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**UNITED STATES ENVIRONMENTAL PROTECTION AGENCY**
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OFFICE OF
AIR AND RADIATION

MEMORANDUM

SUBJECT: Emission Modeling for Recreational Vehicles

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TO: Docket A-98-01

EPA has developed a Nonroad Emissions Model, which computes nationwide emission levels for a wide variety of nonroad engines. The purpose of this memorandum is to describe the Nonroad Emissions Model and, in particular, its calculation of emissions from nonroad engines found in recreational vehicles[1].

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

[1] Recreational vehicles are subdivided into three categories: 1) off-road motorcycles, 2) All-Terrain Vehicles (ATVs), and 3) snowmobiles

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

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

Emission and Deterioration Factors

For recreational vehicles, emissions are measured on either an engine dynamometer or chassis dynamometer, depending on the application. For ATVs and snowmobiles, 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). For off-road motorcycles, vehicle emissions are measured on a chassis dynamometer, with results reported as a mass of emissions per unit of distance (g/km or g/mi). Test data was compiled from several sources[2]. These tests were all conducted on new or nearly new engines and vehicles. Tables 1 and 2 summarize the test data.

Table 1
Summary of Emission Levels from Recreational Vehicles (g/hp-hr)

| Category | Type | HC | CO | NOx | PM |
|---|---|---|---|---|---|
| ATV/Off-road Motorcycle | 4-stroke | 8.2 | 323 | 1.9 | 0.06 |
| Snowmobiles | 2-stroke | 111 | 296 | 0.86 | 2.7 |

Table 2
Summary of Emission Levels from Recreational Vehicles (g/km)

| Category | Type | HC | CO | NOx | PM |
|---|---|---|---|---|---|
| ATV/Off-road Motorcycle | 2-stroke | 17.3 | 27.5 | 0.2 | 0.01 |

The test data for ATVs and off-road motorcycles were provided by a manufacturer and represents various makes, models, model years, and engine sizes for ATVs and off-road motorcycles. For various reasons, including the fact that ATVs are typically emission tested on an engine test cycle, the tests for the 4-stroke engines were all conducted on the SAE J1088 test cycle and presented in g/hp-hr. The tests for the 2-stroke engines were all conducted on the Federal Test Procedure (FTP) using the test manufacturers recommended shift points and are presented in g/km,

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[2] International Snowmobile Manufacturers Association, Carrol 1999 (SwRI), Wright & White 1998 (SwRI), White et. al. 1997 (SwRI), Hare & Springer 1974 (SwRI)

similar to on-highway motorcycle emission results. Because the design and performance of ATV and off-road motorcycle engines are so similar, we have chosen to use the same emission test data to represent both applications in the Nonroad Emissions Model.

The test data used for snowmobiles came from the International Snowmobile Manufacturers Association (ISMA) and Southwest Research Institute (SwRI). The data from ISMA consists of tests performed by the major snowmobile manufacturers on a variety of makes, models, and engine sizes ranging from 250 cubic centimeters (cc) to 900 cc. All of the engines tested were new or nearly new and the majority of them represented recent model years (1990 - 1996). The test data was generated over the ISMA 5-mode snowmobile test cycle[3]; an engine test cycle with varying speed and load developed by SwRI with assistance from several snowmobile manufacturers. In addition to test data provided by ISMA, we also received data from several SwRI test programs. The majority of the data received from the SwRI programs were tested over the ISMA 5-mode snowmobile cycle, however, a small percentage of the tests conducted on a few older models were tested over a "snowmobile duty cycle" developed by SwRI in 1974 that consisted of different speed and load combinations.

