Regulated and Air Toxic Exhaust Emissions from Nonroad Diesel Engines and Equipment

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ABSTRACT

Exhaust emissions were measured from fifteen nonroad (NR) diesel engines and in-use pieces of NR diesel equipment in three separate engine emission test programs. The test engines derived from construction, utility and agricultural equipment applications, for the most part, and ranged from 7 horsepower (hp) up through 850 hp. The test fuels used varied by sulfur concentration: "2D" diesel at a nominal 350 ppmS; NR-grade diesel at both 2500 and 3300 ppmS; and ultra-low sulfur diesel, nominally less than 10 ppmS. Test engines were run over both steady-state and transient duty cycles, with some of the transient cycles being application-specific, for example, rubber-tire loader, excavator, etc. Carbon monoxide, CO_2, NO_x and PM were quantified for each test engine, as well as, sulfate, ammonia, N_2O and a range of C_1 - C_{12} compounds (aldehydes, ketones, alcohols, etc.). Additional MSAT (mobile source air toxics) emissions were identified in two of the three programs for seven of the fifteen engines. These emission species included, among others, BTEX (benzene, toluene, ethylbenzene and xylene), PAHs, nitrated-PAHs and several metals. Emission results were summarized in both grams/hour and grams/brake-horsepower·hour. With the emission data, EPA will address differences between Tier 1 and unregulated NR diesel emissions, the impact of diesel fuel sulfur level on engine emissions, whether any adjustments to default modeling TAFs (transient adjustment factors) used in

the NONROAD emissions model are warranted by the new data, and the necessity of creating category- (by source classification code) and power-specific NONROAD TAFs.

INTRODUCTION

In an effort to begin quantifying exhaust emissions from nonroad diesel engines, an emission testing plan was created. The plan identified a matrix of engine types used in nonroad diesel equipment which EPA targeted for emissions testing. The engine types themselves were created by pairing engine power classes, or families, and engine management technology categories. The extent of that matrix of engine types and variables may be seen in the columns below.

Rated Power Classes	*Management/Technology Categories*
• less than 50 hp	• "Tier 0 "/ pre-regulation
• 50 hp, and greater	• Tier 1 / late 1990s
• 150 hp, and greater	• Tier 2 / early 2000s
• 300 hp, and greater	(• Tiers 3 & 4 / 2006, and beyond)
• 500 hp, and greater	
• 750 hp, and greater	

Table 1 describes what is meant by a "typical engine" in each of the management/technology categories below.

Table 1. Engine Management and Technology Categories.

"Tier 0"	Tier 1	Tier 2
pre-control regulation	in phases, 1996-2000	in phases, 2000-2006
many 2-stroke engines	more 4-stroke engines	predominately 4-stroke engines
simpler, non-electronic controls	less simple, more electronics	predominately electronic controls

A key goal of testing was to identify trends in the transition from smaller to larger engines and from pre-emission standards regulations engines to more technologically-advanced engine configurations. A path to that goal was seen as creating engine profiles from each of these nonroad engine types from engine emission data.

One concern for the equipment/engines procured under this scheme was the actual "age", in terms of hours of operation of the potential test engine. A older piece of nonroad diesel equipment would also carry some engine emissions "deterioration factor" for its age and history of use. As such, any engine recruited for the test program would need a low number of engine hours of usage, i.e., "newer" status. However, the newer (and larger, for that matter) an engine was at recruitment, the more difficult to find and more expensive to obtain that engine would be for the testing program.

Over time, using these nonroad engine types as test "targets", EPA staff have initiated and directed the testing of various nonroad engines and in-use pieces of nonroad equipment for regulated and unregulated diesel engine emissions. This has been done with an eye toward accumulating emission data for nonroad emission inventories and to support regulatory initiatives in the nonroad equipment arena. Three programs in particular have yielded sufficient data to warrant detailed analysis of the results of the various diesel engine emissions tests and the effects of emission testing variables found in these programs. The first test program, identified in this paper as EPA's Ten Engine Emissions Program, is th eresult of a nonroad engine testing program at Southwest Research Institute (SwRI). The program was jointly administered through the California-Air Resources Board (CARB) and EPA and its full title was "Transient and Steady-State Emissions Testing of Ten Different Nonroad Diesel Engines Using Four Fuels", SwRI # 08.03316. The second program is EPA's "Three Engine Program", identified as EPA Contract #68-C-98-169, and includes work assignments #03-05 and #02-03. It is entitled "Nonroad Duty Cycle Testing for Toxic Emissions." The third program is the "Four In-Use Engines Program" and is identified as EPA Contract #68-C-98-158, work assignment #03-04 and is entitled " Air Toxic Emissions from In-Use Nonroad Diesel Equipment."

The purpose of this paper is to describe these three test programs, including engines, fuels and duty cycles, and to show early results of data summary efforts. Test engine procurement is described, as well as, the level of effort necessary to secure a variety of nonroad engines for laboratory-based engine dynamometer testing. Engine emission test species are listed for each program and descriptions of sampling equipment and methods are outlined in this presentation. The paper will further describe efforts to make test program results available to EPA's constituents in the air quality arena and to the public, at large. Both summary emission results and database-ready formats for the data are being prepared for release.

