**UNITED STATES ENVIRONMENTAL PROTECTION AGENCY**
WASHINGTON, D.C. 20460

January 28, 1999

OFFICE OF
AIR AND RADIATION

MEMORANDUM

SUBJECT: Emission Modeling for Large SI Engines

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TO: Docket A-98-01

EPA is developing its updated Nonroad Emissions Model, which computes nationwide emission levels for a wide variety of nonroad engines. The purpose of this memorandum is to describe the model and, in particular, its calculation of emissions from nonroad spark-ignition engines rated above 19 kW (25 hp) and all engines used in recreational equipment.[1]

The model incorporates information on emission rates, operating data, and engine population to determine annual emission levels of various pollutants. Operating data and population are determined separately for dozens of different applications. The model uses the following equation to calculate total emissions for each group of engines; individual parameters are described further below:

Emissions = EF × DF × P × LF × Hours × Units

Where,
EF = emission factor in g/hp-hr
DF = deterioration factor (dimensionless)
P = rated engine power in horsepower
LF = load factor (dimensionless)
Hours = operating hours per year for each unit
Units = population of engines operating in a given year

[1]These engines are referred to in this document as Large SI engines and recreational engines.

Emission and Deterioration Factors

Engine emissions are measured on an engine dynamometer, with results reported as a mass of emissions per unit of work (g/kW-hr or g/hp-hr). Southwest Research Institute recently compiled a listing of test data from past and current testing projects.[2] These tests were all conducted on new or nearly new engines. Table 1 summarizes this test data. All engines were operated on the ISO C2 duty cycle, except for two engines that were tested on the D2 cycle. The results from the different duty cycles were comparable, which is not surprising, given the similarity between the cycles. Lacking adequate test data for engines fueled by natural gas, EPA models those engines to have the same emission levels as those fueled by liquefied petroleum gas (LPG), based on the similarity between engines using the two fuels. Emission factors for recreational engines, also listed in Table 1, show a sharp contrast between two-stroke and four-stroke engines, especially for HC and PM emissions.

Table 1
Summary of New-Engine Emission Levels from Nonroad SI Engines (g/hp-hr)

| Category | Type | Fuel | NOx | HC | CO | PM |
|---|---|---|---|---|---|---|
| Recreational | 2-stroke | Gasoline | 0.47 | 153.6 | 390 | 2.4 |
| | 4-stroke | | 3.50 | 5.2 | 409 | 0.06 |
| Large SI | 4-stroke | LPG | 11.99 | 1.68 | 28.23 | 0.06 |
| | | Gasoline | 7.13 | 6.22 | 203.4 | 0.06 |

Emission levels often change as an engine ages. In most cases, emission levels increase with time, especially for engines equipped with technologies for controlling emissions. Table 2 details the deterioration factors established for these engines. These deterioration factors represent the degree to which emissions at the end of the useful life are greater or less than from a new engine. For example, the deterioration factor of 2.1for HC multiplied by the emission factor of 7.13 g/hp-hr for new gasoline industrial engines indicates that modeled emission levels increase to 15.0 g/hp-hr at the end of the useful life period.

[2]"Three-Way Catalyst Technology for Off-Road Equipment Powered by Gasoline and LPG Engines; Volume 2, Cost-Effectiveness Analysis," Jeff J. White, Melvin N. Ingalls, Lit-Mian Chan, May 1998.

Table 2
Deterioration Factors from Nonroad SI Engines

| Category | Type | Fuel | NOx | HC | CO | PM |
|---|---|---|---|---|---|---|
| Recreational | 2-stroke | Gasoline | 1.0 | 1.2 | 1.2 | 1.2 |
| | 4-stroke | | 1.0 | 2.1 | 1.9 | 2.1 |
| Large SI | 4-stroke | LPG | 1.0 | 2.1 | 1.9 | 2.1 |
| | | Gasoline | 1.0 | 2.1 | 1.9 | 2.1 |

Rated Power and Load Factor

The model relies on the OE Link database from Power Systems Research to provide market information for individual engine models, each with an established power rating.[3] Engines typically operate, however, at a variety of speeds and loads, such that operation at rated power is rare. To take into account the effect of operating at idle and partial load conditions, a load factor indicates the degree to which average engine operation is scaled back from full load. For example, at a 0.3 (or 30 percent) load factor, an engine rated at 100 hp would be producing an average of 30 hp over the course of normal operation. For highly mobile equipment, this can vary widely (and quickly) between 0 and 100 percent of full power. Generators (and similar equipment) typically experience much less variation in load factor. Tables 3 and 4 show the load factors, as developed by Power Systems Research, that apply to the various applications of nonroad equipment.

