 | 10.041 | 190.1 |
| 3597 - 9706 | Crawler Dozer | John Deere | 550H | 1999 | 84 | 7.339 | 21.708 | 10.235 | 94.6 |
| 8925 - 2466 | Track Dozer | Caterpillar | 953C | 1999 | 170 | 9.798 | – | – | 115.670 |
| 9960 - 6086 | Articulated Loader | Komatsu | WA180 | Unk | 124 | 41.719 | 48.321 | 9.932 | 241.867 |
| 0229 - 3781 | Excavator | Case | 1085B | 1985 | 120 | 59.833 | 83.368 | 9.878 | 252.600 |
| 0229 - 0045 | Backhoe loader | John Deere | 410D Turbo | 1995 | 75 | 16.626 | 34.575 | 10.080 | 159.959 |
| 9960 - 5674 | Excavator | Komatsu | PC300LC | 2003 | 255 | 8.167 | 27.687 | 10.147 | 63.790 |
| 8391 - 3333_1 | Excavator | John Deere | 450D | 2006 | 349 | 3.123 | 15.865 | 10.202 | 61.504 |
| 8391 - 3333_2 | Excavator | John Deere | 450D | 2006 | 349 | – | – | – | – |
| 8418 - 0097_1 | Track Dozer | Caterpillar | 963CB | 1995 | 160 | 9.848 | 45.187 | 10.129 | 103.027 |
| 8418 - 0097_2 | Track Dozer | Caterpillar | 963CB | 1995 | 160 | 11.231 | 41.139 | 10.118 | 98.014 |
| 8418 - 0377_1 | Track Dozer | Caterpillar | 963 | 1985 | 150 | 20.602 | 60.225 | 10.039 | 103.908 |
| 8418 - 0961 | Excavator | Komatsu | PC300LC-6LC | 1998 | 232 | 7.803 | 18.434 | 10.187 | 139.045 |

| Test ID | Equipment Type | Manufacturer | Model | Model Year | Rated HP | HC (g/gal) | CO (g/gal) | $CO_2$ (kg/gal) | $NO_x$ (g/gal) |
|---|---|---|---|---|---|---|---|---|---|
| 8418 - 0377_2 | Track Dozer | Caterpillar | 963 | 1985 | 150 | – | – | – | – |
| 0349 - 1836 | Track Dozer | Caterpillar | 953 | 1988 | 121 | 6.057 | 46.626 | 10.138 | 121.849 |
| 0349 - 2422 | Excavator | Caterpillar | 320B | 1997 | 128 | 10.217 | 18.396 | 10.200 | 105.217 |
| 9272 - 3481 | Excavator | Komatsu | PC400LC | 2000 | 321 | 5.266 | 19.054 | 10.248 | 80.685 |
| 9272 - 2494_1 | Track Dozer | Caterpillar | 963B | 1998 | 220 | 6.731 | 32.345 | 10.192 | 97.136 |
| 9272 - 2494_2 | Track Dozer | Caterpillar | 963B | 1998 | 220 | 4.406 | 26.056 | 10.214 | 99.771 |
| 9272 - 0853 | Excavator | Komatsu | PC400LC | 1993 | 330 | 8.227 | 17.829 | 10.232 | 140.608 |
| 0062 - 0748 | Backhoe Loader | John Deere | 310J | 2007 | 84 | 9.771 | 47.829 | 10.119 | 123.384 |
| 0062 - 6092 | Backhoe Loader | John Deere | 310G | 2006 | 84 | – | – | – | – |
| **Note: Various sources of bias and uncertainty exist in the emission estimates provided in this table, and reported fuel-based gaseous emissions could vary by as much as 6% from "true" emission values, as listed in Appendix AO. In addition, these "in-use" estimates may differ from laboratory-derived emission rates due to differences between laboratory test cycles and this study's "in-use" work cycles.** | | | | | | | | | |

### Table 6.2-6 PEMS Gaseous Results, Overall Average Time-Based Emissions

| Test ID | Equipment Type | Manufacturer | Model | Model Year | Rated HP | HC (mg/sec) | CO (mg/sec) | $CO_2$ (g/sec) | $NO_x$ (mg/sec) |
|---|---|---|---|---|---|---|---|---|---|
| 2208 - 1918 | Backhoe loader | John Deere | 410B Turbo | 1983 | 75 | 7.806 | 15.456 | 3.576 | 58.198 |
| 0685 - 2214 | Track Loader | Caterpillar | 963C | 2002 | 160 | 10.384 | 22.631 | 12.030 | 141.136 |
| 0685 - 1214 | Grader | Komatsu | GD655 | 2005 | 197 | 6.506 | 53.435 | 6.473 | 42.209 |
| 0008 - 1644 | Backhoe loader | JC Bamford Excavators | 210S Series 2 | 1977 | 64 | – | – | – | – |
| 1688 – 1462 | Boring Machine | Vermeer | Navigator D16x20A | 2006 | 64 | – | – | – | – |
| 0619 - 0968 | Track Loader | Caterpillar | 953C | 2004 | 128 | 2.569 | 20.987 | 8.860 | 54.869 |
| 3858 - 1482 | Crawler Dozer | Caterpillar | D4CXL | 1996 | 87 | – | 29.342 | 5.723 | 104.069 |
| 3858 - 1482-1 | Crawler Dozer | Caterpillar | D4CXL | 1996 | 87 | – | 25.088 | 4.705 | 84.790 |
| 3858 - 5754 | Wheel Loader | Case | 480FLL | 1992 | 63 | 9.515 | 10.525 | 1.632 | 23.183 |
| 2523 - 0713 | Track dozer | Caterpillar | D6RXL | 1997 | 175 | 15.137 | 56.051 | 11.324 | 70.980 |
| 2523 - 6087 | Articulated Loader | John Deere | 544H | 2003 | 130 | 5.456 | 20.842 | 5.811 | 60.361 |
| 2523 – 0210 | Track Excavator | Caterpillar | 325D | 2006 | 300 | 10.126 | 40.708 | 13.846 | 60.595 |

| Test ID | Equipment Type | Manufacturer | Model | Model Year | Rated HP | HC (mg/sec) | CO (mg/sec) | $CO_2$ (g/sec) | $NO_x$ (mg/sec) |
|---|---|---|---|---|---|---|---|---|---|
| 3597 - 095K | Roller Compactor | Hyster | C340C | 1997 | 83 | – | – | – | – |
| 3597 - 0726 | Grader | Caterpillar | 12H | 1996 | 140 | – | – | – | – |
| 2745 - 1190 | Well Driller | Cummins / JW Bell | 4B-3.9 | 1987 | 76 | 11.691 | 18.719 | 3.606 | 63.415 |
| 3858 - 4862-1 | Telescopic Lift | Caterpillar | TH83 | 2002 | 101 | 1.962 | 7.464 | 3.435 | 34.729 |
| 3858 - 4862-2 | Telescopic Lift | Caterpillar | TH83 | 2002 | 101 | 1.309 | 6.416 | 3.113 | 29.881 |
| 3597 - 4734 | Tractor Loader | Case | 570 LXT | 1997 | 68 | 5.645 | 13.756 | 1.597 | 30.240 |
| 3597 - 9706 | Crawler Dozer | John Deere | 550H | 1999 | 84 | 4.370 | 12.925 | 6.094 | 56.333 |
| 8925 - 2466 | Track Dozer | Caterpillar | 953C | 1999 | 170 | 10.955 | – | – | 129.332 |
| 9960 - 6086 | Articulated Loader | Komatsu | WA180 | Unk | 124 | 13.566 | 15.714 | 3.230 | 78.652 |
| 0229 - 3781 | Excavator | Case | 1085B | 1985 | 120 | 13.085 | 18.232 | 2.160 | 55.243 |
| 0229 - 0045 | Backhoe loader | John Deere | 410D Turbo | 1995 | 75 | 5.929 | 12.331 | 3.595 | 57.048 |
| 9960 - 5674 | Excavator | Komatsu | PC300LC | 2003 | 255 | 9.398 | 31.860 | 11.676 | 73.403 |
| 8391 - 3333_1 | Excavator | John Deere | 450D | 2006 | 349 | 5.582 | 28.359 | 18.237 | 109.943 |
| 8391 - 3333_2 | Excavator | John Deere | 450D | 2006 | 349 | – | – | – | – |
| 8418 - 0097_1 | Track Dozer | Caterpillar | 963CB | 1995 | 160 | 7.656 | 35.130 | 7.874 | 80.096 |
| 8418 - 0097_2 | Track Dozer | Caterpillar | 963CB | 1995 | 160 | 16.972 | 62.167 | 15.291 | 148.115 |
| 8418 - 0377_1 | Track Dozer | Caterpillar | 963 | 1985 | 150 | 42.267 | 123.562 | 20.597 | 213.185 |
| 8418 - 0961 | Excavator | Komatsu | PC300LC-6LC | 1998 | 232 | 10.204 | 24.107 | 13.322 | 181.831 |
| 8418 - 0377_2 | Track Dozer | Caterpillar | 963 | 1985 | 150 | – | – | – | – |
| 0349 - 1836 | Track Dozer | Caterpillar | 953 | 1988 | 121 | 5.797 | 44.626 | 9.703 | 116.623 |
| 0349 - 2422 | Excavator | Caterpillar | 320B | 1997 | 128 | 13.492 | 24.293 | 13.470 | 138.950 |
| 9272 - 3481 | Excavator | Komatsu | PC400LC | 2000 | 321 | 11.192 | 40.498 | 21.782 | 171.489 |
| 9272 - 2494_1 | Track Dozer | Caterpillar | 963B | 1998 | 220 | 7.642 | 36.724 | 11.572 | 110.286 |
| 9272 - 2494_2 | Track Dozer | Caterpillar | 963B | 1998 | 220 | 5.881 | 34.775 | 13.632 | 133.157 |
| 9272 - 0853 | Excavator | Komatsu | PC400LC | 1993 | 330 | 15.619 | 33.851 | 19.426 | 266.961 |
| 0062 - 0748 | Backhoe Loader | John Deere | 310J | 2007 | 84 | 3.726 | 18.241 | 3.859 | 47.056 |
| 0062 - 6092 | Backhoe Loader | John Deere | 310G | 2006 | 84 | – | – | – | – |

**Note: Various sources of bias and uncertainty exist in the emission estimates provided in this table, and reported time-based gaseous emissions could vary by as much as 6% from "true" emission values, as listed in Appendix AO. In addition, these "in-use" estimates may differ from laboratory-derived emission rates due to differences between laboratory test cycles and this study's "in-use" work cycles.**

Table 6.2-7 lists work-based (grams/kW-hr) PM and gaseous emissions for the first three filters collected for each PEMS test. By-filter results are provided on a fuel basis (mass per gallon) and a time basis (mass per second) in Appendix AH. If more than three filters were collected for a test, these additional results are also provided in Appendix AH.

Although not always possible, Filter 1 was generally collected on a cold-start, while filters two and three were collected once the engine had been warmed. Additional details pertaining to each filter collected are provided in Appendix V, PEMS Filter Log.

Uncertainties associated with each filter are listed in Table 6.2-7. As described in Appendix AO, several factors contribute to the large range in uncertainties associated with each filter. These factors include changes in proportionality from one test (or filter) to the next, and the relative magnitude of filter contamination and laboratory measurement uncertainty (described in Appendix AO) to filter mass. For filters with light loading (low PM accumulation due to high dilution, low sample times or low PM emission rates), the relative magnitude of filter contamination and lab measurement uncertainty (both absolute numbers in mg) increases, thereby increasing the uncertainty in the overall PM emission rate.

## Table 6.2-7 By-Filter PEMS Results, Average Work-Based Emissions

| Test ID | Equip Desc. | Filter 1 Results HC | Filter 1 Results CO | Filter 1 Results $NO_x$ | Filter 1 Results $CO_2$ | Filter 1 Results PM | Filter 1 Results PM + / - | Filter 2 Results HC | Filter 2 Results CO | Filter 2 Results $NO_x$ | Filter 2 Results $CO_2$ | Filter 2 Results PM | Filter 2 Results PM + / - | Filter 3 Results HC | Filter 3 Results CO | Filter 3 Results $NO_x$ | Filter 3 Results $CO_2$ | Filter 3 Results PM | Filter 3 Results PM + / - |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | g/kW-hr | | | kg/kwh | g/kW-hr | | g/kW-hr | | | kg/kwh | g/kW-hr | | g/kW-hr | | | kg/kwh | g/kW-hr | |
| 2208 - 1918 | ’83 Deere 410B | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 0685 - 2214 | ‚02 Cat 963C | – | – | – | – | – | | 0.70 | 1.09 | 11.9 | 0.65 | 0.48 | 0.43<br>0.40 | – | – | – | – | – | |
| 0685 - 1214 | ’05 Kmtsu GD655 | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 0008 - 1644 | ’77 JCB 210S | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 1688 – 1462 | ’06 Vmr D16X20A | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 0619 - 0968 | ’04 Cat 953C | 0.56 | 5.95 | 9.02 | 1.14 | 0.28 | 0.10<br>0.11 | 0.48 | 3.08 | 7.54 | 1.19 | 0.55 | 0.17<br>0.14 | 0.38 | 2.88 | 7.77 | 1.20 | 0.44 | 0.13<br>0.10 |
| 3858 - 1482 | ’96 Cat D4CXL | – | 17.8 | 13.3 | 0.72 | 0.23 | 0.09<br>0.09 | – | 6.83 | 14.5 | 0.74 | 0.22 | 0.07<br>0.05 | – | 4.12 | 14.4 | 0.74 | 0.16 | 0.05<br>0.04 |
| 3858 - 1482-1 | ’96 Cat D4CXL | – | 20.1 | 13.7 | 0.74 | 0.28 | 0.15<br>0.22 | – | 4.39 | 13.3 | 0.73 | 0.37 | 0.14<br>0.15 | – | 3.71 | 13.9 | 0.72 | 0.18 | 0.06<br>0.05 |
| 3858 - 5754 | ’92 Case 480FLL | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 2523 - 0713 | ’97 Cat D6RXL | 1.93 | 5.82 | 5.44 | 0.71 | 0.64 | 0.21<br>0.16 | 2.08 | 4.58 | 4.75 | 0.69 | 0.29 | 0.09<br>0.07 | 1.00 | 3.56 | 4.47 | 0.73 | 0.47 | 0.15<br>0.12 |
| 2523 - 6087 | ’03 Deere 544H | 1.54 | 6.53 | 6.40 | 0.68 | 0.19 | 0.08<br>0.11 | 1.11 | 3.86 | 7.70 | 0.71 | 0.26 | 0.08<br>0.06 | 1.02 | 3.82 | 7.16 | 0.70 | 0.22 | 0.07<br>0.05 |
| 2523 – 0210 | ’06 Cat 325D | 0.88 | 3.62 | 7.52 | 0.76 | 0.57 | 0.18<br>0.14 | 0.93 | 2.01 | 2.76 | 0.77 | 0.30 | 0.09<br>0.07 | 0.62 | 2.66 | 3.48 | 0.77 | 0.10 | 0.03<br>0.03 |
| 3597 - 095K | ’97 Hyster C340C | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 3597 - 0726 | ’96 Cat 12H | – | – | – | – | – | | – | – | – | – | 5.54 | 1.7<br>1.3 | – | – | – | | 3.06 | 0.94<br>0.72 |
| 2745 - 1190 | ’87 Cmns 4B-3.9 | 1.82 | 4.60 | 16.3 | 0.71 | 0.31 | 0.10<br>0.08 | 2.16 | 3.31 | 14.6 | 0.72 | 0.14 | 0.04<br>0.03 | 2.16 | 3.01 | 12.6 | 0.69 | 0.12 | 0.04<br>0.03 |