Emission levels can change as an engine ages. In most cases, emission levels increase with time, especially for engines equipped with technologies for controlling emissions. Table 3 details the deterioration factors established for these vehicles. These deterioration factors represent the degree to which emissions at the end of the useful life are greater than those from a new engine. For example, the deterioration factor of 1.2 for HC multiplied by the emission factor of 111 g/hp-hr for snowmobiles indicates that the modeled emission levels increase to 133 g/hp-hr at the end of the useful life. We were unable to obtain any information on the deterioration rate of emissions over the useful life period for 2-stroke and 4-stroke engines found in recreational vehicles. It is our belief that due to malmaintenance alone, some level of deterioration occurs for recreational vehicles over the useful life. Therefore, we are using the deterioration factors developed for spark ignition, gasoline-powered 2-stroke lawn and garden equipment for 2-stroke ATVs, off-road motorcycles, and snowmobiles. For 4-stroke ATVs and off-road motorcycles, we use deterioration factors based on pre-1978 uncontrolled 4-stroke on-highway motorcycles from the MOBILE model.

Table 3
Deterioration Factors from Recreational Vehicles

| Category | Type | HC | CO | NOx | PM |
|---|---|---|---|---|---|
| ATV/Off-Road MC | 2-stroke | 1.2 | 1.2 | 1.0 | 1.2 |
| | 4-stroke | 1.15 | 1.17 | 1.0 | 1.2 |
| Snowmobile | 2-stroke | 1.2 | 1.2 | 1.0 | 1.2 |

[3] SAE paper 982017, Wright, et. al., "Development and Validation of a Snowmobile Engine Emission Test Procedure."

Rated Power and Load Factor

Rated power is the maximum amount of power that an engine can produce. Engines typically operate at variety of speeds and loads, and operation at rated power is rare. To take into account the effect of operating at idle and partial load conditions, as well as transient operation, a load factor is developed to indicate the average proportion of rated power used. 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. Load factor can very widely for most engines, including recreational engines, depending on their usage. Because recreational vehicles tend to have a high power-to-weight ratio, it is uncommon for recreational vehicles to ever operate at rated power. Table 4 shows the load factors used for ATVs, off-road motorcycles, and snowmobiles.

For snowmobiles, the load factor is derived from work done by SwRI in developing the 5-mode snowmobile test cycle discussed above[4]. The cycle development work encompassed operation over varied conditions, including moderate and aggressive trail riding, lake riding, off-trail freestyle riding, and operation with single and double riders. Snowmobiles have a greater surface area in contact with the ground than either off-road motorcycles or ATVs, which results in a greater "rolling" resistance for snowmobiles. This larger rolling resistance combined with operation through potentially dense snow would suggest that a load factor for snowmobiles at least similar to, or perhaps even greater than, off-road motorcycles and ATVs. Therefore, absent any other information on off-road motorcycle and ATV load factors, we are using the snowmobile load factor for off-road motorcycles and ATVs.

Table 4
Operating Parameters and Population Estimates for Recreational Vehicles

| Application | Type | Load Factor | Hours per Year | Mileage per Year | 1998 Population | 2010 Population |
|---|---|---|---|---|---|---|
| ATVs | 2-stroke | 0.34 | 350 | ---- | 3,800,000 | |
| | 4-stroke | | ---- | 7,000 | | |
| Off-Road Motorcycles | 2-stroke | 0.34 | 120 | ---- | 1,196,000 | |
| | 4-stroke | | ---- | 2,400 | | |
| Snowmobiles | 2-stroke | 0.34 | 57 | ---- | 1,567,000 | |

Operating Hours

In determining what operating hours to use for recreational vehicles, there are a number of sources that provide varying estimates. For snowmobiles, there is activity information from studies done on the economic impact of snowmobile operation for eight different states, consumer satisfaction survey results from the snowmobile industry, survey results from Bluewater Network

[4] SwRI-7574, Buckingham, et. al., 1996, "Development of Snowmobile Test Cycle."

(an environmental organization), and Power Source Research (PSR) estimates. PSR was the only source that provided operating hours; all of the other sources presented information for average or typical miles operated per year. In order to convert the mileage estimates to operating hours, we had to estimate the average speed for typical snowmobile operation.

The information available on average speed ranges from 14 to 32 mph, although the bulk of the data falls in the area of 20 to 30 mph. Because of the large variation in speed estimates, it is difficult to determine what average speed is the most representative. We know that the correct speed is somewhere within this range and that the mode of the estimates fell at the mid point of the range. Therefore, we are using an average speed of 23 mph for snowmobile operation. We believe this is a reasonable value and it is supported by the snowmobile manufacturers per a recent discussion.

