Exhaust Emission Factors for Nonroad Engine Modeling--Compression-Ignition

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Purpose

This report describes and documents exhaust emission factors used for compression ignition (CI) engines in the U.S. Environmental Protection Agency's (EPA) NONROAD emission inventory model. It covers factors for all diesel-fueled engines. Emission factors for spark ignition engines (including gasoline and natural gas/propane) are covered in a separate report, NR-010. Other EPA reports will describe additional issues relating to emission factors including adjustments to emission rates due to variations in fuel and temperature (NR-001) and adjustments to emission rates as equipment deteriorates with time and use (NR-011).

Introduction

The NONROAD model estimates air pollution from more than 80 types of compression ignition (CI) and spark ignition (SI) nonroad sources including such items as lawnmowers, motorboats, portable generators and construction equipment. By bringing together information on equipment populations, equipment use, and emission factors, the NONROAD model estimates mass emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM) and carbon dioxide (CO_2) for specific states and counties for past and future years, providing a flexible tool that can be applied to a wide variety of air quality modeling and planning functions.

The NONROAD calculations rely on emission factors--estimates of the amount of pollution emitted by a particular type of equipment during a unit of use. Typically emission factors for nonroad sources are reported in grams per horsepower-hour, but they also may be reported in grams per mile, grams per hour, and grams per gallon. The emission factors in the NONROAD model are based on emissions test data, adjusted when necessary to account for the effects of fuel sulfur and in-use operation that differ from the typical test conditions. Emission factors are stored in NONROAD's data input files. Emission changes with the age of the engine, often called 'deterioration,'are described in Report No. NR-011.

Currently EPA is preparing a version of the NONROAD model. A final version of NONROAD is planned for release late in 1998. EPA expects to use the CI emission factors described here in both the and the final version of the model. If comments on this document or other information gathered during stakeholder and peer review cause us to rethink this approach, we will document the changes in a subsequent report.

Background

There is little test data available on nonroad engines. In developing the emission factors for NONROAD we have considered data from various sources.

Previous Inventories

Prior to the NONROAD model, there have been three major efforts to estimate nonroad emission inventories from CI engines. These are:

- EPA's Nonroad Engine and Vehicle Emission Study ("NEVES").[1] Published in November, 1991, this study was mandated by Congress to determine whether nonroad sources made a significant contribution to urban air pollution. It covers HC, CO, NO_x, PM, SO_x and other pollutants. It provides inventories for 19 ozone and 16 CO nonattainment areas.

- California Air Resources Board's (ARB) nonroad model ("OFF-ROAD") [2], designed to estimate nonroad emissions for the state of California only. A version of this model was released in late summer 1997. It covers HC, CO, NO_x, PM, SO_2, and CO_2.

- EPA's "Nonroad Engine Model"-- Designed as an internal tool for analyzing various control scenarios, EPA has used this model primarily to estimate the effect of recently proposed regulations on emissions from compression-ignition (CI) engines over 37 kW (50 hp).[3] The model computes national-level inventories of nonroad diesel HC, NO_x, CO and PM.

All of these models/studies estimate emissions from uncontrolled engines. The California model also includes California emission standards, and the EPA's Nonroad Engine Model includes proposed Federal emission standards. The sources of the emission factors used in these inventories are described in Appendix A. Many of the emission factors are based on data from the 1970s and early 1980s.

New Data

In addition to the data considered in developing previous emission factors, there is a limited amount of new emission test data on newer (post-1988) uncontrolled engines. The post-1988 engines were not designed to meet any new emission regulations, but the test data indicates that emissions from these post-1988 engines (especially hydrocarbons and particulate matter) are lower than the emission factors used in earlier inventories. EPA's review of this data is described in Appendix B.

Emission Standards

In addition to estimating emissions from uncontrolled engines, the NONROAD model is designed to account for the effect of federal emissions standards. NONROAD will not cover California emission standards or proposed federal standards that are not yet final. However, because EPA expects to finalize a set of recently proposed standards for nonroad diesel engines before the release of the final NONROAD model, these proposed standards have been included in the version of the model. Thus, this document describes emission factors under two regulations that establish three tiers of emission standards:

- "Determination of Significance for Nonroad Sources and Emission Standards for New Nonroad Compression Ignition Engines at or above 37 Kilowatts." This rule establishes "Tier 1" standards for CI engines at or above 50 hp (37 kW). [4]

- "Control of Emissions from Nonroad Diesel Engines." This proposed rule lists "Tier 1" and "Tier 2" standards for CI engines below 50 hp, and "Tier 2" and "Tier 3 " standards for engines of 50 hp and greater. [5] " "

Of course, if changes are made to the proposed rule, the final version of the model will reflect those changes. The standards are phased in over a number of years, and NONROAD's emission factors will follow the final schedule implementing the new standards.

The NONROAD emission factors for engines subject to the existing and proposed rules are based on the factors used in the regulatory support documents for the proposed rule, "Draft Regulatory Impact Analysis: Control of Emissions from Nonroad Diesel Engines." However, as explained below, the NONROAD model's emission factors for pre-control engines differ from the RIA in their use of EPA's new data on cleaner post-88 engines.

Steady State Emission Factors--HC, CO, NOx and PM

Nonroad engines are primarily tested with steady-state tests. However, the steady-state operation typically used for emission testing is not always representative of the operation of engines in many nonroad applications. Some of the differences can be due to load or engine speed, and other differences can be due to transient demands. We will apply "in-use adjustment factors" to the emission factors derived from steady state tests. The derivation and application of these factors are described in Appendix C. EPA will create input files for NONROAD by applying in-use adjustment factors to the steady-state emission factors described in this section.

The remainder of this section describes steady-state fuel consumption and emission factors for HC, CO, NO_X and PM. These factors are listed in Table 1. We have used engine model year and horsepower as categories to group NONROAD emission factors. These groupings are consistent with emission standards for CI engines and with emissions test data. Data on pre-controlled engines (see Appendix B) indicates that engines of more than 100 hp have significantly different emission characteristics than engines under 100 hp. Perhaps for future versions of NONROAD, emission factors may be distinguished by technologies such as turbo-charging, fuel metering pumps, and cylinder size; however, there is not enough emissions data at present to support such distinctions in NONROAD emission factors.