Operating Hours

Power Systems Research also specifies a value for annual operating hours that apply to various applications. These figures represent the operating levels that apply through the median lifetime of equipment. That is, for the period during which at least half the units from a given year's production are still in operation, the operating rate for all engines is projected to be that listed in Tables 3 and 4.

Population

Power Systems Research provides estimated populations of the individual engine and equipment models using historical sales information adjusted according to survival and scrappage rates. Based on a study of the forklift market, EPA has determined that Power Systems Research

[3]Power Systems Research is a firm that provides marketing data on engines and equipment. The OE Link database is a compilation of historical annual sales for individual engine models sold in the U.S. The database is available from Power Systems Research (612-454-0144).

substantially underestimates the population of forklift trucks.[4] That study identified a 1996 population of 491,321 for Class 4 through 6 forklifts, which includes all forklifts powered by internal combustion engines. Approximately 80 percent of those were estimated to be fueled by propane, with the rest running on either gasoline or diesel fuel. Assuming an even split between gasoline and diesel for these remaining forklifts leads to a total population of spark-ignition forklifts of 442,000.

For other applications, the split between LPG and gasoline also warrants further attention. Engines are typically sold without fuel systems, which makes it difficult to assess the distribution of engines sales by fuel type. Also, engines are often retrofitted for a different fuel after a period of operation, making it still more difficult to estimate the prevalence of the different fuels. The high percentage of propane systems for forklifts, compared with about 60 percent estimated by Power Systems Research, can be largely attributed to expenses related to maintaining fuel supplies. LPG cylinders can be readily exchanged with minimal infrastructure cost. Installing and maintaining underground tanks for storing gasoline has always been a significant expense, which has now become increasingly costly due to the new requirements for replacing underground storage tanks. Natural gas systems typically offer the advantage of pipeline service, but the cost of installing high-pressure refueling equipment is an obstacle to increased use of natural gas systems.

Some applications of nonroad SI equipment face much different refueling situations. Lawn and garden equipment is usually not centrally fueled and therefore operates almost exclusively on gasoline, which is more readily available. Agriculture equipment is predominantly powered by diesel engines. Most of these operators likely have storage tanks for diesel fuel. For those who use spark-ignition engines in addition to, or instead of, the diesel models, EPA would expect them in many cases to be ready to invest in gasoline storage tanks as well, resulting in little or no use of LPG or natural gas for those applications. For construction, general industrial, and other equipment, there may be a mix of central and noncentral fueling, and motive and portable equipment. EPA therefore believes that estimating an even mix of LPG and gasoline for these engines is most appropriate. The estimated distribution of fuel types for the individual applications are listed in Table 3. Recreational engines operate almost exclusively on gasoline.

An additional issue related to population figures is the level of growth factored into emission estimates for the future. The Nonroad Emission Model incorporates application-specific growth figures. The projected growth is reflected in the population estimates included in Tables 3 and 4.

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[4] "The Role of Propane in the Fork Lift/Industrial Truck Market: A Study of its Status, Threats, and Opportunities," Robert E. Myers for the National Propane Gas Association, December 1996.

Table 3
Operating Parameters and Population Estimates for
Various Applications of Engines Rated above 19 kW