| Test ID | Equip Desc. | Filter 1 Results | | | | | | Filter 2 Results | | | | | | Filter 3 Results | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HC | CO | $NO_x$ | $CO_2$ | PM | PM + / - | HC | CO | $NO_x$ | $CO_2$ | PM | PM + / - | HC | CO | $NO_x$ | $CO_2$ | PM | PM + / - |
| | | g/kW-hr | | | kg/kwh | g/kW-hr | | g/kW-hr | | | kg/kwh | g/kW-hr | | g/kW-hr | | | kg/kwh | g/kW-hr | |
| 3858 - 4862-1 | ’02 Cat TH83 | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 3858 - 4862-2 | ’02 Cat TH83 | 0.57 | 3.53 | 15.1 | 1.20 | 0.60 | 0.19<br>0.15 | 0.50 | 2.69 | 11.3 | 1.09 | 0.40 | 0.13<br>0.10 | 0.54 | 2.69 | 11.5 | 1.18 | 0.58 | 0.19<br>0.15 |
| 3597 - 4734 | ’97 Case 570LXT | 2.06 | 8.44 | 14.1 | 0.72 | 0.16 | 0.06<br>0.08 | 2.54 | 7.40 | 14.3 | 0.72 | 0.07 | 0.04<br>0.05 | 2.56 | 6.42 | 14.3 | 0.72 | 0.07 | 0.03<br>0.03 |
| 3597 - 9706 | ’99 Deere 550H | 1.15 | 1.97 | 6.89 | 0.72 | 0.28 | 0.09<br>0.07 | 1.30 | 3.83 | 9.35 | 0.72 | 0.09 | 0.05<br>0.07 | 0.57 | 1.13 | 6.55 | 0.72 | 0.16 | 0.05<br>0.04 |
| 8925 - 2466 | ’99 Cat 953C | 0.73 | 5.25 | 6.93 | 0.69 | 0.24 | 0.07<br>0.06 | 0.56 | 4.46 | 6.53 | 0.73 | 0.37 | 0.11<br>0.09 | | | | | | |
| 9960 - 6086 | Kmtsu WA180 | 4.23 | 7.50 | 10.3 | 0.73 | 0.14 | 0.06<br>0.07 | 5.27 | 6.64 | 9.65 | 0.72 | 0.17 | 0.06<br>0.07 | 5.52 | 7.08 | 9.01 | 0.73 | 0.17 | 0.06<br>0.07 |
| 0229 - 3781 | ’85 Case 1085B | 4.41 | 11.1 | 9.90 | 0.65 | 0.35 | 0.13<br>0.14 | 5.67 | 8.47 | 11.2 | 0.65 | 0.18 | 0.06<br>0.07 | 3.59 | 3.93 | 20.8 | 0.70 | 0.14 | 0.04<br>0.03 |
| 0229 - 0045 | ’95 Deere 410D | 0.99 | 2.52 | 11.0 | 0.71 | 0.30 | 0.09<br>0.07 | 1.14 | 2.13 | 11.0 | 0.71 | 0.07 | 0.03<br>0.03 | 1.32 | 2.73 | 11.3 | 0.71 | 0.14 | 0.04<br>0.03 |
| 9960 - 5674 | ,03 Kmtsu PC300LC | 0.76 | 1.00 | 4.79 | 0.80 | 0.38 | 0.12<br>0.09 | 0.66 | 1.62 | 4.54 | 0.80 | 0.12 | 0.04<br>0.03 | 0.57 | 1.49 | 4.42 | 0.81 | 0.11 | 0.03<br>0.03 |
| 8391 - 3333_1 | ’06 Deere 450D | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 8391 - 3333_2 | ’06 Deere 450D | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 8418 - 0097_1 | ’95 Cat 963CB | 0.68 | 3.38 | 7.41 | 0.72 | 0.74 | 0.23<br>0.17 | – | – | – | – | – | | – | – | – | – | – | |
| 8418 - 0097_2 | ’95 Cat 963CB | 0.54 | 3.09 | 6.35 | 0.70 | 0.54 | 0.16<br>0.13 | 0.77 | 2.57 | 6.91 | 0.71 | 0.41 | 0.12<br>0.10 | 0.83 | 2.86 | 6.88 | 0.71 | 0.36 | 0.11<br>0.09 |
| 8418 - 0377_1 | ’85 Cat 963 | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 8418 - 0961 | ’98 Kmtsu PC300LC | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 8418 - 0377_2 | ’85 Cat 963 | – | – | – | – | – | | – | – | – | – | – | | – | – | – | – | – | |
| 0349 - 1836 | ’88 Cat 953 | – | – | – | – | 0.23 | 0.07<br>0.05 | 0.53 | 3.60 | 10.2 | 0.69 | 0.14 | 0.04<br>0.03 | 0.36 | 2.82 | 8.72 | 0.73 | 0.29 | 0.09<br>0.07 |

| | | Filter 1 Results | | | | | | Filter 2 Results | | | | | | Filter 3 Results | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Test ID** | **Equip Desc.** | **HC** | **CO** | **$NO_x$** | **$CO_2$** | **PM** | **PM + / -** | **HC** | **CO** | **$NO_x$** | **$CO_2$** | **PM** | **PM + / -** | **HC** | **CO** | **$NO_x$** | **$CO_2$** | **PM** | **PM + / -** |
| | | **g/kW-hr** | | | **kg/kwh** | **g/kW-hr** | | **g/kW-hr** | | | **kg/kwh** | **g/kW-hr** | | **g/kW-hr** | | | **kg/kwh** | **g/kW-hr** | |
| 0349 - 2422 | '97 Cat 320B | 0.79 | 1.21 | 7.63 | 0.73 | 0.22 | 0.07 0.05 | 0.81 | 1.50 | 7.47 | 0.73 | 0.12 | 0.04 0.04 | 0.69 | 1.29 | 7.67 | 0.74 | 0.02 | 0.01 0.01 |
| 9272 - 3481 | '00 Kmtsu PC400LC | 0.44 | 1.09 | 5.59 | 0.65 | 0.18 | 0.06 0.04 | 0.45 | 1.28 | 5.47 | 0.68 | 0.15 | 0.05 0.04 | 0.56 | 1.52 | 5.57 | 0.70 | 0.15 | 0.05 0.04 |
| 9272 - 2494_1 | '98 Cat 963B | 0.61 | 2.48 | 6.76 | 0.71 | 0.33 | 0.39 0.33 | – | – | – | – | – | | – | – | – | – | – | |
| 9272 - 2494_2 | '98 Cat 963B | 1.16 | 3.77 | 9.63 | 0.62 | 0.40 | 0.13 0.10 | 0.78 | 2.58 | 7.33 | 0.67 | 0.47 | 0.15 0.12 | 0.28 | 1.79 | 7.13 | 0.73 | 0.19 | 0.06 0.05 |
| 9272 - 0853 | '93 Kmtsu PC400LC | 0.75 | 1.50 | 13.3 | 0.95 | 0.28 | 0.09 0.07 | 0.73 | 1.51 | 13.2 | 0.92 | 0.16 | 0.05 0.04 | 0.78 | 1.51 | 12.9 | 0.94 | 0.16 | 0.05 0.04 |
| 0062 - 0748 | '07 Deere 310J | 1.49 | 7.75 | 16.6 | 0.70 | 0.51 | 0.18 0.20 | 1.59 | 6.23 | 13.9 | 0.70 | 0.61 | 0.19 0.14 | 0.85 | 3.14 | 8.78 | 0.74 | 0.28 | 0.08 0.07 |
| 0062 - 6092 | '06 Deere 310G | 10.1 | – | 93.9 | – | 1.08 | 0.69 1.06 | 11.2 | – | 71.4 | – | 0.57 | 0.36 0.56 | 7.74 | – | 83.3 | – | 1.35 | 0.43 0.33 |

**Note: Various sources of bias and uncertainty exist in the emission estimates provided in this table, and reported work-based gaseous emissions could vary by as much as 20% from "true" emission values, as listed in Appendix AO. Uncertainties for work-based PM emissions are listed in the PM +/- column for each filter. The "in-use" estimates reported in this table may differ from certification standards due to differences between the certification test cycles and this study's "in-use" work cycles**

Figures 6.2-1 through 6.2-14 present PM and gaseous emissions on a “brake specific” or mass / work basis (in units of grams or kg per kw-hr), by equipment category. These brake specific emissions, Ebs(N,t), were calculated using vehicle brakes specific fuel consumption curves, $bsfc_{max}$ (N), with time resolved engine speed, N, estimated fuel consumption, fc(N,t), and the gaseous and PM emissions measurements, E(N,t)

$$Ebs(N,t) = bsfc_{max}(N) * E(N,t) / fc(N,t)$$

where

$$bsfc_{max}(N) = fc_{max}(N) / P_{max}(N) \cdot \Delta t$$

is the fuel consumption at maximum engine load, $P_{max}$ (N) , for a given engine speed, N, and time interval, Δt. Appendix AD give the details of the calculations and an analysis detailing the validity of using the estimation,

$$P(N,t) / P_{max}(N) \approx fc(N,t) / fc_{max}(N).$$

From these time resolved estimates, test sums and averages could then be computed. PM emissions are based on the first three filters collected, and gaseous emissions are based on the overall test average (including times when filters were and were not sampled). Uncertainty designations are provided in these figures based on the methodology presented in Appendix AO.

Engine tier designations listed in Figures 6.2-1 through 6.2-28 are based on categories shown in Table 6.2-8 (Dieselnet, 2009). However, the emission limits shown in Table 6.2-8 are based on test methods that differ from the in-use work that generated data reported here, and direct comparisons should not be made between the work-based emission standards listed in Table 6.2-8 and the work-based emission results presented in Tables 6.2-4 and 6.2-7.

## Table 6.2-8 Nonroad Emission Standards Summary

| EPA Tier 1-3 Nonroad Diesel Engine Emission Standards, g/kWh (g/bhp·hr) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Engine Power** | **Tier** | **Year** | **CO** | **HC** | **NMHC+NOx** | **NOx** | **PM** |
| kW < 8 (hp < 11) | Tier 1 | 2000 | 8.0 (6.0) | - | 10.5 (7.8) | - | 1.0 (0.75) |
| | Tier 2 | 2005 | 8.0 (6.0) | - | 7.5 (5.6) | - | 0.8 (0.6) |
| 8 ≤ kW < 19 (11 ≤ hp < 25) | Tier 1 | 2000 | 6.6 (4.9) | - | 9.5 (7.1) | - | 0.8 (0.6) |
| | Tier 2 | 2005 | 6.6 (4.9) | - | 7.5 (5.6) | - | 0.8 (0.6) |
| 19≤ kW < 37 (25 ≤ hp < 50) | Tier 1 | 1999 | 5.5 (4.1) | - | 9.5 (7.1) | - | 0.8 (0.6) |
| | Tier 2 | 2004 | 5.5 (4.1) | - | 7.5 (5.6) | - | 0.6 (0.45) |
| 37 ≤ kW < 75 (50 ≤ hp < 100) | Tier 1 | 1998 | - | - | - | 9.2 (6.9) | - |
| | Tier 2 | 2004 | 5.0 (3.7) | - | 7.5 (5.6) | - | 0.4 (0.3) |
| | Tier 3 | 2008 | 5.0 (3.7) | - | 4.7 (3.5) | - | -† |
| 75 ≤ kW < 130 (100 ≤ hp < 175) | Tier 1 | 1997 | - | - | - | 9.2 (6.9) | - |
| | Tier 2 | 2003 | 5.0 (3.7) | - | 6.6 (4.9) | - | 0.3 (0.22) |
| | Tier 3 | 2007 | 5.0 (3.7) | - | 4.0 (3.0) | - | -† |
| 130 ≤ kW < 225 (175 ≤ hp < 300) | Tier 1 | 1996 | 11.4 (8.5) | 1.3 (1.0) | - | 9.2 (6.9) | 0.54 (0.4) |
| | Tier 2 | 2003 | 3.5 (2.6) | - | 6.6 (4.9) | - | 0.2 (0.15) |
| | Tier 3 | 2006 | 3.5 (2.6) | - | 4.0 (3.0) | - | -† |
| 225 ≤ kW < 450 (300 ≤ hp < 600) | Tier 1 | 1996 | 11.4 (8.5) | 1.3 (1.0) | - | 9.2 (6.9) | 0.54 (0.4) |
| | Tier 2 | 2001 | 3.5 (2.6) | - | 6.4 (4.8) | - | 0.2 (0.15) |
| | Tier 3 | 2006 | 3.5 (2.6) | - | 4.0 (3.0) | - | -† |
| 450 ≤ kW < 560 (600 ≤ hp < 750) | Tier 1 | 1996 | 11.4 (8.5) | 1.3 (1.0) | - | 9.2 (6.9) | 0.54 (0.4) |
| | Tier 2 | 2002 | 3.5 (2.6) | - | 6.4 (4.8) | - | 0.2 (0.15) |
| | Tier 3 | 2006 | 3.5 (2.6) | - | 4.0 (3.0) | - | -† |
| kW ≥ 560 (hp ≥ 750) | Tier 1 | 2000 | 11.4 (8.5) | 1.3 (1.0) | - | 9.2 (6.9) | 0.54 (0.4) |
| | Tier 2 | 2006 | 3.5 (2.6) | - | 6.4 (4.8) | - | 0.2 (0.15) |

† Not adopted, engines must meet Tier 2 PM standard.