We do not address gasoline engines in this discussion of nonroad engine emissions because spark-ignition nonroad equipment comprises a much smaller percentage of the nonroad equipment population than compression-ignition, or diesel (for the most part), engines. Presumably, nonroad spark-ignition engine emissions have also benefitted from technology changes required of their more and earlier regulated passenger and on-highway, heavy-duty gasoline engine counterparts.

METHODS

Ten Engine Emissions Program

Engine emission data were generated for the ten engines in this study over various transient and steady-state duty cycles using at least two different diesel fuels per engine. Steady-state engine duty testing included 40 operating conditions, including a typical eight-mode steady-state cycle. Transient testing included running up to six different cycles per engine, each in triplicate. Brake-specific emissions for total hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_X), particulate matter (PM) and selected unregulated emissions were quantified using full-flow exhaust dilution.

Test Engines and Fuels

In this study, emission testing was performed to characterize regulated and select unregulated emissions using ten different diesel engines representing a cross-section of nonroad equipment and applications and was jointly administered by California-EPA Air Resources Board (CARB) and the EPA.[1] The ten engines tested in this program were all four-stroke, diesel engines ranging in power from 7 to 850 horsepower (hp). Nine of the ten engines were obtained in cooperation with the Engine Manufacturers Association (EMA) and its member companies and one engine, the Deere 6101, was obtained from an in-use excavator. The engine was returned to its original owner and restored to its former usefulness at the close of emission testing.

The five lower-powered engines and five higher-powered engines were obtained from various sources, and each was mounted in a transient-capable emissions test cell to run the desired testing. They are described in Table 2 below.

TABLE 2. Descriptions of Ten Nonroad Diesel Test Engines.

Intended Application	Engine Mfr and Model	Model Year	Engine Control	Disp., liters	Rated Condition	
					hp	rpm
utility	Yanmar 2TNE68	1998	Mechanical	0.5	14	3600
utility	Yanmar L100AE-DE	1998	Mechanical	0.2	9	3600
forklift truck	Kubota V2203B	1999	Mechanical	2.2	49	2800
generator/pump	Lombardini LDW903-FOCS	1999	Mechanical	0.92	20	3600
utility/pump	Hatz B130	1999	Mechanical	0.35	7	3600
tractor/trailer	Navistar B250-F	1998	Electronic	7.4	250	2600
construction equipment	Cummins QSL-9	1999	Electronic	8.3	330	2000
excavator	John Deere 6101	1997	Mechanical	10.0	320	2000
construction/ agriculture use	DDC Series 60	1999	Electronic	12.7	400	2100
mining truck	Caterpillar 3508	1999	Electronic	34.5	850	1750

A total of four diesel fuels were used in this program, ranging from a high sulfur nonroad-grade diesel to an ultra low sulfur diesel fuel. The fuels used in this study were a Certification-grade Type-2D diesel fuel, a high-sulfur Nonroad-2D diesel fuel, a California 2D fuel, and a clean emissions control diesel obtained from ARCO®, deemed “ECD” fuel. The regular 2D and nonroad-2D fuels had similar distillation curves and similar hydrogen-to-carbon ratios. However, the 2D fuel had a sulfur level of 390 ppm and an API gravity of 36.1 and the nonroad diesel had 2,570 ppm sulfur and 34.8 API gravity. Apart from sulfur content, the California and ARCO® diesels differed from the other diesel fuels in this study primarily in having a lower aromatics and higher saturates composition, which lead to a higher cetane number, as well.. The California-grade 2D fuel had a sulfur level of 50 ppm and an API gravity of 39.1 and the ARCO® ECD-type ultra-low sulfur fuel had a nominal sulfur level of 2 ppm and an API gravity of 42.7. A fifth fuel, nonroad grade 3300 ppm sulfur diesel, was introduced for limited emission testing on the in-use Deere 6101 engine because previous EPA work had generated emission data on such fuel with that same engine. Results are presented for tests using three fuels for the Deere excavator engine rather than just two different fuels.

<u>Engine emission test cycles</u>

Steady-state emission measurement procedures adhered to CFR 40 Part 89 and generally satisfied ISO 8178-1 and 8178-4 requirements. An ordered sequence of over forty steady-state operating modes was used for conducting steady-state emission tests, with additional subsets of those modes conducted on most engines. The additional steady-state testing consisted of the eight operating modes specified in CFR 40, Part 89 (also referred to as an ISO (International Standards Organization) eight mode, C1-weighted steady-state test), and the eleven-mode ISO-8178 Type-C2 points in combination with three partial-load modes to complete an ISO-8178 "E3" 14-mode steady-state test[2].

After steady-state testing was complete, each of the ten engines was individually mounted in a transient-capable emission test cell. The test cells were each equipped with a DC electric dynamometer and a control system capable of motoring and absorbing loads during transient operation. Dynamometers and associated control hardware were calibrated prior to performing emission tests, in accordance with procedures outlined in the Code of Federal Regulations (CFR), Title 40, Part 86. For each engine, suitable dynamometer and throttle control strategies were developed to achieve "passing" regression values for cycle performance criteria over the FTP cycle. For most engines, subsequent operation over different transient cycles employed the strategy developed over the FTP. In contrast, the strategy for the Deere 6101 engine was to tune the operation of the engine for a crawler-dozer application cycle, as it had been in a prior emissions testing program.