Fuel sulfur levels affect PM emissions. NONROAD users can adjust for local fuel sulfur levels, but the model has a default diesel fuel sulfur level of 0.33 mass percent, the national average for nonroad diesel [6], and the emission factors in NONROAD's input files are intended to be consistent with the default fuel sulfur level. Where emission tests were known to have been performed with fuels with other sulfur contents the test results have been adjusted as described in Appendix B.

Due to lack of data, the brake-specific fuel consumption (BSFC) for the 1988-and-later uncontrolled engines is used for all engines, both earlier uncontrolled engines and later engines subject to emissions standards. While it is likely that fuel consumption varies between these categories, there is not sufficient data available at this time for EPA to specify alternate values.

Pre-1988, Engines < =50 hp:

There are no known tests of pre-1988 CI engines of less than 50 hp. Thus NONROAD will use the same emission factors as for the 1988 through Tier 1 years for engines of this size described below.

Pre-1988, Engines > 50 hp:

For pre-1988 CI engines of 50 hp or greater, NONROAD's steady-state emission factors are based on the emission factors used in NEVES. These vary by application. However, NEVES includes an adjustment for in-use operation. Since NONROAD uses a different in-use adjustment factor than NEVES (see Appendix C), the NEVES adjustment is removed to determine pre-1988 average steady-state emissions.

Because the testing fuel is generally unknown, we assume that the NEVES PM factors are appropriate for the default fuel sulfur content of 0.33 wt.% sulfur used in NONROAD.

A conversion from gram per gallon to gram per horsepower-hr was made to NEVES emission rates for the greater than 50 horsepower engines for the diesel recreational marine categories; inboard, outboard, and sailboat auxiliary. Outboard and sailboat auxiliary engines above 50 hp were converted from the NEVES gram per gallon to gram per horsepower using the higher fuel consumption of 0.408 lbs/hp-hr and 7.1 lbs/gallon fuel density because these engines are primarily less than 100 hp. The NEVES emission rate for inboard engines was converted using the lower fuel consumption rate of 0.367 lbs/hp-hr because these engines are primarily above 100 horsepower.

1988 to Tier 1, Engines <= 50 hp:

For 1988-and-later pre-control engines less than or equal to 50 hp, we will use the emission factors described in the documentation for ARB's OFF-ROAD model. [2] We have combined the direct injection and indirect injection factors using the technology fractions listed in the EPA's Regulatory Impact Analysis (RIA) for the proposed new emission standards. [5] Again, because the sulfur content of fuels used in generating these emission factors is unknown, we have assumed that the PM emission factors are appropriate for default fuel sulfur of 0.33% sulfur.

1988 to Tier 1, Engines > 50 hp:

Recent studies have indicated that, in general, emission rates from 1988-and-later pre-control engines of greater than 50 hp are lower than the rates used in NEVES, necessitating a revision to the NEVES emission factors.

For these engines we will use emission factors calculated from recent studies. These studies are described in detail in Appendix B. As explained in Appendix B, a correction for fuel sulfur content is applied.

Tier 1, Engines < =25 hp

The NONROAD model's emission factors for Tier 1 <25 hp are based on data from ARB, which already regulates engines <25 hp. EPA expects engines meeting federal Tier 1 standards to employ similar technology and emit at similar levels. As described in the RIA, EPA weighted the California data using the national fractions of direct and indirect injection engines for this size category. [5]

HC and NO_x -- California certification data was used to split the combined $HC+NO_x$ standard into single pollutant emission factors.
CO -- California certification data was used.
PM -- Emission factors for PM are estimated to be the Tier 1 standard for PM. We assume that engines will meet the standard on default sulfur fuel.

Tier 1, Engines 25-50 hp

Data is not available on engines meeting this proposed standard. As in the RIA, emission factors were estimated based on California data on smaller engines, but weighted to reflect the estimated national fractions of direct and indirect injection engines for this size category . [5]

HC and NO_x -- California certification data for engines 11-25 hp was used to split the combined HC-NO_x standard into single pollutant emission factors.
CO -- California certification data for engines 11-25 hp was used.
PM -- Emission factors for PM are estimated to be the Tier 1 standard for PM. We assume that engines will meet the standard on default sulfur fuel.

<u>Tier 1, Engines 50-175 hp</u>

EPA has limited Tier 1 certification data on Tier 1 engines 50-175 hp.

NOx--EPA estimates that Tier 1 NO_x emissions are at the Tier 1 standard.
HC and CO--Emission factors are estimated using EPA's Tier 1 certification data.
PM--Because no emission standard was promulgated for Tier 1, PM emissions for pre-control, 1988-and-later engines were used.

<u>Tier 1, Engines >175 hp</u>

EPA has limited Tier 1 certification data on Tier 1 engines > 175 hp.

NOx--EPA estimates that Tier 1 NO_x emissions are at the Tier 1 standard.
HC and CO--Emission factors are estimated using EPA's Tier 1 certification data.
PM--Because pre-Tier 1 PM emissions were below the Tier 1 standard (when the standard was adjusted for fuel sulfur), we have assumed that Tier 1 PM emissions are at the same PM levels as pre-control, 1988-and-later engines.

<u>Tier 2, Engines < =50 hp</u>

Data is not available on engines meeting this proposed standard. Emission factors were estimated as in the RIA based on ARB data.

HC and NOx--As in the RIA, EPA assumes minimum HC emissions of 0.6 g/hp-hr (0.8 g/kW-hr) based on ARB data on indirect injection (IDI) engines under 25 hp (19 kW). EPA used this value to split the combined HC+NOx standard into single pollutant emission factors.
CO--The same as under Tier 1.
PM–Because of uncertainties in PM emissions, NONROAD does not estimate a reduced PM emission rate from the Tier 1 level at this time. EPA will continue to evaluate this emission rate based on available data.

<u>Tier 2, Engines > 50 hp</u>

Data is not available on engines meeting this proposed standard.

