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Office of Mobile Source Air Pollution Control
Emission Control Technology Division
2565 Plymouth Road
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# Recommended Revisions to Gaseous Emission Factors From Several Classes of Off-Highway Mobile Sources

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# Recommended Revisions to Gaseous Emission Factors From Several Classes of Off-Highway Mobile Sources

by

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Prepared for

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Office of Mobile Source Air Pollution Control
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# FOREWORD

This project was conducted for the U.S. Environmental Protection Agency by the Department of Emissions Research of Southwest Research Institute. The project was begun in August 1983 and completed in September 1984. The project was conducted under Work Assignment 8 of Contract 68-03-3162, and was identified within Southwest Research Institute as Project 03-7338-008.

Mr. Robert J. Garbe of the Emission Control Technology Division, Office of Mobile Source Air Pollution Control, Environmental Protection Agency, Ann Arbor, Michigan, served as EPA Project Officer until August 1984. Mr. Craig A. Harvey of the same office served as Project Officer after August 1984. Mr. Robert I. Bruetsch, of the same EPA Division was the Branch Technical Representative. Mr. Charles T. Hare, Manager, Advanced Technology, Department of Emissions Research, Southwest Research Institute, served as the Project Manager. The project was under the supervision of Melvin N. Ingalls, Senior Research Engineer, who served as Project Leader and principal investigator.

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# SUMMARY

This study examined three categories of off-highway mobile emission sources to determine current emission factors of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen ($NO_x$), together with the national and regional impact of these sources. The three sources examined were locomotives, construction equipment, and marine vessels. The emission factors for these sources, as listed in the EPA publication, "Compliation of Emission Factors" (generally referred to by its original report number, AP-42), are approximately ten years old. A literature search was conducted to identify changes in engine design and operation over the past ten years that would cause changes in emission factors. Additional measured emission data were also sought to broaden the data bases on which emission factors for these sources were based.

## Locomotives

For locomotives, it was found that rising fuel prices had led to improvements in engine design as well as changes in railroad operation. The principal operating change was to curtail the practice of running locomotives at idle when not in use. With locomotives being shut down more often when not in use, the duty cycles on which the locomotive emission factors were based needed to be changed. From a calculated estimate of line haul and switch engine operating time, new locomotive duty cycles were developed. The literature search found additional locomotive emission test data not used in the current listing of locomotive emission factors. Using the new duty cycles and the additional emissions test data, new locomotive emission factors were developed. A comparison of the new national average emission factors and the current AP-42 factors in terms of pounds of pollutant per 1000 gallons of fuel is shown below.

| | Locomotive National Average Emission factors, lb/1000 gal. of fuel | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| Revised locomotive estimate | 41.3 | 187 | 533 |
| Current AP-42 locomotive factors | 94 | 130 | 370 |

The revised factors are recommended as replacements for the current AP-42 locomotive emission factors.

The new national locomotive emission factors, together with the total railroad fuel usage in 1981, were used to calculate the national annual locomotive emissions of HC, CO, and $NO_x$. These emissions in terms of percentages of emissions from all sources for each pollutant, and in terms of the percentage of emissions from mobile sources are:

|  | Annual Locomotive Emissions As: |  |
|---|---|---|
|  | Percent of All Sources | Percent of Mobile Sources |
| HC | 0.3 | 0.9 |
| CO | 0.4 | 0.5 |
| $NO_x$ | 4.6 | 11 |

Three previous studies of locomotive emissions in several regions of the country were examined. In general, the HC and CO emissions from locomotives were well below two percent of HC or CO emissions from all sources in the regions examined. Locomotive $NO_x$ emissions were higher percentages of $NO_x$ emissions from all sources in each area. The Chicago area had one of the highest locomotive contributions to total $NO_x$, ranging from 3.6 to 8.1 percent of total $NO_x$ emissions, depending on the method used to determine the locomotive emissions. As stationary and on-highway $NO_x$ controls become more effective in the future, these percentages could increase.

## Construction Equipment

Early in the literature search for information on construction equipment, it was learned that the State of California had recently completed a study that included construction equipment. In response to that study, and as an input to the study, a consortium of industry groups sponsored a study of its own. This industry study, known as the CAL/ERT study, produced a set of construction equipment diesel emission factors based on the most comprehensive survey of construction equipment emissions to date. These diesel emissions factors do not differ greatly from the construction equipment emission factors in AP-42. Nevertheless, the new factors are recommended as replacements to the current AP-42 factors, because of the more extensive data base used. Each type of construction equipment (wheeled tractor, crane, etc.) has its own emission factor. However, an unweighted average was calculated for both the new recommended factors and the AP-42 factors. The comparisons of the averages and the ranges of HC, CO, and $NO_x$ between the new factors and the AP-42 factors are shown below.

|  | Diesel Emission Factors, g/bhp hr |  |  |
|---|---|---|---|
|  | HC | CO | $NO_x$ |
| Current AP-42 Const. Equip. Avg. | 0.83 | 2.70 | 11.7 |
| CAL/ERT Const. Equip. Avg. | 0.90 | 3.80 | 10.3 |
| Current AP-42 Const. Equip. Range | 0.36 to 1.39 | 1.80 to 4.40 | 6.6 to 15.7 |
| CAL/ERT Const. Equip. Range | 0.36 to 1.80 | 1.54 to 7.80 | 6.6 to 14.7 |

The CARB estimates of construction equipment annual emissions in California were scaled to provide an estimate of nationwide construction equipment annual emissions, as shown below.

| | Construction Equipment Nationwide Annual Emission As A: | |
|---|---|---|
| | Percent of All Sources | Percent of Mobile Sources |
| HC | 0.2 | 0.6 |
| CO | 0.6 | 0.7 |
| $NO_x$ | 2.0 | 4.7 |

Several areas in California were examined in the CAL/ERT study as well as by the California Air Resources Board (CARB) for regional impact of construction equipment emissions. In the South Coast Air Basin (Los Angeles area) and Fresno County the impact were:

| | Construction Equipment Emissions as Percent of Total Species Emissions | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| CAL/ERT Estimate, South Coast Air Basin | 0.08 | 0.20 | 0.91 |
| CARB Estimate, South Coast Air Basin | 0.25 | 0.64 | 2.45 |
| CAL/ERT Estimate, Fresno County | 0.18 | 0.60 | 2.20 |

## Marine Vessels

Marine vessels have also been affected by the rise in fuel costs over the past ten years. One of the more significant changes caused by this fuel cost change was the increased use of diesel powered vessels by the U.S. merchant fleet. Marine diesel engine manufacturers are also working to enable their engines to operate on poorer grades of fuel. The marine emission factors in AP-42 are based primarily on emission tests conducted in 1972 on 13 Coast Guard Cutters. There are few emission studies in the literature since that time. None of the literature surveyed provided sufficient valid information to determine new marine diesel engine emission factors. In addition there is insufficient usable information available to define either the numbers of various classes of marine vessels or the number of the various makes and models of diesel engines.

An estimate of national impact of marine vessels was obtained from railroad impact using the fact that inland waterway traffic carries about 42 percent of the freight railroads carry, and requires approximately 81 percent of the fuel per revenue ton-mile. The coastal and foreign shipping contributions were then included, to provide the estimate of marine vessels emission contribution to national emissions shown below. On a regional basis, marine vessels were estimated to contribute 1.5 percent of the total $NO_x$ in the New York area, and possibly as much as 2.5 percent of the total $NO_x$ in the Houston area.

|  | National Annual Marine Vessel Emissions As: |  |
|---|---|---|
|  | Percent of All Sources | Percent of Mobile Sources |
| HC | 0.2 | 0.6 |
| CO | 0.2 | 0.2 |
| $NO_x$ | 2.1 | 5.0 |

## Conclusions and Recommendations

The three off-highway emission sources investigated in this study are not yet major sources of gaseous pollutants. However, as more on-highway vehicles meet the current and future emission standards, uncontrolled off-highway emission sources will increase in importance. At the present time, the information required to accurately assess the pollution contribution of these off- highway sources is not available. While marine vessels require the most research to satisfy these information needs, railroad locomotives and construction equipment also require additional research. In fact, this study has shown that while marine emissions are based on the weakest data, emissions factors from the other two categories are not much better.

For locomotives, the most important information need is for a definition of locomotive duty cycles (in terms of hours per day in each throttle notch). The duty cycles should be based on a twenty-four hour day and include the time the engine is shut down. For construction equipment, where emission factors are based on new equipment, there is a need for in-service emissions measurements. These in-service measurements would allow the emission factors for new equipment to be adjusted to reflect actual emissions in the field.

It is recommended that a survey be made to determine how marine vessels should be classed for emission studies. The population of each class in U.S. waters should be obtained. In addition, the diesel engine population by manufacturer, model, and design horsepower should be obtained. Typical duty cycles in terms of power indication on the vessel (1/3, standard, full, etc.) should be defined from data collected during actual in-harbor operation of each class of vessel and the more popular engines. Finally, measurement of actual marine diesel exhaust emissions and fuel consumption is required at the engine operating conditions defined by the duty cycles.

# I. INTRODUCTION

Reliable information on air pollutant emissions from all sources is required by Federal, state, and local government environmental officials for air quality planning, standard setting, and evaluation of control requirements and strategies. Such information is also required by various public and private sector personnel performing site-specifc environmental impact analyses related to proposed construction projects. Information on emissions of pollutants from sources is usually in the form of emission factors. An emission factor is the measure of the rate at which a single source entity emits pollutants while performing its intended work function. Emission factors from almost all conceivable sources have been assembled in the EPA document, "Compilation of Air Pollutant Emission Factors" (AP-42).(1)* This document has become the standard reference for individuals and organizations requiring pollutant emission information.

In the category of Mobile Sources, on-highway vehicles, because of their great numbers, have received the most attention. There are currently national gaseous emissions standards for passenger cars, motorcycles, light trucks, and heavy duty truck engines. Off-highway mobile sources have received less attention, since past studies have shown them to be less important air pollutant sources. Currently, of all off-highway sources, only aircraft engines have regulations for gaseous emissions.

Studies are now projecting that off-highway sources will become a larger part of mobile source emissions, especially $NO_x$ emissions, in the future. In counties which do not meet one or more of the gaseous pollutant ambient air quality standards, off-highway mobile source emissions may require closer scrutiny. The latest edition (March 1981) of AP-42 (as the emission factor document has traditionally been called) did not include revision of the off-highway mobile source emission factors. Obviously, if off-highway mobile sources become a more significant part of the total air pollution burden, accurate off-highway emission factors are required. This project was performed to review the AP-42 gaseous emission factors for several off-highway mobile source categories.

## Objective

The objective of this study was to determine if any changes have occurred in gaseous emission levels from several off-highway mobile source categories since the last listing of their emission factors in AP-42. Only the regulated gaseous emissions, HC, CO and $NO_x$, were included in this study. If new emission factors were needed, they were recommended. The magnitude of each source category's contribution to the total pollutant emissions in representative regions was also determined. Recommendations were also made as to what, if any, additional testing, data collection or modeling is needed for these major off-highway sources.

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*Numbers in parentheses designate references at the end of the report.

## Selection of Source Categories

There are numerous categories of off-highway mobile sources, including:

- locomotives
- aircraft (military and commercial)
- marine vessels (military, shipping and fishing)
- farm equipment
- construction equipment
- industrial equipment
- lawn and garden implements
- transport refrigeration units
- off-highway recreational vehicles
- recreational aircraft (general aviation)
- inboard recreational marine craft
- outboard marine craft
- snowmobiles
- helicopters

The time and resources available to this project did not permit an investigation of emission factors from all categories of off-highway mobile sources. It was decided to select three of the major off-highway mobile source categories for study. After discussions with the EPA Branch Technical Representative, locomotives, construction equipment and marine vessels were selected for study. Each of these categories is discussed in a separate section of the body of this report.

