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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
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OFFICE OF
AIR AND RADIATION

MEMORANDUM

SUBJECT: Updated Emission Modeling for Large SI Engines

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TO: Docket A-98-01

The Environmental Protection Agency (EPA) has developed the NONROAD Emissions Model to compute nationwide emission levels for a wide variety of nonroad engines. The purpose of this memorandum is to describe the inputs to the NONROAD model and present estimated emission contributions from nonroad spark-ignition engines rated above 19 kW (25 hp). These engines are referred to in this document as Large SI engines. These modeling results support the Agency's final finding that these engines contribute to air pollution in the United States.

The NONROAD 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:

$$\text{Emissions} = EF \times DF \times P \times LF \times TF \times \text{Hours} \times \text{Units}$$

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

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.[1] These tests were all conducted on new or nearly new engines. Table 1 summarizes this test data. All engines were operated on the steady-state ISO C2 duty cycle, except for two engines that were tested on the steady-state D2 cycle. The results from the different duty cycles were comparable. Lacking adequate test data for engines fueled by natural gas, we model 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 (in the case of hydrocarbon emissions, this is based on nonmethane measurements). The listed emission levels for gasoline engines represent a composite of emissions from air-cooled and water-cooled engines.

Table 1
New-Engine Emission Factors for Large SI Engines (g/hp-hr)

Fuel	NOx	THC	CO	PM
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. We developed deterioration factors for uncontrolled Large SI engines based on measurements with comparable highway engines.[2] Table 2 shows the deterioration factors that apply at the median lifetime estimated for each type of equipment. For example, a deterioration factor of 1.26 for hydrocarbons multiplied by the emission factor of 6.22 g/hp-hr for new gasoline engines indicates that modeled emission levels increase to 7.84 g/hp-hr when the engine reaches its median lifetime. The deterioration factors are linear multipliers, so the modeled deterioration at different points can be calculated by simple interpolation.

Table 2
Deterioration Factors

Pollutant	Median Life Deterioration Factor
THC	1.26
CO	1.35
NOx	1.03

Operating Parameters

The NONROAD 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.[a] Engines typically operate at a variety of speeds and loads, such that operation at rated power is rare. To take into account the effect of operation 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. Table 3 shows the load factors that apply to the various applications of nonroad equipment.

Emissions during transient operation can be significantly higher than during steady-state operation. Based on emission measurements from highway engines comparable to uncontrolled Large SI engines, we have measured transient emission levels that are 30 percent higher for HC and 45 percent higher for CO relative to steady-state measurements.[3] The NONROAD model therefore multiplies steady-state emission factors by 1.3 for HC and 1.45 for CO to estimate emission levels during normal, transient operation. Test data do not support adjusting NOx emission levels for transient operation. Also, the model applies no transient adjustment factor for generators, pumps, or compressors, since engines in these applications are less likely to experience transient operation.

Power Systems Research also specifies a value for annual operating hours that apply to various applications, as shown in Table 3. These figures represent an average annual usage that applies over the course of an engine's lifetime.

Population

The NONROAD model generally uses population data based on information from Power Systems Research, which is based on historical sales information adjusted according to survival and scrappage rates. We are, however, using different population estimates for forklifts based on a recent market study.[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. The NONROAD model therefore uses this estimate for the forklift population, which is significantly higher than that estimated by Power Systems Research. Table 3 shows the estimated population figures used in the NONROAD model for each application, adjusted for the year 2000.

The split between LPG and gasoline in various applications 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

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[a]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).

Systems Research, can be largely attributed to expenses related to maintaining fuel supplies. LPG cylinders can be readily exchanged with minimal infrastructure cost as compared to gasoline storage. 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, we 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. We therefore believe 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 used in the NONROAD model are listed in Table 3.

An additional issue related to population figures is the level of growth factored into emission estimates for the future. The NONROAD model incorporates application-specific growth figures based on projections from Power Systems Research. The projected growth is reflected in the population estimates included in Table 3. The model also projects growth rates separately for the different fuels for each application.

