

In-Use Emissions from Non-road Equipment for EPA Emissions Inventory Modeling (MOVES)

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ABSTRACT

Because of U.S. EPA regulatory actions and the National Academies National Research Council suggestions for improvements in the U.S. EPA emissions inventory methods, the U.S. EPA' Office of Transportation and Air Quality (OTAQ) has made a concerted effort to develop instrumentation that can measure criteria pollutant emissions during the operation of on-road and off-road vehicles. These instruments are now being used in applications ranging from snowmobiles to on-road passenger cars to trans-Pacific container ships. For the betterment of emissions inventory estimation these on-vehicle instruments have recently been employed to measure time resolved (1hz) in-use gaseous emissions (CO_2 , CO, THC, NO_x) and particulate matter mass (with teflon membrane filter) emissions from 29 non-road construction vehicles (model years ranging from 1993 to 2007) over a three year period in various counties in Iowa, Missouri, and Kansas. In coincidence with the pollutant measurements exhaust flow, engine speed, and in a few cases engine power from the vehicle engine control module have been measured. From these exhaust and engine operation measurements pollutant mass emission rates, mass concentrations, mass per fuel use, and mass per energy (work or brake specific) emissions have been determined. The brake

specific emissions were estimated from the engine speed measurements and brake specific fuel consumption (bsfc) curves. There were about 35 tests completed on these 33 vehicles ranging in time from about 10 to 600 minutes with an average test time of about 220 minutes.

INTRODUCTION

In response to a National Academy of Sciences (NAS) report¹ which indicated the need to use more representative emissions data for the EPA's mobile source emissions estimation tool (previously called MOBILE, now the Motor Vehicle Emissions Simulator or MOVES)² and for regulatory purposes³ the EPA's Office of Transportation and Air Quality (OTAQ) has put a great deal of effort to develop and acquire equipment capable of measuring in-use gaseous and particulate mass emissions. Since this effort initiated by OTAQ there have been many studies of the equipment, improvements in the equipment, and deployment of the equipment on passenger and heavy duty diesel vehicles^{4,5,6,7,8,9,10,11,12,13} and now on nonroad vehicles for inventory development. This data is envisioned to populate the emissions database of the MOVES model and to help meet the recommendations of the NAS. Additionally, this data will supplement the dynamometer based

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measurements of vehicle and engine emissions collected during driving cycles which have been the standard method of verifying vehicles and engines are meeting current federal emissions regulations.

In the MOBILE models dynamometer emissions measurements collected over specific driving cycles have been used as a basis to estimate emission inventories or the total pollutant emissions in a particular area due to the use of a given population of vehicles at a defined time and set of conditions. However, average or typical driving cycles does not necessarily give an accurate estimate of everyday vehicle use. Nor do they yield the typical power demands on the vehicle's engine when run on a dynamometer. And, of course, the vehicle emissions are mainly dependent on the engine power demand and the efficiency of the emissions controls (catalytic converter, exhaust gas recirculation, etc.) installed on the vehicle. In view of this, both the accuracy of the emissions inventories and the determination of how well the vehicle or engine is keeping within the emissions regulations, have been under review. In particular, the National Academy of Sciences report¹ indicated that EPA must collect more real-world data in order to more accurately predict the effects of its own emissions regulations.

In response, the USEPA has made a commitment to developing and using portable emissions measurement systems (PEMS) for emissions regulatory and inventory work. In fact, the USEPA and others^{4,5,6,7,8,9,10,11,12,13,14,15,16} have begun many campaigns to measure on-road vehicle emissions data. On the regulatory side the motivation has been via a federal court order, and an ensuing measurement allowance program for gaseous PEMS has been completed. Currently, heavy duty engine manufacturers have begun taking on-road gaseous emissions data from on-highway vehicles for certification. On the particulate matter (PM) regulatory side, three time-resolved PM measurement instruments have been submitted in the PM measurement allowance program which is in its final stages. Additionally, a non-road vehicle regulatory program for construction equipment is being planned. For the purpose of inventory development, the U.S. EPA has multiple programs completed, taking place, and in the planning stages that are in collaboration with other organizations and state governments. These inventory programs have started on a small scale with 10's of vehicles in a limited geographical area and have grown to a larger scale which encompasses larger geographical areas. Light duty vehicles, city buses, heavy duty trucks, and off road construction vehicles have been outfitted with PEMS. Moreover, EPA's new inventory model for highway vehicles, MOVES¹⁷, has been designed in response to the NRC report.