## Off-Highway Mobile Sources and Photochemical Oxidants

At this point, a brief comment is in order to point out that the effect of the off-highway sources upon ambient photochemical chemical oxident levels is not covered in the report, and to explain the reason these effects are not covered. Two of the gaseous emissions from off-highway mobile sources HC and $NO_x$ contribute to the formation of photochemical oxidants in the ambient air. The amount of ozone($O_3$) in the air is taken as a measure of the photochemical oxidants level. There is currently an ambient air quality standard for ozone, but none for HC. It is due to the relationship between HC and ozone that there are HC emission standards for on-highway mobile sources. Hydrocarbons and $NO_x$ interact in the formation of ozone, but the interaction is complex and dependent on a number of variables other than the concentrations of HC and $NO_x$. In general, increasing the ambient HC concentration at constant $NO_x$ concentration either has no effect, or increases $O_3$ concentrations. The effect of $NO_x$ and $O_3$ formation varies with HC concentration. For a constant high ambient HC concentration, an $NO_x$ concentration increase is associated with an $O_3$ concentration increase. At low ambient HC concentrations, an $NO_x$ concentration increase can be associated with an $O_3$ concentration increase, no change in $O_3$, or an $O_3$ decrease.

Determining the effect of HC and $NO_x$ emission changes on ozone concentration requires the use of a computer model. One popular model is the EPA area-specific EKMA (Empirical Kinetic Modeling Approach) model. Plots from the EKMA program showing the relationship between HC, $NO_x$ and $O_3$ for

Fresno County and Sacramento, California, are included in Appendix A as examples of the complex relationship between the three pollutants. The estimation of ozone concentrations for an area in the future requires modeling that area with assumptions about all possible air pollution sources. Such a task is beyond the effort allotted for this study. Therefore, in examining each of the off-highway mobile sources, the effect on ozone concentrations due to changes in emission levels from these sources will not be discussed. It should be pointed out, however, that since most of the off-highway mobile sources investigated in this project are powered by diesel engines, the $NO_x$ emissions are far larger than the HC and CO emissions. In addition, while in 1982 there were only 11 counties in the country that exceeded the ambient $NO_x$ air quality standard, there were 477 counties where all or part of the county exceeded the ambient $O_3$ air quality standard.

# II. LOCOMOTIVES

While railroads are not presently the extensive mode of transportation they were 75 years ago, they still carry over 35 percent of the nation's freight, making them an important off-highway emission source. Since the early 1960's railroad locomotives in the U.S. have been almost exclusively diesel-powered. Over the past 20 years, there have been only a few models of locomotive diesel engines used in the United States. Operationally, the locomotive diesel is controlled by a throttle with eight distinct positions or "notches", in addition to idle and dynamic braking settings. These facts make the evaluation of locomotive emissions somewhat less complicated than other off-highway sources, since emission measurements are required at only ten different throttle settings of a few models of engines.

The time spent in each of these throttle notches determines the total amount of gaseous pollutants put into the air on a daily basis. This time-throttle position schedule is referred to as a duty cycle, and is comparable to the vehicle speed-time driving cycles used for automobile emissions. The determination of average locomotive duty cycles for line haul and switch engines is an important and integral part of determining locomotive emission factors.

After reviewing the locomotive emission factors in AP-42, a thorough search was conducted for published literature on locomotive emissions, changes in locomotive engines since 1972, changes in railroad operating practices, and statistics on number, size and manufacturer of locomotives in service. The search started with work done at SwRI, including literature collected by various individuals at SwRI working on locomotive engine studies. As part of this effort, a computerized search was conducted on the following data bases: SAE reports, ASME reports, NTIS, Doctoral Dissertations, and Engineering Index. The computerized search resulted in 583 abstracts, of which 28 appeared to be useful. Of the 28, 20 were on hand. The remaining eight were obtained for this project. The NTIS published search entitled "Emission Factors" was also consulted. The annual review and forecast issues of "Railway Age" magazine since 1970 were consulted for changes in locomotives, locomotive engines, and railway operations.

As part of the literature search, the EPA library at Research Triangle Park, which has a complete collection of OAQPS reports, was visited for a stack search of any reports not found by other means. In addition, representatives, of the U.S. suppliers of locomotives were contacted for information on their products. The Association of American Railroads (AAR) was contacted for emissions information and statistics. The Federal Railway Administration was also contacted for any information it might have.

## AP-42 Emission Factors

The locomotive emission factors in AP-42 were last updated in 1973. Locomotive emission factors in AP-42 are presented for a national average locomotive mix. Emission factors are also presented for two-stroke blower scavenged engines on both switching and road operating cycles, two-stroke turbocharged engines on road cycles, and four-stroke engines on both switching and road cycles. These emissions are presented in terms of pounds per 1000 gallons of fuel, kilograms per 1000 liters of fuel, grams per horsepower hour, and grams per metric horsepower hour. The HC, CO, and $NO_x$ emission factors were apparently derived from a study of three locomotive engines done at SwRI in 1972.(2) in addition, and approximate load factors of 0.4 was given for the road cycle, and a load factor of 0.06 for the switching cycle.

## Recent Trends in Railroad Operations and Locomotive Engines

The changes in the railroad industry that affect emissions are in two areas: railroad operations and locomotive engines. The literature and verbal information resulting from the information search indicated that there had been a great deal of change in the railroad industry over the past ten years. To begin with, there were fewer railroad companies in 1982 than there in 1972, mostly as a result of mergers. Railroads are divided in several classes by the Interstate Commerce Commission, depending on operating revenue. In 1965 Class I railroads had operating revenues above 5 million dollars. In 1976 the threshold for Class I railroads was raised to 10 million dollars, and in 1978 to 50 million dollars. The 1983 operating revenue threshold for Class I railroads was approximately 82 million dollars. In 1970 there were 71 Class I line haul railroad companies and 273 Class II railroad companies.(3) In 1979 there were 40 Class I and 23 Class II railroad companies.(3) By June 1982, the Class I railroad companies had dropped to 33 companies.(4)

The miles of track have also decreased from 331,129 in 1972 to 290,000 in 1980. Yet the revenue ton-miles of freight hauled increased from $771{,}168 \times 10^6$ in 1970 to $926{,}000 \times 10^6$ in 1981. The revenue passenger miles during the same period increased slightly from $10{,}903 \times 10^6$ to $11{,}800 \times 10^6$.(5)

Over the past ten years, the railroads have made a serious effort to reduce their fuel consumption. The reason for this effort is the sharp increase in fuel price, as shown in Figure II-1. In 1981, the average cost of a gallon of railroad diesel fuel was over nine times that for 1971.(5) The success of these fuel-saving efforts is shown by the fact that Class I railroads hauled 22 percent more ton-miles of freight per gallon of fuel in 1981 than they did in 1971.(5)

From an operational standpoint, the railroads instituted a number of changes to reduce fuel spillage and waste.(6) The change that affects emissions most is a change in the practice of allowing locomotives to idle when not in use. When fuel was cheap, it had been the practice of railroads never to shut down a locomotive in service. This practice was the result of design factors of locomotive diesels, which make start-up and warm-up a labor-intensive, time-consuming process. However, as fuel costs rose, the economies of having engines idling when not in use were examined. Many railroads instituted a policy of shutting down their locomotives if possible. While the guidelines vary from railroad to railroad, locomotives are in general shut down if they will not be needed within a following time period varying from one half to four hours. This practice is used as long as the ambient temperature is above some minimum, usually between 40° and 50°F.

The number of locomotives has remained relatively constant over the past ten years. In 1971 there were 27,189 locomotives in service, of which 26,897

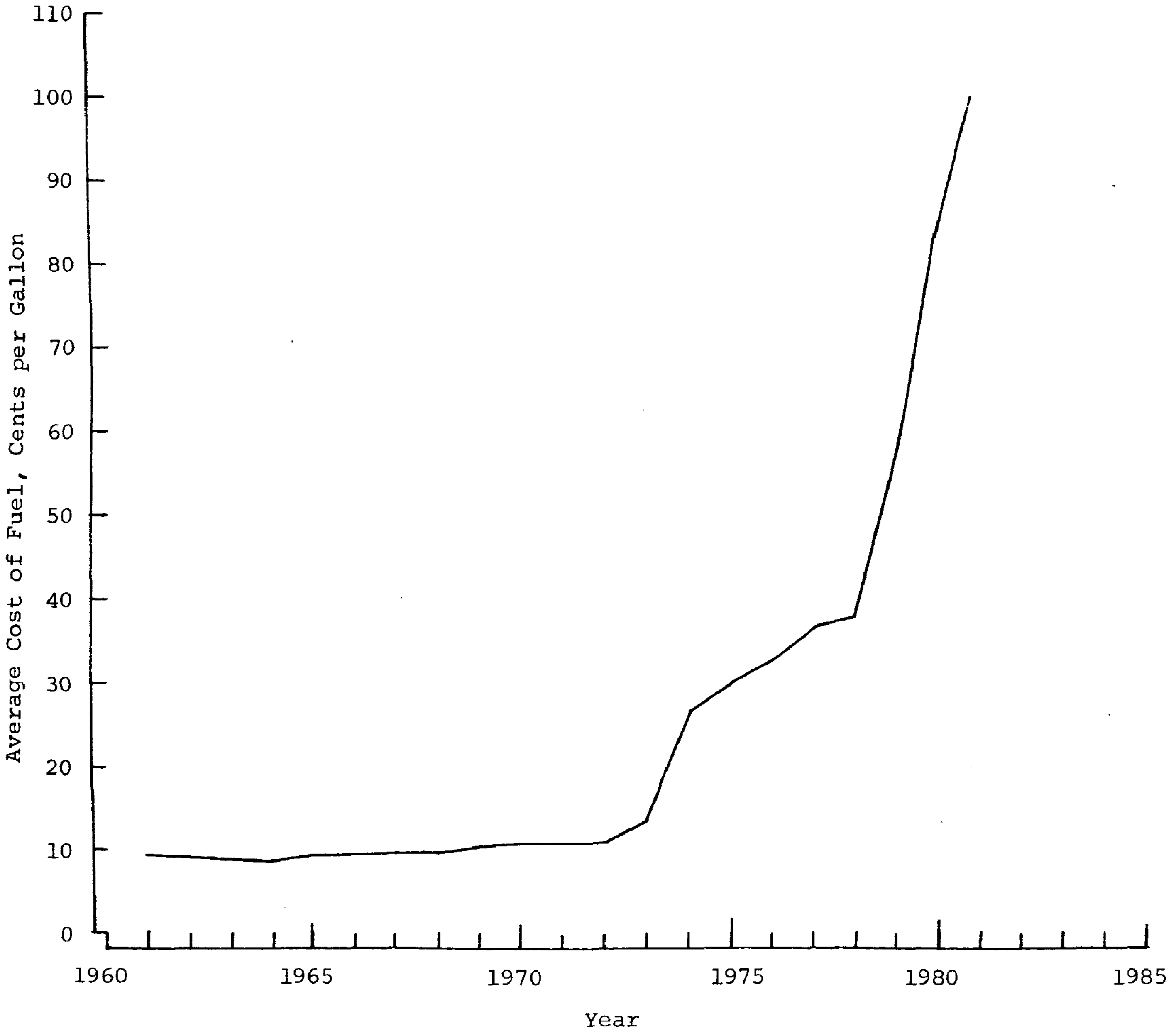

Figure II-1. Average cost of railroad diesel fuel by year were diesel electric units.(5) In 1981, there were 28,067 locomotives in service, of which 27,981 were diesel electric units. While the number of locomotives has increased only slightly, the total horsepower available has increased from 54.2 million in 1971 to 65 million in 1981.(5) The number of new locomotives delivered each year since 1972 is shown in Figure II-2. The age distribution is shown in Figure II-3. Note that 25 percent of the locomotives have been built since 1975, while approximately 28 percent of the locomotives in service were built before 1960.

There are currently only two manufacturers of locomotives in the United States, General Electric (G.E.) and Electro Motive Division of GM (EMD), and one in Canada (Bombardier). This has been the situation since 1969, when Alco ceased production in the U.S. Alco engines have continued to be used in Canada, first by MLW, then by its successor, Bombardier. Occasionally over the past ten years MLW/Bombardier has sold a few engines to U.S. Railroads; but all the remaining locomotives are either EMD or G.E., with EMD having the larger share of the market. Table II-1 lists the locomotives models currently sold by EMD and G.E.