NOx and HC--As in the RIA, NONROAD uses the proposed European NOx standard to split the Tier 2 combined HC+NOx standard into single pollutant emission factors.
CO-- The same as under Tier 1.
PM–Because of uncertainties in PM emissions, NONROAD does not estimate a reduced

PM emission rate from the Tier 1 level at this time. EPA will continue to evaluate this emission rate estimate based on available data.

Tier 3

The proposed Tier 3 standard applies only to engines greater than 50 hp and less than or equal to 750 hp. Data is not available on engines meeting this proposed standard.

NOx and HC--For Tier 3 HC and NO_x, NONROAD follows the RIA in using engineering judgement to assume minimum HC emissions of 0.2 g/hp-hr. This rate is then subtracted from the combined HC+NOx standard to split the standard into single-pollutant emission factors.

CO–We estimate at this time that CO will be the same as Tier 1.

PM–EPA has not yet established the Tier 3 PM standards. Therefore, we are estimating the same credit as Tier 2.

Table 1--Steady-State Emission Factors* for CI Engines in the NONROAD Model

Engine Power (hp)	Model Year	Regulation	BSFC (lb/hp-hr)	Emission Factors (g/hp-hr)			
				HC	CO	NO_x	PM
>0 to 11	pre-88	--	0.408**	1.5	5.0	10.0	1.0
	88-99	--		1.5	5.0	10.0	1.0
	00-04	Tier 1		1.6	5.6	5.9	0.75
	05-	Tier 2		0.6	5.6	5.0	0.75
>11 to 16	pre-88	--	0.408**	1.5	5.0	10.0	1.0
	88-99	--		1.5	5.0	10.0	1.0
	00-04	Tier 1		0.7	2.0	5.2	0.6
	05-	Tier 2		0.6	2.0	5.0	0.6
>16 to 25	pre-88	--	0.408**	1.8	5.0	6.9	0.8
	88-99	--		1.8	5.0	6.9	0.8
	00-04	Tier 1		0.7	2.0	5.2	0.6
	05-	Tier 2		0.6	2.0	5.0	0.6
>25 to 50	pre-88	--	0.408**	1.8	5.0	6.9	0.8
	88-98	--		1.8	5.0	6.9	0.8
	99-03	Tier 1		0.8	2.5	5.5	0.6
	04-	Tier 2		0.6	2.5	5.0	0.6
>50 to 100	pre-88	--	0.408	Vary by application, see NEVES			
	88-97	--		0.99	3.49	8.30	0.72
	98-03	Tier 1		0.7	1.0	6.9	0.72
	04-07	Tier 2		0.4	1.0	5.2	0.72
	08-	Tier 3		0.2	1.0	3.3	Same as Tier 2
>100 to 175	pre-88	--	0.367	Vary by application, see NEVES			
	88-96	--		0.68	2.70	8.38	0.40
	97-02	Tier 1		0.4	1.0	6.9	0.40
	03-06	Tier 2		0.4	1.0	4.5	0.40
	07-	Tier 3		0.2	1.0	2.8	Same as Tier 2

Table 1, continued.

Engine Power (hp)	Model Year	Regulation	BSFC (lb/hp-hr)	Emission Factors (g/hp-hr)			
				HC	CO	NO_x	PM
>175 to 300	pre-88			Vary by application, see NEVES			
	88-95			0.68	2.70	8.38	0.40
	96-02	Tier 1		0.4	1.0	6.9	0.40
	03-05	Tier 2		0.4	1.0	4.5	0.40
	06-	Tier 3		0.2	1.0	2.8	Same as Tier 2
>300 to 600	pre-88	--	0.367	Vary by application, see NEVES			
	88-95	--		0.68	2.70	8.38	0.40
	96-00	Tier 1		0.3	1.0	6.9	0.40
	01-05	Tier 2		0.3	1.0	4.5	0.40
	06-	Tier 3		0.2	1.0	2.8	Same as Tier 2
>600 to 750	pre-88	--	0.367	Vary by application, see NEVES			
	88-95	--		0.68	2.70	8.38	0.40
	96-01	Tier 1		0.3	1.0	6.9	0.40
	02-05	Tier 2		0.3	1.0	4.5	0.40
	06-	Tier 3		0.2	1.0	2.8	Same as Tier 2
>750	pre-88	--	0.367	Vary by application, see NEVES			
	88-99	--		0.68	2.70	8.38	0.40
	00-05	Tier 1		0.3	1.0	6.9	0.40
	06-	Tier 2		0.3	1.0	4.5	0.40

*Prior to listing in NONROAD input files, these ISO-C1 emission factors are adjusted for in-use operation as explained in Appendix C.

**BSFC for engines <50 hp is assumed to be the same as 50-100 hp engines

Emission Factors--CO_2 and SO_2

Emission factors for CO_2 and SO_2 are rarely measured, instead they typically are calculated based on brake-specific fuel consumption (BSFC).

The NONROAD model uses in-use adjusted BSFC to compute CO_2 emissions directly. BSFC and engine activity provides the means to estimate the tons of fuel consumed. We assumed that all of the carbon in the fuel is converted to CO_2. The average carbon fraction of the fuel is estimated to be 87%. This does not require a CO_2 emission factors input file.

The model does not require an SO_2 emission factors input file either. EPA will calculate SO_2 emission factor as shown in the equation below.

$$SO_2 = (BSFC * 453.6 * (1 - 0.022) - HC) * 0.0033 * 2$$

where

SO_2 is in g/hp-hr
BSFC is the in-use adjusted fuel consumption in lb/hp-hr
453.6 is the conversion factor from pounds to grams
1-0.022 is an adjustment for sulfur converted to direct PM
HC is the in-use adjusted hydrocarbon emissions in g/hp-hr
0.0033 is the default wt. fraction of sulfur in nonroad diesel fuel
2 is the grams of SO_2 formed from a gram of sulfur

This equation includes corrections for the fraction of sulfur that is converted to direct PM and for the fraction of sulfur remaining in unburned fuel. The direct PM correction factor (0.022) was calculated by assuming that the direct sulfur PM is H2SO4:7H20 (sulfuric acid hydrated seven times) and converting the direct sulfur PM (described in Appendix B) to a molar fraction of sulfur which is subtracted from the fuel consumption. We also assume that the unburned fuel, as indicated by HC emissions, has the same sulfur level as the base fuel.