Figure 6.2-1  PM Emissions from Backhoe Loaders, Work Basis, Filters 1 - 3

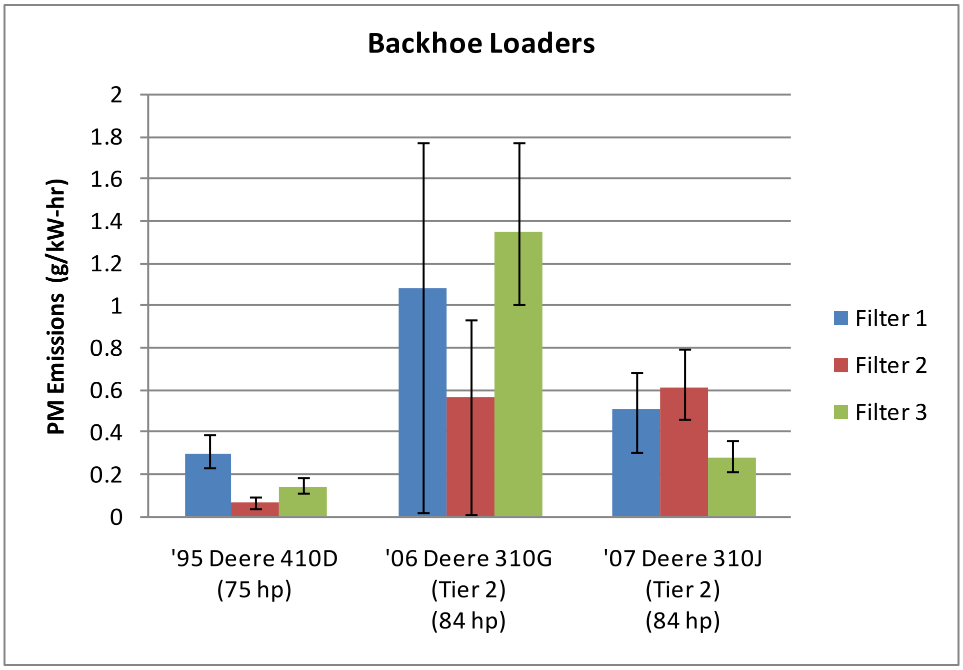



Figure 6.2-2  Gaseous Emissions from Backhoe Loaders, Work Basis, Overall test

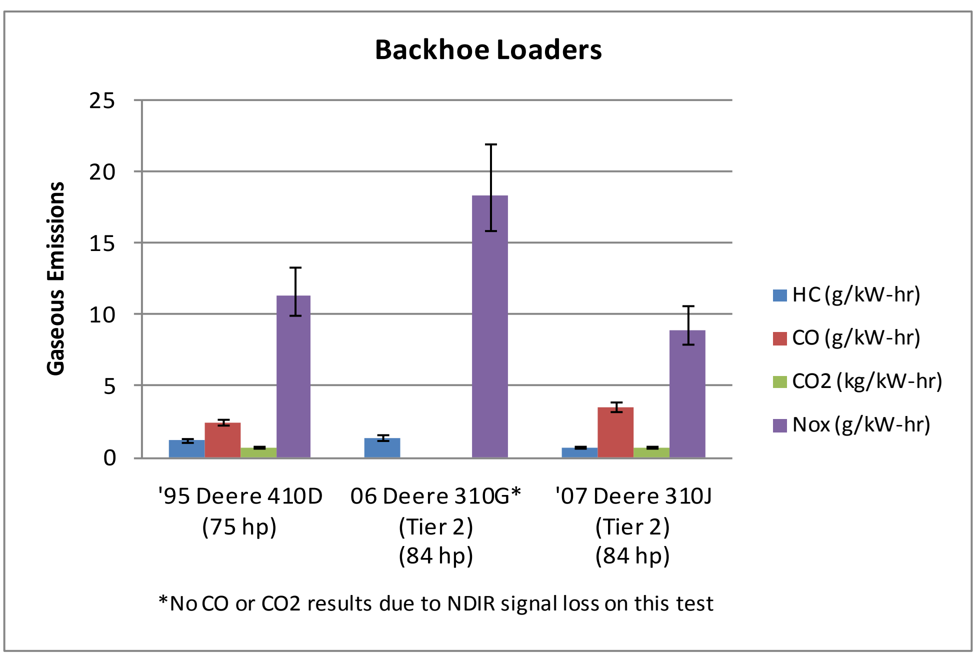


**Figure 6.2-3 PM Emissions from Dozers, 50-99 hp, Work Basis, Filters 1 – 3**

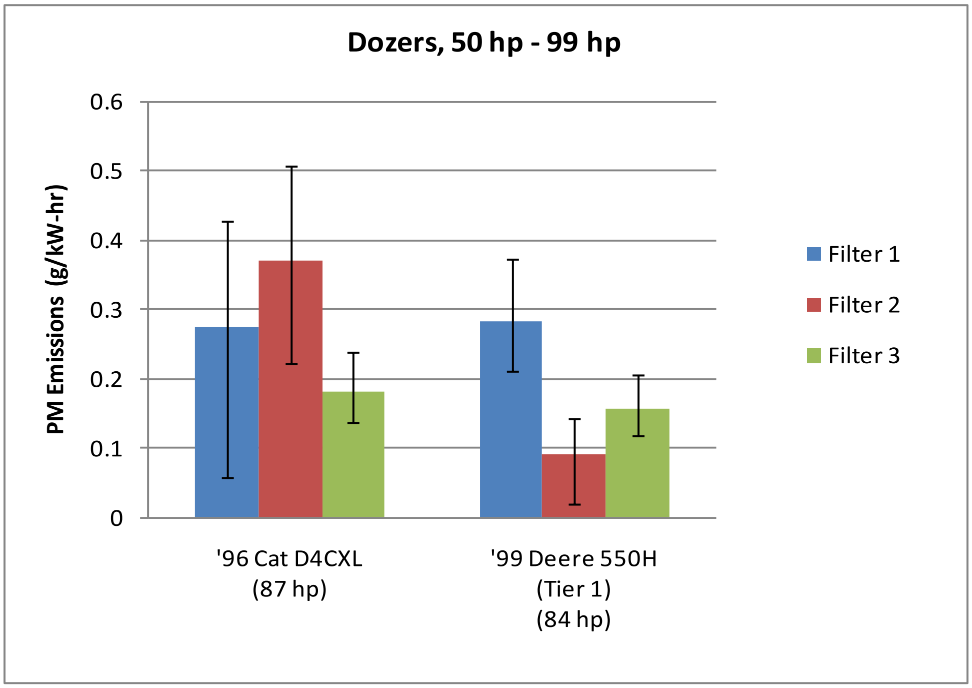



**Figure 6.2.4 PM Emissions from Dozers, ≥ 100 hp, Work Basis, Filters 1 - 3**

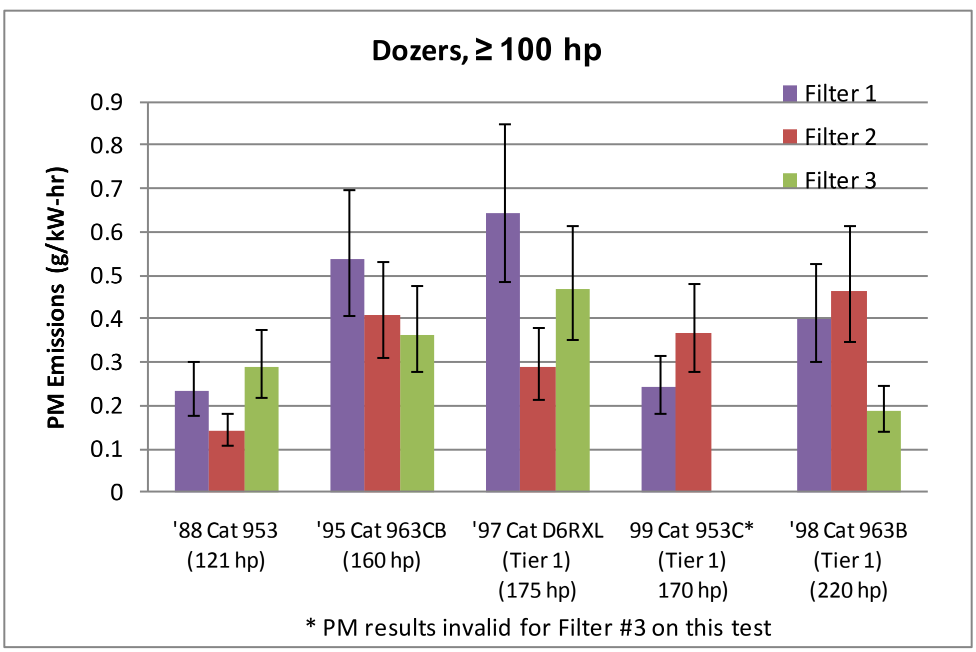


**Figure 6.2-5 Gaseous Emissions from Dozers, 50-99 hp, Work Basis, Overall test**

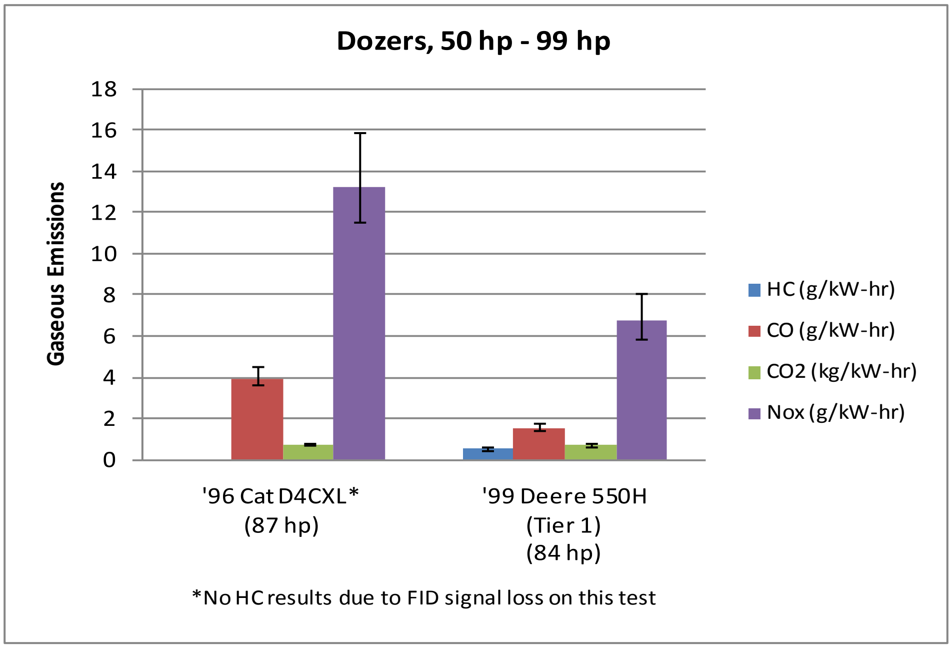



**Figure 6.2-6 Gaseous Emissions from Dozers, ≥ 100 hp, Work Basis, Overall test**

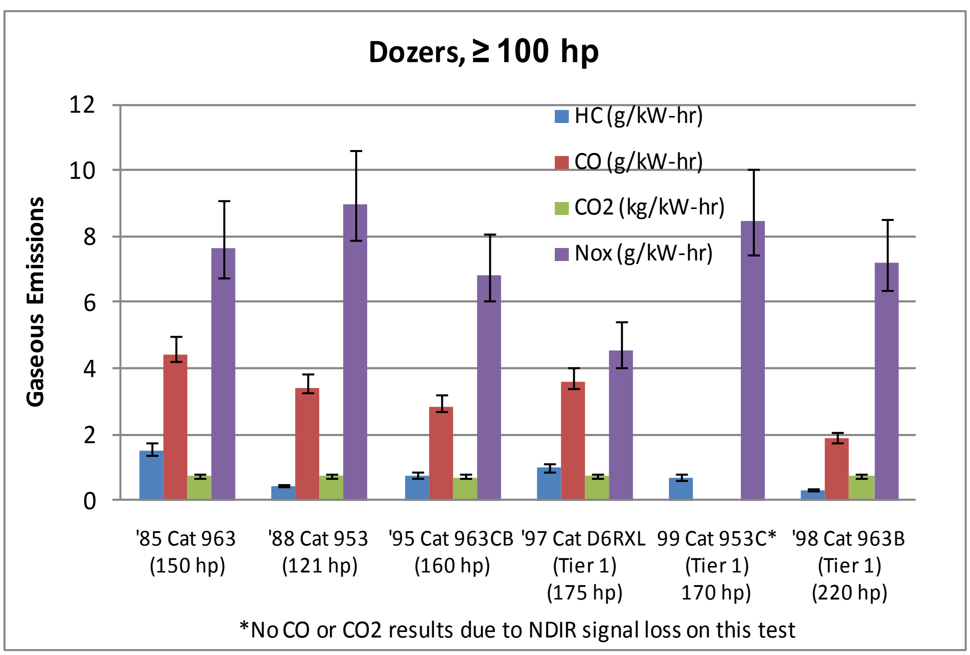


**Figure 6.2-7 PM Emissions from Excavators, < 300 hp, Work Basis, Filters 1 - 3**

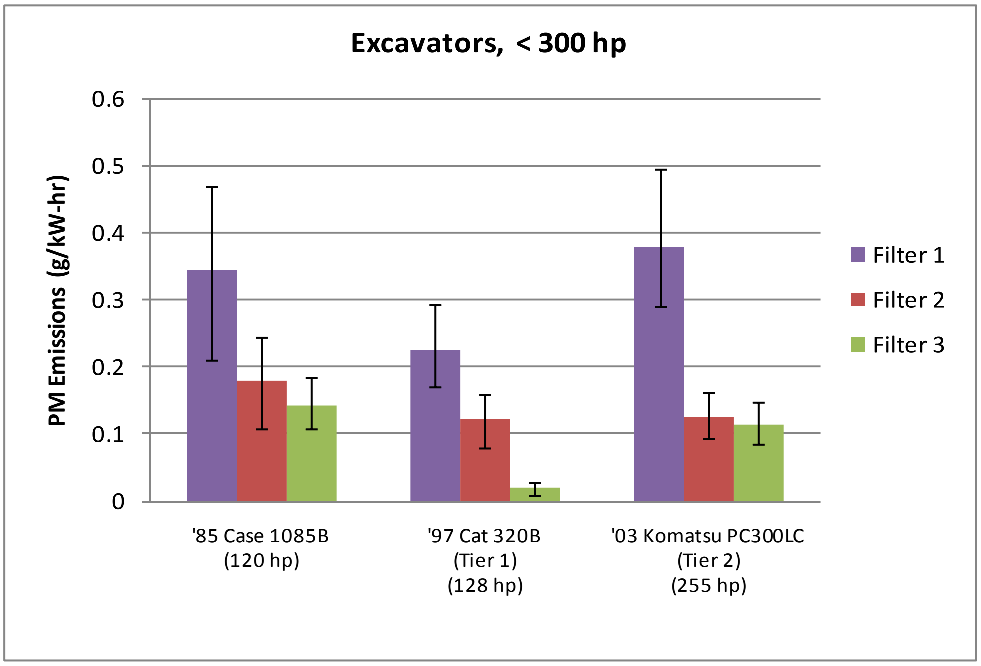



**Figure 6.2-8 PM Emissions from Excavators, ≥ 300 hp, Work Basis, Filters 1 - 3**

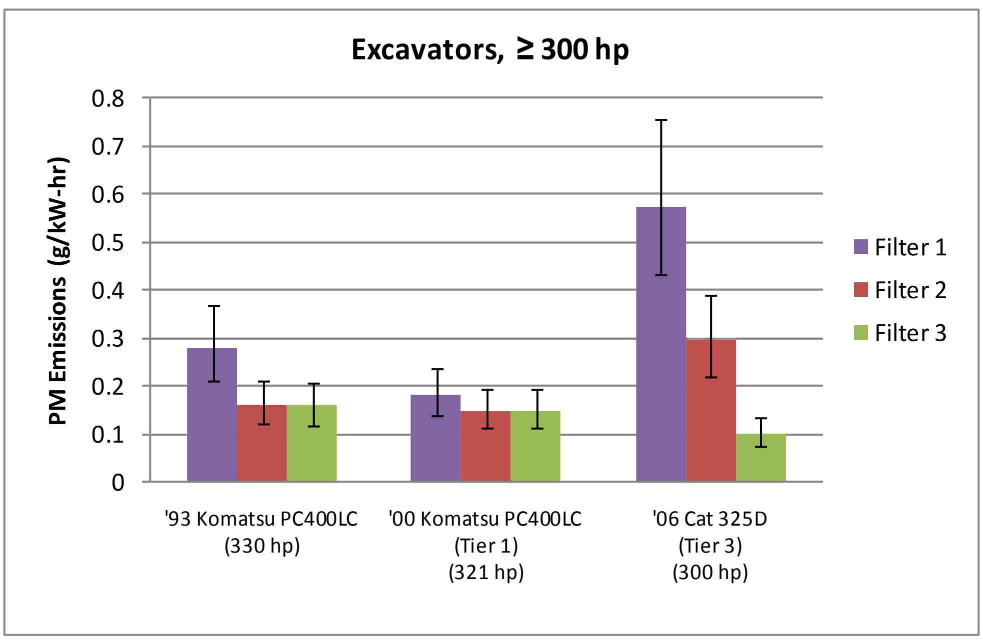


**Figure 6.2-9 Gaseous Emissions from Excavators, < 300 hp, Work Basis, Overall Test**

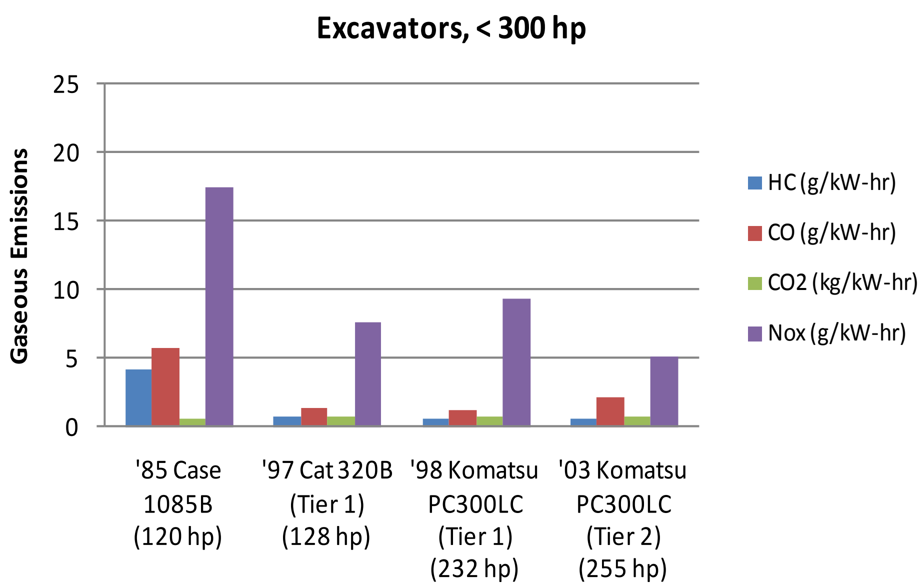



**Figure 6.2-10 Gaseous Emissions from Excavators, ≥ 300 hp, Work Basis, Overall Test**

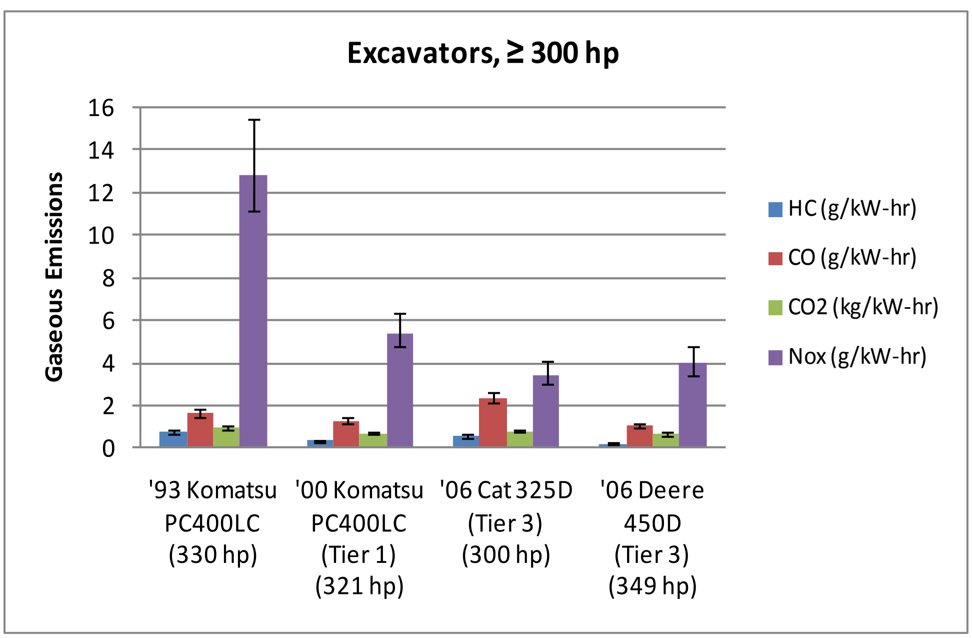


**Figure 6.2-11  PM Emissions From Loaders, Work Basis, Filters 1 - 3**

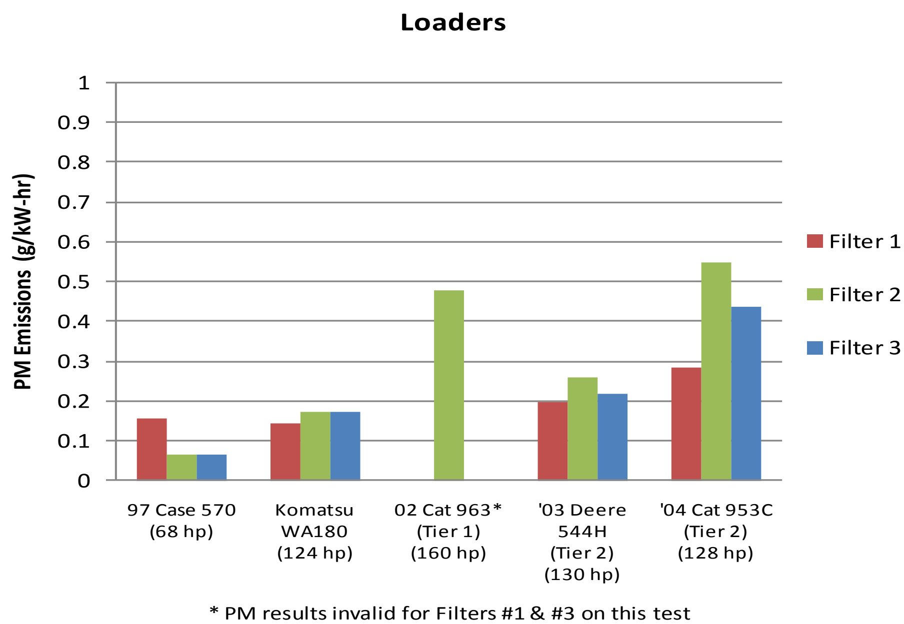



**Figure 6.2-12  Gaseous Emissions From Loaders, Work Basis, Overall test**

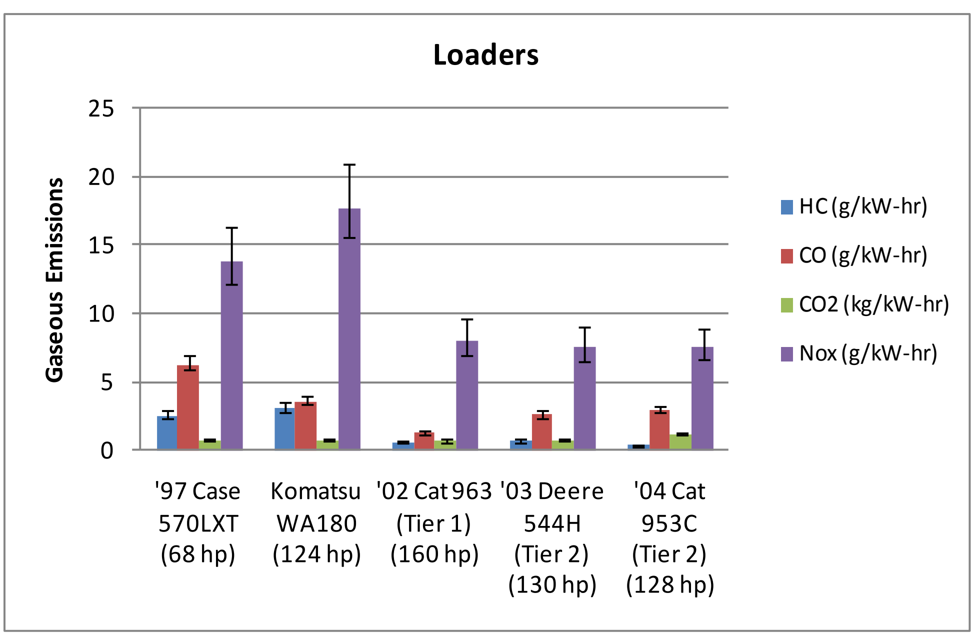


**Figure 6.2-13 PM Emissions From Other Equipment, Work Basis, Filters 1 - 3**

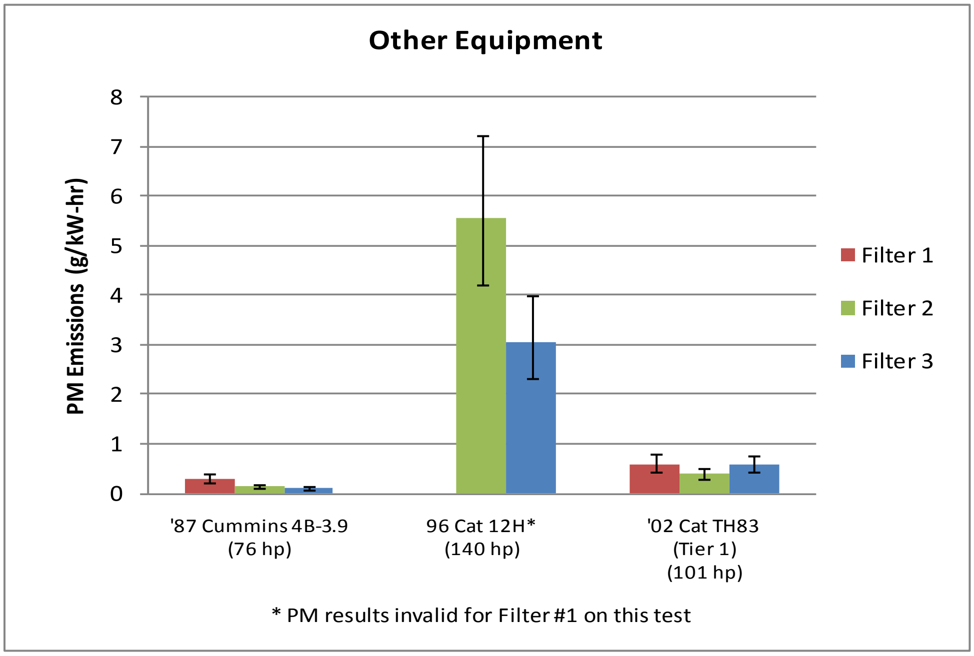