MODELING RESULTS

Total mobile-source emission estimates for the years 2000 and 2007 are summarized in Tables 4 and 5. These tables show relative contributions of the different mobile source categories to the overall mobile source emissions inventory. The emission figures are projected to change somewhat between 2000 and 2007. Population growth and the effects of other regulatory control programs are factored into the later emissions estimates. Of the total mobile-source emissions in 2007, Large SI engines are estimated to contribute about 3 percent of HC, NOx, and CO emissions, and about 0.3 percent of PM emissions. The appendix shows how the different Large SI applications contribute to the total emissions for the category.

Table 3
Operating Parameters and Population Estimates for Various Applications of Large SI Engines

Application	Avg. Rated HP	Load Factor	Hours per Year	2000 Population	2007 Population	Percent LPG/CNG
Forklift	69	0.30	1800	504,696	603,099	95
Generator	59	0.68	115	146,246	217,525	100
Welder	67	0.58	408	19,246	27,008	50
Commercial turf	28	0.60	682	55,433	64,265	0
Pump	45	0.69	221	35,981	50,340	50
Air compressor	65	0.56	484	17,472	24,404	50
Baler	44	0.62	68	18,659	20,977	0
Irrigation set	97	0.60	716	5,367	3,917	50
Aerial lift	52	0.46	361	38,901	38,565	50
Scrubber/sweeper	49	0.71	516	13,363	13,252	50
Chipper/grinder	66	0.78	488	13,015	15,102	50
Leaf blower/vacuum	79	0.94	282	11,797	13,621	0
Oil field equipment	44	0.90	1104	7,855	7,845	100
Trencher	54	0.66	402	3,627	3,950	50
Specialty vehicle/cart	66	0.58	65	9,145	9,635	50
Skid/steer loader	47	0.58	310	7,436	8,099	50
Rubber-tired loader	71	0.71	512	3,177	3,460	50
Gas compressor	110	0.60	6000	788	1,005	100
Paving equipment	39	0.59	175	1,109	1,207	50
Terminal tractor	93	0.78	827	2,716	2,687	50
Bore/drill rig	78	0.79	107	2,607	2,839	50
Ag. tractor	82	0.62	550	1,599	1,798	0
Concrete/industrial saw	46	0.78	610	2,266	2,468	50
Roller	55	0.62	621	1,362	1,483	50
Crane	75	0.47	415	1,240	1,351	50
Other material handling	67	0.53	386	1,605	1,591	50
Paver	48	0.66	392	1,367	1,488	50
Other agriculture equipment	162	0.55	124	5,501	6,102	0
Other construction	126	0.48	371	1,276	1,390	50

Application	Avg. Rated HP	Load Factor	Hours per Year	2000 Population	2007 Population	Percent LPG/CNG
Pressure washer	39	0.85	115	1,227	1,722	50
Aircraft support	99	0.56	681	910	1,131	50
Crushing/processing equip	63	0.85	241	235	256	50
Surfacing equipment	40	0.49	488	314	342	50
Tractor/loader/backhoe	58	0.48	870	360	392	50
Hydraulic power unit	50	0.56	450	330	351	50
Other lawn & garden	61	0.58	61	402	466	0
Refrigeration/AC	55	0.46	605	169	201	100
Total Population				915,678	1,127,323	

Table 4
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
Large SI	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 Levels for
Mobile Source Categories in 2007 (thousand short tons)

Category	NOx		HC		CO		PM	
	tons	percent	tons	percent	tons	percent	tons	percent
Large SI	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%

REFERENCES

1. “Three-Way Catalyst Technology for Off-Road Equipment Powered by Gasoline and LPG Engines—Interim Report Volume 2: Cost-Effectiveness Analysis” Jeff J. White, et al, May 1998, p. 15 (Docket A-98-01, document II-D-4).

2. “Revisions to the June 2000 Release of NONROAD to Reflect New Information and Analysis on Marine and Industrial Engines,” EPA memorandum from Mike Samulski to Docket A-98-01 (Document IV-B-1).

3. “Regulatory Analysis and Environmental Impact of Final emission Regulations for 1984 and Later Model Year Heavy Duty Engines,” U.S. EPA, December 1979, p. 189 (Docket A-98-01, document IV-B-2).

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 (Docket A-98-01, document II-D-2).