References

[1] EPA, “Nonroad Engine and Vehicle Emission Study” (NEVES), U.S. EPA, Office of Air and Radiation, 21A-2001. November, 1991.

[2] EEA, “Documentation of Input Factors for the New Off-Road Mobile Source Emissions Inventory Model,” (“Inputs...”) Energy and Environmental Analysis, Inc. for California Air Resources Board. February, 1997.

[3] Caffrey, P., “Memorandum: Operation of the Nonroad Emissions Model” from Peter Caffrey, U.S. EPA Office of Mobile Sources, Engine Programs and Compliance Division, to the Docket A96-40, Draft 6/13/97.

[4] 59 FR 31306, June 17 1994.

[5]   EPA, "Draft Regulatory Impact Analysis: Control of Emissions from Nonroad Diesel Engines." U.S. EPA Office of Mobile Sources, Engine Programs and Compliance Division. August 1997.

[6] Korotney, David. "Estimates for In-Use Nonroad Diesel Fuel Levels," Memorandum to Docket A-96-40. July 1, 1997.

Appendix A
Sources of Previous Emission Factors for
Nonroad Compression Ignition Engines

There is little test data available on nonroad engines. Table A1 lists the data sources used for EPA's Nonroad Engine and Vehicle Study's (NEVES) diesel emission factors. These factors were also used for EPA's internal Nonroad Emission Model. Table A2 lists the data sources used for California's Air Resources Board (ARB) OFF-ROAD diesel emission factors. The studies listed in the tables are described below.

Table A1--Data sources for NEVES Diesel Emission Factors

Application	Emissions Test Data Source	Notes
Lawn and Garden and Light Commercial	None	NEVES emission factors were based on factors for "continuous service diesel < 50 hp" SwRI, 1991, which are based on Radian, 1988 factors for truck/container refrigeration units.
Agriculture	Cal/ERT, 1982	
Construction	EMA SwRI, 1973 Cal/ERT, 1982	NEVES emission factors were based on EMA when possible. For PM and for applications not available from EMA, factors were taken from AP-42, which relies on Cal/ERT for most emission factors and on SwRI, 1973 for PM and SOx.
Logging (skidders)	EMA	
Industrial and Airport Service Equipment	SwRI, 1973	
Recreational Marine (Inboard)	NMMA	

Table A2--Data sources for ARB Diesel Emission Factors

Horsepower Class	Emissions Test Data Source	Notes
0-15 hp	Manufacturers' data-- 2 Yanmar engines 1 Deutz engine	
15-25 hp	Manufacturers (ARB Off-Road Equipment Study, 1990)	
25-50 hp	Manufacturers Submissions (ARB Off-Road Equipment Study, 1990)	
50-125 hp	Manufacturers (CA HD Construction Study, 1988)	
125-250 250+	Manufacturers (CA HD Construction Study, 1988)	ARB factors on all engines from 125 hp and above are based on the same data, but the weighting between turbo-charged and naturally aspirated engines is different in the two horsepower categories listed here.

Description and Citations of Sources used for Previous Emission Factors

Radian, 1988. Radian's estimates of HC, CO, NOx and PM for truck/container refrigeration units are not based on testing, but on Radian's estimates for "typical small direct injection and indirect injection diesel engines." (Weaver, C.S., "Feasibility and Cost Effectiveness of Controlling Emissions from Diesel Engines in Rail, Marine, Construction, Farm and Other Mobile Off-Highway Equipment." Final Report by Radian Corporation for U.S. EPA, Office of Policy Analysis, under contract 68-01-7288, February, 1988.)

SwRI, 1973. Southwest Research Institute tested 8 diesel engines for HC, CO, NOx and PM. Emissions of SOx were calculated for no. 2 diesel fuel assuming sulfur content of 0.22%. BSFC is not stated. The emissions tests were given different weightings to estimate industrial, construction and farm equipment emission factors. (Hare, C.T and K.J. Springer. Exhaust Emission from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines, Final Report, Part 5, Heavy Duty Farm, Construction and Agricultural Engines. San Antonio TX: Southwest Research Institute, October 1973.)

EMA. Emission factors for 17 applications based on unknown number of tests, unknown horsepower engines. Engine vintage unknown, but data was submitted by the Engine Manufacturers Association to EPA prior to NEVES (1991). (Listed in NEVES table I-06.)

Cal/ERT, 1982. Data from 13 engine manufacturers representing 391 models of construction equipment. Raw data was aggregated by an accounting firm prior to analysis and reporting. (Environmental Research and Technology, Inc. "Feasibility, Cost and Air Quality Impact of Potential Emission Control Requirements on Farm, Construction and Industrial Equipment in California", Document PA841, sponsored by the Farm and Industrial Equipment Institute, Engine Manufacturers Association, and Construction Industry Manufacturers Association, May 1982.)

NMMA. The National Marine Manufacturers Association submitted data to EPA on HC, CO, NOx and BSFC for 3 diesel inboard motors. Engine vintage unknown, but data was submitted to EPA prior to NEVES (1991). (NEVES, Table I-11(e).)

ARB Off-Road Study, 1990. A study of lawn and garden and utility emissions. (Manufacturer Submissions to ARB on Exhaust Emission Standards for Utility and Lawn and Garden Equipment Engines. California ARB, October 1990. EPA requests assistance in locating this study)

ARB Heavy Duty Construction Study, 1988.[1] Reports HC, NOx and PM emission factors based on emission information from four manufacturers. Does not include information on test programs. It is not clear how data collected in the study was used to create the inputs for the ARB model. (Energy and Environment Analysis, Inc. " Feasibility of Controlling Emissions from Off-Road, Heavy-Duty Construction Equipment." Final Report to the California Air Resources Board. Arlington, VA, December 1988.)

