Methodology for Activity, Fuel Use, and Emissions Data Collection and Analysis for Nonroad Construction Equipment

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ABSTRACT

Nonroad construction equipment is a significant source of nonroad mobile source air pollutant emissions. Emissions from nonroad construction equipment are typically quantified based on steady-state modal engine dynamometer tests. However, such tests do not represent real-world activity. Therefore, there is a need to quantify energy use and emissions from construction equipment based on in-use measurement methods. The purpose of this paper is to develop standard procedures for field data collection and analysis for nonroad construction equipment. The methodology is based on second-by-second measurement of in-use activity and emissions using a portable emissions measurement system (PEMS). The procedure for field data collection includes development of a study design, installation of the PEMS, field measurements, data quality assurance, and analysis of the data. Installation of the PEMS must take into account the configuration of the vehicle and the amount of time required to install the PEMS. After field data collection, the raw data undergo a quality assurance procedure to check and correct synchronization between engine and emission data; identify missing data, and remove incorrect data. The screened data are analyzed in terms of the effect of engine activity on fuel use and emissions, and in terms of the effect of real world activity. One of the most significant challenges to data collection is vibration of the vehicle that is transmitted to the instrument, which may cause internal damage to the PEMS. Recommendations are made regarding preferred data collection, quality assurance, and analysis procedures in order to obtain valid energy use and emissions data for nonroad construction equipment.

INTRODUCTION

Nonroad diesel powered equipment is coming under increased scrutiny because it is a significant source of nonroad mobile source air pollutant emissions. Emissions from nonroad construction equipment are typically quantified based on steady-state engine dynamometer tests. However, such tests do not represent actual duty cycles. Therefore, there is a need to quantify energy use and emissions from construction equipment based on in-use measurement methods. Compared with other types of vehicles, there has been relatively little real world measurement of in-use emissions of nonroad diesel powered vehicles. The purpose of this paper is to recommend a set of standard procedures for field data collection and analysis for this equipment. A methodology for collecting and analyzing real-world in-use data from nonroad construction equipment is presented. This methodology is being used in ongoing projects to measure the in-use activity and emissions of front-end loaders, bulldozers, excavators, backhoes, off-highway trucks, skid steer loaders, motor graders, and generators. The results from the application of the methodology summarized here will improve the characterization of in-use activity and emissions of these vehicles, which can further support the development of highly accurate emission inventories and improved approaches to air quality management. The data collected can be used for ongoing study.

METHODOLOGY

The methodology is based on second-by-second measurement of in-use activity and emissions using a portable emissions measurement system (PEMS). The procedure for field data collection includes the development of a study design, installation of the PEMS, field measurement, data quality assurance, analysis of the data, and reporting of the results.

Development of the Study Design

The key elements of a study design for field data collection of in-use activity and emissions are briefly summarized here:

1) **Study Location** – The primary study area has been on or near the North Carolina State University (NCSU) campus. NCSU is undergoing significant construction activities, and there are numerous construction sites on campus. Most of the contractors working for NCSU are willing to cooperate with our project.
2) **Vehicle Selection** – The types of construction vehicles selected for data collection were prioritized based on analyses using the U.S. Environmental Protection Agency's NONROAD model. The selected equipment is estimated to contribute 70% of nonroad construction emissions in the United States. The selected equipment includes excavators, dozers, off-highway trucks, backhoes, front-end loaders, skid steer loaders, and generators.
3) **Vehicle Activities** – Vehicle activities have been characterized for each type of construction equipment. These activities are recorded in terms of task-oriented "modes" for each type of equipment such as idle, moving, loading, and scraping, and in terms of engine-based modes, based on stratification of second-by-second PEMS data with respect to engine manifold absolute pressure (MAP).
4) **Data Collection Scheduling** – Prior to data collection, cooperation must be obtained from the owner, the supervisor and the equipment operator to access nonroad equipment for installation of the PEMS. Permission must also be obtained to interact with the operator during data collection.
5) **Driver/Operator** – The driver or operator was assigned based on the contractor's schedule. On occasion, the operator might alter their work schedule because of construction project needs, or there may be unanticipated problems with the equipment itself resulting in data collection delays.