The list of transient regulatory and application duty cycles[3] used in this study is as follows:

- U.S. On-Highway Heavy-Duty Federal Test Procedure (FTP) cycle
- European On-Highway Transient Duty Cycle (ETC)[4]
- Agricultural tractor nonroad duty cycle (AGT)
- Backhoe loader nonroad duty cycle (BHL)
- Crawler-dozer nonroad duty cycle (CRT)
- Composite excavator nonroad duty cycle (CEX)
- Arc welder typical (AWT) nonroad duty cycle
- Arc welder high transient torque (AWQ) nonroad duty cycle
- Rubber-tired loader typical (RTL) nonroad duty cycle
- Rubber-tired loader high transient torque (RTQ) nonroad duty cycle
- Skid steer loader typical (SST) nonroad duty cycle
- Skid steer loader high transient torque (SSQ) nonroad duty cycle

Because the ten engines differed significantly in horsepower and are found normally in various pieces of nonroad equipment, a transient duty cycle was assigned to a particular test engine if that cycle was considered representative of actual or potentially applicable nonroad applications for that engine.

All engines, with exception of the Hatz engine, were tested over the FTP and the BHL transient duty cycles and only one engine, the Yanmar 2TNE68, was not tested on the ETC. Additionally, most engines were tested over the AGT and CRT cycles. All the rest of the cycles were tested on either two or three engines, with the exception of the SSQ (one engine only).

Engine Emissions Sampled

Information on regulated exhaust emissions, total hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_X) and particulate matter (PM), was generated for each engine at numerous steady-state conditions and over six transient cycles using two fuels per engine. Each emission test cell was fitted with a constant volume sampling (CVS) system and related hardware, with dedicated gaseous emissions analyzers and systems for sampling dilute exhaust by various methodologies from the full-flow exhaust emission tunnel. This study included measuring regulated and a limited number of unregulated emissions. Gaseous samples for HC and NO_X were quantified using dedicated analyzers at each test cell. Bagged samples of proportionally gathered dilute exhaust were analyzed to quantify CO and CO_2 concentrations. Total PM was measured using a double dilution system to draw a portion of the dilute CVS exhaust flow through a series of 90 millimeter diameter Pallflex T60A20 filter media. All filter media was baked in a vacuum oven prior to its use in testing. Sampling methods for measuring emissions over transient cycles and steady-state tests adhered to calibration requirements and procedures outlined in CFR 40, Parts 86 and 89, respectively.

Unregulated emissions were quantified only over duplicate BHL cycles and the eight ISO Type-C1 operating modes using one fuel per engine, generally the fuel with the lowest sulfur content of the two used for testing that engine. For these selected tests, additional samples were obtained to quantify the specific unregulated emissions. Namely, an array of impingers, or "bubblers", in a DNPH solution was used during emission tests to capture gaseous samples of dilute exhaust for later quantifying aldehyde and ammonia levels. Ammonia emissions were measured using a Dionex® ion chromatograph and calibrated to analyze NH3 samples. In addition, a 40 percent segment or "pie slice" was cut from the same 90 mm PM filter pairs that were used to express total PM levels and was shaken in a mixture of 60:40 isopropanol and water. The solution was then injected into the same Dionex® instrument setup equipped with a conductivity detector to measure sulfate levels. Finally, bagged samples of proportionally-gathered dilute exhaust were used to measure nitrous oxide (N_2O) levels.

Three Engine and Four Engine In-Use Test Programs

Regulated emissions testing in these two programs used full-flow CVS dilution techniques to quantify brake-specific levels of regulated emissions. However, the primary focus of data collection from these seven engines in these two programs was to gather and analyze additional nonroad engine emission samples to quantify selected unregulated diesel exhaust emissions. Numerous samples were gathered and analyzed using special sampling techniques and related hardware to quantify levels for specific unregulated emissions, or "toxics." These are the same Mobile Source Air Toxics (MSATs) described in EPA's March 29th, 2001 *Federal Register* notice (66 FR, 17235).

Three Engine Test Program

The three engines tested under this program were run using two different diesel fuels under limited steady-state and transient test cycle operations to quantify both regulated and numerous unregulated emissions.[5] The engines tested in this program were a 50 hp Kubota V2203E, a 330 hp Cummins QSL9, and a 480 hp Caterpillar 3408 engine. Each engine had accumulated between 125 and 250 hours of operation. The Kubota and Cummins engines originally had been obtained from their respective manufacturers for use in the separate CARB-EPA ten engine study, described above. As such, one set of regulated and limited unregulated engine emission results already existed for these two engines from the earlier study. The third engine was mounted in the engine test cell specifically for use in this study. The three test engines are described briefly in Table 3 below.

TABLE 3. Three Different Nonroad Test Engines.

Intended Application	Engine Mfr and Model	Model Year	Engine Control	Number of Cylinders	Disp., liters	Rated Condition	
						hp	rpm
forklift truck	Kubota V2203E	1999	Mechanical	Inline-4	2.2	50	2800

construction equipment	Cummins QSL9	1999	Electronic	Inline-6	8.8	330	2000
rubber-tired loader	Caterpillar 3408	1999	Electronic	V-8	18	480	1800

NOTE: Kubota and Cummins engines carried over from Ten Engine Emission test program to capture air toxic emissions data.