Appendix B
1988-1995 Steady-State Emission Factors and Fuel Sulfur Adjustment for Nonroad Compression Ignition Engines

Introduction

EPA's 1991 Nonroad Engine and Vehicle Emission Study (NEVES) (1) used emission factors for diesel engines based primarily on tests of older engines. All the NEVES particulate matter (PM) emission factors are from tests conducted in 1972 and many of the other emissions factors in NEVES are based on data from tests prior to 1982.

To better characterize emissions from more recent, pre-controlled engines, EPA analyzed available emission test data on 1988-1995 nonroad diesel engines. This analysis provides the basis for NONROAD emission factors for 1988-and-later engines greater than 50 hp, as described in the main body of this report. The analysis indicated a significant difference in emissions based on engine power. Engines between 50 and 100 horsepower in general had higher emissions and fuel consumption than engines larger than 100 horsepower. Table B1 summarizes these results.

Table B1-- Average Emission Test Results for 1988 to 1995 Model Year Engines

Engine (Reference)	HC (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)	BSFC (lb/hp-hr)
Average (50 to 100 hp)	0.99	3.49	8.30	0.722	0.408
Average (>=100 hp)	0.68	2.70	8.38	0.402	0.367

A summary of test results for individual engines is presented in Table B2. Note that testing was conducted using the current certification test procedure, also known as ISO-C1. The procedure uses eight steady-state modes weighted by time to produce one number in units such as grams per horsepower-hour. EPA adjusted this test data to account for differences between the test fuel and typical in-use fuel sulfur levels of 0.33 wt. percent as explained below.

Table B2--Summary of ISO-C1 Emission Results for 1988 through 1995 Engines

Engine (Reference)	Model Year	Age (Hrs)	Fuel Sulfur (wt. %)	Power Level (hp)	HC (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)	BSFC (lb/hp-hr)
Ford New Holland (2)	1991	0	0.26	127	1.02	7.70	7.48	1.10	0.358
John Deere 7068T (2)	1990	0	0.26	139	0.45	2.98	11.74	0.41	0.349
Volvo TD 71G (avg. of 2) (3)	1984	0	0.046	144	0.47	1.64	12.68	0.149	0.373
Volvo TD73 KBE (avg. of 2) (3)	1992	0	0.046	139	0.64	0.85	4.52	0.12	0.386
Weterbeke 32BEDA (4)	1995	0	0.033	95	1.95	7.43	7.99	1.50	0.484
Caterpillar 3176B (4)	1995	0	0.033	451	0.09	2.94	6.37	0.213	0.358
Cummins KTA19-M3 (4)	1995	0	0.033	599	0.68	3.26	8.78	0.257	0.359
Caterpillar 3306 (Nonroad) (5)	1990	0	0.26	285	1.1	1.4	6.5	0.18	0.354
Cummins 4BT (Nonroad) (5)	1990	0	0.26	100	0.8	2.1	11	0.39	0.365
John Deere 4039D (6)	1991	0	0.25	72	0.6	3.5	7.2	0.59	0.385
Caterpillar 3116 (7)	1991	2,511	0.28	201	0.07	2.51	9.38	0.406	0.352
			0.035					0.350	
Caterpillar 3054 (7)	1991	1,964	0.28	85	0.66	1.00	7.53	0.387	0.393
			0.035					0.340	
John Deere 4039 (7)	1994	2,265	0.28	86	0.41	2.17	11.22	0.384	0.389
			0.035					0.256	
John Deere 7076 (7)	1993	3,300	0.28	174	0.53	2.05	10.22	0.250	0.385
			0.035					0.205	

(table continued from previous page)

Consolidated Diesel 6TA-830 (7)	1990	4,370	0.28	226	0.86	1.50	6.53	0.397	0.365
			0.035					0.338	
John Deere 6619 (7)	1993	4,970	0.28	275	0.82	4.69	7.29	0.662	0.397
			0.035					0.556	
Consolidated Diesel 4039 (7)	1988	3,570	0.28	71	1.32	3.37	7.57	0.581	0.389
			0.035					0.484	
Caterpillar 3306 (7)	1990	6,700	0.28	278	1.27	1.46	6.52	0.248	0.373
			0.035					0.245	
Average (50 to 100 hp)			**0.33**		**0.99**	**3.49**	**8.30**	**0.722***	**0.408**
Average (>=100 hp)			**0.33**		**0.68**	**2.70**	**8.38**	**0.402***	**0.367**

* Adjusted to the national average fuel sulfur level of 0.33 weight percent

<u>Fuel Sulfur Adjustment</u>

PM emissions from diesel engines are highly dependent on the sulfur content of the fuel the engine is burning. PM emissions from diesel engines are generally comprised of unburned or partially burned fuel, engine oil, and sulfur compounds. When the engine burns fuel, the fuel sulfur is oxidized to both sulfur dioxide and sulfur trioxide. The sulfur trioxide rapidly absorbs water to form hydrated sulfuric acid which condenses and is collected on filters as particulate matter (PM) during emission testing.

Because the sulfur content of diesel fuel can vary considerably, it is important to account for fuel sulfur in establishing emission factors for PM. To adjust emission test data to the default sulfur level used in NONROAD (0.33 wt. percent), EPA followed the approach described below.

EPA measured particulate emissions from nine nonroad diesel engines using fuel with two different sulfur levels, a typical highway diesel fuel at a sulfur level of 0.035 weight percent and a typical nonroad diesel fuel doped to a sulfur level of 0.28 weight percent to simulate more closely the average nonroad diesel fuel sulfur level of 0.33 weight percent. Most data from this study is listed in Table B2, above. In addition, the study included a 1997 John Deere nonroad engine. This engine is not shown in Table B2 because it certified for the Tier 1 emission regulations and should not be used to determine an overall emission factor for pre-controlled engines. Its PM emissions for high and low sulfur levels were 0.186 and 0.129 g/hp-hr, respectively, with an average fuel consumption of 0.350 lb/hp-hr. (7) Test results from this study (including all 9 engines tested) were used to determine the emission adjustment associated with fuel sulfur level. Other fuel parameter differences such as cetane and fuel distillation that might also have affected particulate emissions were ignored for this analysis.