Ten years ago it was possible to obtain statistics of the number of locomotives by size and manufacturer from the periodical, "Railway Locomotives and Cars." This magazine ceased publication in 1974. Since that time, it has been difficult to obtain statistics on the manufacturer and horsepower of locomotives in service. In a telephone conversation with Mr. Richard Cataldi of the Association of American Railroads (AAT), it was learned that sometime in 1984 the AAR will have a computerized data base of locomotives entitled "ULMER LOCOMOTIVE".(7) This data will be able to provide a breakdown of locomotives by manufacturer and horsepower. However, it will not be available for this project.

As a possible source of this information, Mr. Cataldi suggested the publication "Diesel Locomotive Rosters, U.S., Canada and Mexico".(8) This booklet is published for railroad hobbyists, and was available from a local hobby shop. The booklet contains a detailed roster of locomotives by railroad for over 70 railroads. The locomotives rosters were entered into a computer file, and processed to obtain a listing by horsepower and manufacturer using the SPSS statistical program. This distribution is shown in Table II-2. Note that over 80 percent of the locomotives are powered by EMD engines, and that EMD and G.E. account for approximately 95 percent of all locomotives. The total number of locomotives given in Table II-2 is greater than the total number of locomotives given in the text above. The number in Table II-2 includes railroads other than Class I railroads, while the other total reflected only locomotives in service on Class I railroads.

Over the past ten years, both U.S. manufacturers have worked to improve not only the efficiency of their diesel engines, but also the efficiency of their total drive system, including controls and drive wheel traction. A list of some of the changes made by both manufacturers from 1972 to 1982 is shown in Table II-3. It was reported that some of these changes are available as retrofit kits for older locomotives, but exactly what hardware is available for retrofit was not able to be determined.

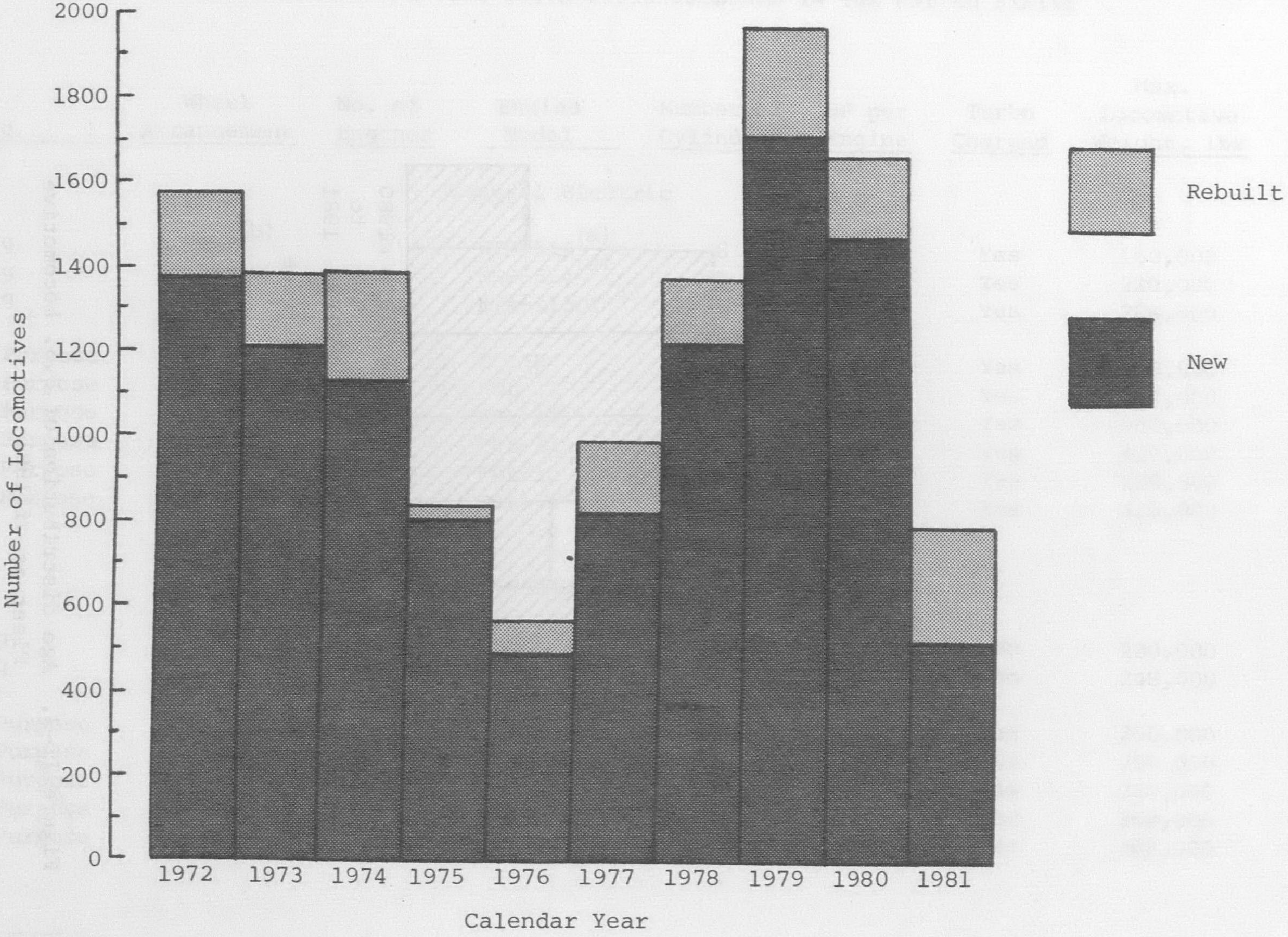

Figure II-2. Locomotive deliveries by year

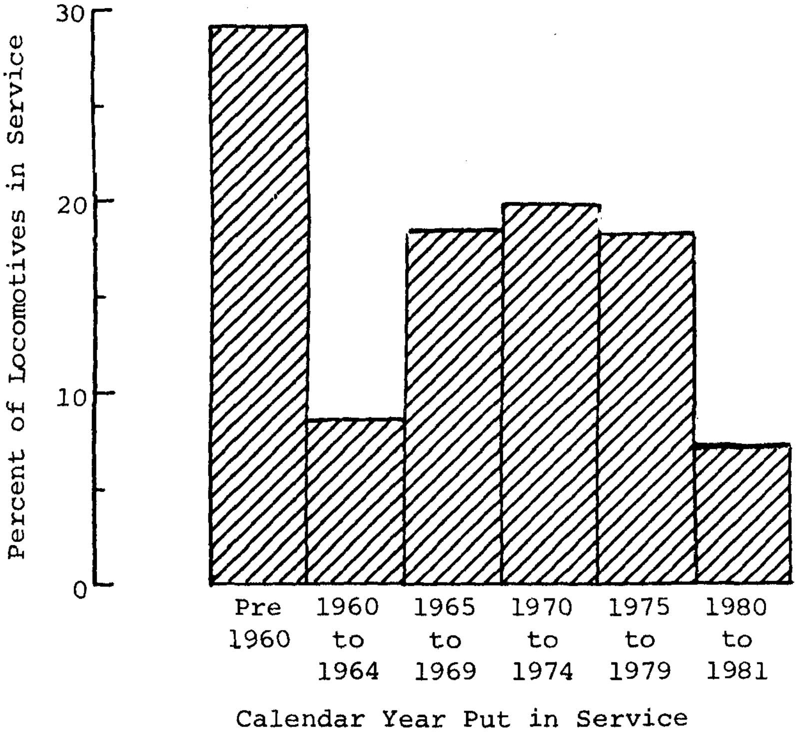

Figure II-3. Age distribution of U.S. Locomotive Fleet as of 1981

### TABLE II-1. LARGE DIESEL ELECTRIC LOCOMOTIVES PRODUCED IN THE UNITED STATES

| Model | Use | Wheel Arrangement | No. of Engines | Engine Model | Number of Cylinders | HP per Engine | Turbo Charged | Max. Locomotive Weight, lbs | Max. Speed, mph |
|---|---|---|---|---|---|---|---|---|---|
| | | | | General Electric | | | | | |
| SL80 | Switching | B-B[b] | 2 | NT855L4[a] | 6 | 300 | Yes | 160,000 | 21 |
| SL110 | Switching | B-B | 2 | NT855L4[a] | 6 | 300 | Yes | 220,000 | 21 |
| SL144 | Switching | B-B | 2 | KTA-1150L[a] | 6 | 550 | Yes | 288,000 | 35 |
| B18-7 | General Purpose | B-B | 1 | FDL-8 | 8 | 1800 | Yes | 268,000 | 70 |
| B23-7 | General Purpose | B-B | 1 | FDL-12 | 12 | 2250 | Yes | 280,000 | 70 |
| B30-7A | General Purpose | B-B | 1 | FDL-12 | 12 | 3000 | Yes | 280,000 | 70 |
| C30-7A | General Purpose | C-C[c] | 1 | FDL-12 | 12 | 3000 | Yes | 420,000 | 70 |
| B36-7 | General Purpose | B-B | 1 | FDL-16 | 16 | 3600 | Yes | 280,000 | 70 |
| C36-7 | General Purpose | C-C | 1 | FDL-16 | 16 | 3600 | Yes | 420,000 | 70 |
| | | | | EMD | | | | | |
| SW1001 | Switching | - | 1 | 8-645E | 8 | 1100 | No | 230,000 | 65 |
| MP15 | Switching | - | 1 | 12-645E | 12 | 1650 | No | 248,000 | 65 |
| GP38-2 | General Purpose | B-B | 1 | 16-645E | 16 | 2200 | Yes | 250,000 | 65 |
| GP40-2 | General Purpose | B-B | 1 | 16-645E3B | 16 | 3300 | Yes | 256,000 | 65 |
| GP50 | General Purpose | B-B | 1 | 16-645F3 | 16 | 3800 | Yes | 260,000 | 70 |
| SD40-2 | General Purpose | C-C | 1 | 16-645E3B | 16 | 3300 | Yes | 368,000 | 65 |
| SD50 | General Purpose | C-C | 1 | 16-645F3 | 16 | 3800 | Yes | 368,000 | 70 |

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(a) Manufactured by Cummins
(b) B-B is two sets of two axles
(c) C-C is two sets of three axles

## TABLE II-2. DISTRIBUTION OF LOCOMOTIVES BY MANUFACTURER AND HORSEPOWER[a]

| Horsepower Range | Manufacturer | | | | | |
|---|---|---|---|---|---|---|
| | EMD | GE | Alco. | Bombardier | Other and Unknown | Total |
| < 1000 | 481 | 8 | 8 | - | 3 | 500 |
| 1000-1499 | 2644 | 0 | 67 | - | 106 | 2817 |
| 1500-1999 | 7459 | 116 | 169 | - | 699 | 8443 |
| 2000-2499 | 4648 | 895 | 141 | 5 | 86 | 5775 |
| 2500-2999 | 1491 | 649 | 86 | 2 | 5 | 2233 |
| 3000-3999 | 8555 | 2451 | 32 | - | 1 | 11039 |
| 4000-4999 | 5 | 44 | - | - | 13 | 62 |
| 5000-5999 | 9 | 22 | - | - | - | 31 |
| 6000-6999 | 45 | 0 | - | - | - | 45 |
| Unknown | 22 | 25 | 19 | - | 195 | 261 |
| Total | 25359 | 4210 | 522 | 7 | 1108 | 31206 |

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[a] as of 1981

TABLE II-3. CHANGES IN DIESEL ELECTRIC LOCOMOTIVES - 1972 to 1981

| Year | G.E. | EMD |
|---|---|---|
| 1972 | Fluid amplifier water cooling system. New engine water filling and draining system. New wheel-slip detection and correction arrangement. | Introduced "Dash 2" series of locomotive with major changes in electrical controls |
| 1974 | Modification of speed-throttle notch schedule reduced smoke by 50%. | Changes in cylinder liners, pistons and fuel injectors for less smoke (1972-1974) |
| 1978 | Higher-efficiency turbocharger on 12-cylinder C28-7 locomotive. New two engine switch lomocotive (one engine can be shut down at idle), including more efficient traction motors. | |
| 1979 | Improvements in turbocharger, turbo seal system, optimization of engine speed schedule, modification in radiator fan and dynamic braking system. Claims a 7.2% fuel saving on B36-7 locomotive over the earlier U36B locomotive. | Production of the B version of the 645-E engine with improvements to give 3.3% fuel savings per locomotive. Changes: reduced idle speed, greater thermal efficiency, modifications in operation and control of dynamic braking and cooling fans. Use of automatic engine purge control. |
| 1980 | Production of the B36-7. Claims 8% less fuel consumption. Also 28 to 44% more adhesion, based on a new adhesion system. | Production version of the GP50 locomotive. Claims 3% less fuel consumption, 17% more power from same engine. Also 33% more adhesion based on a new adhesion system. Using the new 645F series engine. |
| 1981 | Production of C36-7 locomotive (six axle version of the B36-7) | Production of the SD50 (six axle version of the GP50) |

Many of the changes that resulted in fuel economy improvements have the potential to change the locomotive emission factors as currently listed in AP-42, due to changes in the locomotive duty cycle and changes in engine efficiency. The fuel economy improvements may result in changes to national and regional locomotive emission impact estimates as well, due to a reduction in hours of operation per ton-mile as well as changes in emission factors. Thus it is apparent that both the locomotive duty cycles and the emission factors given in AP-42 require revision.