The diesel fuels used in testing were an emissions certification test grade Type-2D and a Nonroad-2D diesel. The 2D fuel had a sulfur level of 390 ppm and an API gravity of 36.1, and the nonroad diesel had 2,570 ppm sulfur and an API gravity of 34.8. In each case, a thorough fuel change procedure was completed, with new fuel filters and sufficient engine operation to purge the system of any previous fuel prior to emissions testing on the next fuel. Each engine's torque map was measured using both fuels for use in applicable emissions testing, but engine power output did not differ significantly from fuel-to-fuel.

Four Engine In-Use Test Program

In this program, four diesel engines were obtained from different pieces of "in-use" nonroad equipment.[6] A particular piece of nonroad equipment and its engine, once identified, were selected based on the engine power class and management technology categories defined earlier under EPA's test plan. Each engine was removed from its host piece of equipment and mounted in a dynamometer test cell. Test engines were run over a variety of steady-state operating conditions, and over several transient duty cycles, to generate samples for quantifying regulated and selected unregulated engine emissions using two different diesel fuels.

The four different engines tested represent a cross-section of engines found in nonroad equipment applications. Each engine was an in-line, six-cylinder diesel engine equipped with charge air cooling. Table 4 below identifies the in-use equipment and briefly describes the engines selected for this test program.

TABLE 4. Description of four in-use test engines/equipment.

NR Application	Model Year	Hour Meter	Engine Model	Engine Control	Disp., liters	Rated Condition	
						hp	rpm
motor grader	1996	2,289	Deere 6068T	Mechanical	6.8	160	2200
excavator	1997	4,107	Cummins M11C	Mechanical	10.7	270	1700
agricultural tractor	2001	416	Caterpillar 3196	Electronic	10.0	420	2100
telescoping boom excavator	2001	868	Cummins ISB190	Electronic	5.9	194	2300

NOTE: the Cummins ISB190 engine is emissions-certified for on-highway operation so that piece of nonroad equipment can travel on city streets to move between work sites.

The two fuels used in this program were an emissions certification grade Type-2D diesel fuel, and a high-sulfur Nonroad-2D diesel fuel. These two fuels had similar distillation curves, and similar hydrogen to carbon ratios. However, the 2D fuel had a sulfur level of 390 ppm and an API gravity of 36.1, and the nonroad diesel had 2,570 ppm sulfur and 34.8 API gravity.

Engine Emission Test Cycles Used in the Three Engine and Four Engine In-Use Test Programs

Testing for each engine included sampling for regulated and unregulated emissions at all modes of an eight mode ISO-type C1 emissions test and over two different transient test cycles, the on-highway FTP for heavy-duty diesel engines and the EPA backhoe loader (BHL) cycle.

Emissions testing under steady-state engine operation was accomplished using an eight-mode, C1-weighting test cycle, running eight individual modes, to establish regulated and selected unregulated emission levels on both low- and high-sulfur diesel fuels. Sampling systems were prepared for running the eight-mode C1 test to collect emission samples for use in quantifying the various emissions. Calibration and sampling methods adhered to test procedures in the Code of Federal Regulations (CFR) Part 89 and, generally, satisfied International Standards Organization ISO-8178-1 guidelines. In addition, the Kubota engine was tested over the eight mode C1 test using a "stacked PM" approach, where PM emissions are accumulated from all operating modes into a single time-weighted PM emission sample for each set of analyses. This involves using one set of particulate filters over the eight different modes, while running each mode for a time proportional to the applicable C1 weighting factor. There was no "stacked" steady-state testing performed on the Cummins or Caterpillar engines from the three engine work.

The transient duty cycles used in testing each of these seven engines were the on-highway FTP cycle and the BHL cycle. Prior to running the core test program, duplicate FTP transient cycle tests were performed on each engine using Type-2D fuel to quantify transient regulated emission levels of HC, CO, NO_X, and total PM. Engine emissions were then sampled under transient operating conditions for each engine using a test cell control strategy developed for commanding dynamometer and throttle control for each engine over the on-highway FTP cycle. Minimal tuning subsequently improved transient control and cycle performance for testing over the BHL and/or SAT nonroad cycles. Prior to emissions testing, engines were run over a preparatory test cycle, followed by a 20-minute engine-off soak period. After engin soak, each transient emission test was run from a hot-start utilizing procedures and sampling processes given in CFR 40, Part 86, Subpart N. Another 20-minute engine-off soak period separated any duplicate runs of a test cycle. In addition, duplicate runs of the recently-developed nonroad transient composite duty cycle, or SAT cycle, was used to provide further baseline information for regulated emissions on each engine using only 2D fuel.