In this study a report on the in-use emissions measurements for MOVES of nonroad diesel engine powered construction

equipment is given. Nonroad construction vehicles were outfitted with PEMS and portable activity measurement systems (PAMS). This study was a multi-year pilot study¹⁸ 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 nonroad diesel equipment in various economic sectors. In this pilot study sampling techniques, the latest activity and emissions measurement technology, and rigorous quality assurance and quality control methods were combined to characterize in-use, real-world emissions from nonroad diesel engines within the commercial construction sector of EPA Region 7. This study area encompassed five counties within 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 (detailed elsewhere¹⁸) for ultimately expanding the study to other commercial sectors that operate fleets of nonroad diesel engines in their daily operations such as agriculture, mining, and utility sectors. 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 79 of those establishments, and emissions and/or activity measurements were performed at work sites of 29 establishments. Emissions tests were ultimately conducted on 29 different pieces of nonroad equipment, and activity information was collected from 58 pieces of nonroad equipment. [Table 1](#) is a summary of the successful equipment emissions measurements that were done during each of the three phases of the study and the geographical areas in which they were conducted. 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. Additionally, various ways of establishing a rapport with and minimize the testing burden on participants were explored throughout the study.

The 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)¹⁹, where it may be used to help expand and improve the data currently supporting emission inventory modeling for nonroad engines.

EXPERIMENTAL

Portable on-board emission measurement systems (PEMS) were used to perform onboard measurements compliant with the Code of Federal Regulations (CFR) Title 40 Part 1065²⁰



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Table 1. Summary of data collected throughout the Nonroad PEMS Study

ES Phase / PSU	PEMS Successful			PAMS
	Gaseous	PM	RPM	Data Collected
ES Ph 1, Summer 07 Jackson, MO (PSU 1)	3	2	1	7
Es Ph 2, Fall 07 Linn, IA (PSU 2) & Scott, IA (PSU 3)	10	10	9	10
ES Ph3, Summer&Fall 08 Clay, MO (PSU 4) & Shawnee, KS (PSU 5)	16	15	15	12
Totals	29	27	25	29

of gaseous and aggregate particulate matter (PM) exhaust emissions on 37 kW or greater diesel engines in nonroad construction equipment. The emissions instruments used were all manufactured by Sensors, Inc.. The gaseous unit was a SEMTECH DS²¹, the proportional sampling unit for PM sampling was a SEMTECH Microportional Sampler (MPS)^{22,23,24}, and the PM sample collection was done with a SEMTECH Portable 47 mm filter system²⁵. The MPS units were built in 2007 and had subsequent software and hardware revisions made to them during the course of this three year measurement program. The portable filter holders were also built in 2007. All of these instruments along with the 12 volt D/C power supply and dilution air pump were enclosed in a single metal box to enable a secure installation onto the nonroad equipment to be tested. SEMTECH exhaust flow meters (EFM)²¹ were also secured onto the metal enclosure. The exhaust flow was routed from the equipment's exhaust stack to the flow meter by flexible tubing. The heated gaseous sample line extended from the exhaust flow meter to the SEMTECH DS. The PM sample line extended from a 90° bend at the outlet of the exhaust flowmeter. [Figure 1](#) illustrates the major components of the sampling apparatus. Instrument power was provided by a gasoline fueled portable Honda A/C generator secured to the vehicle.

The SEMTECH-DS consists of a non-dispersive infrared (NDIR) analyzer for CO and CO₂, a non-dispersive ultraviolet (NDUV) analyzer for NO and NO₂, a heated flame ionization detector (FID) for hydrocarbons, an electrochemical O₂ sensor, and an averaging pitot tube based exhaust flowmeter. Its system computer architecture allows for data logging onto flash memory cards, a vehicle interface port for communication with the on-vehicle engine controller area network (CAN), and an RJ45 port (or antennas) for (wireless) interface to a digital computer. The SEMTECH-DS is controlled externally with a LabView based software application installed on an external computer. The external computer can communicate with the SEMTECH-DS via an

Ethernet cable with an RJ-45 connector or a wireless [Institute of Electrical and Electronics Engineers (IEEE) standards 802.11b and 802.11g] connection. Once data acquisition has been initiated the computer can be disconnected from the SEMTECH DS and it will continue data acquisition and instrument control independent of the external computer. A complete description of the SEMTECH DS can be found elsewhere²¹.

The SEMTECH MPS is a two stage dilute proportional sampler based on a work by Brockmann, et al.²³. In the MPS, sample flow is extracted from the exhaust flow and controlled to be a constant fraction of the varying exhaust flow. The sample flow is controlled by both the first and second dilution stages. 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 the exit of the MPS. The MPS total flow, sample plus primary dilution plus secondary dilution is held to a constant. The software interface to this device is also Labview based. Details of this diluter have been published elsewhere^{22,24}.