Once average speed has been determined, it is possible to convert the estimated average yearly mileage into yearly operating hours. The range of average yearly mileage estimates available to us is 540 to 1,800 miles. Manufacturers have indicated to us that for good winters, with average or above average snowfall, the average yearly mileage is approximately 1,500 miles and that for poorer winters, with less than average snowfall, the average yearly snowfall is approximately 1,200 miles. These estimates fall well within the range of estimates given above. In fact, several of the state economic studies indicated that their estimates for mileage were low due to poor snowfall during the winter in which they performed their studies. Therefore, based on all of the available information, we estimate that the average yearly mileage for snowmobile operation is 1,300 miles. With an average speed of 23 mph and an average mileage of 1,300 miles, the average yearly operating hours of 57 hours can be calculated.

For ATVs, the best source of information on yearly operating hours comes from a study conducted by the United States Consumer Product Safety Commission (CPSC)[5] that estimated the mean yearly hours of operation is 252 hours per rider. In this study, usage is expressed as “rider-usage” (hours/rider-yr). For our purposes, it is necessary to convert this value to “machine usage” (hours/ATV-yr). To perform this conversion, we calculated total rider usage (hours/rider-yr * rider population) as a proportion of the total ATV population, as follows:

$$\text{machine usage}\,(hr/ATV\cdot yr) = \frac{\text{rider usage}\,(hr/rider\cdot yr)\circ[\text{total rider pop.} - \text{inactive rider pop.}\,(riders)]}{\text{machine pop.}\,(ATVs)}$$

To avoid overestimating total rider usage, we subtracted an estimate of inactive riders from the total population. We estimated the active rider population by estimating the number of riders associated with inactive machines. We calculated the number of inactive machines directly as the difference between the total and active ATV populations (3.96 million total - 3.66 million “active” = 250,000 “inactive” machines).

5 “All-Terrain Vehicle Exposure, Injury, Death, and Risk Studies,” April 1998, United States Consumer Product Safety Commission

We multiplied the number of inactive ATVs by the average rider: ATV ratio to obtain an estimate of "inactive" riders:

$$\frac{1.5\, riders}{ATV} \cdot 250{,}000\; inactive\; ATV \;=\; 373{,}000\; inactive\; riders$$

We calculated this ratio from the following average results:

$$\frac{1.5\; rider}{ATV} = \frac{2.44\; rider\,/\,household}{1.63\, ATV\;/\,household}$$

Based on these calculations, we estimated machine usage as:

$$\frac{\dfrac{252\, hours}{rider \cdot yr} \cdot \left(5.85E\,6\; total\; riders - 3.73E\,5\; inactive\; riders\right)}{3.96E\,6\;\; ATVs}$$

$$= \quad \frac{350\; hours}{ATV \cdot yr}$$

Machine usage is greater than rider usage, reflecting the fact that the rider population is greater than the ATV population, and that machines are used by multiple riders.

However, because ATVs use 2-stroke and 4-stroke engines, and our emission factors for 2-stroke engines are based on grams per kilometer instead of grams per horsepower-hour, the value of 350 hours can only be used with the 4-stroke emission factors. Therefore, for 2-stroke equipped ATVs we again have to convert hours to mileage. Based on limited data for off-road motorcycles and ATVs we have selected an average speed of 20 mph. This estimate is consistent with the average speed used by California in their modeling of off-road motorcycle and ATV. By multiplying the average hours of 350 by the average speed of 20 mph, the result is an estimated mileage of 7,000 miles per year. This value is considerably higher than estimates of activity from the Motorcycle Industry Council (MIC) for off-road motorcycles. However, MIC did not provide any comments on operation or yearly mileage for ATVs. Our estimate for ATVs is higher than that for off-road motorcycles, but we feel this is appropriate since a number of sources including individual manufacturers and the Specialty Vehicle Institute of America, have indicated that ATVs are increasingly used for nonrecreational or work-related purposes in their operation.