Installation of the PEMS

Installation of the PEMS must take into account the configuration of the nonroad equipment and the amount of time required to install the PEMS. PEMS have been used for a number of years for light duty vehicles. However, for construction vehicles, the installation procedure is more complicated. The general procedures include pre-installation, installation, and decommissioning. In order to have sufficient time to set up the PEMS without interfering with construction work, the data collection crew pre-installs major components of the PEMS one day prior to each test. This includes installing all wiring, hoses, engine sensors, and a safety cage. The engine is instrumented with a "sensor array" for the collection of RPM, MAP, and intake air temperature data. The sensor array can be used on all equipment, avoiding the need for expensive proprietary engine diagnostic interfaces that are often manufacturer- or vehicle-specific. The safety cage protects the PEMS from possible damage such as from contact with low-hanging tree limbs or any other obstruction that might come in contact with the equipment

On the day of the test, the main unit is secured inside the safety cage and is connected to the hoses and cables that were installed during pre-installation. The GPS receiver is attached magnetically to an upper exterior surface of the vehicle. A separate laptop computer, located away from the vehicle where vehicle activity can be observed, is used by a research assistant to manually record modes of activity for the vehicle. The data collection crew synchronizes the clock of the laptop computer to that of the main unit of the PEMS. The PEMS must be warmed up for at least 45 minutes prior to collecting data.

Two persons are involved in installation. The typical time required for pre-installation is 2 hours and 30 minutes, and for installation the typical time required is 1 hour and 30 minutes.

After data collection is complete, all equipment is removed from the vehicle and the site. This decommissioning takes approximately 35 minutes. The PEMS is cleaned and stored in the laboratory.

Field Measurement

During field measurement, the data collection crew assesses and records field conditions, collects emissions data, monitors vehicle activity, and archives the field data. Data are recorded for typical 3 to 5 hours.

One of the most significant challenges to data collection is vibration from the vehicle that is transmitted to the instrument. This may cause internal damage to the PEMS. Foam pads are placed between the safety cage and the surface of the nonroad vehicle, and between the PEMS and the interior of the safety cage, in order to reduce the transmission of vibration from the nonroad equipment to the PEMS.

Data Quality Assurance

Data screening and quality assurance procedures involve reviewing the field data in order to produce a valid database of vehicle activity, fuel use, and emissions. These procedures are used to: (a) determine whether any errors or problems exist in the data; (b) correct such errors or problems where possible; and (c) remove invalid data if errors or problems cannot be corrected.

A number of possible errors and problems have been identified from previous work (*1*, *2*), such as gas analyzer "freezing" (continuous seconds with no change in readings), inter-analyzer discrepancy (when comparing measurements of the two gas analyzers that measure exhaust gas in parallel), missing or unusual values of MAP, unusual engine speed, unusual intake air temperature, and air leakage. Criteria for detecting these problems have been developed. Where possible, the data are corrected. For example, if MAP data are missing for one second, the missing MAP data can be estimated by interpolation. If data correction is not possible, then the erroneous or suspect data are excluded from the final database that is used for analysis. For example, if engine speed is out of the normal range, the data are excluded from the final database. Most of the quality assurance procedures are applied automatically using macros that were developed in this work.

Analysis of the Data

The field data results were analyzed in terms of the effect of engine activity on fuel use and emissions. Based on exploratory analysis of data from several vehicles, MAP has been consistently identified as the engine variable most highly correlated with variations in fuel use and emission rates. Therefore, a procedure for estimating modal emission rates based upon ranges of MAP has been developed.

The data were also analyzed in terms of the fuel use and average emission rate for task-oriented modes. A task-oriented mode can include idling, movement of the equipment for repositioning purposes, use of a blade or bucket, and so on, depending on the type of equipment. For each of these two different types of analysis, which are referred to as engine-based versus task-oriented, respectively, emission factors were estimated on a per time basis and on a per gallon of fuel consumed basis.

FIELD ISSUES

After applying these procedures to real-world measurements, numerous lessons were learned regarding practical aspects of collecting data in a real-world construction environment. Some of these lessons are summarized here in terms of recruiting test vehicles, installation of the PEMS, field measurement, data quality assurance, and analysis of the data.

Recruiting Test Vehicles

The first step in this work is to identify the equipment to be tested. This includes considering type of equipment, engine size, and age. Locating a specific vehicle is the next step. We have been successful in obtaining cooperation from local construction contractors, who allow access to their vehicles. In some cases, this process is informal, while in others it requires discussion with upper level management. Once corporate permission has been obtained, local cooperation on the construction site is critical and requires cooperation from the field supervisor and equipment operator.

Installation of the PEMS

The PEMS is vulnerable to damage from impact with trees and other obstacles since it is often located on top of a vehicle that is working on an often cramped work site. The PEMS must be protected from damage by tree branches or other potential obstacles that might be encountered at a construction site. Vibration from the equipment and dust from the construction site are two other key considerations. Each of these factors can potentially damage the system in serious ways. A safety cage was designed to secure the PEMS to avoid any collisions. Rubber and foam pads are used in order to reduce vibrations coming from the chassis of the test equipment to the cage and to the main unit. A porous cloth protective cover is used to protect the PEMS from direct sunlight and large particles or dust.