Engine Emissions Sampled in the Three Engine and Four Engine In-Use Test Programs

Testing for regulated engine emissions used full-flow dilution techniques to quantify brake-specific levels of HC, CO and NO_X. Total PM was quantified using a double dilution technique. Measurements of unregulated emissions consisted of carbonyls (generally, aldehyde and ketone species), ammonia, N_2O and sulfate. Several hydrocarbon species from C_1 through C_{12} were quantified for each test. Proportional bag samples of dilute exhaust were analyzed via gas chromatography to speciate hydrocarbons from C_1 through C_{12} using a method similar to the Phase II Auto-Oil method.[7] Selected hydrocarbon species, benzene, 1,3-butadiene, ethylbenzene, n-hexane, styrene, toluene and xylene, were all of particular interest in these studies. These seven hydrocarbon compounds constitute a short list of important mobile source air toxics (MSATs). Specifically, MSATs are toxic pollutants emitted by on-highway vehicles and off-highway, or nonroad, equipment. In a rulemaking published in 2001,[8] EPA identified 21 MSATs, of which six are of major public health concern - acetaldehyde, acrolein, benzene, 1,3-butadiene, formaldehyde, and diesel particulate matter.

Sample collection and procedures to determine carbonyls, ammonia, nitrous oxide, and sulfate were the same throughout the three emission test programs. To quantify sulfate levels, a 40 percent segment or "pie slice" was cut from the 90 millimeter diameter T60A20 Pallflex® filter pair used to quantify total PM, and shaken in a mixture of 60:40 isopropanol and water. The solution was then injected into a Dionex® ion chromatograph equipped with a conductivity detector to measure sulfate levels. Ammonia levels were quantified using the same Dionex® instrument setup and calibrated to analyze ammonia samples. For ammonia and carbonyls, an array of impingers was used during each emission test to capture gaseous samples of dilute exhaust for later analyses. Formaldehyde and acetaldehyde were measured using a DNPH technique, as outlined in CFR Title 40, Part 86. A liquid chromatograph was used to quantify aldehydes and ketones captured by the impingers in a 2,4-dinitrophenyl hydrazine (DNPH) solution. Finally, bagged samples of proportionally-gathered dilute exhaust were analyzed for N_2O levels using a gas chromatograph equipped with an electron capture detector.

Mass emission rates for lead, manganese, nickel, arsenic, and chromium were determined in the solid phase. Trace levels of elemental inorganic metals were quantified for particulate captured on 47 millimeter diameter Fluoropore® filters using an inductively-coupled plasma - mass spectrometry (ICP-MS) technique to detect the selected elements. ICP-MS is useful for a quantitative determination of multi-elements and isotopes in a wide variety of sample types at trace and ultra-trace concentration levels. The detection limits of the procedure, under ideal conditions, range from 0.01 to 50 ng/L, depending on the element(s) under investigation. The ICP-MS method used in this study digested PM-laden filters in a mixture of nitric and perchloric acid, followed by aqua regia.

In addition, mercury was sought in the gas phase using an impinger containing a solution of potassium permanganate (K_2MnO_4). Resulting solutions were analyzed by ICP for selected inorganic elements. The instrument was standardized using NIST traceable standard reference materials. Immediately after the standard check sample was run, a blank sample was run to verify the zero setting of standardization. Check samples are required to be within the control limits of 90-110% recovery of the certified value. Absolute value of the check blank was required to be below the reporting limit for the samples. If either condition had not been met, the analysis would be terminated and the instrument re-standardized and re-checked.

Additional PM and gas phase particulate samples were collected to quantify selected polynuclear aromatic hydrocarbons (PAH) and nitrated-PAH (n-PAH) compounds. The solid particulate emission phase was sampled using a single 20-inch by 20-inch square sheet of Pallflex® T60A20 filter media. Semi-volatile, gaseous phase PAH and n-PAH compounds were sampled separately using a pair of emission-trapping polyurethane foam (PUF) canisters mounted in parallel and located downstream of the particulate phase collection filter. Each PUF trap consisted of two pieces of 4-inch diameter by 1.5-inch thick polyurethane foam disks separated by a thin layer of XAD resin. In the interest of economy, the extract of solid phase and extract of gaseous phase particulate samples for a given test were combined into one set for analysis, with the combined extract used to quantify both PAH and n-PAH compounds. Both sampling media were extracted, then combined prior to concentrating the samples, and finally, analyzed using a gas chromatograph-mass spectrometer (GC/MS), operated in the selective ion monitoring (SIM) mode.

Listed below are the sixteen PAH compounds chosen for speciation in these two programs. They are the same compounds identified and measured in EPA Method 610[9] and tracked in EPA's National Emissions Inventory (NEI) and National Air Toxics Assessment (NATA).

- Benzo(a)anthracene
- Benzo(a)pyrene
- Benzo(b)fluoranthene
- Benzo(k)fluoranthene
- Chrysene
- Acenaphthylene
- Anthracene
- Benzo(ghi)perylene
- Fluoranthene
- Fluorene

• Dibenz(a,h)anthracene • Naphthalene
• Indeno(1,2,3-cd)pyrene • Phenanthrene
• Acenapthene • Pyrene

The seven compounds, in the following list, are those n-PAHs targeted for speciation and measurement by these two programs.

• 2-Nitro Fluorene • 9-Nitro Anthracene
• 3-Nitro Fluoranthene • 1-Nitro Pyrene
• 6-Nitro Chrysene • Dinitro Pyrenes
• 6-Nitro Benzo(a)pyrene

RESULTS AND ANALYSIS

Emission results for the ten engine program were presented in three subsections. The first gives results of regulated emission levels measured at steady-state conditions; the second lists regulated emission levels over transient cycles; and the third subsection presents unregulated emission levels. Unregulated emissions were only quantified using one fuel per engine. Testing for the two Yanmar engines did not include quantifying unregulated emissions.