## Revised Duty Cycles

Before new emission factors can be developed, the problem of how changes in railroad operations over the past ten years have affected the locomotive duty cycles must be resolved. As explained earlier, railroads no longer allow locomotives to idle for long periods of time when not in use. Since the duty cycles developed in the past were based on throttle clocks that ran when the engine was running, the standby idle time was included in the duty cycle. However, the duty cycles did not necessarily represent 24 hours-a-day operation, since the time the engine was not running was not included in the duty cycle. While some locomotives may have run for days at a time, on a yearly basis there were undoubtedly periods of engine shutdown for maintenance and inspection. The currently-used line haul and switching cycles are shown in Table II-4. Duty cycles reflecting current operating practices should show less time at idle. Any new duty cycle should also include a new category of "engine off", to reflect a 24 hour day status of the locomotive.

TABLE II-4. CURRENT LOCOMOTIVE DUTY CYCLES USED
FOR LINE HAUL AND SWITCHING LOCOMOTIVES

| | Percent Time in Mode | | |
|---|---|---|---|
| | G.E. Engines | EMD Engines | |
| Throttle Setting | G.E. Avg. 1 Cycle | EMD Line Haul (1972) | G.E. & EMD Engines ATSF Switching |
| Notch 1 | 5 | 3 | 10 |
| Notch 2 | 2.5 | 3 | 5 |
| Notch 3 | 2.0 | 3 | 4 |
| Notch 4 | 5.0 | 3 | 2 |
| Notch 5 | 2.0 | 3 | 1 |
| Notch 6 | 2.0 | 3 | 1 |
| Notch 7 | 2.5 | 3 | 0 |
| Notch 8 | 21 | 30 | 0 |
| Idle | 54 | 41 | 77 |
| Dynamic Braking | 4 | 8 | 0 |

The problem of defining new operational duty cycles is twofold: one, to define the time fraction for the various throttle notches during engine operation; and two, to define how many hours a day (on a yearly average) the locomotive operates on this duty cycle. In discussing this problem with representatives of the AAR and the two engine manufacturers, it appears that no duty cycle studies are available that reflect the current operational patterns of railroad locomotives. The lack of current duty cycles and information on percent of total time locomotives are in operation are important deficiencies in the information needed to determine accurate emission factors for locomotives. Since the duty cycle is so critical to usable locomotive emission factors, it was decided to attempt to develop revised switching and line haul duty cycles from available information.

A statistical summary published by the Association of American Railroads (AAR) provided the information necessary to calculate the average number of hours per day a locomotive is in actual use.(9) For 1980, the latest statistics available, an average freight locomotive was in actual operation 9.2 hours per day. Appendix B contains the details of the calculations for this value.

Currently published and utilized duty cycles were developed from throttle clocks which did not account for the time a locomotive engine was not running. It is assumed that locomotives are available approximately 96 percent of the time. Then on the average, a locomotive is available 23 hours per day. The 1980 freight locomotive operation (non-idle) time of 9.2 hours, is then approximately 40 percent of 23 hours. The "G.E. Average 1" (G.E. A1) duty cycle, with 46 percent non-idle time, comes closer to having 40 percent non-idle time than the EMD line haul cycle, with 59 percent non-idle time. Thus, the "G.E. A1" cycle will be used as the basis for a new line-haul duty cycle.

To adjust the G.E. A1 cycle to reflect current railroad operating practices, it is necessary to make some estimate of the decrease in average daily idle time that has resulted from shutting engines down when not needed (at ambient temperatures above 50°F). Using the "Climatic Atlas of the United States,"(10) it was estimated that, considering the entire country, conditions allow locomotive engine shutdown in approximately 55 percent of the occurrences. The basis of this estimate is shown in Appendix B. A revised 24-hour line haul operating cycle based on the G.E. A1 cycle, 96 percent locomotive availability (23 hours per day), and idle time equal to 45% of the original 12.42 hours of idle (54 percent of 23 hours) is presented in Table II-5.

TABLE II-5. REVISED LINE HAUL LOCOMOTIVE DUTY CYCLE

| Engine Condition | Percent of Total Time | Hours of a 24 Hour Day |
|---|---|---|
| Engine Off | 32.6 | 7.83 |
| Idle | 23.3 | 5.59 |
| Dynamic Braking | 3.8 | 0.92 |
| Notch 1 | 4.8 | 1.15 |
| Notch 2 | 2.4 | 0.58 |
| Notch 3 | 1.9 | 0.46 |
| Notch 4 | 4.8 | 1.15 |
| Notch 5 | 1.9 | 0.46 |
| Notch 6 | 1.9 | 0.46 |
| Notch 7 | 2.4 | 0.58 |
| Notch 8 | 20.1 | 4.83 |

A similar, but simplified, analysis can be performed to give a new switching cycle. For the switching cycle, it is assumed that the ATSF switching cycle is correct, and that switch engines are also available 96 percent of the time. For a 23-hour day, the ATSF switching cycle has 17.7 hours at idle and 6.3 hours non-idle operation. From the AAR statistics an average switch engine travels 83.4 miles/day (see Appendix B). This gives an average switch engine speed of approximately 13 miles per hour while operating. If it is again assumed that idle time has been reduced by 55 percent, then the revised 24-hour switching cycle is as shown in Table II-6.

TABLE II-6. REVISED SWITCHING LOCOMOTIVE DUTY CYCLE

| Engine Condition | Percent of Total Time | Hours of a 24 Hour Day |
|---|---|---|
| Engine Off | 44.7 | 10.74 |
| Idle | 33.2 | 7.97 |
| Dynamic Braking | 0.0 | 0.00 |
| Notch 1 | 9.6 | 2.30 |
| Notch 2 | 4.8 | 1.15 |
| Notch 3 | 3.8 | 0.92 |
| Notch 4 | 1.9 | 0.46 |
| Notch 5 | 1.0 | 0.23 |
| Notch 6 | 1.0 | 0.23 |
| Notch 7 | 0.0 | 0.00 |
| Notch 8 | 0.0 | 0.00 |

## Revised Emission Factors

The literature search revealed only a small amount of published information on emission factors. The locomotive emission factors in AP-42 are apparently based solely on the three engines tested at SwRI in 1972.(2) Previous to the SwRI work, some emission tests were done under sponsorship of the AAR and three railroad companies.(11) Subsequent to the 1972 work, SwRI measured emissions on a limited number of railroad engines for a variety of organizations in the 1972 to 1975 time period. Most of this work has been published as contract final reports and ASME papers.(12,13) There are also two papers in which EMD reported some results of their own emission tests.(14,15) Table II-7 lists the published studies and the engines tested. The AAR has recently completed an emission study of 40 locomotives, both before and after rebuilding. The data analysis is not completed, and a published final report on that study is not expected until late 1984.

The published studies listed in Table II-7 which presented actual emissions measurements were reviewed. There are only six useful studies which present emission measurements, but some of the studies have resulted in more than one publication. For purposes of this project, these studies have been numbered chronologically and referred to as Study 1 through Study 6. The studies are listed in Table II-8, which contains the study number, report references, date of study, and engines on which emissions were measured.

## TABLE II-7. PUBLISHED STUDIES OF MEASURED LOCOMOTIVE EMISSIONS

| Report Title | Study Sponsor | Report Date | Report Number | Locomotive Engines Tested |
|---|---|---|---|---|
| "Report on Exhaust Emission of Selected Railroad Diesel Locomotives" | AAR and AT&SF, SP, and UP Railroads | March 1972 | --- | one G.E. FDL-16<br>Two EMD 645E3 (turbo)<br>One EMD 645E1 (roots blown) |
| "Status Report on Locomotives as Sources of Air Pollution" by Max Ephraim Jr. | EMD | 1972 | SAE 720604 | Unknown number of EMD 645E |
| "Exhaust Emissions fron Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Part I - Locomotive Diesel Engines and Marine Counterparts" by Charles Hare and Karl Springer, Southwest Research Institute | EPA | October 1972 | | One EMD 12-567<br>One EMD 16-645E3<br>One G.E. 7FDL-16 |
| "Locomotive Exhaust Emissions and Their Impact" by Charles Hare, Karl Springer, and Thomas Huls | EPA | April 1974 | ASME 74-DGP-3 | (same tests as Oct. 1972 study) |
| "$NO_x$ Studies with EMD 2-567 Diesel Engine" by John Storment, Karl Springer, and K. Hegenrother | DOT and EPA | April 1974 | ASME 74-DGP-14 | One EMD 2-567 |
| "Exhaust Emissions of Selected Railroad Diesel Locomotives" by A.H. Bryant and T.A. Tennyson | AAR and AT&SF, SP, and UP Railroads | November 1974 | ASME 74-WA/RT-1 | (same tests as March 1982 study) |
| "Four Cycle Diesel Electric Locomotive Exhaust Emissions: A Field Study" by J.G. Hoffman, Jr., Karl Springer, and T.A. Tennyson | General Electric and SP Railroad | April 1975 | ASME 15-DGP-10 | Seven G.E. 7FDL-16 |

## TABLE II-8. CHRONOLOGICAL LIST OF LOCOMOTIVE EMISSION STUDIES USED

| Study | Test Dates | Locomotives Tested | References |
|---|---|---|---|
| 1 | March, April 1971 | two EMD 645E3 turbo, 20 cyl.<br>one EMD 645E blown, 16 cyl.<br>one G.E. FDL turbo, 16 cyl. | 11, 16, 17 |
| 2 | Report Date 1972 | unknown number of 1972 EMD 645E engines both turbo and blown | 14 |
| 3 | April 1972 | one EMD 567 blown, 12 cyl.<br>one EMD 645E3 turbo, 16 cyl.<br>one G.E. 7FDL turbo, 16 cyl. | 2, 18 |
| 4 | Nov. 72 to March 73 | one EMD 567 blown, 2 cyl. with three different injectors | 12, 19 |
| 5 | 1972 to 1974 | seven G.E. 7FDL turbo, 16 cyl. | 13, 20 |
| 6 | Report Date 1983 | unknown number of EMD 645F3B turbocharged engines | 15 |

Results from tests of nine G.E. locomotives are available. Test results from two EMD 567 engines and four EMD 645E engines (3 turbocharged and 1 roots-blown) are available. The average emissions from an unknown number of EMD 645E engines (turbocharged and roots-blown calculated separately) as measured by EMD are also available. Finally, the cycle emissions from an EMD 645F engine tested on the UIC/ORE duty cycle are available. The tests of all these engines were performed between 1971 and 1982, and include the SwRI tests on which the current AP-42 emission factors are based. As far as can be ascertained, this is a complete collection of all the measured locomotive emission published in the open literature. While these data can be used to enlarge the AP-42 data base, there is little published information on which to base emission factors of the new fuel-efficient engines being produced by both G.E. and EMD. A request was made for unpublished data from the locomotive engine manufacturers but none were obtained.