For off-road motorcycles, there are two sources of information on activity or usage rates. The first source is information provided by the Motorcycle Industry Council. MIC periodically conducts surveys to obtain information on motorcycles use. The survey also gathers information on motorcycle usage. MIC has two methods of estimating off-road motorcycle usage from the survey results. Method one is based on the results of a single question that asks the respondant how many miles they rode in the last year. Method two is based on the multiplication of the response from three questions: 1) how many months ridden per year, 2) how many days of riding per month, and 3) how many miles ridden per day. The MIC estimates for method one is 222 miles per year and 1,260 miles per year for method two. MIC has suggested that method one is the more appropriate estimate because method two may compound any error that exists in the results of each of the three questions. We have concerns with the results of the MIC survey because the values for method one and two are dramatically different.

The second source of information is a study done in 1994 by the Oak Ridge National Laboratory (ORNL) titled, "Fuel Used for Off-Road Recreation." ORNL estimated total average fuel usage for off-road motorcycles. They provide a medium estimate of average fuel usage for off-road motorcycles of 59 gallons per year. Recent data from California combined with some older data from SwRI, suggests that the average fuel economy for off-road motorcycles is approximately 50 miles per gallon (mpg), as tested over the FTP. This estimate may be too high for actual in-use operation off-road, so we assume an estimate of 40 mpg. By multiplying the average fuel used per year by the average fuel economy, we arrive at an estimate of approximately 2,400 miles per year.

Another study performed by ORNL[6], cites fuel usage estimates developed by MIC that estimate a mean value of 214 gallons per year. If we used our estimate of 40 mpg, 214 gallons per year would yield 8,560 miles. Because of the large discrepancies in the MIC survey results, we are using the estimate of 2,400 miles per year for 2-stroke motorcycles and 120 hours per year (i.e., 2,400 miles ÷ 20 mph) for 4-stroke motorcycles derived from the 1994 ORNL study.

The operating hours and milage used for recreational vehicles are listed in Table 4.

Population

The estimates of population for snowmobiles, ATVs, and off-road motorcycles is listed in Table 3. The 1999 ORNL study estimated the total snowmobile population for 1998 based on state registrations. They also developed a methodology for estimating the number snowmobiles unregistered in each state, which works out to be approximately five percent of the total. Thus, they estimate a total population of snowmobiles of 1,567,000. ISMA also estimated the total number of snowmobiles by summing the total number of registered snowmobiles in those states that require snowmobile registration. However, they did not estimate the number of unregistered snowmobiles. Therefore, we use the value presented by ORNL as the estimate of total snowmobiles.

There is a range of population estimates for ATVs. MIC estimates the total population for 1998 to be 3.3 million, while the CPSC study estimates a 1997 population of 3.9 million. With sales of ATVs in 1998 of approximately 400,000 units, the CPSC estimate would be 4.3 million. The actual population likely falls somewhere between these two estimates so we have chosen an estimate of 3.8 million.

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[6] ORNL/TM - 1999/100

For off-road motorcycles, the only source is MIC[7]. They projected a total population for 1998 of 1,196,000 off-road motorcycles nationwide.

Modeling Results

Emission modeling runs, summarized in Tables 4 and 5 for the years 2000 and 2007, show relative contributions of the different recreational vehicle categories to the overall emissions inventory. Of the total emissions from mobile sources, recreational vehicles contribute 0.16 percent of NOx emissions, 8 percent of HC emissions, 5 percent of CO emissions, and 0.8 percent of PM emissions in the year 2000.

These emission figures are projected to change somewhat by 2007. The contribution of emissions from recreational vehicles increases to 0.22 percent for NOx emissions, 11 percent for HC emissions, 6 percent for CO emissions, and 0.9 percent for PM emissions. The emission inventories presented here take into account all rules that have been finalized as well as the proposed 2007 highway diesel rule. Growth rates for most nonroad engine categories in NONROAD are based on a simple linear regression of historical population estimates from Power Systems Research. For recreational equipment the projected linear annual growth is 0.6% of the 1996 populations[8]. Table 5 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 and vehicle populations.