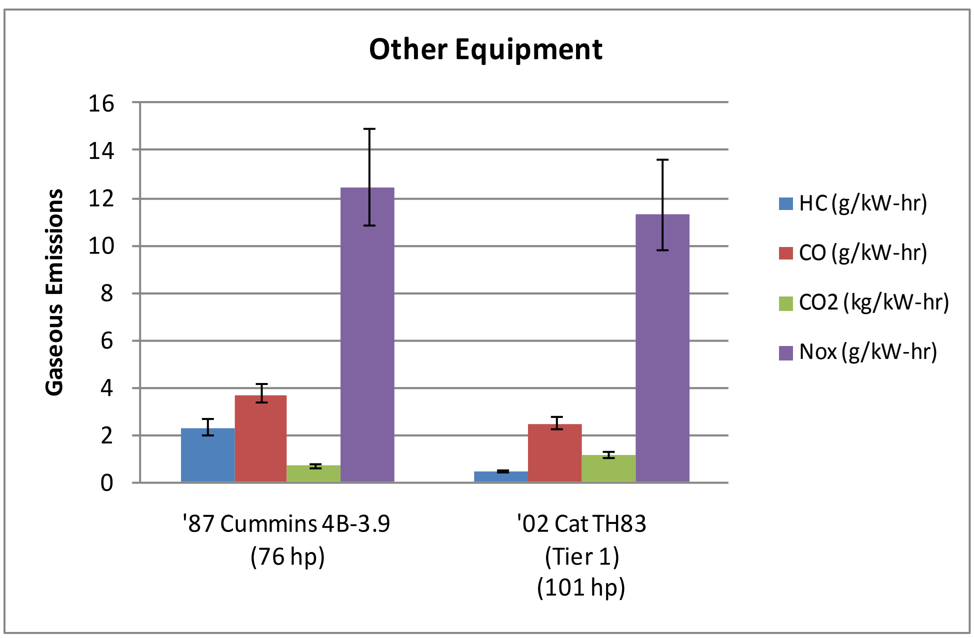



**Figure 6.2-14 Gaseous Emissions From Other Equipment, Work Basis, Overall Test**



Figures 6.2-15 through 6.2-28 present PM and gaseous emissions on a fuel basis (grams or kg of emissions per gallon of fuel consumed), rather than a work basis, again grouped by equipment category. PM emissions are based on the first three filters collected, and gaseous emissions are based on the overall test average (including times when filters were and were not sampled).

Using a fuel basis to evaluate emissions eliminates several of the points of uncertainty inherent in work basis estimates. In particular, errors in the estimated engine speed (RPM) have no effect on emissions, and since load is not used in the emissions estimate, errors associated with the use of "generic" lug curves, and errors in engine load and efficiency estimations are eliminated. However, the way a piece of equipment is used (heavy load and high RPM vs. low load and light RPM or extensive idle periods) can have an influence on the fuel-based emissions from one test (or piece of equipment) to another. Also, as with the work-based emissions, the accuracy of the PM measurements are still dependent on the performance of the micro-proportional sampler. In addition, any errors associated with the SEMTECH-DS' determination of the second-by-second (and hence cumulative) fuel consumption rate will affect the accuracy of the fuel-based emissions estimates. These errors have been estimated in Appendix AO, Nonroad Error Estimates, and are shown in Figures 6.2-15 through 6.2-28.