The study found that emissions of all pollutants were reduced by using highway fuel as compared to the nonroad fuel; however, only the average PM reduction was statistically significant at the 90% confidence level.

The particulate sulfur emission rate should be proportional to the fuel consumption and the fuel sulfur level. By dividing the difference in particulate emissions by the fuel consumption, EPA calculated the average effect of fuel sulfur levels for the nine engines. This analysis provided the constant "A" in the equation below, which describes the relationship between particulate emissions and fuel sulfur content, with the national average sulfur level of 0.33 weight percent (8) as the default sulfur level.

*PMBase = PM + BSFC * A * (0.0033 - Fuel Sulfur)*

where

PMBase = PM emissions with default fuel, in g/hp-hr
PM = PM emissions with test fuel, in g/hp-hr
BSFC = Brake Specific Fuel Consumption in g/hp-hr
A = 0.157 g PM/hp-hr/Weight Fraction sulfur/BSFC
0.0033= the default weight fraction of fuel sulfur for nonroad diesel
Fuel Sulfur = Weight Fraction of sulfur in test fuel

EPA then used this equation for all tests listed in Table B2 to correct PM emissions from the test-fuel sulfur level to a fuel sulfur level of 0.33 wt.% before computing the averages listed in Table B1 and at the bottom of Table B2.

References

(1)"Nonroad Engine and Vehicle Emission Study" (NEVES), U.S. EPA, Office of Air and Radiation, 21A-2001. November, 1991.

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(4) Carroll, J.N. and C. M. Urban. "Emission Testing of Nonroad Compression Ignition Engines." Draft Final Report. Southwest Research Institute, 6886-802. September 1995.

(5) Fritz, S. G., "Dynamometer Testing of Heavy-Duty Diesel Engines to Support Non-Road Regulations," SwRI Report No. 08-3426-010, Work Assignment 0-10 of EPA Contract No. 68-C0-0014 (September 1991).

(6) Smith, Michael. "Dynamometer Testing of Nonroad Diesel Engines to Support Nonroad Regulations." Southwest Research Institute, 08-4855-150, EPA Docket A-91-24, June 1992.

(7) Fritz, S. G., "Emission Factors for Compression Ignition Nonroad Engines Operated on Number 2 Highway and Nonroad Diesel Fuel," Southwest Research Institute. EPA contract # 68-C5-0077, SwRI 08-7601-822. Report expected 1998.

(8) Korotney, David. "Estimates for In-Use Nonroad Diesel Fuel Levels," Memorandum to Docket A-96-40. July 1, 1997.

Appendix C
Adjustment for In-Use Operation of
Nonroad Compression Ignition Engines

Nonroad engines often operate under conditions unlike that of the steady-state ISO-C1 testing procedure typically used in emissions testing. This alternate operation can cause a change in the emission characteristics of nonroad compression ignition (CI) engines. As in NEVES, the NONROAD model accounts for in-use operation in CI engines by applying an adjustment to emission factors generated using the ISO-C1 tests. Unlike NEVES, the NONROAD model uses in-use adjustment factors derived from emission testing designed to represent operational behavior of nonroad equipment. Note that the in-use adjustments are not applied by the NONROAD model, but are applied by EPA during the creation of the NONROAD emission factor input files.

Development of In-Use Adjustment Factors

In NEVES, EPA adjusted the ISO-C1-derived emission factor data available at the time to account for in-use operation by applying a set of multipliers. These factors were derived from a comparison of only a few engines tested with both the ISO-C1 test procedure and the highway Federal Test Procedure (FTP). (1) These factors shown in Table C1 were applied in NEVES only to engines used in applications judged to be sufficiently transient in nature.

Table C1 NEVES Test Cycle Adjustment from ISO-C1 Emission Factors

	HC	CO	NOx	PM
NEVES Adjustment	1.4	2.0	1	1.6

The NEVES adjustment was derived from tests of engines operating on steady-state cycles and the Federal Test Procedure for highway heavy-duty engines. However, the highway test procedure may not simulate engine behavior when used in nonroad applications. Therefore, a joint EMA\EPA project was initiated to develop more realistic test cycles for nonroad engine emissions characterization. The project developed cycles to represent typical operation of an agricultural tractor, a crawler dozer, and a backhoe\loader. (2) The cycles were developed from data acquired from instrumenting one piece of each type of equipment. This data was used to construct appropriate test cycles from statistical criteria developed by EMA and EPA. Southwest Research Institute (SwRI) then tested nine late-model nonroad engines using the steady-state ISO-C1 certification procedure and the three nonroad test cycles. (3) These test results average to the adjustment factors shown in Table C2.

Table C2 In-use Adjustment Factor (Ratio of Application Test Cycle to Steady-State ISO-C1 Emissions)

Test Cycle	HC	CO	NOx	PM	BSFC
Agricultural Tractor	0.89	0.42	0.99	0.64	0.98
Backhoe\Loader	2.19	2.31	1.03	2.04	1.18
Crawler Dozer	0.93	1.27	0.99	1.21	0.98

Table C3 lists summarizes the cycle specific results for individual engines. Individual engine steady-state results are listed in Table B2 of Appendix B with the exception of the John Deere 6101. The ISO-C1 results for the John Deere 6101 were 0.47 g/hp-hr for HC, 0.86 for CO, 5.55 for NOx, 0.186 for PM, and 0.350 lb/hp-hr for BSFC. The John Deere 6101 engine was not included in Appendix B because it was designed for and meets the Tier 1 emission standard. Therefore the average ISO-C1 results shown in Table C1 are lower than the average given in Appendix B, Table B2.