Considerable effort was expended to try to reconcile and aggregate these results into on cohesive set of emission factors. This effort was complicated by results being presented using different duty cycles, different measurement techniques for $NO_x$ and the fact that some $NO_x$ values were corrected for humidity and some were not. Some studies also presented throttle notch-by-throttle notch emissions; others presented only composite cycle emissions.

To include as much data as possible, it was decided to initially calculate composite cycle emission factors based on two different, but similar current duty cycles. The cycle called the "G.E. average 1" cycle was used for the G.E.

engines, and the cycle called the "EMD line haul" cycle was used for the EMD engines. The percent time spent in each throttle notch for these two cycles is shown previously in Table II-4. After the emission factors for the various engine models were determined using the current duty cycles, they were adjusted for the revised duty cycles.

It was decided that the chemiluminescent technique for $NO_x$ would be used as the reference measurement method of $NO_x$. In study 1, where a chemiluminescent $NO_x$ analyzer was not used, the NDIR NO readings were multiplied by 0.95 to approximate chemiluminescent $NO_x$ values. For study 2, the $NO_x$ reading was multiplied by 0.89, to reflect EMD in-house experience. All $NO_x$ values were corrected for humidity by multiplying the $NO_x$ value by a humidity correction factor, k, defined as:

$$k = \frac{1}{1-0.0025(H-75)}$$

Where H is the specific humidity in grams per pound of dry air.

Table II-9 presents a summary of all the emissions data available by engine type, expressed in terms of g/bhp-hr on the current line haul cycles. These data are not the recommended emission factors. Rather, these measured emissions require evaluation and alteration based on demonstrated relationships between engine types and conversion to the revised duty cycles to arrive at final emissions factors.

The G.E. engines were examined first. G.E. changed the throttle stop-engine speed schedule about 1974. Fortunately, Studies 3 and 5 tested G.E. engines using both speed schedules. There are emissions data available from five G.E. engines using the new speed schedule. The average of these engines was taken as the basis for all G.E. engine emissions. Two other configurations of G.E. engines were calculated. One configuration used the original speed schedule; the other configuration was with the new speed schedule and a low sac injector. There were four G.E. locomotives tested with the old speed schedule.

Study 3 tested one locomotive on both speed schedules, and Study 5 tested two locomotives on both schedules. The differences in the average HC and CO emissions between the four engines with the old speed schedule and the five engines with the new speed schedule agree with the changes seen on the individual engines in Studies 3 and 5. However, the difference in the average $NO_x$ value is less than the difference seen in the individual engine tests. Studies 3 and 5 both showed a 4.5 percent decrease in $NO_x$ emissions when an engine was changed from the old speed schedule to the new speed schedule. Since the new speed schedule values are serving as the basis for the G.E. engine emission values, the recommended $NO_x$ emission factor for the old speed schedule is 4.5 percent higher than the new speed schedule value, or 14.8 g/bhp hr. Study 5 presented data on one engine with low sac injectors. These data are used to calculate the emission factors for new G.E. engines.

## TABLE II-9. MEASURED LOCOMOTIVE EMISSIONS FROM PUBLISHED STUDIES EXPRESSED IN GRAMS PER HORSEPOWER HOUR ON LINE HAUL CYCLES

| Engine Description | Number Tested | Avg. Emissions, g/bhp-hr, (range) HC | CO | $NO_x$ |
|---|---|---|---|---|
| **General Electric Engines** | | | | |
| FDL, old speed schedule (1957 to approx. 1974) | 4 | 2.2 (1.7 to 2.5) | 4.2 (3.6 to 4.5) | 14.0 (10.9 to 18.9) |
| FDL, new speed schedule (approx. 1973 to present) | 5 | 2.3 (2.0 to 2.6) | 2.5 (2.0 to 3.0) | 14.2 (10.4 to 19.7) |
| FDL, new speed sch. low sac injectors | 1 | 0.6 | 1.8 | 10.7 |
| **Electromotive Division** | | | | |
| EMD 567 spherical injectors pre 1959 | 1 | 2.7 | 6.4 | 12.1 |
| EMD 567 needle injectors 1959 to 1966 | 1 | 1.2 | 10.7 | 9.8 |
| EMD 567 low sac injectors (retrofit after 1972) | 1 | 0.7 | 7.4 | 13.0 |
| EMD 645E blown, needle injector (1966 to 1972) | unknown | 1.1 | 10.8 | 12.5 |
| EMD 645E turbo, needle injectors (1966 to 1972) | | 0.8 (0.7 to 0.9) | 3.2 (2.5 to 4.0) | 11.6 (8.7 to 11.6) |
| EMD 645F3B turbo, low sac injectors | unknown | 0.4(a) | 0.6(a) | 14.1(a) |

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(a) on UIC/ORE cycle

The analysis of the EMD engine emissions is more involved. SAE paper 720604 (Study 2) presents the average emissions results from a number of new 645E engines as tested by EMD. These engines were tested in 1972. Apparently, they were equipped with the standard (not low sac) needle injectors. In a telephone discussion of EMD emissions measurements with Mr. Hugh Williams of EMD(20) it was learned that during this time period, EMD used NDIR instrumentation for NO measurement and UV for $NO_2$. EMD has since converted to measurement of $NO_x$ by chemiluminescence (CL). Their experience is that CL $NO_x$ measurements are 11 percent lower than $NO_x$ levels measured using NDIR and UV. Applying this 11 percent to the $NO_x$ values in Study 2 gives $NO_x$ values of 12 g/bhp hr for the turbocharged, and 13 g/bhp hr for blown version of the EMD 645 engine. Since this study appears to use the largest number of engines, it will be used as the basis for the EMD emission factors.

The HC emissions from one of the 645E turbocharged engines tested in Study 1 and the 645 turbo engine tested in Study 3 agree with the HC emission level of Study 2, giving a range of HC values from 0.7 to 0.9 g/bhp-hr. The $NO_x$ levels from all three 645E turbo engines tested in Studies 1 and 3, while lower than the Study 2 average, show fair agreement with the average $NO_x$ (adjusted to CL $NO_x$) values from Study 2. The CO levels from one of the 645E turbo engines from Study 1 and the CO level from the 645 turbo engine tested in Study 3 agree with the Study 2 values, giving a CO range from 2.5 to 4.0 g/bhp-hr. The HC and CO emissions from one 645E turbo engine tested in Study 1 (locomotive SP8803) did not agree well with HC and CO emission levels from the other studies. Therefore, these emissions were not used in the final analysis of the EMD 645 emission factors.

The emission factors for both the G.E. and EMD line haul engines using current duty cycles are presented in Table II-10. Since the emission factors, which represent fleet averages, are based on very few engine tests, there is no justification for presenting them to more than two significant figures. The purpose in this analysis was to obtain the emission relationships between the various engine models using as many data as possible. Once these trends were established, the emission factors using the revised duty cycles could be calculated.

Where emissions data were available by individual notch setting, revised emission factors were obtained using the revised duty cycle percent time-in-notch as revised weighting factors. Where only composite emission factors were available, revised composite emission factors were developed by changing the original ones in proportion to change made in the notch-by-notch factors. The resulting revised emission factors, recommended as replacements for the current AP-42 emission factors, are shown in Tables II-11 and II-12.

These emission factors are in terms of mass of emissions per power output. To use these factors for regional impact, total horsepower hours for the region by line haul and switch engines must be known. This information is generally not readily available. What is normally available is the number of locomotives in a region. From the data in Table II-2 and some assumptions about which locomotives are line haul and which are switchers, it should be possible to determine an average horsepower for line haul and switch engines.

TABLE II-10. LINE HAUL LOCOMOTIVE BASED ON CURRENT DUTY CYCLES EMISSION FACTORS

| Engine Description | Line Haul Emission Factor, g/bhp hr HC | CO | $NO_x$ |
|---|---|---|---|
| General Electric Locomotives | | | |
| FDL, old speed schedule (1957-1974) | 2.2 | 4.2 | 14 |
| FDL, new speed schedule (1974 to approx. 1980) | 2.3 | 2.5 | 14 |
| FDL, after approx. 1980 | 0.6 | 1.8 | 14 |
| Electromotive Division | | | |
| 567 spherical injectors (pre 1959) | 2.7 | 6.4 | 12 |
| 567 needle injectors (1959 to 1966) | 1.2 | 11 | 10 |
| 645E needle injectors, blown (1966 to 1972) | 1.1 | 11 | 13 |
| 645E needle injectors, turbo (1966 to 1972) | 0.8 | 3.2 | 12 |
| 567 low sac injectors (retrofit after 1972) | 0.7 | 7.4 | 13 |
| 645E low sac, blown (1972 - ) | 0.6(a) | 7.6(a) | 17(a) |
| 645E low sac, turbo (1972 - ) | 0.5(a) | 2.2(a) | 16(a) |
| 645F low sac, turbo (1982 - ) | 0.4 | 0.6 | 14 |

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(a) estimated from 567 trends

## TABLE II-11. RECOMMENDED LINE HAUL LOCOMOTIVE EMISSION FACTORS BASED ON SWRI 1983 OPERATING CYCLE

| | Line Haul Emission Factor g/bhp-hr | | | Cycle | |
|---|---|---|---|---|---|
| Engine Description | HC | CO | NOx | Load Factor | Cycle BSFC |
| **General Electric Locomotives** | | | | | |
| FDL, old speed schedule (1957-1974) | 2.1 | 4.2 | 14 | 0.275 | 0.364 |
| FDL, new speed schedule (1974 to approximately 1980) | 2.2 | 2.4 | 14 | 0.279 | 0.344 |
| FDL, after approximately 1980 | 0.6 | 1.6 | 14 | 0.279 | 0.344 |
| **Electromotive Division** | | | | | |
| 567 spherical injectors (pre 1959) | 2.7 | 6.1 | 12 | 0.268 | 0.516 |
| 567 needle injectors (1959 to 1966) | 1.2 | 10 | 10 | 0.269 | 0.507 |
| 645E needle injectors, blown (1966 to 1972) | 1.1 | 11 | 13 | 0.270 | 0.409 |
| 645E needle injectors, turbo (1966 to 1972) | 0.8 | 3.2 | 11 | 0.277 | 0.379 |
| 567 low sac injectors (retrofit after 1972) | 0.6 | 7.1 | 13 | 0.273 | 0.469 |
| 645E low sac, blown (1972 - ) | 0.6(a) | 7.6(a) | 17(a) | 0.274(a) | 0.378(a) |
| 645E low sac, turbo (1972 - ) | 0.5(a) | 2.2(a) | 15(a) | 0.281(a) | 0.351(a) |
| 645F low sac, turbo (1982 - ) | 0.4 | 0.6 | 14 | 0.281(b) | 0.336(c) |

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(a) Estimated from 567 trends
(b) Estimated from 645E
(c) Estimated from 645E and Reference 1.