**Figure 6.2-15 PM Emissions From Backhoe Loaders, Fuel Basis, Filters 1 - 3**

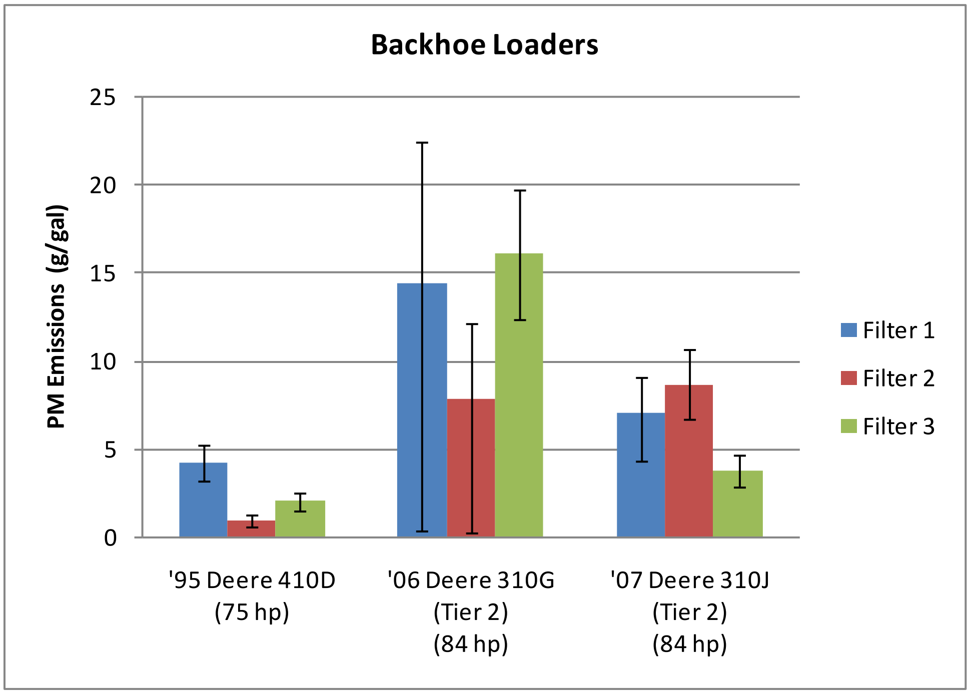


**Figure 6.2-16 Gaseous Emissions From Backhoe Loaders, Fuel Basis, Overall Test**

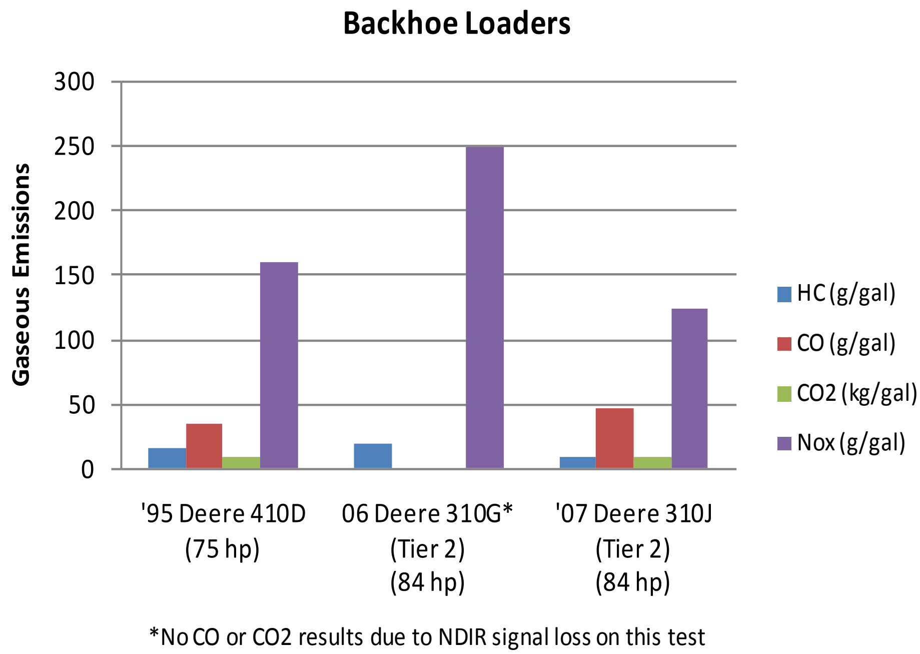



**Figure 6.2-17 PM Emissions From Dozers, 50-99hp, Fuel Basis, Filters 1 – 3**

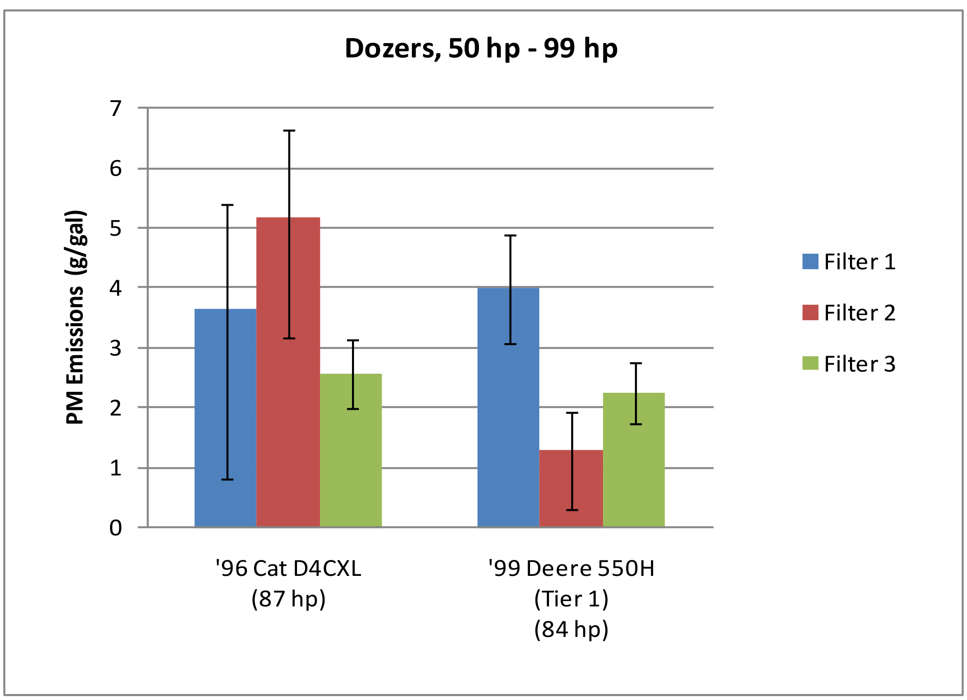


**Figure 6.2.18  PM Emissions From Dozers, ≥ 100 hp, Fuel Basis, Filters 1 - 3**

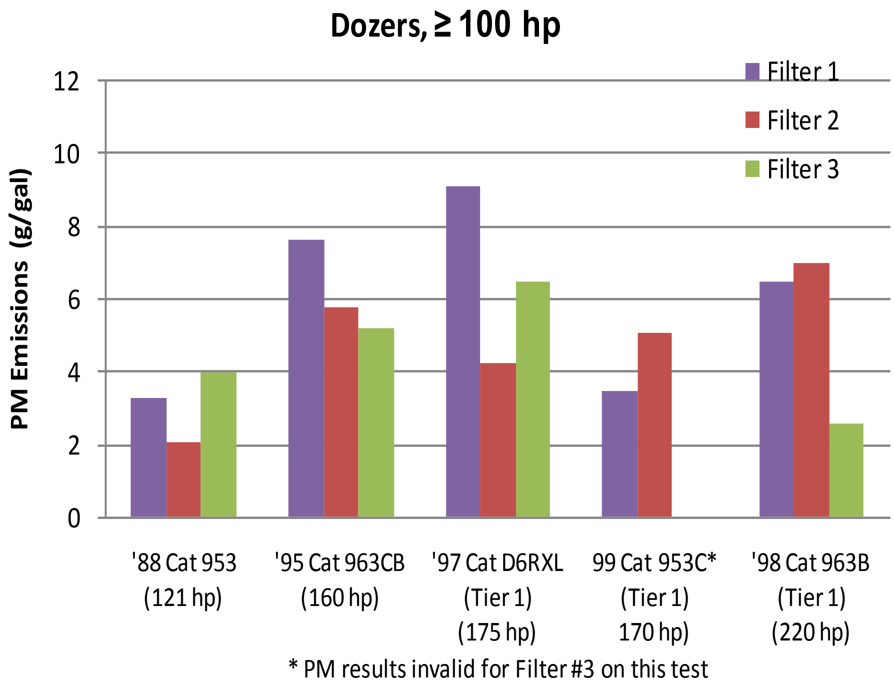



**Figure 6.2-19  Gaseous Emissions From Dozers, 50-99 hp, Fuel Basis, Overall Test**

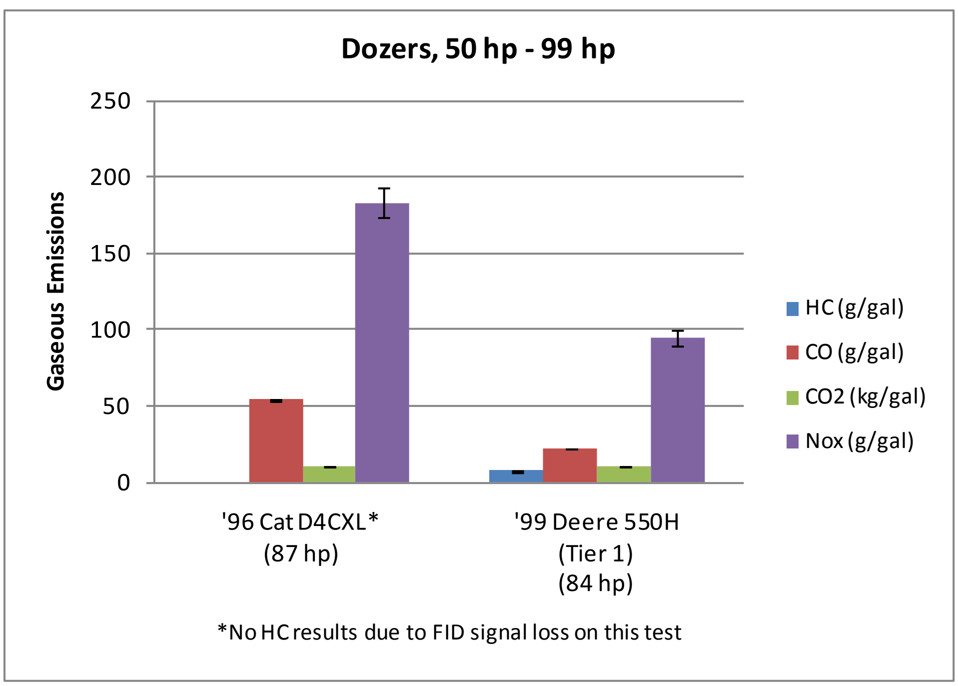


**Figure 6.2-20 Gaseous Emissions From Dozers, ≥ 100 hp, Fuel Basis, Overall Test**

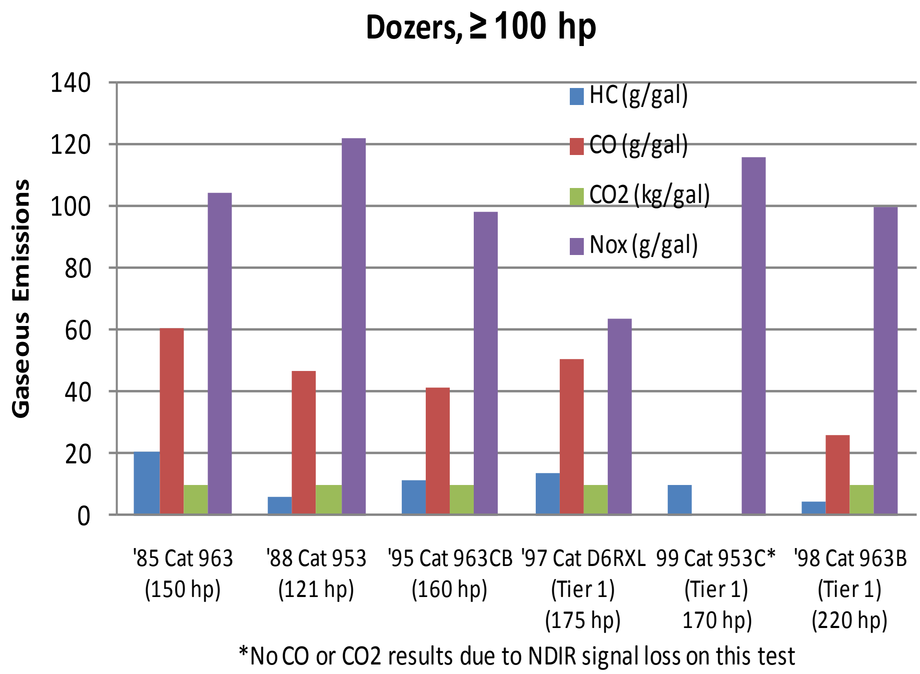



**Figure 6.2-21 PM Emissions From Excavators, < 300 hp, Fuel Basis, Filters 1 - 3**

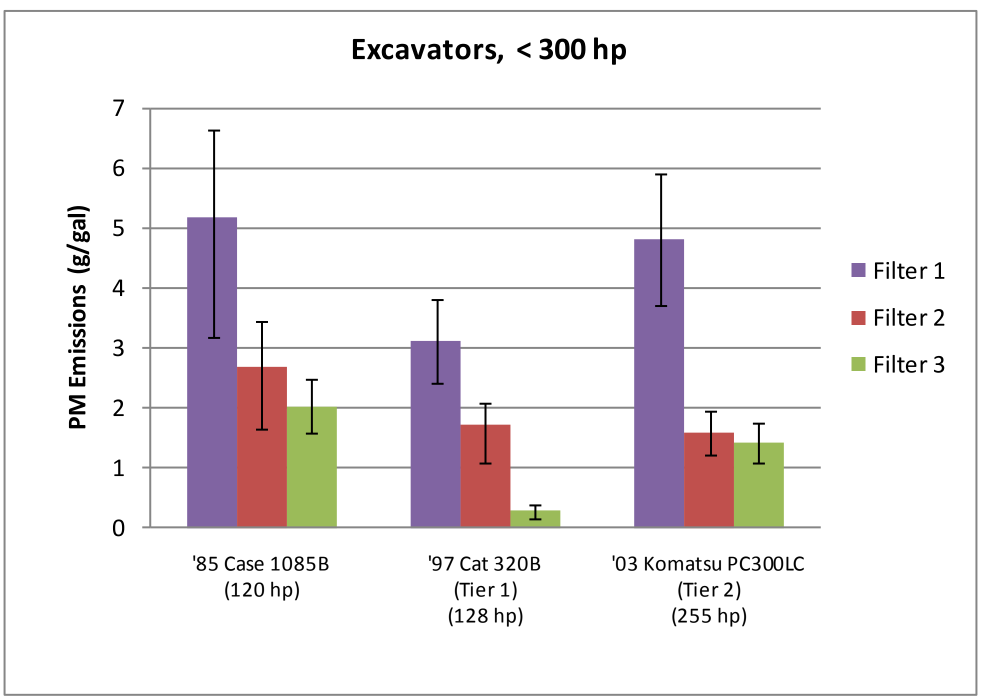


**Figure 6.2-22 PM Emissions From Excavators, ≥ 300 hp, Fuel Basis, Filters 1 - 3**

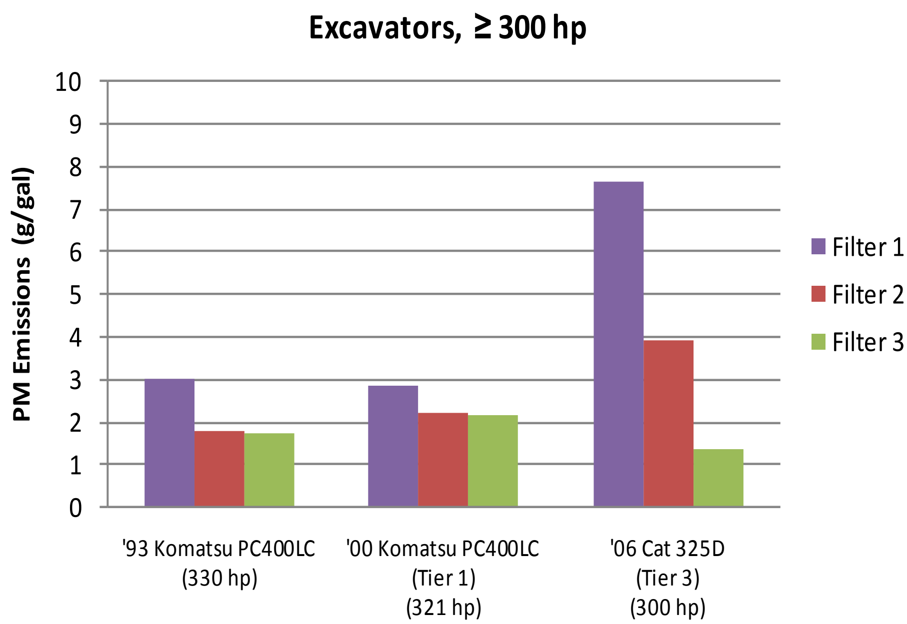



**Figure 6.2-23 Gaseous Emissions From Excavators, < 300 hp, Fuel Basis, Overall Test**

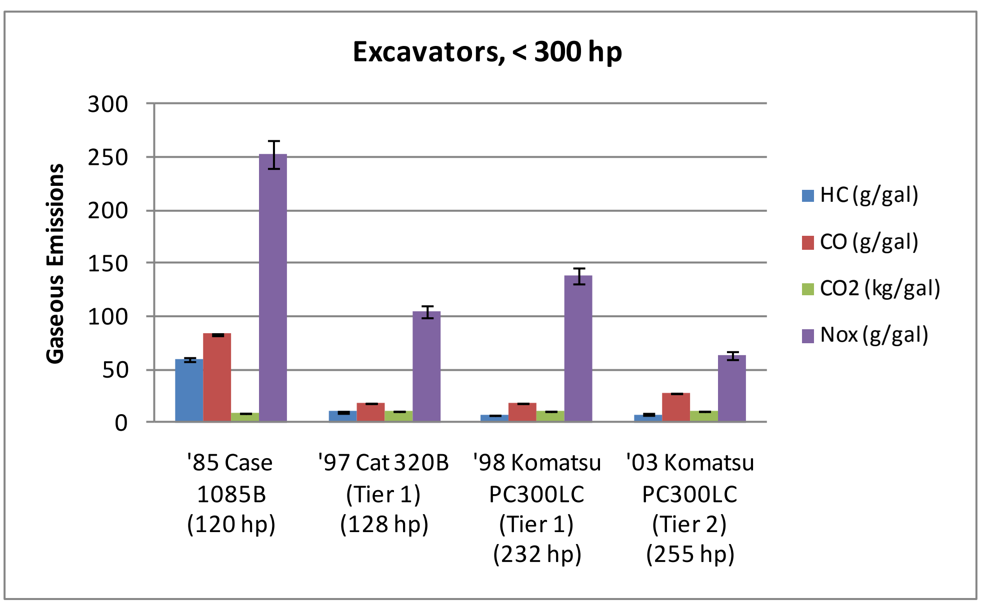


**Figure 6.2-24 Gaseous Emissions From Excavators, ≥ 300 hp, Fuel Basis, Overall Test**

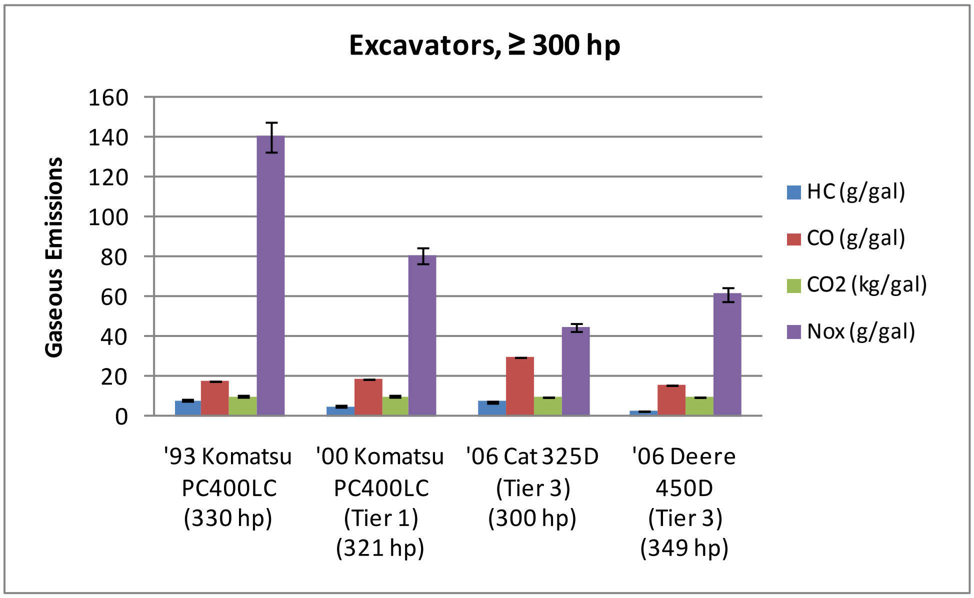



**Figure 6.2-25 PM Emissions From Loaders, Fuel Basis, Filters 1 - 3**

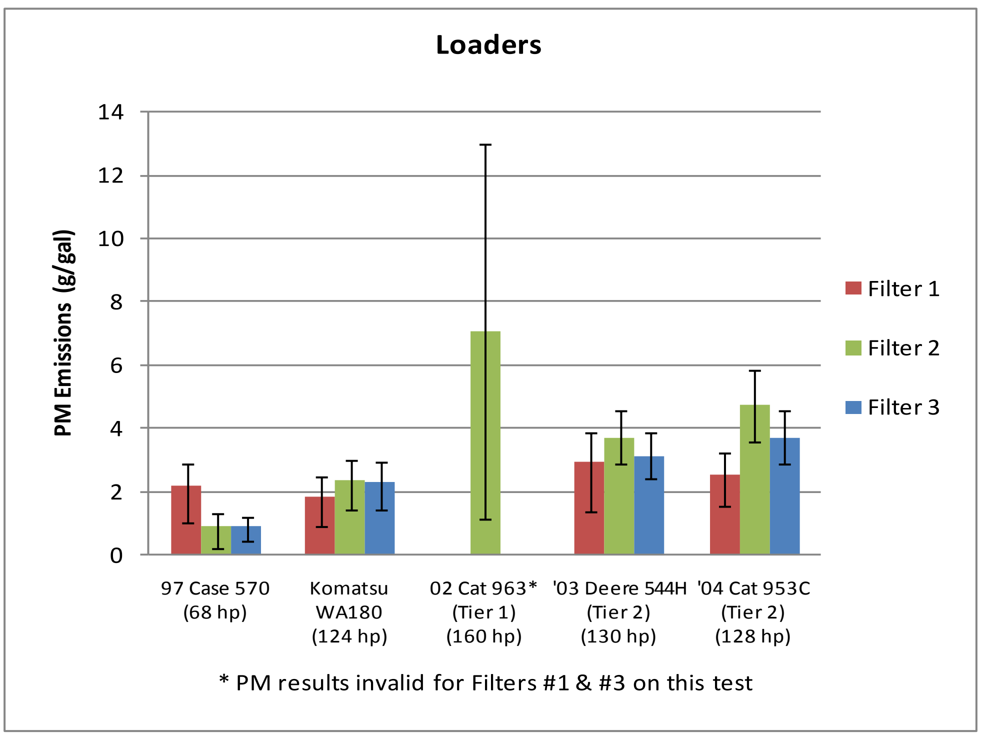


**Figure 6.2-26  Gaseous Emissions From Loaders, Fuel Basis, Overall Test**

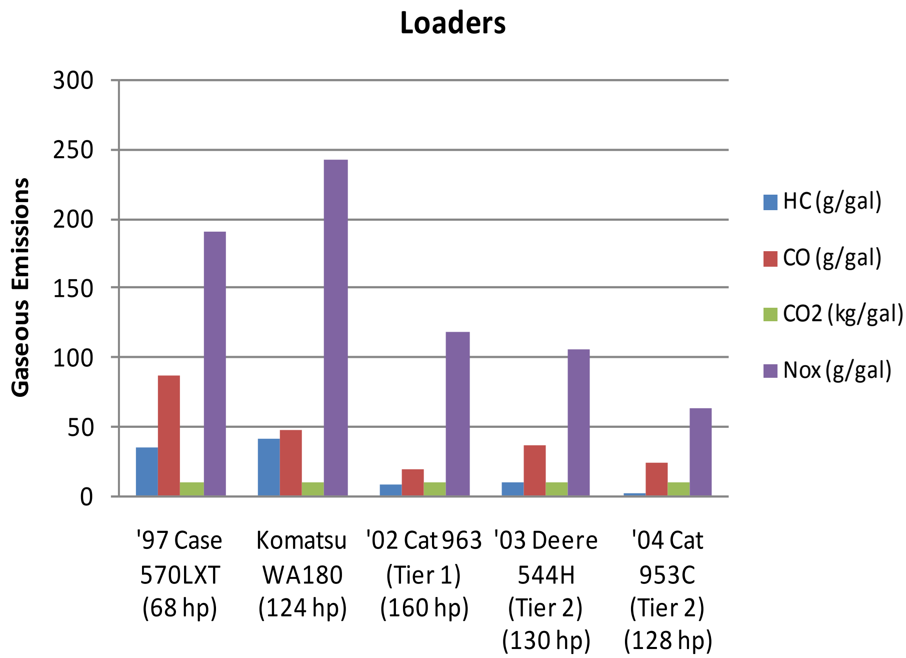



**Figure 6.2-27  PM Emissions From Other Equipment, Fuel Basis, Filters 1 - 3**

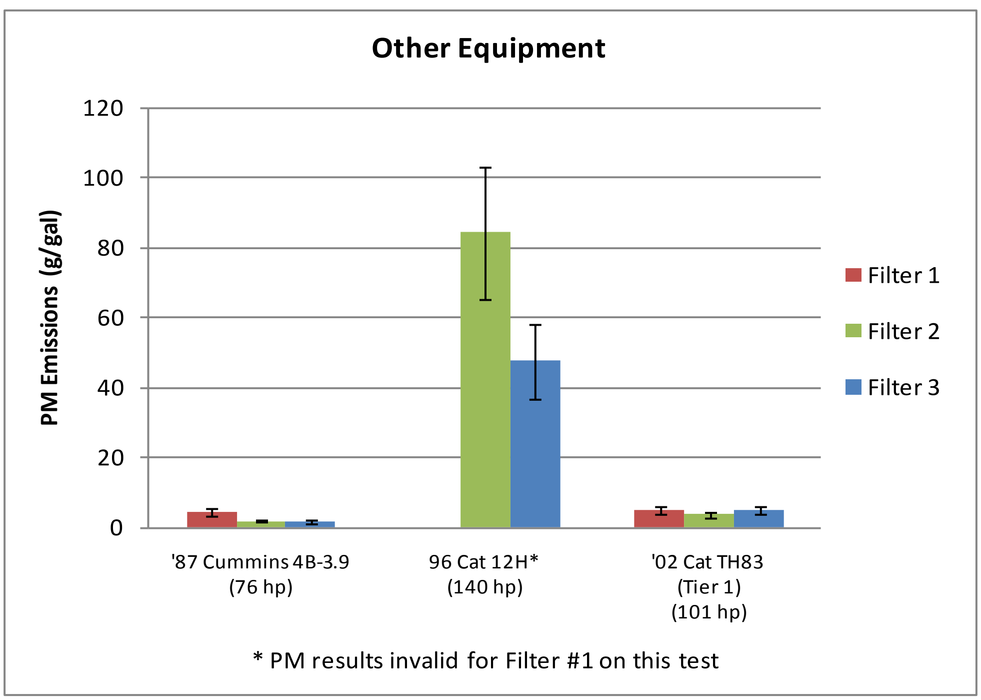
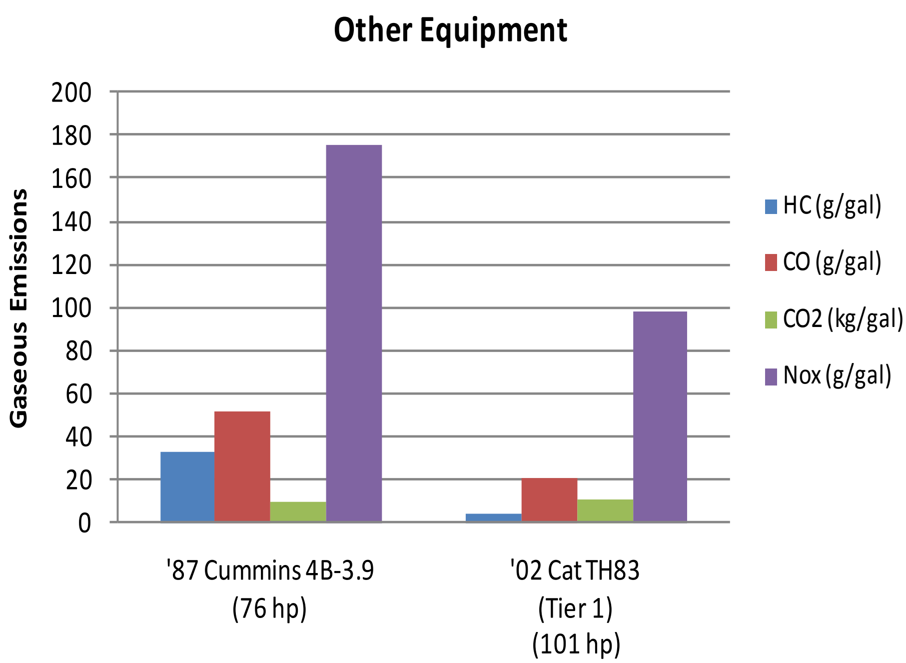


**Figure 6.2-28 Gaseous Emissions From Other Equipment, Fuel Basis, Overall Test**




Comparing the profiles of the work basis and fuel basis emissions results between equivalent plots (i.e., comparing Figure 6.2-1 with 6.2-15, 6.2-2 with 6.2-16, etc.) may help illustrate the differences between work-based and fuel-based (or other) emissions estimates. As previously described in Section 6.2.2, extensive idle (or low engine speed / load) operation may result in higher work-based (brake specific) emissions than work-based emissions calculated over periods of higher speed/load operation.

Reviewing data and emissions plots from this study suggests engine size and regulatory tier may not be meaningful stratification variables for estimating emissions rates of diesel engines, as emission rate variations appear to be influenced less by these observational parameters as by other parameters such as engine speed range and engine load. The type of work being done (power-take off, equipment transport, or both) might be a good indicator of both engine speed ranges and loads used and may be a good operational parameter to consider when selecting stratification variables for future work. Although potentially limited by the small sample size, data collected during this study could be evaluated in an effort to identify appropriate stratification variables for future studies, considering both observational and operational parameters in a regression analysis. Such an analysis was beyond the scope of work in this study.

### 6.3 PAMS Measurement Results

Table 6.3-1 lists a summary of activity measurements made throughout the study. In this table, "weekday days" refers to operation on Mondays through Fridays, 7 am – 7:59 pm. "Weekday nights" operation is defined as operation on Mondays thru Fridays, beginning at 8 pm each evening (Monday through Friday) and ending at 6:59 am the following morning (Tuesday through Saturday). Weekend operation is defined as operation beginning Saturday at 7 am and ending Monday at 6:59 am.

## Table 6.3-1 Activity Measurement Result Summary

| | | | | | Calendar Days | | Total Minutes of Operation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Test ID | Equipment Category | Equip Type | Mfr | Model | PAMS Installed | Equip Used | Overall | Weekday days | Weekday Nights | Weekend Days/Nights |
| 2208-1918 | Backhoe loader | Backhoe loader | John Deere | 410B Turbo | 45 | 17 | 1,861 | 1861 | 0 | 0 |
| 3858-5754 | Backhoe loader | Backhoe loader | Case | 480FLL | 39 | 30 | 6,069 | 5247 | 19 | 803 |
| 2535-9216 | Backhoe loader | Backhoe loader | Case | 580 Super L | 42 | 18 | 868 | 697 | 0 | 171 |
| 2535-2754 | Backhoe loader | Backhoe loader | Case | 580 Super M | 42 | 18 | 1,966 | 1962 | 0 | 3 |
| 0229-0045 | Backhoe loader | Backhoe loader | John Deere | 410D Turbo | 28 | 20 | 1,003 | 991 | 12 | 0 |