Problems with several of the test engines required involvement by representatives of the respective engine manufacturers. Minor problems were handled by telephone, and more invasive procedures involved their on-site support. All but one engine completed the planned testing. There were no problems with the Yanmar 2TNE68 engine but the first Yanmar L100AE-DE engine was scrapped at 35 hours into testing (broken engine output shaft) and a second engine of the same type procured. The second L100AE-DE successfully completed the planned testing. The engine throttle lever broke on the four cylinder Kubota V2203B engine prior to emission testing, was repaired and the engine successfully completed the planned testing. During emissions testin g, the Lombardini showed intermittent unstable performance and erratic HC emission levels were observed. Fuel system adjustments were made, a new fuel injector installed and the engine successfully completed the planned testing. After all planned steady-state testing was completed on the Hatz B130, and during preparatory activities prior to conducting transient duty emission testing, lubricating oil and combustion gases were observed escaping from the engine's single cylinder. No timely remedy was available and the Hatz engine was removed from the study without generating emissions data over transient cycles.

No problems were encountered with either the Cummins or the Navistar engines. However, the Navistar engine is certified to on-highway, heavy-duty emission standards (for the tractor/trailer market) and was procured because of its similarity to equally powerful nonroad engines and for its availability. All other engines in this study were directly applicable to nonroad equipment and generally had higher emissions. The Deere 6101 was the only engine in this group which was obtained from the field for use in testing; it was removed from a John Deere 992-E excavator. Limited emissions testing was conducted on the engine in "as received" condition prior to effecting two minor gasket repairs. The JD6101 then completed all planned testing without further incident. Detroit Diesel (DDC) Series 60 was unique in that it had an electronic variable speed governor (VSG) but was tested, nonetheless, in its "as received" configuration. This engine was programmed to operate within a somewhat narrow window of speed and load points but after some dynamometer and throttle tuning efforts, the engine was passing the established on-highway FTP duty cycle performance and statistical regression values. The Caterpillar 3508, being a larger engine, presented some installation difficulties and showed only a minor starting problem, which was soon cleared. Testing of the engine proceeded without incident.

The original test plan for the Deere 6101 was to conduct testing using nonroad-grade diesel fuel at 3300 ppp sulfur (HS fuel), but unscheduled maintenance interrupted testing to repair coolant leaks in th eengine. The supply of HS fuel was diminished, and CARB and EPA opted to start over using NR fuel. Emission tests performed using HS fuel prior to the unscheduled maintenance included select transient cycles and an 8-mode steady-state test. Another 8-mode test was conducted after the maintenance using HS fuel to bracket unscheduled procedures. At that point, work on the Deere 6101 switched to begin using NR fuel, and planned testing again started from the beginning for that engine.

Composite eight mode, C-1 weighted steady-state emission levels for the ten engine program are shown in Table 5 below:

TABLE 5. Composite Eight Mode, C-1 Weighted Steady-State Emission Levels for Ten Different Nonroad Engines Using Low and High Sulfur Diesel Fuels.

Engine Model		Fuel ID	TYPE-C1 WEIGHTED EMISSION LEVELS, g/hp-hr				
			HC	CO	NO_X	PM	CO_2
1	Yanmar 2TNE68	2D	0.328	2.878	4.320	0.460	843
		NR	0.534	5.648	4.167	0.929	825
2	Yanmar L100AE-DE	2D	1.512	8.305	6.407	1.263	719
		NR	1.556	9.344	6.159	1.587	706
3	Lombardini LDW903	CA	0.242	2.766	3.004	0.609	767
		NR	0.619	3.072	3.355	0.636	798
4	Kubota V2203B	2D	0.075	1.053	4.253	0.600	668
		NR	0.090	1.234	4.272	0.615	671
5	Hatz 1B30	2D	0.633	4.025	5.347	0.510	783
		NR	0.628	4.220	5.126	0.523	758
6	Navistar B250	2D	0.086	0.439	4.358	0.077	582
		NR	0.097	0.408	4.668	0.102	572
7	Cummins QSL9	EC	0.038	1.196	4.093	0.098	478
		2D	0.054	1.176	4.209	0.124	493
8	Deere 6101	CA	0.489	0.800	5.308	0.124	502
		NR	0.486	0.949	5.704	0.192	503
9	DDC Series 60	EC	0.032	0.782	5.847	0.074	462
		CA	0.040	0.787	6.077	0.082	461
10	Caterpillar 3508	2D	0.233	1.189	11.703	0.159	501
		NR	0.363	1.240	12.042	0.215	506

Notes:	2D - Emissions grade Type-2D (390 ppm sulfur) diesel fuel NR - High sulfur (~2,500 ppm) nonroad 2D diesel fuel CA - California low-sulfur (50 ppm sulfur) diesel fuel EC - Arco® "ECD" ultra-low sulfur (~2 ppm) diesel fuel

Nine of the ten engines completed the planned transient cycle emissions testing. Each engine was tested over six different transient cycles. Most engines were tested in triplicate over the selected cycles using two fuels. The two Yanmar engines were tested in duplicate using 2D fuel, and single tests using NR fuel. The Yanmar 2TNE68 engine was not tested over the European transient cycle (ETC). Otherwise, the on-highway FTP and ETC cycles were run for each engine and four nonroad transient application cycles were chosen specifically for testing a given engine. Eight of the ten engines included testing to quantify select unregulated emissions. The two Yanmar engines did not include these measurements, and the Hatz engine did not complete transient testing.