## TABLE II-12. RECOMMENDED SWITCHING LOCOMOTIVE EMISSION FACTORS BASED ON SWRI 1983 OPERATING CYCLE

| Engine Description | Switching Emission Factor, g/bhp-hr | | | Load Factor | Cycle BSFC |
|---|---|---|---|---|---|
| | HC | CO | NOx | | |
| General Electric Locomotives | | | | | |
| FDL, old speed schedule (1957-1974) | 3.0 | 8.4 | 19 | 0.043 | 0.464 |
| FDL, new speed schedule (1974 to approx. 1980) | 3.5 | 4.6 | 19 | 0.049 | 0.432 |
| FDL, after approximately 1980 | 0.8 | 3.3 | 14 | 0.049 | 0.432(b) |
| Electromotive Division | | | | | |
| 567 spherical injectors (pre 1959) | 5.9 | 2.7 | 15 | 0.033 | 0.924 |
| 567 needle injectors (1959 to 1966) | 3.3 | 3.0 | 15 | 0.035 | 0.815 |
| 645E needle injectors, blown (1966 to 1972) | 2.2 | 7.1 | 29 | 0.036 | 0.520 |
| 645E needle injectors, turbo (1966 to 1972) | 2.2 | 7.8 | 13 | 0.043 | 0.482 |
| 567 low sac injectors (retrofit after 1972) | 1.1 | 1.8 | 17 | 0.040 | 0.616 |
| 645E low sac, blown (1972 - ) | 0.7(a) | 4.3(a) | 33(a) | 0.041(a) | 0.393(a) |
| 645E low sac, turbo (1972 - ) | 0.7(a) | 4.7(a) | 15(a) | 0.049(a) | 0.364(a) |
| 645F low sac, turbo (1982 - ) | 0.9 | 1.6 | 17 | 0.049(b) | 0.349(c) |

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(a) Estimated from 567 trends

(b) Assumed value

(c) Estimated from 645E and Reference 1.

If a weighted percent horsepower (load factor) is known with the brake specific emission factor for each cycle, then emissions in grams per hour and per year can be calculated from available data. Sometimes fuel consumption is the best information available. In these cases, a cycle BSFC would allow the use of the g/bhp-hr emission factors. To facilitate these calculations, cycle load factors and cycle BSFC values are included in Tables II-11 and II-12.

These detailed emission factors are useful for studies where detailed information about locomotives is available. This availability is not generally the situation. The remaining task was to combine the factors, using information on age distribution of each manufacturers locomotives and the percentage of the locomotive population represented by each manufacturer, to obtain a set of revised national average emission factors in terms of pounds per thousand gallons of fuel. These factors can be compared to the national average factors currently in AP-42. The data put on computer file from "Diesel Locomotive Rosters"(8) were used to determine the fraction of total locomotives in each of the year brackets shown in Tables II-11 and II-12 for both manufacturers, with line haul and switch engines calculated separately. These values are shown in Tables II-13 and II-14.

TABLE II-13. DISTRIBUTION OF EMD ENGINES BY YEAR OF MANUFACTURER, TYPE OF ENGINE AND ENGINE MODEL

| | 1965 or Earlier | 1966-1971 | 1972-1981 |
|---|---|---|---|
| | Percent of EMD Switch Engines | | |
| 567 with needle injectors | 33.7 | -- | -- |
| 567 with low sac injectors | 33.6 | -- | -- |
| 645 blown w/ needle injectors | -- | 3.9 | -- |
| 645 turbo w/ needle injectors | -- | 3.9 | -- |
| 645 blown w/ low sac injectors | -- | 3.9 | 6.9 |
| 645 turbo w/ low sac injectors | -- | 3.9 | 10.3 |
| | Percent of EMD Line Haul Engines | | |
| 567 with needle injectors | 16.0 | -- | -- |
| 567 with low sac injectors | 16.0 | -- | -- |
| 645 blown w/ needle injectors | -- | 6.6 | -- |
| 645 turbo w/ needle injectors | -- | 6.6 | -- |
| 645 blown w/ low sac injectors | -- | 6.6 | 16.7 |
| 645 turbo w/ low sac injectors | -- | 6.6 | 25.0 |

TABLE II-14. DISTRIBUTION OF G.E. ENGINES BY YEAR OF MANUFACTURER

| | Percent of G.E. Engines by Type | | | |
|---|---|---|---|---|
| | 1973 or Earlier | 1974-1980 | 1981 or Later | Total |
| Switching | 100 | 0 | 0 | 100 |
| Line Haul | 65.4 | 34.3 | 0.3 | 100 |

National average line haul and switch engine emission factors in terms of g/bhp hr were then calculated using the national fractions as weighting factors for the emissions values and BSFC from Tables II-11 and II-12. The emission factors were converted to lbs per 1000 gallons of fuel using the national average weighted BSFC. These national average line haul and switching emission factors are shown in Table II-15. Line haul engines represent 80.1 percent of the engines in service, with switch engines the remaining 19.9 percent.(9) Using these percentages, total national average locomotive emission factors were calculated. These factors are also shown in Table II-15.

TABLE II-15. NATIONAL AVERAGE LOCOMOTIVE EMISSION FACTORS

| | Emission Factors, pounds/1000 gallons of fuel | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| Switch Engines | 47.4 | 86.8 | 468 |
| Line Haul Engines | 38.9 | 226 | 558 |
| All Engines | 41.3 | 187 | 533 |
| Current AP-42 Factor | 94 | 130 | 370 |

## National and Regional Impact

Using the national average emission factors shown in Table II-15 and the total nationwide railroad fuel used in 1981 from Reference 5, the nationwide annual railroad emissions in 1981 were determined. The total nationwide emissions for each gaseous pollutant from all sources were obtained from the EPA summary of 1981 emissions.(21) From the nationwide emissions from all sources, the locomotive emissions as percentages of emissions from all sources and from mobile sources were calculated. The results of the calculation are shown in Table II-16.

TABLE II-16. NATIONAL IMPACT OF LOCOMOTIVE EMISSION

| | Nationwide | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| All sources, metric tons/year | 21 x $10^6$ | 91 x $10^6$ | 19.5 x $10^6$ |
| All mobile sources, metric tons/year | 7.5 x $10^6$ | 70 x $10^6$ | 8.2 x $10^6$ |
| Locomotives, metric tons/year | 70,371 | 318,631 | 908,184 |
| Locomotives, percent of all sources | 0.3 | 0.4 | 4.6 |
| Locomotives, percent of mobile sources | 0.9 | 0.5 | 11 |

Three studies were obtained that examined the impact of locomotive emissions on a regional basis(22,23,24). One of the reports (reference 24) was a draft of the EPA "Report to Congress on Railroad Emissions." This draft report presented the results of an examination of railroad emissions impact or five different areas: Philadelphia, Chicago, St. Louis, Kansas City and Los Angeles. Reference 22 reports on the study done by Walden Research Division of Abcor, Inc., to determine locomotive emissions in the St. Louis area for the RAPS (Regional Air Pollution Study) program. The remaining study, done by the University of Michigan (UofM) School of Public Health under an EPA grant, examined the impact of locomotive emissions in the Chicago area.

The draft Report to Congress used three different methods to determine the railroad emissions in each of the five areas studied. The first method used an estimate of the number of locomotives in the area together with duty cycles in terms of number of hours per day in various throttle notches and emissions in grams per hour to obtain the total locomotive emissions in each area. The second method used gross ton miles of freight hauled and pounds of fuel burned per ton-mile of freight to get non-idle fuel consumption. Fuel consumption at idle and for switch engines was estimated from non-idle line haul fuel consumption. The third method used county-by-county annual fuel consumption (estimated from statewide annual fuel consumption) and the national average emission factors in AP-42 in terms of pounds of emissions per thousand pounds of fuel.

The Walden Research study used the most detailed methodology with the most measured data. It allocated railroad activity by maps of track location and a complete, one-day inventory of railroad activity including:

- Routing, routine and locomotive information for each train in the study area
- Total active and idle hours and locomotive information for each rail yard in the AQCR
- Interyard transfer routing and run time

The annual horsepower hours of operation in each grid were determined from the railroad activity information, data from the manufacturers, and the SwRI locomotive study for EPA.(2) The fuel used in each grid was computed from the annual horsepower hours of operation in each grid and fuel consumption derived from AP-42. The grid emissions were then calculated using the emission factors for each engine type in terms of pounds per thousand pounds of fuel as given in AP-42. Total annual emissions in the AQCR were obtained by summing the emissions from each grid.

The Chicago study by UofM determined the annual emissions using an average engine horsepower and load factor and annual hours of locomotive operation in the AQCR, together with emission factors in grams per horsepower hour from the SwRI locomotive study. The calculation of hours of locomotive operation was begun by determining the miles of track in the AQCR, then expressing this track mileage as a fraction of total national track mileage. The hours of line haul operation and switchyard activity in the Chicago AQCR were both assumed to be this same fraction of the total national line haul and switchyard hours of activity.

The locomotive emissions in tons per year from each of the studies are presented in Table II-17. As can be seen from the table, the individual estimates for each area vary widely. Except for the values of HC, the St. Louis estimates made by the EPA study do not differ too greatly from the St. Louis estimates made in the Walden Research study. As stated above, the Walden Research study appears to be based on the greatest amount of measured or sampled data, and so is considered to have the best credibility. Comparing the St. Louis estimates with the Chicago estimates, it is obvious that the UofM study underestimates the locomotive emissions in the Chicago area. It would be reasonable to expect the Chicago emissions to be much larger than the St. Louis emissions, yet the Chicago emissions estimates from the UofM study are nearly equal to the St. Louis estimates from the Walden Research study. Because the Chicago estimates from the UofM study are apparently too low, they will be dropped from this discussion.

The locomotive emissions as percentages of the total emissions in the AQCR are presented in Table II-18. These percentages are based on the 1977 National Emissions Report. Note that regardless of the method or study, locomotive HC emissions are always below two percent of total HC emissions, and are often less than one percent. Except for the Method 1 CO estimates in Chicago and Kansas City, locomotive CO emissions are always below one half percent of the total CO emissions. The locomotive $NO_x$ emissions constitute the highest percentage of the total area emissions of any of the three pollutants studied.

Locomotive $NO_x$ emissions as a percentage of total $NO_x$ emissions also vary widely from area to area; and within an area, from method to method. The cities most affected by locomotive $NO_x$ emissions appear to be Chicago and Kansas City. Depending on the methodology used, the locomotive $NO_x$ emissions vary from approximately four to eight percent of the total $NO_x$ emissions in either city.

## TABLE II-17. ANNUAL LOCOMOTIVE EMISSIONS IN SEVERAL REGIONS

| | | Emissions, tons/year | | |
|---|---|---|---|---|
| | | HC | CO | $NO_x$ |
| Chicago | | | | |
| Ref 24 | M1 | 14,856 | 34,633 | 61,260 |
| | M2 | 11,839 | 8,395 | 27,193 |
| | M3 | 9,264 | 12,813 | 36,463 |
| Ref 23 | | 3,900 | 4,380 | 11,300 |
| St. Louis | | | | |
| Ref 24 | M1 | 2,341 | 5,442 | 10,221 |
| | M2 | 2,947 | 2,738 | 8,977 |
| | M3 | 1,936 | 2,679 | 7,627 |
| Ref 22 | | 4,220 | 4,350 | 11,935 |
| Philadelphia | | | | |
| Ref 24 | M1 | 1,833 | 4,266 | 7,778 |
| | M2 | 1,915 | 1,564 | 5,111 |
| | M3 | 2,935 | 4,056 | 11,548 |
| Kansas City | | | | |
| Ref 24 | M1 | 2,549 | 5,936 | 10,733 |
| | M2 | 2,511 | 1,968 | 6,448 |
| | M3 | 2,201 | 3,044 | 8,662 |
| Los Angeles | | | | |
| Ref 24 | M1 | 2,261 | 5,261 | 9,700 |
| | M2 | 2,443 | 2,228 | 7,266 |
| | M3 | 6,151 | 8,508 | 24,214 |

## TABLE II-18. LOCOMOTIVE CONTRIBUTIONS TO AREA TOTAL ANNUAL EMISSIONS

| | | Percent of Total Annual Emissions[a] | | | |
|---|---|---|---|---|---|
| | | HC | CO | $NO_x$ | Revised $NO_x$[b] |
| Chicago | | | | | |
| Ref 24 | M1 | 1.65 | 1.04 | 8.12 | |
| | M2 | 1.32 | 0.25 | 3.61 | |
| | M3 | 1.03 | 0.38 | 4.84 | 6.9 |
| St. Louis | | | | | |
| Ref 24 | M1 | 0.74 | 0.39 | 2.36 | |
| | M2 | 0.93 | 0.20 | 2.08 | |
| | M3 | 0.61 | 0.19 | 1.76 | 2.5 |
| Ref 22 | | 1.33 | 0.31 | 2.75 | |
| Philadelphia | | | | | |
| Ref 24 | M1 | 0.26 | 0.18 | 2.24 | |
| | M2 | 0.27 | 0.07 | 1.47 | |
| | M3 | 0.41 | 0.17 | 3.33 | 4.8 |
| Kansas City | | | | | |
| Ref 24 | M1 | 1.03 | 0.79 | 7.49 | |
| | M2 | 1.01 | 0.26 | 4.50 | |
| | M3 | 0.89 | 0.40 | 6.05 | 8.6 |
| Los Angeles | | | | | |
| Ref 24 | M1 | 0.15 | 0.09 | 1.71 | |
| | M2 | 0.17 | 0.04 | 1.28 | |
| | M3 | 0.42 | 0.14 | 4.28 | 6.1 |

---

[a] Based on 1977 emissions.