Finally, PM mass was collected onto a 47 mm filter using a SEMTECH portable gravimetric three filter sampler box which was heated to 47°C. Filter flow was controlled at 20 liters per minute. The filter sampler box consists of 3 URG stainless steel 47 mm filter holders²⁶, a stainless steel URG PM 2.5 micron cutoff cyclone²⁶, a Teledyne Hastings mass flow controller²⁷, and pneumatically controlled valves for switching between filters. Whatmann 47 mm Teflon membrane filters²⁸ were the filter media used to collect the PM mass. The sampled filters were shipped to the U.S. EPA's National Vehicle and Fuel Emissions Laboratory (NVFEL) for mass measurement on a Mettler-Toledo balance²⁹ housed in a CFR 1065²⁰ compliant clean room.



Figure 1. Sampling enclosure with instruments : (1.) SEMTECH MPS sample line, (2.) SEMTECH MPS, (3.) exhaust flowmeter, (4.) heated gaseous sample line, (5.) ambient humidity and temperature sensors, (6.) SEMTECH DS, (7.) space for SEMTECH filter box (not installed), and (8.) batteries for backup power.

The filter sampler automatically switched between the three gravimetric filters, based on an integral timer, or input voltage signal indicating engine start, or the filter could also be switched remotely using the SEMTECH-DS software on an external computer with the wireless connection. One filter was used to capture the first start at the beginning of the day (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.

The equipment and supplies were stored and transported in a trailer. This trailer was transported to and from EPA Region 7 and the various work locations within the region using a flatbed truck with a boom lift. This boom lift allowed the PEMS installation team members to place the approximately 400-pound PEMS rack onto each piece of equipment being tested (e.g., Figure 2).

The PEMS collected the following time resolved ($\leq 1\text{Hz}$) data and recorded them in 1 second intervals : engine speed in revolutions per minute, ambient temperature, ambient relative humidity, ambient barometric pressure, exhaust stream oxygen concentration in percent by weight, carbon-dioxide concentration in percent by weight, nitrogen oxides in parts per million, carbon monoxide in percent by weight,

total hydrocarbon in parts per million carbon, and particulate matter mass by gravimetric filter in grams.

Engine speed was measured and recorded in several different ways, including a Capelec voltage processor connected to the vehicle's battery, an optical sensor with reflective tape attached to a flywheel or pulley that was rotated by the engine drive shaft, a magnetic pickup mounted near a flywheel or pulley to which a magnet was affixed that was being rotated by the engine drive shaft, or by non-destructively tapping into the equipment's electronic tachometer signal. Non-destructive taps were made using supplemental connectors with harnesses which were connected inline with the equipment's original harness. The engine speed data were stored with the emissions data through an analogue interface to the SEMTECH DS.

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.

Automated zero calibrations of the SEMTECH-DS analyzers were performed throughout the sampling period using ambient air which was scrubbed with carbon and particulate filters. Daily calibrations of PEMS equipment were

Installed instrumentation box
with exhaust tubing



Figure 2. Truck with boom used to install PEMS units on the construction equipment. In the background is an excavator with a PEMS unit installed.

performed, and laboratory calibration and verification of flowmeter measurements and SEMTECH gaseous measurement linearity results were performed prior to and following each phase of the fieldwork.

All PEMS data was monitored during collection followed by extensive quality control (QC) and processing performed after data collection was completed. For PEMS data, QC and analysis included time-alignment, engine speed scaling, estimation of brake-specific emissions based on engine speed 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 engine speed 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 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. Details of these analyses are given elsewhere¹⁸.

EMISSIONS CALCULATIONS

A complication for in-use testing of heavy-duty engines comes from the historical dynamometer data. Emissions measurements for these types of vehicles are typically reported in brake specific units or mass per unit work, i.e., grams/ kW-hr or grams/ hp-hr. Furthermore, the equipment tested did not have easy access to the engine CAN network which would have allowed for determination of engine load at the drive axle needed to calculate the brake specific emissions. One solution to this would be to collect both in-use data and engine dynamometer data. However, to do this on a large population of non-road diesel equipment is impractical and costly. A large part of the cost and difficulty comes from having to remove the engine from the vehicle for the laboratory based engine dynamometer test. Transporting the engines to an engine test facility would pose additional cost and logistical problems including the removal of the vehicle from a proprietor's fleet. So, an approximation was used to determine the engine power at the drive shaft (or the power given in an engine power or torque curve, i.e., the brake specific power) using fuel rate calculations based on the emissions measurements and published brake specific fuel consumption (bsfc) curves for the engine in the equipment. The difference between the fuel rate and the brake power is mainly engine friction. In the following section, the feasibility and an assessment of the errors involved in using this approximation will be outlined.