The ten-engine study measured emission levels over the various transient cycles that differ significantly for different size and technology engines. Engines were tested over many of the same transient cycles. Several of the smaller engines included measuring emissions during activities typical of skid steer loader and arc welder duty cycles, whereas several of the larger engines included running cycles based on excavators and a rubber tired loader. Most engines were tested using a low sulfur fuel and a high sulfur fuel. Levels for PM were generally elevated using high sulfur fuels, with negligible performance differences. The Cummins and DDC engines were tested using EC fuel. This ultra low sulfur and higher cetane fuel affected emissions by consistently lowering both NOX and PM levels over all operations.

As expected, all engines from the three engine and four engine in-use test programs generally had elevated PM levels when using the higher sulfur fuel. Composite eight mode, C1-weighted test emission levels were computed for each engine using results obtained on the two diesel test fuels. Duplicate "stacked" tests for the Kubota on each fuel showed good test-to-test emissions repeatability, and compared reasonably well to composite eight mode, C1 PM levels (see Table 6 below).

TABLE 6. Composite Eight Mode Type C-1 Weighted Steady-State Emission Levels for Seven Different Nonroad Engines Using Low and High Sulfur Diesel Fuels.

Test Engine	Fuel ID	Weighted Transient Emissions, g/hp-hr					BSFC, lb/hp-hr
		HC	CO	NO_X	N_2O	PM	
Kubota V2203E (3-engine study)	2D	0.04	0.97	4.13	0.009	0.472	0.447
		0.03	1.07	4.20	0.008	0.438	0.447
		0.04	0.88	3.98	0.009	0.431	0.433
	NR	0.07	1.05	4.05	0.012	0.525	0.438
		0.07	0.99	3.95	0.010	0.548	0.423
		0.07	1.00	4.08	0.020	0.530	0.440
Cummins QSL9 (3-engine study)	2D	0.08	1.19	4.43	0.007	0.118	0.365
	NR	0.08	1.32	4.38	0.026	0.162	0.377
Caterpillar 3408 (3-engine study)	2D	0.02	0.95	4.03	0.004	0.134	0.376

	NR	0.02	0.95	4.03	0.008	0.162	0.359
Deere 6068T	2D	0.37	0.96	10.35	0.006	0.229	0.361
	NR	0.34	1.00	10.51	0.022	0.303	0.359
Cummins M11C	2D	0.27	0.57	6.07	0.004	0.134	0.343
	NR	0.29	0.75	5.99	0.011	0.165	0.342
Caterpillar 3196	2D	0.07	0.83	6.04	0.004	0.076	0.325
	NR	0.06	0.84	5.98	0.012	0.122	0.324
Caterpillar 3408	2D	0.05	0.49	3.85	0.004	0.072	0.375
	NR	0.04	0.48	3.42	0.006	0.112	0.373

Notes: Shaded results are "**stacked**"; time-weighted sampling of 8 steady-state modes
C1 - ISO Type-C1 weighted emissions computed from individual runs of each mode
2D - Emissions grade Type-2D (~500 ppm sulfur) diesel fuel
NR - High sulfur (~2,500 ppm) nonroad 2D diesel fuel

Emission data and cycle performance repeatability were generally good for duplicate transient cycle testing performed on each engine using both fuels. Engines generally ran the different cycles without problems and each was able to pass the cycle control criteria for the FTP cycle. The Kubota V2203E passed the cycle performance criteria over the FTP and BHL transient cycles. In contrast, the Cummins QSL-9 and Caterpillar 3408 had mixed performance over the different cycles, as they passed the FTP on some runs, but sometimes failed to do so in duplicate testing. Table 7 compares emission levels across transient and steady-state tests for these two engines. Cycle control of the Cummins engine passed some runs of the BHL cycle and not others, while cycle control of the Caterpillar engine did not pass the BHL cycle. It should be noted that minimal additional tuning was done after a given engine passed the FTP cycle, so subsequent testing over nonroad cycles used the same engine and dynamometer cycle control strategy established in FTP tuning efforts.

TABLE 7. Comparison of Averaged Regulated Emission Levels for Two Nonroad Engines Over Selected Cycles Using Type-2D Diesel Fuel.