| 0062-6976 | Backhoe loader | Backhoe loader | John Deere | 310G | 36 | 22 | 2,705 | 2610 | 0 | 95 |
| 9429-7232 | Backhoe loader | Backhoe loader | Caterpillar | 420E | 35 | 18 | 2,715 | 2715 | 0 | 0 |
| 1688-0216 | Boring / Trenching | Horizontal Boring Machine | Vermeer | D20 x 22 | 48 | 27 | 4,592 | 4590 | 2 | 0 |
| 1688-1462 | Boring / Trenching | Horizontal Boring Machine | Vermeer | D16 x 20A | 48 | 26 | 3,300 | 3300 | 0 | 0 |
| 9429-0323 | Boring / Trenching | Directional Boring Machine | Ditch Witch | JT2020 | 37 | 19 | 2,888 | 2888 | 0 | 0 |
| 3858-1482 | Dozer | Crawler Dozer | Caterpillar | D4CXL | 39 | 27 | 4,565 | 4109 | 13 | 442 |
| 0062-0934 | Dozer | Tracked Dozer | Caterpillar | D4C | 36 | 22 | 4,892 | 4892 | 0 | 0 |
| 0229-3781 | Excavator | Wheeled Excavator | Case | 1085B | 31 | 23 | 369 | 369 | 0 | 0 |
| 8542-1271 | Excavator | Mini Track Excavator | IR Bobcat | 329G | 30 | 10 | 801 | 437 | 60 | 303 |
| 0349-0567 | Excavator | Track Excavator | Caterpillar | 330D | 33 | 18 | 1,573 | 1321 | 0 | 252 |

| | | | | | Calendar Days | | Total Minutes of Operation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Test ID** | **Equipment Category** | **Equip Type** | **Mfr** | **Model** | **PAMS Installed** | **Equip Used** | **Overall** | **Weekday days** | **Weekday Nights** | **Weekend Days/Nights** |
| 1437-0399 | Loader | Compact Skid Steer Loader | IR Bobcat | 873 Turbo | 48 | 13 | 1,008 | 606 | 48 | 355 |
| 1437-1396 | Loader | Skidsteer loader | IR Bobcat | S300 Turbo | 46 | 25 | 2,846 | 2423 | 26 | 397 |
| 1911-1916 | Loader | Tracked Loader | IR Bobcat | T300 Turbo | 22 | 14 | 1,006 | 1006 | 0 | 0 |
| 8555-2757 | Loader | Compact Skid Steer Loader | IR Bobcat | S185 Turbo | 31 | 11 | 666 | 628 | 2 | 36 |
| 8597-1096 | Loader | Compact Track Loader | IR Bobcat | T190 | 31 | 21 | 1,330 | 1294 | 24 | 12 |
| 8597-0194 | Loader | Compact Track Loader | IR Bobcat | T250 | 30 | 20 | 1,828 | 1388 | 435 | 5 |
| 9679-6459 | Loader | Skid Steer Loader | New Holland | LX665 Turbo | 35 | 27 | 3,310 | 2811 | 42 | 457 |
| 1911-9540 | Other | Concrete Saw | Core Cut | CC6560 XLS | 14 | 11 | 1,960 | 1960 | 0 | 0 |
| 3597-095K | Other | Roller Compactor | Hyster | C340C | 44 | 20 | 1,768 | 1456 | 5 | 307 |
| 3854-9162 | Other | Straight-Mast Lift Truck | Case | 586D | 43 | 10 | 296 | 296 | 0 | 0 |
| 3868-0304 | Other | Wheeled Crane | Grove | RT640C | 29 | 6 | 340 | 340 | 0 | 0 |
| 3928-1649 | Telescope Forklift | Telescopic Lift Truck | Lull | 644B-42 | 48 | 16 | 1,602 | 1343 | 101 | 158 |
| 3868-8720 | Telescope Forklift | Telescopic Lift Truck | Ingersoll Rand | VR-90B | 37 | N/A | 2,599 | N/A | N/A | N/A |
| 3702-9726 | Telescope Forklift | Telescopic Lift Truck | Skytrak | 6042 | 44 | 36 | 2,255 | 2189 | 0 | 66 |

Table 6.3-2 lists total usage in hours, summed by equipment category. These summed categories are shown graphically in Figure 6.3-1. Figure 6.3-2 shows these same categories normalized to percentages.

**Table 6.3-2 Activity Summary by Equipment Category (in Hours)**

| Equipment Category | Overall | Weekday days | Weekday Nights | Weekend Days/Nights |
|---|---|---|---|---|
| Backhoe loader | 286.5 | 268.1 | 0.5 | 17.9 |
| Boring / Trenching | 179.7 | 179.6 | 0.0 | 0.0 |
| Dozer | 157.6 | 150.0 | 0.2 | 7.4 |
| Excavator | 45.7 | 35.5 | 1.0 | 9.2 |
| Loader | 199.9 | 169.3 | 9.6 | 21.0 |
| Other | 72.7 | 67.6 | 0.1 | 5.1 |
| Telescope Forklift | 107.6 | 58.9 | 1.7 | 3.7 |

**Figure 6.3-1 Activity Summary by Equipment Category (in Hours)**

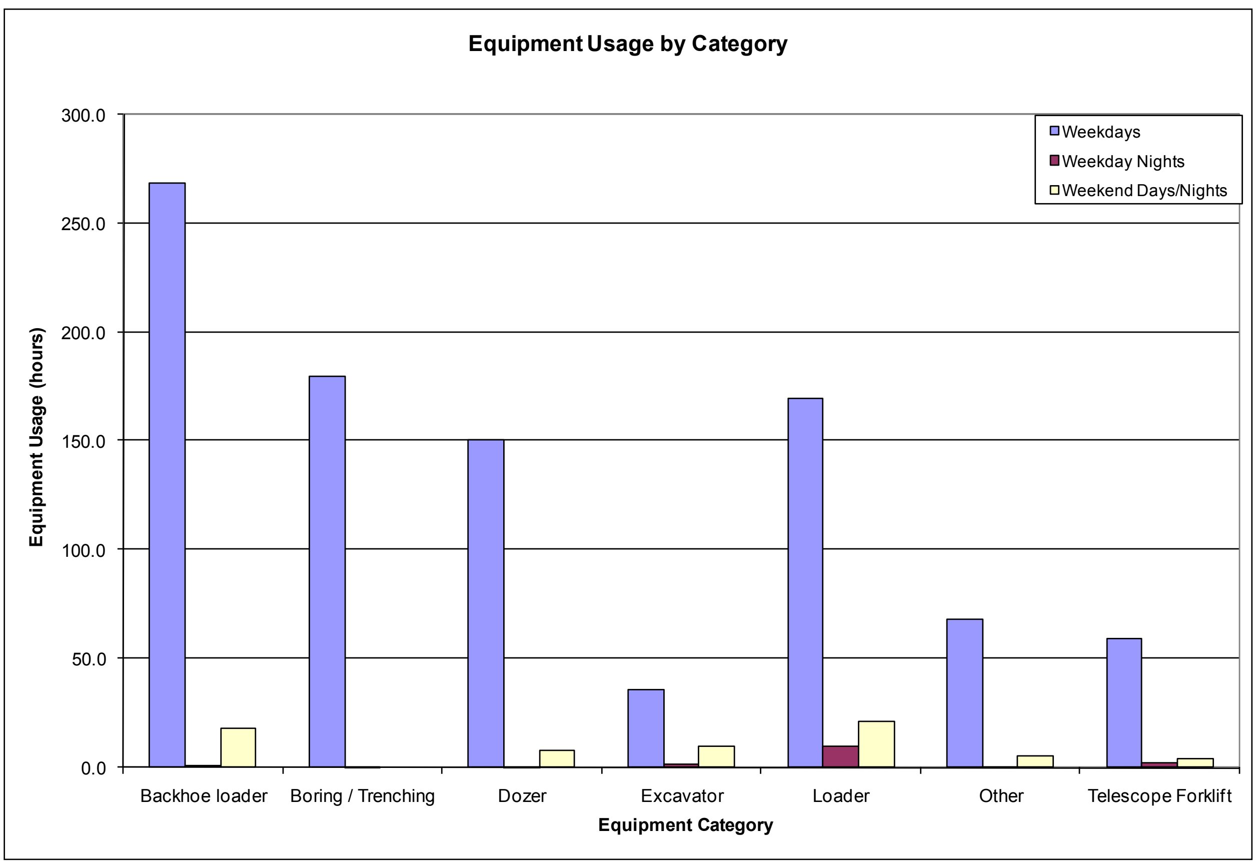
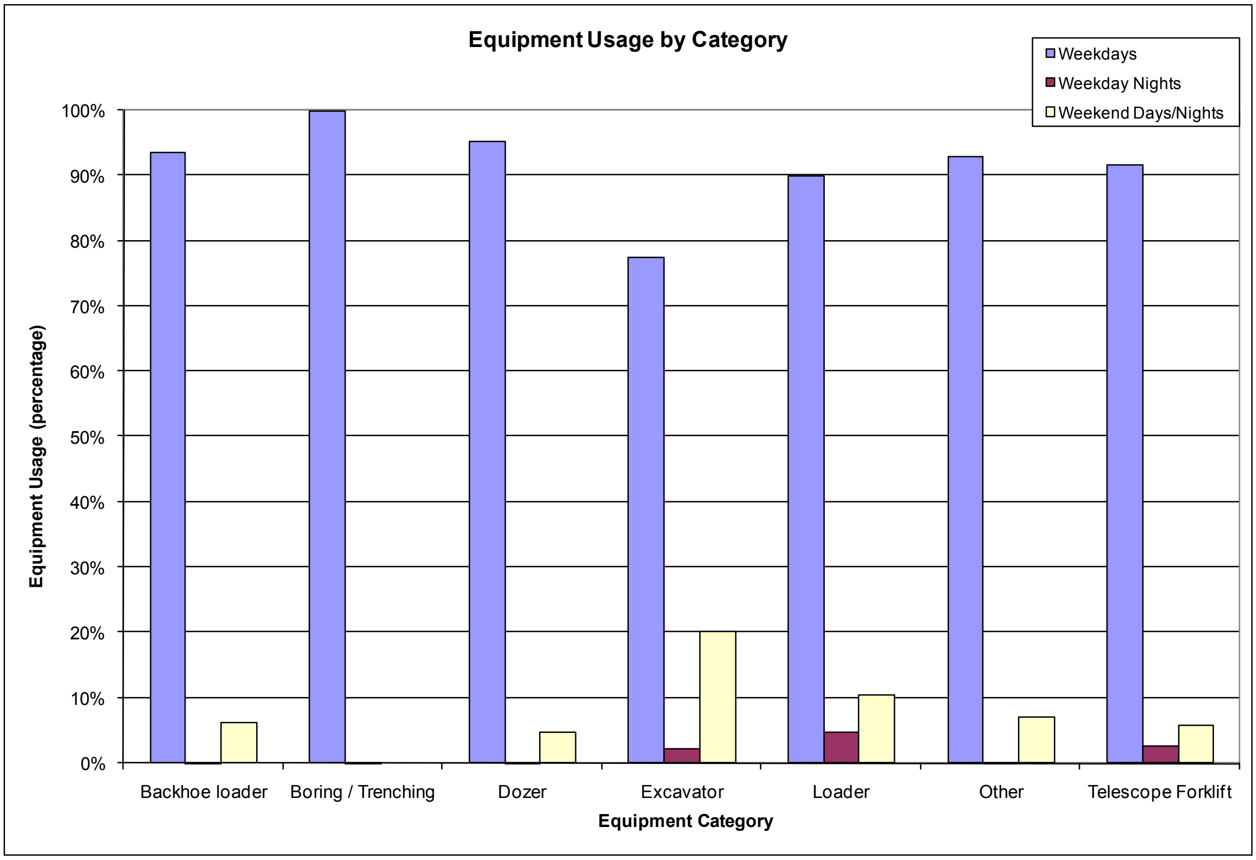


**Figure 6.3-2 Activity Summary by Equipment Category (in Percentages)**




With consideration of the small sample set of data collected, reviewing the PAMS usage data does suggest the majority of equipment usage occurs during typical weekday hours. Some types of equipment did appear to have higher night / weekend usage rates, although this could be attributed in part to rain, mud and other conditions which prevented operations during typical hours. Throughout the three ES phases of fieldwork, our experience does indicate that the type of industry in which each establishment worked did have an effect on what days and times equipment was operated. Type of work (and hence equipment type) may therefore be a good indicator of hours of operation (days / nights / weekends). Work hours did appear to be fairly consistent within establishments.