Table C3 Summary of the Emission Results of Various Nonroad Test Cycles

Engine	Test Cycle	HC (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)	BSFC (lb/hp-hr)
Caterpillar 3116 (3)	Ag. Tract.	0.04	0.75	9.40	0.280	0.357
	Backhoe	0.36	7.47	9.46	0.652	0.411
	Dozer	0.09	7.30	8.70	0.713	0.362
Caterpillar 3054 (3)	Ag. Tract.	0.46	0.47	9.46	0.263	0.377
	Backhoe	1.22	3.34	5.45	0.759	0.446
	Dozer	0.51	1.06	8.28	0.384	0.372
John Deere 4039 (3)	Ag. Tract.	0.20	0.56	11.70	0.173	0.361
	Backhoe	1.00	2.62	9.57	0.447	0.471
	Dozer	0.33	1.42	11.70	0.254	0.372
John Deere 7076 (3)	Ag. Tract.	0.54	0.57	9.45	0.168	0.366
	Backhoe	1.13	4.82	14.35	0.522	0.493
	Dozer	0.52	2.22	10.14	0.303	0.370
Consolidated Diesel 6TA-830 (3)	Ag. Tract.	0.90	1.07	5.62	0.304	0.377
	Backhoe	2.08	9.86	6.69	1.698	0.438
	Dozer	0.83	3.76	6.06	0.805	0.370
John Deere 6619 (3)	Ag. Tract.	0.87	1.16	6.77	0.283	0.400
	Backhoe	1.99	6.89	8.29	1.102	0.466
	Dozer	0.80	3.31	7.01	0.698	0.398
Consolidated Diesel 4039 (3)	Ag. Tract.	0.86	2.50	7.28	0.430	0.367
	Backhoe	2.89	3.31	6.52	0.725	0.436
	Dozer	1.22	2.10	7.40	0.413	0.364
Caterpillar 3306 (3)	Ag. Tract.	1.33	0.82	6.46	0.201	0.372
	Backhoe	2.30	5.14	7.22	0.813	0.415
	Dozer	1.16	2.70	6.54	0.436	0.370
John Deere 6101 (3)	Ag. Tract.	0.50	0.32	4.93	0.125	0.362
	Backhoe	1.07	1.92	6.36	0.430	0.434
	Dozer	0.51	1.17	5.25	0.246	0.362
Average	**Ag. Tractor**	**0.63**	**0.91**	**7.90**	**0.247**	**0.371**
	Backhoe	**1.56**	**5.04**	**8.21**	**0.794**	**0.446**
	Dozer	**0.66**	**2.77**	**7.88**	**0.473**	**0.371**
	ISO-C1	**0.71**	**2.18**	**7.98**	**0.389**	**0.377**

Because the in-use adjustment factors used in NEVES were based on limited testing and unrepresentative test procedures, EPA plans to replace in them NONROAD with the more representative factors shown in Table C2. These factors will be continually evaluated and improved, but, because of the need to produce a working version of NONROAD, EPA is including the above SwRI-derived factors in the version as the best available estimation. EPA is aware that some of these factors are quite different than those used in NEVES and will have a large impact on the corresponding emission inventories. Users of this version of NONROAD should note that these factors, and the list of applications to which the factors are applied, may change in later releases. EPA may reconsider the in-use adjustment factors due to comments received during testing and peer review or due to the following issues and activities planned by EPA:

- Generation of additional in-use test cycles and engine testing on these cycles
- Evaluation of technology effects on adjustment factors
- Contribution of load factor differences to the SwRI-derived adjustment factors
- Representativeness of engine\equipment model and work activity used to generate the data upon which the nonroad cycles were generated
- Appropriateness of statistical criteria (such as time in mode weighting factors) used to generate the backhoe\loader, crawler dozer, and agricultural tractor cycles

EPA also plans to continue investigating the effects of in-use behavior which may change the understanding of the correction from the ISO-C1 steady-state test results. This continuing evaluation may prompt EPA to revise the emission factors used in NONROAD as part of a new release of the model. EPA is interested in comments about the approach outlined here.

Applying In-use Adjustment Factors

To apply the in-use adjustment factors listed in Table C2 to the entire CI equipment population, EPA matched nonroad applications with the test cycle that most closely represents the nonroad activity for the application. Table C4 lists the nonroad application used in the NONROAD model and the in-use adjustment most representative of that application. If steady-state operation is typical of an application no adjustment was made, and the cycle adjustment is listed as ‘none’. Some applications have no diesel engines, and therefore an adjustment is not applicable and is indicated by ‘N\A’.

The steady-state emission factors listed in the main body of this report were then multiplied by the appropriate in-use adjustment factor to create NONROAD’s emission factor inputs for CI engines.

Table C4 Diesel Engines, In-Use Emission Factor Adjustment by Application Category

SCC	SCC Description	Cycle Adjustment
2270000000	All Diesel Off-Highway Vehicle: Total	
2270001000	Recreational Vehicles Total	

(table continued from previous page)