Engine	**Cummins QSL9**				**Caterpillar 3408**			
Cycle	**C1**	**FTP**	**SAT**	**BHL**	**C1**	**FTP**	**SAT**	**BHL**
HC, g/hp-hr	0.08	0.13	0.08	0.19	0.02	0.02	0.02	0.04
CO, g/hp-hr	1.2	2.5	1.6	2.8	1.0	2.4	1.8	3.3
NO_x, g/hp-hr	4.43	4.51	4.00	4.26	4.03	4.06	3.85	5.02
PM, g/hp-hr	0.12	0.17	0.16	0.18	0.14	0.28	0.30	0.45
BSFC, g/hp-hr	0.365	0.365	0.357	0.370	0.376	0.421	0.411	0.435
Ref. Work, hp-hr	na	25.04	44.97	21.17	na	33.80	61.26	25.83

FTP U.S. on-highway transient duty cycle hot-start levels
C1 Steady-state composite weighted ISO Type-C1 values
SAT EPA composite nonroad transient duty cycle hot-start levels
BHL Backhoe loader nonroad transient duty cycle hot-start levels

Unregulated Emission Results

Data summaries give results on both a mass and brake-specific basis. In all cases, the resulting emission levels are shown after correcting for background and diesel exhaust sampling tunnel blank contributions. When an emission result was not quantifiable, or its concentration was quantifiable at a level below the minimum detection limit, null values and/or "nd" were reported as with much of the metals emission results. "Trace" results were reported when an emission level was quantifiable at less than twice the detection limit. Nitrous oxide, sulfate, ammonia and carbonyl emission results are expressed in units of milligrams per brake horsepower hour. Test-to-test variability was good for most compounds, and general trends can be seen in the results for each engine. Sulfate emissions tend to track the sulfur level in the diesel fuel used in testing. Nitrous oxide levels were typically very low, and often approached ambient background levels. PAH and n-PAH emission results were reported on both a concentration and a brake-specific (brake horsepower-hour) basis in micrograms and nanograms, respectively.

DISCUSSION

The emission data from these three nonroad diesel engine emission studies are expected to answer many questions for EPA and its many constituents, but the data appear to carry with them several unanswered questions, as well. The data will help elucidate differences between pre- and post-Tier 1 engines in these test groups and begin to gauge the impacts of fuel composition and sulfur level on nonroad diesel engine emissions. In the arena of air toxic emissions, this group of engines represents one of the larger data sets and the emissions data will be used to better characterize levels of PAHs and n-PAHs, metals, like mercury and lead, and carbonyl compounds in nonroad diesel engines. We will look at the effect of engine duty cycle on engine emissions, as well, with respect to engine displacement and management technologies.

To successfully operate an engine transiently on a dynamometer depends largely on how well that engine responds to changes in fuel flow and keeps up with the demands of the transient duty cycle, which it is following.. This performance over a transient cycle, in statistical regression terms, can then be refined over many practice runs of the same cycle, the refinement process being called a control strategy. In these three test programs, it was decided to run all transient duty cycles using a dynamometer control strategy and engine settings similar to those used for the running of an FTP cycle, except the Deere excavator engine, as noted. In general, engine performance over all transient cycles largely met, or "passed," the established cycle performance criteria from CFR 40 Part 86, Subpart N for testing over the on-highway heavy-duty FTP cycle. However, few of these engines achieved "passing" values over cycle-specific performance criteria for more than one or two of the transient cycles over which they were tested. While engines were not individually "tuned" to run each cycle, the repeatability of engine emissions from multiple FTP, SAT and nonroad transient application duty cycle runs was generally considered good for these nonroad engines.

Preliminary analyses of the nonroad emission dataset from these engines are still in progress, but some trends are emerging from the data. Brake-specific PM emissions seem to track falling sulfur levels for each engine's respective test fuel(s), but as engine displacement and power falls, regardless of fuel, total PM may be rising. Likewise with falling engine displacement and power, there may be a rise in ammonia and N20 exhaust emissions in these engines, though these are generally a small percent of overall diesel engine emissions. On a concentration basis, formaldehyde emission levels seemed to stay "fairly stable," but other aldehyde emissions appeared to increase as engine displacement and power dropped.. The overall effect of different transient cycles on emissions from the same engine was quite varied, suggesting a need for engine work- or cycle-specific emission profiles. Emissions "profiles" for these engines will include VOC emissions ratioed to total

HC and semi-volatile organics ratioed to total PM.

Uses for new nonroad diesel emission dataset are many. Supporting technical analyses for EPA's upcoming Mobile Source Air Toxics Rule will benefit from the data set for nonroad emissions. Improvements can be made in national, nonroad emissions inventories and the models which track those emissions for the air quality community. EPA's National Emission Inventory (NEI) for HAPs can benefit from this new data, as well. In addition, engine profiles can be created using engine duty cycle-specific emission data, for each engine running over a specific duty cycle typical for that engine. Thes profiles could then be integrated into EPA's Nonroad Mobile Inventory Model (NMIM) and the output of the model then used to update future versions of the NEI.

Finally, nonroad diesel emission data will be converted into database, FoxPro® or MS-Access®, as useful, or spreadsheet formats for ease of use by modelers and to facilitate entering data into OTAQ's Mobile Source Observations Database (MSOD).[10] When loaded into EPA's MSOD database, nonroad engine emission data can be made generally available to the public for querying. Hardcopy and electronic forms on CD-ROM disks of nonroad diesel engine emission data will also be made available for distribution to State, Regional and Local air quality managers, as requested. Air managers could use any new nonroad data, in conjunction with the natioal inventories, to tailor state models and inventories to their own situations.

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KEY WORDS

exhaust
emissions
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diesel
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air toxics
MSATs