| Application | Load Factor | Hours per Year | 1996 Population | 2010 Population | Percent LPG/CNG |
|---|---|---|---|---|---|
| Forklift | 0.30 | 1500 | 442,000 | 547,063 | 95 |
| Generator | 0.68 | 115 | 205,990 | 202,177 | 50 |
| Welder | 0.51 | 208 | 55,495 | 67,872 | 50 |
| Commercial turf | 0.60 | 733 | 41,440 | 55,074 | 0 |
| Pump | 0.69 | 221 | 41,104 | 44,830 | 50 |
| Air compressor | 0.56 | 484 | 24,182 | 28,633 | 50 |
| Baler | 0.62 | 68 | 21,937 | 27,597 | 0 |
| Irrigation set | 0.60 | 716 | 17,800 | 9,724 | 50 |
| Aerial lift | 0.46 | 361 | 15,734 | 15,555 | 50 |
| Scrubber/sweeper | 0.71 | 516 | 14,154 | 13,955 | 50 |
| Chipper/grinder | 0.78 | 488 | 12,218 | 16,262 | 50 |
| Leaf blower/vacuum | 0.75 | 56 | 10,823 | 14,384 | 0 |
| Oil field equipment | 0.90 | 1104 | 8,792 | 8,924 | 100 |
| Sprayer | 0.65 | 80 | 8,635 | 10,863 | 0 |
| Trencher | 0.66 | 402 | 8,168 | 9,604 | 50 |
| Specialty vehicle/cart | 0.58 | 65 | 7,833 | 8,726 | 50 |
| Skid/steer loader | 0.58 | 310 | 7,795 | 9,164 | 50 |
| Other general industrial | 0.54 | 713 | 3,987 | 3,942 | 50 |
| Rubber-tired loader | 0.71 | 512 | 3,476 | 4,088 | 50 |
| Gas compressor | 0.60 | 8500 | 3,023 | 1,620 | 100 |
| Paving equipment | 0.59 | 175 | 2,996 | 3,524 | 50 |
| Terminal tractor | 0.78 | 827 | 2,905 | 2,872 | 50 |
| Bore/drill rig | 0.79 | 107 | 2,618 | 3,080 | 50 |
| Ag. tractor | 0.62 | 550 | 2,152 | 2,707 | 0 |
| Concrete/industrial saw | 0.78 | 610 | 2,133 | 2,509 | 50 |
| Rough terrain forklift | 0.63 | 413 | 1,933 | 2,273 | 50 |
| Roller | 0.62 | 621 | 1,596 | 1,878 | 50 |
| Crane | 0.47 | 415 | 1,584 | 1,864 | 50 |
| Other material handling | 0.53 | 386 | 1,535 | 1,518 | 50 |

| Application | Load Factor | Hours per Year | 1996 Population | 2010 Population | Percent LPG/CNG |
|---|---|---|---|---|---|
| Paver | 0.66 | 392 | 1,337 | 1,573 | 50 |
| Other agriculture equipment | 0.55 | 124 | 1,234 | 1,552 | 0 |
| Other construction | 0.48 | 371 | 1,222 | 1,436 | 50 |
| Pressure washer | 0.85 | 115 | 1,207 | 2,271 | 50 |
| Aircraft support | 0.56 | 681 | 840 | 1,238 | 50 |
| Crushing/processing equip | 0.85 | 241 | 532 | 628 | 50 |
| Surfacing equipment | 0.49 | 488 | 481 | 567 | 50 |
| Tractor/loader/backhoe | 0.48 | 870 | 416 | 489 | 50 |
| Hydraulic power unit | 0.56 | 450 | 339 | 384 | 50 |
| Other lawn & garden | 0.58 | 61 | 333 | 443 | 0 |
| Refrigeration/AC | 0.46 | 605 | 163 | 226 | 100 |

Table 4
Operating Parameters and Population Estimates for Recreational Engines

| Application | Load Factor | Hours per Year | 1996 Population | 2010 Population | Percent 2-stroke |
|---|---|---|---|---|---|
| ATV/Motorcycle | 0.72 | 135 | 1,743,801 | 1,880,196 | 19% |
| Snowmobile | 0.81 | 121 | 1,289,302 | 1,390,148 | 100% |
| Specialty vehicle | 0.58 | 65 | 413,492 | 445,853 | 43% |

## MODELING RESULTS

Emission modeling runs, summarized in Tables 5 and 6 for the years 2000 and 2010, show relative contributions of the different mobile source categories to the overall emissions inventory. Of the total emissions from mobile sources, nonroad SI engines rated above 19 kW contribute 1 percent, 2 percent, 3 percent, and 0.4 percent of HC, NOx, CO, and PM emissions in the year 2000. The results for recreational engines reflect the much different emissions profile from two-stroke engines. These engines are estimated to contribute 15 percent of mobile source HC emissions, 9 percent of CO emissions, and 0.2 percent of NOx emissions in 2000. PM emissions from recreational engines amount to 2 percent of total mobile source emissions. Since highway engines account for a large fraction of mobile source emissions, as shown in Tables 5 and 6, the contribution of these engines as a percentage of total nonroad emissions will be significantly higher than that from total mobile sources emissions.