# 7.0 Lessons Learned and Program Recommendations

## 7.1 Sample Design and Recruitment

**Sample frames**: This study utilized Survey Sampling International (SSI) as the primary sampling frame and tested the use of Equipment Data Associates (EDA) as a replacement or supplemental frame. SSI remains a viable and productive sampling frame; however, as discussed in Section 4.4, we recommend future considerations of the EDA frame as a supplemental fame in a dual-frame design to increase coverage. The relative costs of processing EDA and SSI sample need to be considered and analyzed before implementing this recommendation.

**Two stage sampling**: Given the unexpected low prevalence of eligible establishments in the pilot study, combined with the absence of correlation between data items on the SSI sampling frame and the actual number of eligible equipment pieces for an establishment, we now believe that in most if not all situations a census of establishments will be needed even to instrument a small number of equipment pieces. If censuses are used, then issues of sample design within PSUs become moot.

However, there may be large metropolitan area such as New York City, Chicago or Los Angeles where the number of establishments for sampling would far exceed that needed for this type of study. In these cases we would resist the use of PPS sampling of establishments based on our findings in this pilot. Instead, we would encourage the creation of a few strata based on number of employees as follows: first exploit the skewed Pareto distribution of establishments to create a "large stratum" (say all establishments in the top 20th percentile according to number of employees), a "zero employee" stratum and a residual stratum. Based on our pilot study we expect that the eligibility rates to be highest among the "large stratum" and lowest among the "zero employee" stratum. This could lead to either a proportional allocation sample of establishments, or a mild optimum (Neyman) allocation stratified sample that employs 'best estimates' of eligibility rates across strata. But we would not recommend a PPS sample using number of employees as a measure of size.

**Use of incentives:** While the incentive tests conducted during this study were inconclusive, we cautiously recommend their use in future studies. Section 4.5 discusses a number of explanations for this including possible site or interviewer effects and differences among establishments. Clearly, it is more important to generate follow-through to instrumentation rather than assent at the recruitment stage. As such, we recommend that future research focus on this as the outcome of interest/treatment effect.

**Establishment eligibility:** Clearly, the number of eligibility requirements included in a survey impacts eligibility and ultimately response rates and sample design. Revisions were made to the questionnaire throughout the study to clarify issues such as fuel type (i.e., diesel versus gasoline-fueled equipment) or prime versus subcontractor status (the requirement of being a prime contractor was relaxed following Phase 1). Future studies with other industry sectors or other geographic locations within the construction sector should incorporate modifications made during this study. Appendix AK contains the survey questionnaires used throughout the study, by EOI phase of study.

**Survey instrument introduction:** A number of enhancements were made to the survey instrument introduction over the course of the study to reduce the likelihood that an establishment would refuse to participate in the study at the onset of the interview. The introduction should mention the Environmental Protection Agency and provide a very concise one-sentence description of the study that does not allude to eligibility (allowing prospective establishment to self-determine eligibility at the onset and giving them an easy way to opt out of the survey). For example, rather than, "…we are conducting a study with construction companies about the diesel equipment and machinery used in their daily operations" the following is preferable, "…we are conducting a study with companies about the equipment used in their daily operations."

**Advance letter:** We recommend continuing the use of an advance letter with FAQ brochure and endorsement from trade associations in future work, as these serves a critical function of pre-notifying establishments about the study.

## 7.2 General Fieldwork Lessons and Recommendations

Installations during non-working hours was generally found to be ideal for PEMS and PAMS installations, although occasionally off-hour site access was not possible. When off-hour site access was not possible, installations either took place during working hours when equipment was inactive, or installations were not performed at that particular site. Because of their nature of work, some establishments generally trailered equipment between job sites and the establishment on a daily basis (out to a job site in the morning, returning to the establishment at night). PEMS installations were generally not possible for equipment trailered on a daily basis, because the PEMS rack installed on the equipment was typically higher than could be safely transported on a trailer (due to interference with traffic lights, bridges, and electrical wires). In these situations, PEMS installations were performed during periods of inactivity or were not performed at all.

In general, conducting fieldwork (both PEMS and PAMS testing) required more field personnel than originally anticipated. For the PAMS units, locating and revisiting the units was time consuming because establishments and sites were generally separated by long distances, and equipment and work sites were generally more transient than originally anticipated. A significant amount of time was required to coordinate the logistics associated with ongoing PEMS and PAMS installations and testing.

Due to the transient nature of work of many establishments, fieldwork testing schedules and plans were difficult to establish in advance. Although it was usually possible to make tentative plans with establishments, it was also very typical to not know whether a PEMS installation was going to occur until late in the afternoon the day of the installation. Weather and establishment work and worksite unpredictability both factored largely into this uncertainty, as well as the installation team's need to conduct the installation in as unobtrusive of a manner as possible. This type of field testing required a large degree of flexibility of field team members who could conduct support activities (such as PEMS calibration and maintenance support and PAMS revisits) during times when PEMS installations and testing were not taking place.

For both PEMS and PAMS testing, although quick to install, the Capelec RPM collection devices did not provide a reliable RPM signal. Optical sensors typically worked well, as long as care was taken to mount in a location which minimized exposure to ambient light, dust and dirt and moisture (such as rainwater). Caterpillar optical sensor mounts attached to high-strength magnet bases worked well to hold optical sensors in place. Brackets fabricated on-site using existing bolts for mounting also provided a secure mount for optical sensors. Non-destructive taps into the vehicle's engine speed signal harness also worked well for RPM pickup.

For nonroad equipment which is equipped with a 24-V electrical system, PEMS and PAMS voltage needs to either be taken from a 12V point in the equipments electrical system, or for PAMS installations, a 24V to 12V power transducer is needed to step down the input voltage to within the PAMS operating range.

The ERG team originally intended on developing an Internet-based establishment and equipment sample management system. However, due to the amount of information which needed to be collected and analyzed by many different people, this approach was abandoned in favor of using various spreadsheets transferred among participants via a secure Internet-based file storage, archival and retrieval system (Tortoise Concurrent Versions System (CVS)). For future projects, an Internet-based sample management system could be developed using information gathered and learned during this study.

## 7.3 PEMS Lessons Learned

Depending on the type of equipment being instrumented, PEMS installation and setup times typically ranged from two to four hours the prior evening, with an additional two hours of warm-up and system verification required on the day of testing (prior to the start of emissions testing).

Due to the size and weight of the PEMS measurement system, installation was facilitated through use of an outrigger-equipped flatbed truck with an electric crane (leased as part of this contract). Three to four field staff were needed to safely install PEMS equipment. Many installations took place in muddy, off-road locations, necessitating the use of four-wheel drive installation vehicles.

During the first two ES phases of the study, silicon boots and hoses were used to connect the equipment's exhaust system to the PEMS exhaust flowmeter. However, it was discovered that this silicon exhaust tubing was not always capable of withstanding the high temperatures and exhaust flowrates of some of this equipment, which resulted in exhaust tubing burning, melting through, and delaminating. This process was accelerated for equipment with a tapered, side-exit exhaust tip, as this type of exhaust tip directed the exhaust flow directly onto the inside of the tubing. Figure 7.4-1 shows an image of exhaust tubing which was burned and melted, causing the exhaust connection to come loose from the exhaust tailpipe. Figure 7.4-2 shows exhaust tubing which became delaminated during testing.

**Figure 7.3-1 Burned and Melted Exhaust Tubing**

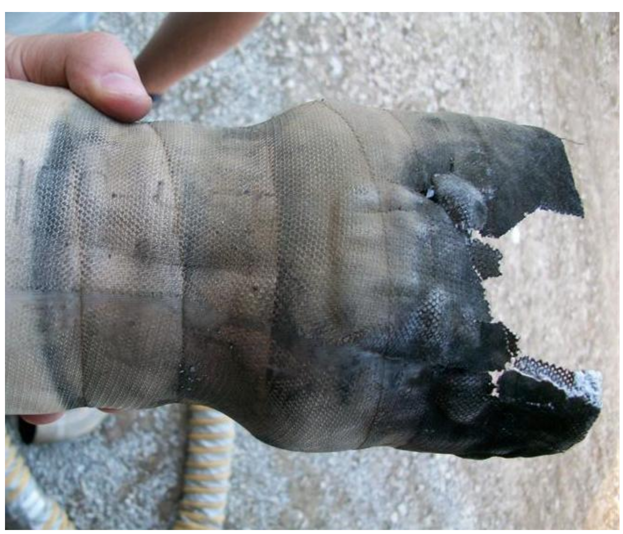


**Figure 7.3-2 Delaminated Exhaust Tubing**

In order to correct this problem, tapered, side-exit exhaust tips were removed from equipment prior to installing exhaust tubing, and the EPA acquired and provided metal tubing and clamps to be used directly from the exhaust pipe to the exhaust flowmeter, with no silicon pieces used. Metal boots joined the tailpipe with heavy-duty truck-style clamps. Figure 7.4-3 shows a backhoe loader in use with metal tubing.

**Figure 7.3-3 Backhoe Loader with Metal Tubing Installed**


Primarily due to equipment space constraints, ambient air was used to zero the instrument. For future studies, portable disposable containers of zero air could be used rather than ambient air. In addition, zeros should be limited to non-sampling episodes because of the resulting bias in emission measurements and work-basis calculations.

EPA laboratory testing performed after the completion of fieldwork identified the potential for leaks to occur at the union leading to the gravimetric filter holder. These leaks would occur if the sample line was not adequately pushed into the sample holder prior to tightening the assembly. In future studies, leak checks of the gravimetric sampling system performed prior to collecting sample on each set of filters would help ensure the system had no leaks. In order to do this, upstream and downstream pressure transducers could be installed prior to and after the gravimetric filter holders, and prior to each test, a vacuum could be applied to the gravimetric assembly, and the rate of vacuum decay could be monitored in order to ensure airtight seals are achieved each time gravimetric filters were replaced. Alternatively, pre and post-filter mass flow measurements could be performed as part of the system setup process.

Although “real-time” data QC was performed as PEMS testing was being performed, some issues identified during analysis performed after the testing was completed revealed additional areas where real-time QC would be beneficial. The “Summary of Nonroad PEMS data QC criteria” include in Appendix I could be used during review of PEMS test parameter plots in the field in order to ensure all systems are functioning properly during PEMS testing. In addition, review of test support data such as pre- and post-test spans (necessary if drift corrections are to be performed) and time stamps should be performed during or immediately after data collection. Appendix I provides a good starting point for PEMs QC review that could be performed in the field.

Accurate RPM collection is critical for developing work-based (brake-specific) emission estimates. Accurate RPM should always be collected using a reliable method (such as an optical sensor or a non-destructive tap into the equipment’s tachometer signal, if so equipped). ECU data can also provide an accurate RPM signal, if the delay in initiating acquisition upon equipment start-up is minimal.

Percent load is also used in determining work-based emission estimates. For this study, fuel used was compared with maximum fuel rate (at any given RPM) from the engine’s lug curve in order to determine percent load. In order to comply with the work assignment goals of minimizing the establishment’s work interference, no requests were made to equipment operators regarding how to operate their equipment. For future work, however, it would be beneficial during PEMS testing to collect data during intentional full load conditions at different engine speeds which could be compared with fuel consumption estimates from lug curves. This could provide information on the accuracy of second-by-second fuel usage estimates used in determining work-based emissions.  Alternatively, load comparisons could be made with ECU data or rack position as measured using a string potentiometer installed with the PEMS assembly.

During ES Phase 3 of this study, an optical sensor's RPM signal was input into an analog channel of the SEMTECH-DS' Automotive Micro-Bench II (AMBII) non-dispersive infrared (NDIR) analyzer bench.  This bench also processes signals for the NDIR CO and $CO_2$ emissions and also $O_2$ emissions (from the oxygen sensor input through another analog channel).  Also during ES Phase 3, output from the AMBII bench was lost on five of the tests, resulting in loss of CO, $CO_2$, $O_2$ and RPM information for at least part of those tests.  Signal losses continued to occur after replacement of the AMBII circuit board, and also after switching PEMS units. Additional investigation of the AMBII board and RPM sensor assembly in order to determine and rectify the root cause of this type of failure would be beneficial.

For future studies of this nature, the acquisition of ECU data collection equipment for nonroad equipment from other manufacturers would be of benefit, especially as SAE J1939 becomes more prevalent in the nonroad sector.

Because of the bias caused in cumulative emission estimates (especially PM relative to gaseous results), autozeros should not be performed during emissions sampling.  If autozeros are necessary, output of an "autozero" flag in the SEMTECH-DS data file is useful to identify and exclude the data from emissions reporting, and autozeros should never be performed during filter sampling.

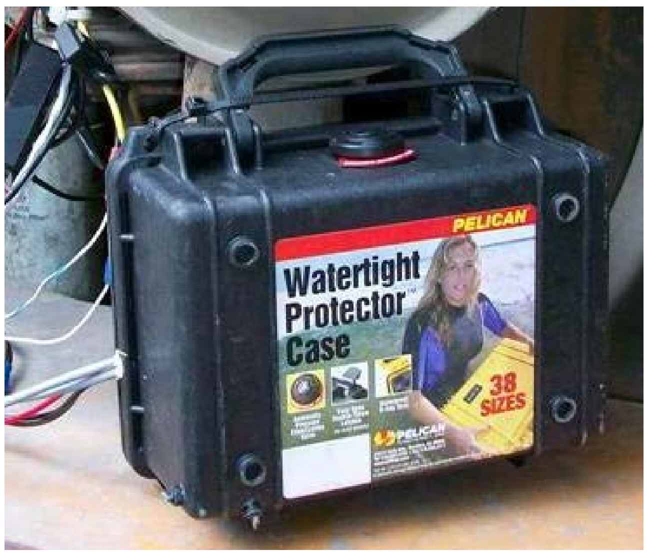
Additional efforts to continue to ruggedize and vibration-isolate the equipment would be beneficial.  Because of the rough usage of some of the tested equipment, some of the test failures which occurred during the study were due to sample lines becoming disconnected or kinking, PEMS rack hardware mounts and harnesses breaking, and breaker switches flipping as an apparent result of heavy vibration.  This usage took its toll on the PEMS rack through the course of the study, and illustrated areas where improvements could be made.

As size was an installation limitation on many pieces of equipment, decreasing the size of the PEMS rack would increase the number of types of equipment eligible for a PEMS test.  As future redesigns of the PEMS rack are being considered, any effort made toward decreasing the size (and mass) of the PEMS rack would be of benefit.

## 7.4 PAMS Lessons Learned

Corsa dataloggers required supplemental protection against water and the elements, so sealed Pelican cases were acquired, modified and used to house the Corsa dataloggers during installations in the later phases of the study. Rubber mounts were placed inside each case to suspend the datalogger within the case, and one-way valves (duckbill valves) were used to allow any water that happened to enter the cases to drain. Silicon sealant was used to seal the cases at the point where the wiring harness passed through, as shown in Figure 7.4-4.