Field Measurement

Ambient conditions, such as temperature, can significantly affect the feasibility of data collection. In hot weather, the PEMS was found to overheat when the ambient temperature was above 90 °F, and thus data collection under such ambient temperatures is to be avoided. In cold weather, residual water in the sampling hoses may freeze. In cold weather, a recommended practice to avoid this problem is to keep sampling hoses in a warm place prior to installation, and to install them only when ready to collect data. Furthermore, data collection should not occur in temperatures below 32°F.

Data Quality Assurance

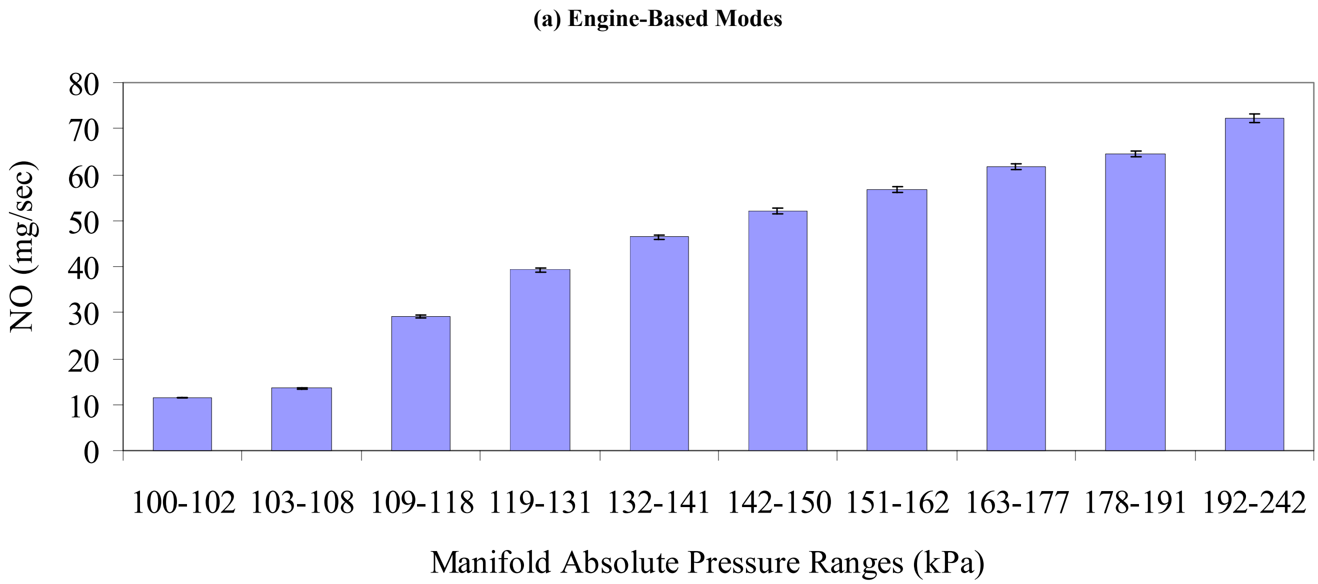
After applying these data screening and quality assurance procedures to the raw data, a number of possible errors and problems have been corrected or removed. Results obtained for 17 construction vehicles for which 78 hours of raw data have been collected show that approximately 4.6 percent of data are deleted as a result of quality assurance checks. The most significant sources of the QA errors are gas analyzer freezing and inter-analyzer discrepancies. Gas analyzer freezing requires re-initialization of the PEMS and thus needs to be corrected in the field if the problem is identified. Inter-analyzer discrepancies are identified based on the initial processing of the data and can indicate that one or both analyzers may be producing inaccurate data. The calibration and performance of each analyzer must be reviewed and a judgment made as to whether additional maintenance or repair is needed for one or both analyzers, as well as to whether data from one or both analyzers should be excluded for one or more pollutants and for what time periods.

Analysis of the Data

To illustrate procedure for data analysis, an example based on a bulldozer was chosen. Bulldozers are the second largest NO_x emission source among nonroad vehicles according to analysis done using EPA's NONROAD model. Examples of both engine-based and task-oriented modal analysis of emission rates are shown in Figure 1. For the engine-based-modes, the second-by-second quality assured data are stratified with respect to ranges of MAP. The example shown in the figure is for the average modal emission rates of NO on a mass per time basis. Also shown are 95 percent confidence intervals on the mean value. The lowest average emission rate occurs for the lowest value of MAP, which are associated with idling of the engine and, hence, low engine load. MAP is a surrogate indicator of engine load. As MAP increases, the average modal emission rate increases. At the highest observed values of MAP, the average NO emission rate is approximately 85 mg/sec compared to only 12 mg/sec at idle. The average emission rate for an entire duty cycle will depend on the proportion of time spent in each mode.