[b] Using the revised national average $NO_x$ emission factor from this study. Applicable to reference 24, method 3 only.

These emissions impact estimates were calculated using essentially the 1972 time frame emissions, either from AP-42 or from studies on which the AP-42 factors were based. The revised national average emission factors calculated in this study (and shown in Table II-15) are lower for HC and higher for CO and $NO_x$ than the present AP-42 national average factors. The method 1 and 2 of reference 24 were not calculated using emission factors that are directly comparable to the emission factors in Table II-15. Method 3 did use emission factors comparable to these revised emission factors. Since $NO_x$ is the emission of most interest, the locomotive $NO_x$ emissions as a percent of annual total $NO_x$ emissions for the five areas were recalculated by multiplying the method 3 percentages by the ratio of the revised emission factors to the Reference 24 emission factor. These revised $NO_x$ emissions as percents of the total $NO_x$ emissions in the area are shown in Table II-18.

There are other factors that will also tend to change the impact presented in Table II-17. The EPA now uses counties rather than AQCR's to evaluate compliance with air quality standards. How this will affect the locomotive emissions in percentages of total area emissions in unknown. It is also assumed that the State Implementation Plans are working, so that in most areas the total tons of the three gaseous emissions have been reduced, which would tend to increase the locomotive share.

Considering all these factors, annual locomotive $NO_x$ emissions as high as ten percent of the total $NO_x$ emissions in a county are conceivable. This level must be put in prospective, however, by considering how many counties fail to meet the current $NO_x$ ambient standard. A computer listing of those counties not in compliance with ambient air standards as of February 1983 was obtained from the EPA Office of Air Quality Planning and Standards.(57) Only 11 counties in the country do not meet the $NO_x$ ambient air standards. Of these eleven, six are in Colorado, four in California, and one in Illinois. The county in Illinois is Cook County, which contains Chicago. The four counties in California are all in Southern California and include Los Angeles and three adjacent counties. The Colorado counties are Denver and surrounding counties.

While Denver was not one of the areas studied, it is not likely that locomotives are a large part of the emissions in the Denver area. Colorado as a whole has a fewer miles of track per square mile of area than any of the States which had study areas, as can be seen from the figures in Table II-19. The locomotive contribution to $NO_x$ in the Los Angeles AQCR has already been shown to be small.(See Table II-18) This leaves Chicago as the only area exceeding the $NO_x$ ambient standard where locomotive $NO_x$ emissions might be important. A more thorough study of locomotive emissions in the Chicago area and their contribution to ambient concentrations (rather than just tons per year of emissions) is recommended.

## TABLE II-19. MILES OF RAILROAD TRAKC PER THOUSAND SQUARE MILES OF AREA FOR SEVERAL STATES

| State | Miles of Track per 1000 Sq. Miles of Area |
|---|---|
| California | 41.15 |
| Colorado | 32.74 |
| Illinois | 179.84 |
| Kansas | 87.54 |
| Missouri | 84.02 |
| Ohio | 173.21 |
| Pennsylvania | 153.55 |

# III. CONSTRUCTION EQUIPMENT

Construction equipment includes machines that dig, move, grade and compact soil; machines that compound, lay, and compact paving materials; machines that lift and move structual components and materials; and machines that generate electricity, pump water and compress air. The equipment is powered primarily by diesel engines, with a small fraction of it powered by gasoline engines. Not all construction equipment is self-propelled; some is mobile in the sense that it can be, and is, moved from place to place. Construction equipment was chosen for investigation in the project because a previous project at SwRI(25) had indicated that the national emissions impact of construction equipment was approximately the same as the locomotive emissions impact.

At the beginning of the literature search, after review of the AP-42 emission factor and source documents, the EPA Branch Technical Representative provided information that the State of California had just completed a study of farm, construction and industrial equipment in California. From contact with State of California personnel, it was learned that not only had the state done a study of construction equipment impact, but a consortium of industry organizations had also commissioned a study of farm, construction and industrial equipment emission factors. Reports on the two studies were obtained. The reports were so comprehensive that no other literature was deemed necessary.

## Current AP-42 Emission Factors

The current AP-42 construction equipment emission factors were last updated in 1975. These factors, listed under "heavy duty construction equipment," were taken from measurements of construction equipment emissions at SwRI during the early 1970's. The AP-42 construction equipment emission factors are included in Appendix D for reference. Gaseous emission factors are listed in AP-42 for ten categories of diesel-powered equipment and five categories of gasoline-powered equipment. In addition, the estimated annual hours of operation are included for ten categories on construction equipment.

## Revised Emission Factors

As mentioned above, two recent reports were obtained on the subject of construction equipment emissions. One report was done by Environmental Research and Technology, Inc.(26) This report was prepared under sponsorship of the Farm and Industrial Equipment Institute (FIEI), Engine Manufacturers Association (EMA) and Contruction Industry Manufacturers Association (CIMA). It is referred to as the CAL/ERT Report. The other report was by the California Air Resources Board (CARB).(27)

The report by the industry groups is the most comprehensive study of emission factors ever done on construction equipment. The procedure used to obtain the emission factors was to have each manufacturer submit measured emissions data to the public accouting firm of Ernst and Whinney. This firm collected and aggregated the data, and presented only the aggregated data to the study contractor, Environmental Research and Technology. In this way, manufacturers' confidential information could be used without compromise. The CARB also used these emission factors in their staff analysis of construction equipment.(27)

The sales-weighted emission factors for diesel construction and industrial equipment from the CAL/ERT study are shown in Table III-1. These factors were compiled from data taken by 13 engine manufacturers, and they represent 391 models of construction equipment. Since these emission factors are based on comprehensive, up-to-date emission measurements, it is recommended that they be used in place of the current AP-42 emission factors, simply because of their more defensible data base. Construction equipment gasoline engine emission factors were not given in the CAL/ERT report. According to the report, less than five percent of sales use gasoline engines, and the trend is toward complete dieselization. If gasoline engine emission factors are needed, the present factors in AP-42 should be sufficient. The new diesel factors will have little effect on any studies that have been or will be done on construction equipment contribution to air pollution, because the emission factors are in good agreement with the factors currently in AP-42 as can be seen by the comparison shown in Table III-2.

## Regional and National Impact

Both the CARB and the construction equipment industry analyzed the impact of construction equipment on regional air quality using the gaseous emission factors shown in Table III-1. The CARB analyzed seven regions of California for air quality impact from construction/industrial equipment, as well as presenting tons per day from construction/industrial equipment for the entire state. The CAL/ERT study analyzed three regions of the state, as well as presenting statewide tons per year from construction/industrial equipment. While both reports contain statewide estimates, the only common region in the two reports is the South Coast Air Basin (SCAB).

A comparison of the construction equipment impact, in terms of tons per year of HC, CO, and NOx, from the two reports for the whole state and the SCAB is presented in Table III-3. Comparing the estimates presented in Table III-3, the CARB statewide tons per year estimates are approximately twice the industry estimates, while the CARB estimates for the SCAB are approximately three times the industry estimates. The CAL/ERT estimate of Fresno County area had the largest fraction of total emissions from construction equipment; 2.2 percent for $NO_x$. If it is assumed that the CARB estimate for this area would also be three times the industry estimate, then the $NO_x$ emissions from construction equipment in Fresno County could be as high as six percent of the total $NO_x$ emissions. For these estimates mobile industrial equipment, such as mining and forestry equipment, was included with construction equipment in the impact analysis.

In discussing the differences between the two emission impact estimates with the CARB staff(28) it was learned that a series of meetings is planned in 1984 between the CARB and the industry trade group consortium. These meeting were planned in an attempt to develop a single set of emission impact estimates upon which both groups can agree.

TABLE III-1. SALES WEIGHTED DIESEL EMISSION FACTORS FOR CONSTRUCTION AND INDUSTRIAL EQUIPMENT FROM CAL/ERT STUDY

| | Emissions Factors (gm/bhp-hr) | | |
|---|---|---|---|
| Equipment Type | HC | CO | $NO_x$ |
| Track Type Tractor, 90+ HP | 0.37 | 1.65 | 6.60 |
| Wheel Load ≥2-1/2 cu. yd. | 0.60 | 2.07 | 8.31 |
| Ind. Wheel Tractor | 1.76 | 7.34 | 11.91 |
| Wheel Tractor Scraper | 0.55 | 2.45 | 7.46 |
| Log Skidder | 0.61 | 3.18 | 9.82 |
| Off-Highway Trucks(a) | 0.37 | 2.28 | 8.15 |
| Motor Graders | 0.36 | 1.54 | 7.14 |
| Hydraulic Excavator, Crawler(c) | 1.22 | 3.18 | 11.01 |
| Trencher<br>Concrete Paver(b)<br>Compact Loader | 1.10 | 4.57 | 10.02 |
| Wheel Loader <2-1/2 cu. yd. | 1.29 | 3.26 | 9.24 |
| Track Type Loader, 90+ HP | 0.47 | 1.56 | 7.76 |
| Track Type Tractor 20.89 HP | 1.33 | 2.91 | 9.63 |
| Track Type Loader, 20-89 HP | 1.80 | 3.02 | 10.97 |
| Roller Compactor, Static | 0.88 | 5.33 | 11.84 |
| Crane Lattice Boom, Wheel & Crawler(d) | 0.59 | 4.99 | 12.45 |
| Hydraulic, Wheel, One Station | 0.80 | 7.80 | 14.69 |
| Hydraulic Excavator, Wheel(c) | 1.22 | 3.18 | 11.01 |
| Roller Compactor, Vibratory | 1.06 | 6.72 | 14.27 |
| Crane, Hyd, Wheel, Multi-Station | 0.68 | 3.71 | 12.47 |
| Bituminous Paver | 0.99 | 5.19 | 11.18 |

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(a) includes pavement cold planer, wheel dozer

(b) includes generator sets, contractor's engine-driven pumps, road wideners

(c) same as hydraulic excavator wheel

(d) includes pipe layers

## TABLE III-2. COMPARISON OF PRESENT AP-42 CONSTRUCTION EQUIPMENT DIESEL EMISSION FACTORS WITH CAL/ERT STUDY DIESEL EMISSION FACTORS

| | Emission Factors g/bhp-hr | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| AP-42 avg. | 0.83 | 2.70 | 11.7 |
| CAL/ERT avg. | 0.90 | 3.80 | 10.3 |
| AP-42 range | 0.26 to 1.39 | 1.80 to 4.40 | 6.6 to 15.7 |
| CAL/ERT range | 0.36 to 1.80 | 1.54 to7.80 | 6.6 to 14.7 |

## TABLE III-3. IMPACT OF CONSTRUCTION EQUIPMENT ON AIR QUALITY IN CALIFORNIA

| | CAL/ERT Report(a) | CARB Report(b) |
|---|---|---|
| 1. Calendar year | 1979 | 1979 |
| 2. Tons/year, Statewide | | |
| HC | 2158 | 4991 |
| CO | 21471 | 52755 |
| $NO_x$ | 20083 | 40332 |
| 3. Tons/year, South Coast Air Basin | | |
| HC | 500 | 1535(c) |
| CO | 5068 | 16196(c) |
| $NO_x$ | 4527 | 12391(c) |
| 4. Construction equipment emissions as a percent of total tons/year from all sources. | | |
| a. South Coast Air Basin | | |
| HC | 0.08% | 0.25(d) |
| CO | 0.20% | 0.64(d) |
| $NO_x$ | 0.91% | 2.45(d) |
| b. Fresno County | | |
| HC | 0.18% | -- |
| CO | 0.60% | -- |
| $NO_x$ | 2.20% | -- |
| c. Sacramento Modeling Grid | | |
| HC | 0.24% | -- |
| CO | 0.36% | -- |
| $NO_x$ | 1.70% | -- |

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(a)Reference 6

(b)Reference 5

(c)Back calculated to 1979 from 1982 data in report using CARB estimate of 1.5% annual growth rate

(d)Calculated from CARB data in 3 and total emissions calculated from CAL/ERT percentage adjusted for larger construction fraction.