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[7] 1999 Motorcycle Statistical Annual, Motorcycle Industry Council

[8] Further details of the growth and geographical allocation methodologies are covered in the paper, "Geographic Allocation and Growth in EPA's NONROAD Emission Inventory Model," by Gary Dolce, Greg Janssen, and Richard Wilcox, presented at the 1998 Air and Waste Management Association Conference.

Table 4
Modeled Annual Emission Level for Nonroad Engines
and Recreational Vehicles in 2000 (thousand short tons)

| Category | NOx | | HC | | CO | | PM | |
|---|---|---|---|---|---|---|---|---|
| | tons | percent | tons | percent | tons | percent | tons | percent |
| Total large nonroad SI | 327 | 2% | 712 | 10% | 6,525 | 8% | 7.2 | 1.0% |
| Nonrecreational nonroad SI > 19 kW | 306 | 2% | 125 | 2% | 2,294 | 3% | 1.6 | 0.2% |
| Recreational SI | 21.3 | 0.16% | 587 | 8% | 4,231 | 5% | 5.6 | 0.8% |
| Nonroad SI < 19 kW | 106 | 0.8% | 1,460 | 20% | 18,359 | 23% | 50 | 7% |
| Marine SI | 32 | 0.2% | 928 | 12% | 2,144 | 3% | 38 | 5% |
| Nonroad CI | 2,625 | 20% | 316 | 4% | 1,217 | 2% | 253 | 36% |
| Marine CI | 1,001 | 7% | 31 | 0% | 133 | 0.2% | 42 | 6% |
| Locomotive | 1,192 | 9% | 47 | 1% | 119 | 0.2% | 30 | 4% |
| Aircraft | 178 | 1% | 183 | 2% | 1,017 | 1% | 39 | 6% |
| Total Nonroad | 5,461 | 41% | 3,677 | 49% | 29,514 | 37% | 459 | 66% |
| Total Highway | 7,988 | 59% | 3,772 | 51% | 49,701 | 63% | 240 | 34% |
| Total Mobile Source | 13,449 | 100% | 7,449 | 100% | 79,215 | 100% | 699 | 100% |

Table 5
Modeled Annual Emission Level for Nonroad Engines
and Recreational Vehicles in 2007 (thousand short tons)

| Category | NOx | | HC | | CO | | PM | |
|---|---|---|---|---|---|---|---|---|
| | tons | percent | tons | percent | tons | percent | tons | percent |
| Total large nonroad SI | 391 | 4% | 757 | 14% | 6,962 | 9% | 7.8 | 1.3% |
| Nonrecreational nonroad SI > 19 kW | 369 | 4% | 141 | 3% | 2,517 | 3% | 1.9 | 0.3% |
| Recreational SI | 22.4 | 0.22% | 616 | 12% | 4,445 | 6% | 5.9 | 0.9% |
| Nonroad SI < 19 kW | 96 | 0.9% | 933 | 18% | 21,406 | 28% | 58 | 9% |
| Marine SI | 42 | 0.4% | 733 | 14% | 2,056 | 3% | 33 | 5% |
| Nonroad CI | 2,253 | 22% | 214 | 4% | 1,128 | 1% | 226 | 36% |
| Marine CI | 1,018 | 10% | 33 | 1% | 142 | 0.2% | 44 | 7% |
| Locomotive | 773 | 8% | 43 | 1% | 119 | 0.2% | 27 | 4% |
| Aircraft | 200 | 2% | 205 | 4% | 1,200 | 2% | 41 | 7% |
| Total Nonroad | 4,773 | 46% | 2,918 | 56% | 33,013 | 43% | 437 | 70% |
| Total Highway | 5,529 | 54% | 2,317 | 44% | 44,276 | 57% | 186 | 30% |
| Total Mobile Source | 10,302 | 100% | 5,235 | 100% | 77,289 | 100% | 623 | 100% |