These emission figures are projected to change somewhat by 2010. The contribution of CO emissions from SI engines above 19 kW increases to 4 percent and the contribution of HC and CO emissions from recreational engines increases to 19 percent and 11 percent. The contribution of CO emissions from SI engines above 19 kW increases to 4 percent and the contribution of HC and CO emissions from recreational engines increases to 19 percent and 11 percent. Population growth and the effects of regulatory control programs are factored into these later emissions estimates. Table 6 shows that relative importance of uncontrolled engines grows over time as other engines reduce their emission levels. The effectiveness of all control programs is offset by the anticipated growth in engine populations.

Table 5
Modeled Annual Emission Levels for
Mobile Source Categories in 2000 (thousand short tons)

| Category | NOx | | HC | | CO | | PM | |
|---|---|---|---|---|---|---|---|---|
| | tons | percent | tons | percent | tons | percent | tons | percent |
| Nonroad SI > 19 kW | 227 | 2% | 57 | 1% | 2,060 | 3% | 3 | 0.4% |
| Recreational Equipment | 25 | 0.2% | 1,100 | 15% | 6,652 | 9% | 16 | 2% |
| Nonroad SI < 19 kW | 82 | 0.7% | 623 | 8% | 13,859 | 19% | 14 | 2% |
| Marine SI | 39 | 0.4% | 609 | 8% | 2,177 | 3% | 30 | 4% |
| Nonroad diesel | 2,803 | 25% | 371 | 5% | 1,002 | 1% | 306 | 44% |
| Marine diesel | 206 | 2% | 45 | 1% | 76 | 0.1% | 30 | 4% |
| Locomotive | 1,075 | 10% | 46 | 1% | 104 | 0.1% | 27 | 4% |
| Aircraft | 178 | 2% | 183 | 2% | 1,017 | 1% | 39 | 6% |
| Total Nonroad | 4,635 | 42% | 3,034 | 40% | 26,947 | 38% | 465 | 66% |
| Total Highway | 6,397 | 58% | 4,482 | 60% | 44,244 | 62% | 238 | 34% |
| Total Mobile Source | 11,032 | 100% | 7,516 | 100% | 71,191 | 100% | 703 | 100% |

Table 6
Modeled Annual Emission Levels for
Mobile Source Categories in 2010 (thousand short tons)

| Category | NOx | | HC | | CO | | PM | |
|---|---|---|---|---|---|---|---|---|
| | tons | percent | tons | percent | tons | percent | tons | percent |
| Nonroad SI > 19 kW | 288 | 3% | 46 | 1% | 2,427 | 4% | 3 | 0.4% |
| Recreational Equipment | 26 | 0.3% | 1,174 | 19% | 6,900 | 11% | 18 | 2% |
| Nonroad SI < 19 kW | 73 | 0.8% | 293 | 5% | 11,528 | 18% | 15 | 2% |
| Marine SI | 49 | 0.5% | 363 | 6% | 2,221 | 3% | 22 | 3% |
| Nonroad diesel | 2,248 | 24% | 249 | 4% | 699 | 1% | 375 | 51% |
| Marine diesel | 211 | 2% | 46 | 1% | 78 | 0.1% | 31 | 4% |
| Locomotive | 1,075 | 11% | 46 | 1% | 104 | 0.2% | 27 | 4% |
| Aircraft | 209 | 2% | 215 | 4% | 1,279 | 2% | 42 | 6% |
| Total Nonroad | 4,179 | 44% | 2,432 | 40% | 25,236 | 39% | 533 | 73% |
| Total Highway | 5,354 | 56% | 3,683 | 60% | 40,201 | 61% | 200 | 27% |
| Total Mobile Source | 9,533 | 100% | 6,115 | 100% | 65,437 | 100% | 733 | 100% |