2270001010	Recreational Vehicles Motorcycles: Off-Road	N\A
2270001020	Recreational Vehicles Snowmobiles	N\A
2270001030	Recreational Vehicles All Terrain Vehicles	N\A
2270001040	Recreational Vehicles Minibikes	N\A
2270001050	Recreational Vehicles Golf Carts	N\A
2270001060	Recreational Vehicles Speciality Vehicle Carts	Backhoe
2270002000	Construction Equipment Total	
2270002003	Construction Equipment Pavers	Dozer
2270002006	Construction Equipment Tampers/Rammers	N\A
2270002009	Construction Equipment Plate Compactors	Backhoe
2270002012	Construction Equipment Concrete Pavers	Unused SCC
2270002015	Construction Equipment Rollers	Dozer
2270002018	Construction Equipment Scrapers	Dozer
2270002021	Construction Equipment Paving Equipment	Dozer
2270002024	Construction Equipment Surfacing Equipment	Dozer
2270002027	Construction Equipment Signal Boards	None
2270002030	Construction Equipment Trenchers	Backhoe
2270002033	Construction Equipment Bore/Drill Rigs	Dozer
2270002036	Construction Equipment Excavators	Backhoe
2270002039	Construction Equipment Concrete/Industrial Saws	Dozer
2270002042	Construction Equipment Cement & Mortar Mixers	None
2270002045	Construction Equipment Cranes	Dozer
2270002048	Construction Equipment Graders	Dozer
2270002051	Construction Equipment Off-highway Trucks	Backhoe
2270002054	Construction Equipment Crushing/Proc. Equipment	Dozer
2270002057	Construction Equipment Rough Terrain Forklifts	Backhoe
2270002060	Construction Equipment Rubber Tire Loaders	Backhoe
2270002063	Construction Equipment Rubber Tire Dozers	Dozer
2270002066	Construction Equipment Tractors/Loaders/Backhoes	Backhoe
2270002069	Construction Equipment Crawler Dozer	Dozer
2270002072	Construction Equipment Skid Steer Loaders	Backhoe
2270002075	Construction Equipment Off-Highway Tractors	Backhoe
2270002078	Construction Equipment Dumpers/Tenders	Backhoe
2270002081	Construction Equipment Other Construction Equipment	Dozer
2270003000	Industrial Equipment Total	
2270003010	Industrial Equipment Aerial Lifts	Dozer
2270003020	Industrial Equipment Forklifts	Backhoe
2270003030	Industrial Equipment Sweepers/Scrubbers	Ag. Tractor
2270003040	Industrial Equipment Other General Industrial Equipment	None
2270003050	Industrial Equipment Other Material Handling Equipment	Backhoe
2270003060	Industrial Equipment AC\Refrigeration	None
2270004000	Lawn & Garden Equipment Total	
2270004010	Lawn & Garden Equipment Lawn mowers (Residential)	N\A
2270004011	Lawn & Garden Equipment Lawn mowers (Commercial)	N\A
2270004015	Lawn & Garden Equipment Rotary Tillers < 6 HP	N\A
2270004016	Lawn & Garden Equipment Rotary Tillers < 6 HP (Commercial)	N\A
2270004020	Lawn & Garden Equipment Chain Saws < 6 HP	N\A
2270004021	Lawn & Garden Equipment Chain Saws < 6 HP (Commercial)	N\A
2270004025	Lawn & Garden Equipment Trimmers/Edgers/Brush Cutters	N\A
2270004026	Lawn & Garden Equipment Trimmers/Edgers/Brush Cutters (Commercial)	N\A

(table continued from previous page)

2270004030	Lawn & Garden Equipment Leafblowers/Vacuums	None
2270004031	Lawn & Garden Equipment Leafblowers/Vacuums (Commercial)	None
2270004035	Lawn & Garden Equipment Snowblowers	None
2270004036	Lawn & Garden Equipment Snowblowers (Commercial)	None
2270004040	Lawn & Garden Equipment Rear Engine Riding Mowers	None
2270004041	Lawn & Garden Equipment Rear Engine Riding Mowers (Commercial)	None
2270004045	Lawn & Garden Equipment Front Mowers	None
2270004046	Lawn & Garden Equipment Front Mowers (Commercial)	None
2270004050	Lawn & Garden Equipment Shredders < 6 HP	None
2270004051	Lawn & Garden Equipment Shredders < 6 HP (Commercial)	None
2270004055	Lawn & Garden Equipment Lawn & Garden Tractors	None
2270004056	Lawn & Garden Equipment Lawn & Garden Tractors (Commercial)	None
2270004060	Lawn & Garden Equipment Wood Splitters	N\A
2270004061	Lawn & Garden Equipment Wood Splitters (Commercial)	N\A
2270004065	Lawn & Garden Equipment Chippers/Stump Grinders	N\A
2270004066	Lawn & Garden Equipment Chippers/Stump Grinders (Commercial)	N\A
2270004070	Lawn & Garden Equipment Commercial Turf Equipment	Unused SCC
2270004071	Lawn & Garden Equipment Commercial Turf Equipment (Commercial)	None
2270004075	Lawn & Garden Equipment Other Lawn & Garden Equipment	None
2270004076	Lawn & Garden Equipment Other Lawn & Garden Equipment (Commercial)	None
2270005000	Farm Equipment Total	
2270005010	Farm Equipment 2-Wheel Tractors	Ag. Tractor
2270005015	Farm Equipment Agricultural Tractors	Ag. Tractor
2270005020	Farm Equipment Combines	Ag. Tractor
2270005025	Farm Equipment Balers	Ag. Tractor
2270005030	Farm Equipment Agricultural Mowers	Ag. Tractor
2270005035	Farm Equipment Sprayers	Ag. Tractor
2270005040	Farm Equipment Tillers > 6 HP	Ag. Tractor
2270005045	Farm Equipment Swathers	Ag. Tractor
2270005050	Farm Equipment Hydro Power Units	None
2270005055	Farm Equipment Other Agricultural Equipment	Ag. Tractor
2270005060	Farm Equipment Irrigation Sets	None
2270006000	Light Commercial Total	
2270006005	Light Commercial Generator Sets	None
2270006010	Light Commercial Pumps	None
2270006015	Light Commercial Air Compressors	None
2270006020	Light Commercial Gas Compressors	None
2270006025	Light Commercial Welders	None
2270006030	Light Commercial Pressure Washers	None
2270007000	Logging Equipment Total	
2270007005	Logging Equipment Chain Saws > 6 HP	N\A
2270007010	Logging Equipment Shredders > 6 HP	None
2270007015	Logging Equipment Skidders	Dozer
2270007020	Logging Equipment Fellers/Bunchers	Backhoe
2270008000	Airport Service Equipment Total	
2270008005	Airport Service Equipment Airport Support Equipment	Backhoe
2270008010	Airport Service Equipment Terminal Tractors	Backhoe
2270009000	Underground Mining Equipment Total	
2270009010	Other Underground Mining Equipment	Backhoe
2270010000	Oil Field Equipment Total	

(table continued from previous page)

2270010010	Other Oil Field Equipment	None
2282005025	Recreational Pleasure Craft, Sailboat Aux. Outboard	None
2285003015	Railway Maintenance	Backhoe
2282005000	Recreational Pleasure Craft, Total	
2282005005	Recreational Pleasure Craft, Inboards	None
2282005010	Recreational Pleasure Craft, Outboards	None
2282005015	Recreational Pleasure Craft, Personal Water Craft	N\A

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(1) EPA, "Nonroad Engine and Vehicle Emission Study" (NEVES), U.S. EPA, Office of Air and Radiation, 21A-2001. November, 1991

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