APPENDIX

Emission Modeling Outputs by Application

APPL.ICATION	2000 Emission Levels by Application				2007 Emission Levels by Application			
	NOx	HC*	CO	PM	NOx	HC*	CO	PM
FORKLIFTS	247,543	56,558	1,242,159	1,178	297,973	64,892	1,357,677	1,408
GENERATORS	9,020	1,402	24,476	42	13,199	2,018	35,025	60
GAS COMPRESSORS	5,979	1,000	17,877	30	7,632	1,277	22,820	38
COMMERCIAL TURF	4,986	6,348	241,464	47	5,781	7,367	280,270	55
OIL FIELD EQUIP.	4,659	961	18,846	22	4,653	960	18,827	22
WELDERS	3,912	2,227	74,983	25	5,633	2,940	96,845	34
AERIAL LIFTS	3,632	2,045	68,709	23	3,842	1,689	53,038	22
CHIPPER/GRINDER	3,512	2,111	71,922	23	4,077	2,450	83,456	26
AIR COMPRESSORS	3,329	1,928	65,182	21	4,741	2,531	83,883	29
PUMPS	2,683	1,473	36,621	27	3,827	1,912	46,876	36
SCRUB/SWEEPER	2,627	1,472	49,412	16	2,784	1,222	38,288	16
IRRIGATION SETS	2,498	1,308	43,082	15	1,623	1,228	43,716	12
LEAFBLOWER/VACUUM	2,166	2,742	104,089	20	2,501	3,173	120,514	24
TERMINAL TRACTORS	1,768	1,014	34,212	11	1,859	836	26,386	11
RUBBER-TIRED LOADER	883	523	17,791	6	978	549	18,417	6
OTH LAWN&GARDEN	818	460	15,437	5	866	381	11,954	5
SKID/STEER LOADER	669	421	14,487	4	737	439	14,944	5
TRENCHERS	558	331	11,243	4	618	347	11,630	4
CONCRETE/IND. SAWS	531	314	10,667	3	587	329	11,044	4
OTH AG.EQUIP.	497	603	22,809	5	546	670	25,338	5
SWATHERS	452	573	21,745	4	506	638	24,178	5
AIRPORT GSE	376	214	7,198	2	482	246	8,042	3
AG. TRACTOR	359	456	17,328	3	404	513	19,495	4
HYD POWER UNIT	356	211	7,163	2	393	221	7,408	2
ROLLERS	308	182	6,203	2	341	191	6,421	2
OTHER CONSTR.	307	182	6,203	2	339	191	6,407	2
BALERS	276	350	13,307	3	310	391	14,807	3
SPECIALTY VEH/CARTS	241	228	5,164	4	254	239	5,407	4
OTH MAT'L HANDLING	225	150	5,212	2	226	118	3,908	1.4
CRANES	196	116	3,943	1.3	217	121	4,074	1.4
BORE/DRILL RIGS	184	109	3,706	1.2	204	114	3,825	1.3
PAVERS	182	108	3,669	1.2	202	113	3,795	1.3
TRACT/LDR/BACKHOE	93	55	1,884	0.6	103	58	1,950	0.6
PRESSURE WASHERS	50	29	980	0.3	72	38	1,253	0.4
PAVING EQUIP.	48	29	969	0.3	53	30	1,001	0.3
HYDR. POWER UNITS	45	27	926	0.3	47	30	1,024	0.3
REFRIGERATION/AC	35	7	138	0.2	41	8	163	0.2
CRUSH/PROC EQUIP.	32	19	652	0.2	36	20	674	0.2
SURFACING EQUIP.	32	19	648	0.2	35	20	671	0.2
RAILWAY MAINT.	11	7	232	0.1	13	8	254	0.1
FRONT MOWERS	9	12	457	0.1	11	14	523	0.1
OTHER LAWN&GARDEN	7	9	336	0.1	8	10	385	0.1
PLATE COMPACTORS	3	4	165	0.03	3	4	167	0.03
COMBINES	3	4	136	0.03	3	4	152	0.03
TOTALS	306,100	88,343	2,293,833	1,557	368,760	100,549	2,516,932	1,854

*The hydrocarbon figures include exhaust emissions, but exclude evaporative emissions.