For the bulldozer, the task-oriented modes are idle, forward motion, backward motion, and use of the blade. The latter refers to situations in which the blade was put into contact with the ground for the purpose of moving dirt. The data shown here were collected while the bulldozer was doing rough grading of a building construction site. The idle emission rate is similar to that for the lowest MAP engine-based mode. The average emission rates during forward and backward movement are approximately the same, at about 55 mg/sec. This rate corresponds to a value between the minimum and maximum engine-based modes and implies that the engine was, on average, at a partial load. The blade mode has an average emission rate that is approximately the same as that for forward motion. The small differences between the forward, reverse, and blade modes imply that the average engine load among these modes is similar. Since these three task-oriented modes do not discriminate substantial differences in average emission rates, alternative definitions of task-oriented modes could be more useful. For example, in this case, idle and non-idle modes could be adequate.

An issue not addressed here, but a subject of ongoing work, is how differences among tasks and duty cycles could lead to differences in overall average emission rates. The data shown here are only for one vehicle, task, and duty cycle. However, similar results have been obtained for other bulldozers performing other tasks, as well as for other kinds of equipment.



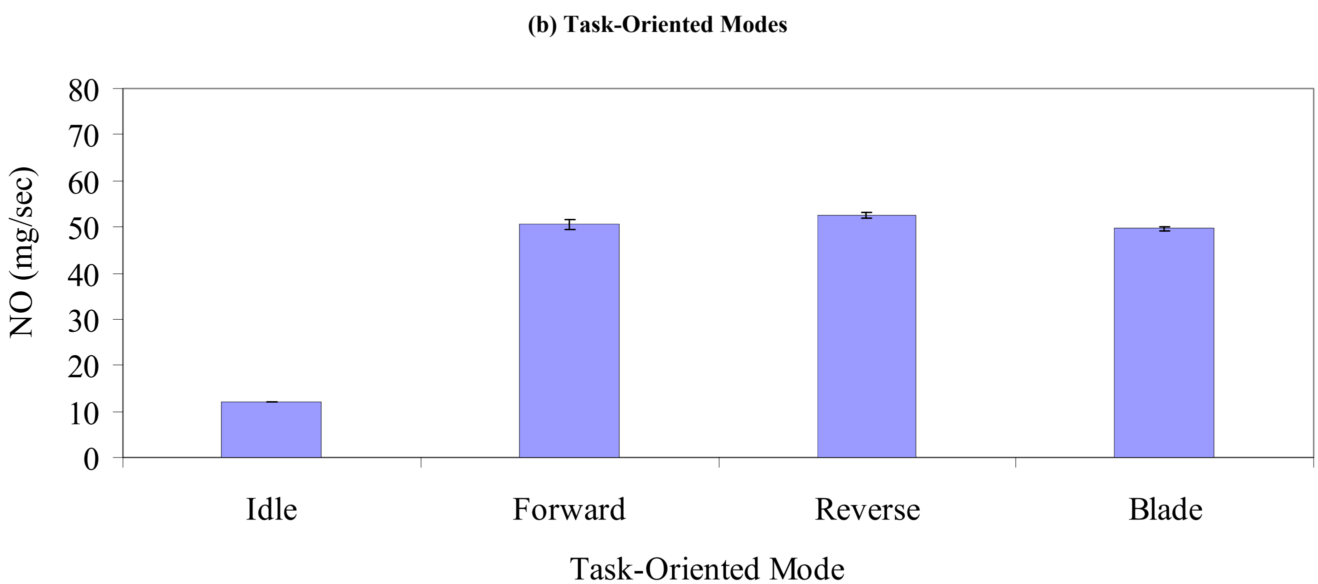


Figure 1. Average NO Emission Rates Measured on September 28, 2005 for a Bulldozer for (a) Engine-Based Modes and (b) Task-Oriented Modes

CONCLUSIONS

The procedures described in this paper are applicable to any construction site and type of nonroad construction equipment. Recommendations are made based on the experience gained in attempting to obtain valid fuel use and emissions data for nonroad construction equipment. Foam should be placed under the main unit of the PEMS and under the safety cage to reduce vibration and equipment damage. An appropriate cover must be installed to prevent damage from dust and the testing must be conducted under moderate temperature conditions. In order to prevent data quality problems, the data collection crew should check the PEMS every 30 minutes periodically during data collection to ensure that no problems have occurred.

In the future, more sophisticated definitions of modes of activity are needed to link emissions to typical construction operations and quantities. More importantly, procedures must be developed to be able to clearly identify and characterize activity data and correctly link them to emissions data.

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KEY WORDS

Construction Equipment Emissions
Real-World Measurement
Emissions Measurement