**Figure 7.4-1 Pelican Case Housing a Corsa Datalogger**




The Corsa dataloggers we used were equipped with an antenna for remote activation and data collection (via a laptop using a Corsa antenna attached through a USB hub). However, wireless retrieval of data was unsuccessful due to the slow transmission speed, so the wireless capability was of little benefit in this type of study. Data was collected by powering down the datalogger and manually removing the compact flash card.

Due to the wireless transmission capabilities which never went into standby, the Corsa dataloggers drew 175 mA in standby mode. On equipment with weak batteries which sat dormant for two or more days, this drain rate was enough to drain the equipment's battery below a charge necessary for starting the equipment. To prevent this, all Corsa installations were eventually performed with switched power used as the main power source.

Isaac dataloggers have low standby drain rate. Setting the Isaac datalogger to enter standby mode based on a switched voltage signal or an RPM on/off value (such as 300 RPM) was found to work well for installations. However, switched power was generally favorable to using an RPM signal as this would likely provide a quicker wake-up time.  Isaac dataloggers were sealed sufficiently well such that an additional enclosure was not warranted, and in fact use of an additional enclosure was discouraged by the manufacturer because of possible system heat retention issues.

## 8.0 Data Conversion and Delivery

Data from this study was provided in the following formats:

- Exports from the recruiting database from all three survey stages were provided, along with the complete establishment sample frames used during the study. These database extracts were provided in Excel workbook format.
- All raw PAMS data files were provided in csv format, along with the SAS code used to import and process the PAMS data
- All raw PEMS data files (containing continuous gaseous emission rates) were provided in both unprocessed xml and processed csv formats, along with the SAS code used to import and process the PEMS data
- All scanned PEMS and PAMS instrumentation forms were provided in PDF format
- All scanned site inventory forms were provided in PDF format
- The project's comprehensive MySQL database was also provided. This deliverable is described below:

### 8.1 MySQL Database Delivery

The data deliverable provided to EPA as part of this project consisted of a MySQL database in script form. The database was designed based on a structure originally outlined in Appendix B of the work assignment, and includes tables, relationships, field names, field formats, and descriptors similar to those proposed.

The following text describes the design of the database, the process of its creation, and issues ERG staff encountered during preparation of the deliverable related to the structure and contents of the data.

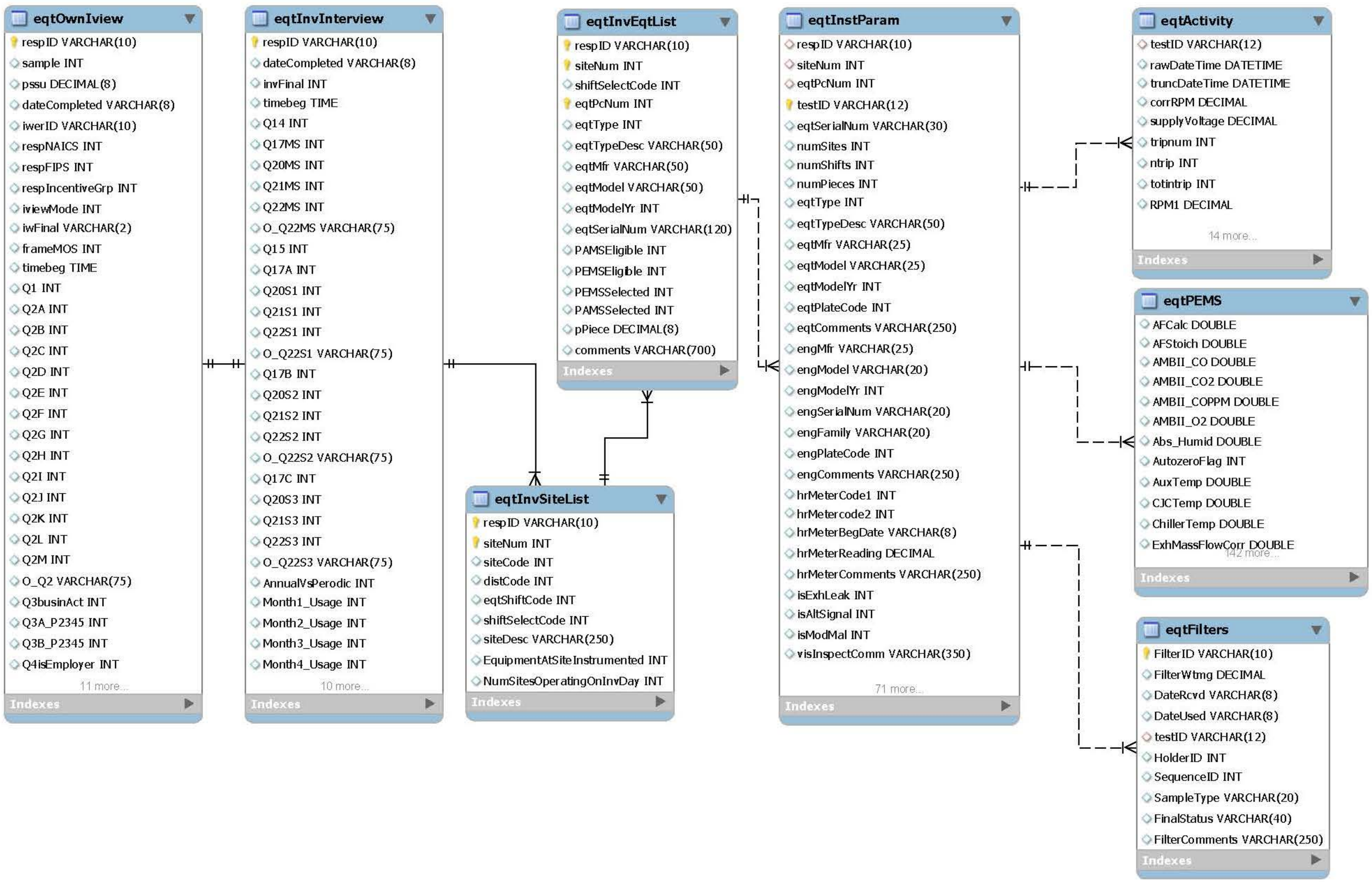
### 8.1.2 Creation and Population of Database

ERG used the MySQL Workbench tool to create tables, fields, format, and descriptors consistent with Appendix B of the work assignment. In some cases, fields were defined in Appendix B that no longer applied to the data collected at the conclusion of the project, or otherwise needed to be changed to reflect the data actually collected. Such fields are noted in more detail in Figure 8.1-1, which presents an entity-relationship diagram (ERD) detailing the structure of the database, which consists of eight separate tables.

With the design of the database complete, ERG began gathering raw data collected over the course of the project, and copying it into Microsoft Excel spreadsheets modeled after each individual table in the database. This data was obtained from a variety of sources, including NuStats interview results, inventories of potential sites, logs of sites and equipment visited in the field, and filter logs. A separate spreadsheet was created for each table to be input into the database, and was populated accordingly using the data described above. Extensive use was made of translation tables supplied as part of Appendix B in the work assignment to populate data fields with applicable codes.

Having populated these spreadsheets, corrections were made to the data in order for it to be readable by the database in the formats described by Appendix B. Examples of the corrections made here include changes to date and time formats, filling of nulls, addition of fields for clarity, and removal of fields no longer applicable to the project. These changes are described in additional detail below for each individual table and field. Once the spreadsheets were fully populated with the appropriate data, they were exported in tab-delimited format in order for each file to be directly imported into the database. In the case of PEMS and PAMS data collected via instrumentation, SAS programs were written at this point to export the previously quality checked data to tab-delimited files that could be read directly into the database. Additional edits were then made to correct line endings and to remove extraneous data characters introduced by the export from Microsoft Excel.

**Figure 8.1-1 Entity-Relationship Diagram for MySQL Database**



Once the tab-files containing the data had been created, we executed a MySQL script (FullDB.SQL) generated by the Workbench tool to create a blank database within a MySQL instance. A separate script (LoadAllData.SQL) was used to load the information contained in the tab-delimited files into the newly created database structure. Some iteration took place at this point to ensure that all of the data loaded into the database without errors related to table relationship integrity, primary key violations or field format errors. Once the data loaded successfully, we exported the database for transport to EPA by executing the backup function of the MySQL Administrator tool, which created a self-executing SQL script containing the entirety of the database. This file was transmitted to EPA via secure FTP and DVD by tracked courier.

### 8.1.3 Table List/Fields of Interest

***Table eqtOwnIview:*** This table was designed to include results from the equipment ownership interview, and is related to its child table eqtInvIview by the RespID field. Fields in this table that required correction or additional explanation include:

- pSSU: This field, the respondent's 2nd stage probability of selection, was originally defined in Appendix B. However, based on the need to integrate the sample and conduct a census (as described in Section 3.8 of this report), the relevance of this field was lost, therefore this field was set to null.
- DateCompleted: This information was adjusted to mmddyyyy format to be consistent with the database structure.
- respNAICS: The data in this field was, in most cases, looked up based on SIC provided by NuStats – these are 4 digit NAICS codes. In some cases in PSU 4 & 5, this data was directly provided – these are the 3 digit NAICS codes. This data is later used as a basis for eqtType codes in subsequent child tables.
- TimeBeg and TimeEnd fields: The times were converted from 4-digit military time using the following Excel formula: ROUNDDOWN(L1,-2) / 2400 + MOD(L1,100) / 1440. The obtained decimal result was then converted to Time format in Excel.

***Table eqtInvIview:*** This table was designed to include results from the interview portion of the on-site equipment inventory, and is related to its child table eqtInvSiteList by the RespID field. Fields in this table that required correction or additional explanation include:

- DateCompleted: This information was adjusted to mmddyyyy format to be consistent with the database structure.
- invFinal: This field is derived from Column D ("Inventoried?") of Appendix AG of this report. The numeric codes were based on suggested values presented in translation tables in Appendix B of the Work Assignment.

- Timebeg and timeend: Times were not recorded for on-site inventories, so these fields were set to null.
- AnnualvsPeriodic: Annual usage information was only collected for some sites in PSUs 4 and 5. If this information was unavailable, the field was set to null. A value of 1 represents annual operation, and 0 represents periodic operation.
- MonthX_Usage: These 12 fields contain usage operating information by month. Values of 1 and 0 represent operation and non-operation, respectively.
- Comments: Derived from column L ("Comments") of Appendix AG of the final report. Note that not all text in that column pertains to inventories; some is relevant only to instrumentation.

***Table eqtInvSiteList:*** This table was designed to include results from the site list portion of the on-site equipment inventory, and is related to its child table eqtInvEqtList by the RespID and Sitenum fields. Fields in this table that required correction or additional explanation include:

- Sitecode: Primary and secondary visits are represented by codes 01 and 02, respectively. The first visit to a given site, by date, was designated primary; any other visits were considered secondary.
- DistCode: According to Appendix B translation tables, this field is related to a variable called traveldistance, which was not recorded. Thus, this field was set to null.
- EquipmentAtSiteInstrumented?: This field replaces the wasSiteSelected field originally proposed in Appendix B. Values of 1 and 0 indicate that equipment at a given site either was or was not instrumented, respectively.
- NumSitesOperatingOnInvDay: This field replaces the pSite field originally proposed in Appendix B, and represents the number of sites a given establishment is operating on the day the inventory was conducted.

***Table eqtInvEqtList:*** This table was designed to include results from the site list portion of the on-site equipment inventory, and is related to its child table eqtInstParam by the RespID, Sitenum, and EqtPcNum fields. Fields in this table that required correction or additional explanation include:

- eqtType: These codes are derived from those provided in Table A-1.2 of Appendix A-1 of the work assignment, and are base on a cross-reference of NAICS codes and equipment descriptions.
- pPiece. This field represents an individual piece of equipment's selection probability, and was calculated based on the Sample Selection Weighting Criteria matrix (Figure Figure 5.1-2 ) presented in Section 5.1.3 of this report. pPiece is equal to the weight for an individual piece divided by the sum of weights at a given site.

***Table eqtInsParam:*** This table was designed to include results from the site list portion of the on-site equipment inventory, and is related to its child tables eqtActivity, eqtPEMS, and eqtFilters by the testID field. Fields in this table that required correction or additional explanation include:

- testID: A code consisting of the last 4 digits of a site's RespID and the last 4 digits of the equipment piece's serial number. This was introduced to the table for linking to PEMS, PAMS, and filter data in child tables.
- numSites: This information was not collected at the testing level, but rather in NuStats questionnaires and during the inventory, both of which are presented above as parent tables. This field was set to null.
- eqtType: These codes are derived from those provided in Table A-1.2 of Appendix A-1 of the work assignment, and are base on a cross-reference of NAICS codes and equipment descriptions.
- engRatePwrUnits: This field was changed from numeric to character, because the codes suggested in Appendix B of the work assignment did not allow for definition of horsepower on an unknown basis (as opposed to gross or net).
- engUnitsRating: Similarly, this field was added in order to distinguish between net, gross, or unknown bases for horsepower.
- tailpipeOD2: this field was added to allow for a second dimension of outside pipe diameter, as specified on data forms used in the field.
- InstCode: This field was intended to distinguish between equipment instrumented with PAMS (code 01) or SEMTECH-D (code 03). We added a code of 05 to allow for equipment that was tested with both types of instruments.
- spotBoxnum: This field was populated with the SEMTECH serial number present in the header of the raw XML data file.
- spotNOxO2sensorID: This field was populated with the NDUV serial number present in the header of the raw XML data file.
- preCalibration fields specified in Appendix B of the work assignment: Due to formatting issues, these fields are not included in the database structure but instead calibration data is provided in Appendices Q, R, S, AB and AC.
- Visit fields: additional fields were added to allow for multiple site visits to check on and maintain PAMS equipment

***Tables eqtActivity, eqtPEMS, and eqtFilters*** were designed to include PAMS, PEMS, and filter data collected in the field, respectively, and have no child tables. The format for these tables were not explicitly specified in Appendix B of the work assignment, so they were created to comprehensively include all of the data contained in the QC'd SAS datasets from which they were derived. In the case of *eqtPEMS*, it is important to note that because of differences in instrumentation settings between different phases of the project, certain fields that apply to data collected in PSU 1, for example, may not have existed in PSUs 4 & 5. In such cases, the fields defined in PSU 1 were set to null for PSU 4 and 5 data. The list of all fields included in these tables is presented in the database schema report provided in Appendix AN.

## 9.0 References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## 10.0 Index of Appendices

Appendices will be provided electronically. The following is a list of the appendices to be provided. Page counts for those appendices formatted for printing are given in parenthesis.

Appendix A - Equipment Ownership Questions *(6 pages)*
Appendix B - Onsite Equipment Questions *(3 pages)*
Appendix C - Onsite Inventory Data Collection Form *(2 pages)*
Appendix D - Onsite Inventory Equipment Selection Template *(9 pages)*
Appendix E - PEMS & PAMS Instrumentation Forms *(16 pages)*
Appendix F - PEMS Installation SOPS *(46 pages)*
Appendix G - PAMS Installation SOPS *(16 pages)*
Appendix H - WA Data Tables *(13 pages)*
Appendix I - PEMS data QC Criteria *(7 pages)*
Appendix J - Onsite Inventory Team Leader Duties *(1 page)*
Appendix K - Onsite Installation Manager Duties *(2 pages)*
Appendix L - Grav Filter Handling SOPS *(2 pages)*
Appendix M - Oil and Diesel Sampling SOPS *(2 pages)*
Appendix N - Nonroad QAPP & Appendices *(217 pages)*
Appendix O - PSU 1 PAMS Purchase Recommendation Memos *(43 pages)*
Appendix P - EPA & DRI PM Blind Study Results *(5 pages)*
Appendix Q - ES Phase 1 SEMTECH Daily Span Results *(1 page)*
Appendix R - ES Phase 2 SEMTECH Daily Span Results *(3 pages)*
Appendix S - ES Phase 3 SEMTECH Daily Span Results *(8 pages)*
Appendix T - Nonroad PEMS Fuel and Oil Analysis Results *(122 pages)*
Appendix U - PEMS and PAMS Testing Details *(155 pages)*
Appendix V - PEMS Filter Log *(7 pages)*
Appendix W - Equipment Inventory Results, all phases *(110 pages)*
Appendix X – PAMS Data Dictionary and Summary Statistics *(6 pages)*
Appendix Y - PEMS Data QC Results *(94 pages)*
Appendix Z - MPS to Exhaust Flow Proportionality Plots *(30 pages)*
Appendix AA - Summary of RPM correlations developed *(17 pages)*
Appendix AB - EFM / MPS calibration verification results *(Not formatted for printing)*
Appendix AC – SEMTECH multipoint linearity verification results *(Not formatted for printing)*
Appendix AD - BSFC Calculation Methodology *(6 pages)*
Appendix AE - PAMS Acquisition Delay Test Results *(1 page)*
Appendix AF - PAMS Data Review Notes *(11 pages)*
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Appendix AI - Advance Mailout Letter *(1 page)*
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Appendix AK – Survey Questionnaires by Phase *(20 pages)*
Appendix AL – Expected Study Dispositions *(5 pages)*
Appendix AM – Cognitive Interview Script *(3 pages)*
Appendix AN – MySQL Database Schema Report *(20 pages)*
Appendix AO – Uncertainty and Bias Estimates for Gaseous and PM Emissions *(11 pages)*