It should be pointed out that a high percentage contribution to total emissions says nothing about whether the area has an air pollution problem. For example, Fresno county has the highest portion of $NO_x$ emissions from construction and industrial equipment (perhaps as high as six percent) of any California area examined. However, Fresno County does not exceed the ambient $NO_x$ standards. The SCAB, which includes part of all four California counties that do not meet the ambient $NO_x$ standard, has between approximately 0.9 and 2.5 percent of total $NO_x$ emissions (depending on which estimate is used) from construction and industrial $NO_x$ emissions.

The national impact of construction equipment on HC, CO, and $NO_x$ emissions was estimated using the CARB estimate of statewide construction equipment emissions. The assumption was made that construction equipment emissions are proportional to population. Thus, Callifornia with 10.45 percent of the national population was assumed to have 10.45 percent of the construction equipment emissions. Using this factor, the national construction equipment emissions were calculated in terms of percent of nationwide emissions from all sources and percent of nationwide mobile source emissions, and are shown in Table III-4. These estimates are based on the 1981 nationwide emissions from Reference 21. This technique may somewhat overestimate the national emissions from construction equipment. Because California is a rapidly growing state it's construction equipment emissions are probably greater than ten percent of the total.

TABLE III-4. ESTIMATED NATIONAL IMPACT OF CONSTRUCTION EQUIPMENT EMISSIONS

| | Construction Equipment Nationwide Annual Emissions as a: | |
|---|---|---|
| | Percent of All Sources | Percent of Mobile Sources |
| HC | 0.2 | 0.6 |
| CO | 0.6 | 0.7 |
| $NO_x$ | 2.0 | 4.7 |

# IV. MARINE VESSELS

The final class of off-highway mobile emission sources investigated was marine vessels. This study excluded outboard engine-powered vessels, since traditionally outboards have been considered as a separate class of off-highway mobile sources. The marine emission factors presented in AP-42, together with the source studies from which the factors were derived, were examined in detail. Trends in propulsion technology for marine vessels were reviewed to determine if there had been changes which would require new emission factors. A study of marine vessel emissions factors just being completed by the EPA Office of Air Quality Planning and Standards (OAQPS), for which a draft final was available, was also reviewed in detail. Finally, several air quality impact studies for marine vessels were reviewed.

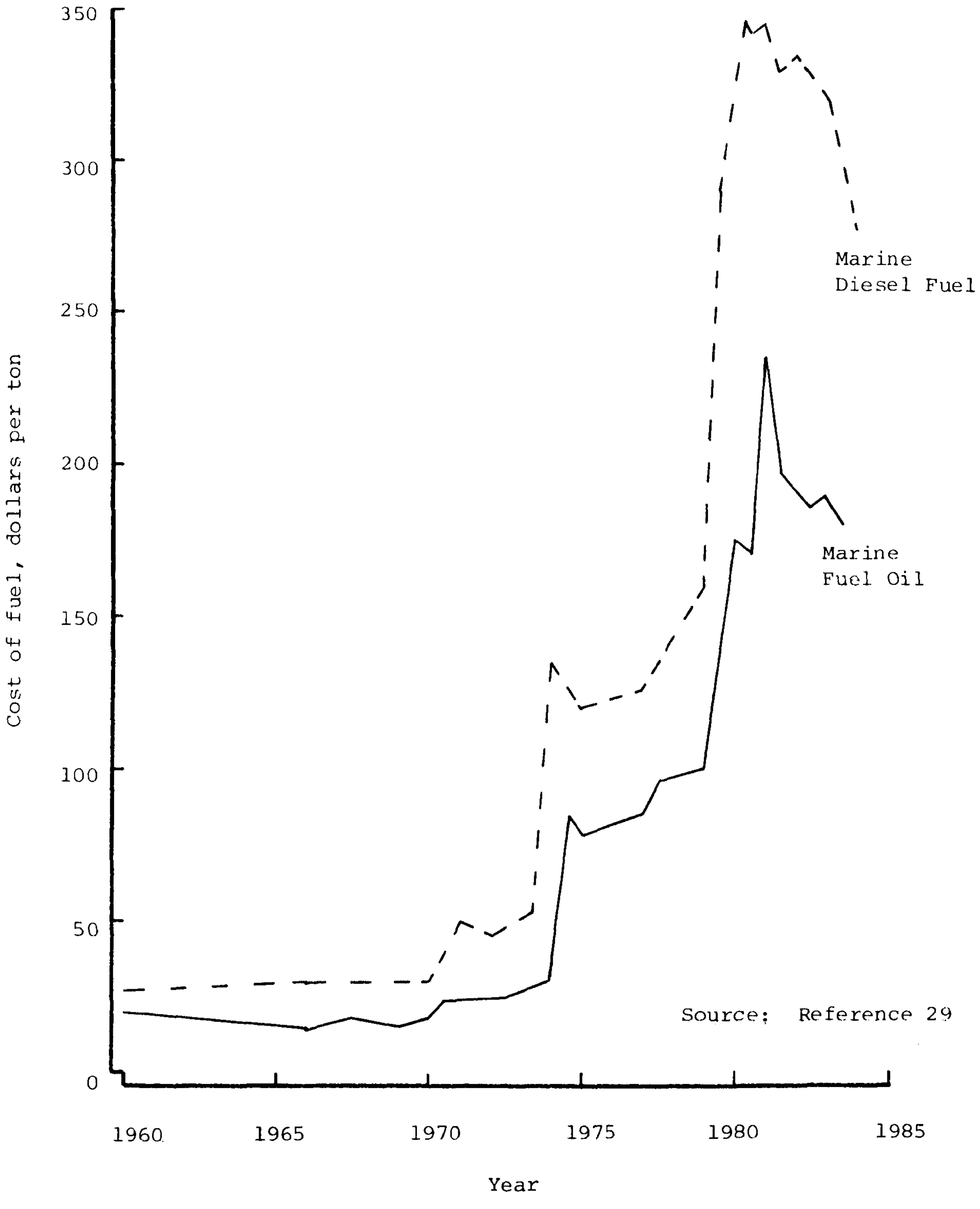
## Current Marine Emission Factors in AP-42

The latest AP-42 marine vessel emission factors were compiled in 1975. Average emission factors in terms of pounds per 1000 gallons fuel and kilograms per 1000 liters of fuel are presented by waterway classification (river, great lakes, and coastal) and by propulsion system (steam boiler and diesel). A set of emission factors is also presented for diesel-powered electrical generators in marine vessels. The narratives accompanying the emission factor tables, as well as table footnotes, indicate that the factors are based on limited data. In addition, the marine diesel emission factor table has an incorrect entry at 1550 horsepower. The emissions given at 1550 horsepower are for a Coast Guard steam boiler propulsion system, not a diesel engine. These facts argue for an update of the AP-42 marine emission factors, even without consideration of changes in marine emissions over the last ten years. The marine vessel section from AP-42 is included in Appendix D for reference.

## Trends in Marine Propulsion

As with locomotives, fuel costs have been the driving factor in marine propulsion changes during the past ten years. The cost of marine fuel over the past twenty years is shown graphically in Figure IV-1. Note that the 1983 costs of both marine diesel and marine fuel oil were approximately seven times their 1973 costs. At this point, a short digression is necessary to examine the terms used to describe marine fuels. Apparently the same marine fuel is called by a variety of common names. Table IV-1 lists some of these names. Thus, the Marine Diesel Fuel and Marine Fuel Oil referred to in Figure IV-1 correspond to No. 4D and No. 6 fuel oil, respectively.

The increase in fuel prices has resulted in several changes in marine propulsion systems. One of the most basic changes is the use of diesel engines in U.S. merchant shipping. Historically, the U.S. merchant fleet (and U.S. Navy) have been powered by steam boiler propulsion systems, while most of the rest of the world's ocean shipping has been powered by diesel engines. Diesel engines, in general, have better thermal efficiency than marine steam propulsion systems.(30) The use of steam propulsion by U.S. ships results from legislative requirements that cargo shipped between U.S. ports be carried in U.S. flag vessels, and that U.S. flag vessels be built in U.S. shipyards using U.S.



Source: Reference 29

Figure IV-1. Bunker Prices, London.

TABLE IV-1. MARINE FUEL TERMINOLOGY

**TABLE I: Marine fuel terminology**

| Description | Color | Common Names | Approximate SR1 Viscosity Range @ 100°F | Approximate SUS Viscosity Range @ 100°F |
|---|---|---|---|---|
| Heavy or Residual | Black, Dark Brown | Marine Fuel Oil (MFO)<br>Bunker Fuel Oil (BFO)<br>Heavy Fuel Oil (HFO)<br>No. 6 Fuel<br>Bunker C | 3500-6000+ | 4000-9000+ |
| Blends of Heavy and Distillate | Black, Dark Brown | Intermediate Fuel Oil (IFO)<br>(Heavy Oil, sometimes)<br>Intermediate Bunker Fuel (IBF)<br>Light Fuel Oil (LFO)<br>Light (Residual)<br>Blended (Diesel Fuel)<br>Light or Medium Marine Fuel Oil<br>No. 4, No. 5 Light, No. 5 Heavy<br>Thin Fuel Oil (TFO) | 200-3000 | 250-3200 |
| Distillate | Dark Colored (Some Residual Content) | Marine Diesel Fuel (MDF)<br>Marine Diesel Heavy<br>Marine Diesel<br>No. 4D<br>B1, B2 | 35-110 | 38-125 |
| | Light Colored (No Residual Content) | Marine Diesel Light<br>Gas Oil<br>Diesel Fuel<br>Diesel Gas Oil<br>No. 2<br>2-D, A2 | 31-42 | 33-47 |

From reference 31

equipment. Until recently, very large slow speed diesels were not manufactured in the U.S. Recently however, these engines have begun to be manufactured in the U.S., mostly under license to European companies. This trend to diesel engines can be seen in Figure IV-2. In this figure, the numbers of active U.S. flag oceangoing vessels of 2000 gross tons and over in 1983 are shown by type of propulsion system. Note the rise of diesel power in ships built in the 1970's and the dominance of diesel in ships built in the 1980's.

Gas turbines were touted highly in 1970's, but their generally lower thermal efficiency (than diesels) has made them uncompetitive as fuel costs have risen. In fact, several U.S. flag container vessels have had their gas turbines removed and replaced with diesel engines. While the first coal fueled ship (and consequently steam powered) built in the U.S. in nearly 50 years was recently launched,(32) problems of boiler stoking and fly ash removal will probably keep the coal/steam propulsion system from being popular.(33)

Worldwide, diesel engines are expected to remain the overwhelmingly predominant marine power source for the forseeable future. In a recent listing of ships of 1,000 gross tons[a] or over being built in shipyards worldwide (excluding military ships), only 10 ships of the 1398 ships listed were not diesel powered.(32) Thus, in 1983, greater than 99 percent of the ships of 1000 gross tons or more under construction or on order were diesel-powered. The horsepower of these diesel ships ranged from 1550 horsepower for a 1500 dead weight ton (DWT)[b] ferry to 44,560 horsepower for a 57,800 DWT container carrier.

A second trend in marine propulsion is the attempt to use cheaper, less refined, more viscous fuels in diesel engines. Since the late 1940's the very slow speed marine diesel engines (under 200 rpm) have been able to operate on residual fuels. Experimental work has been done recently on engines in the 1000 rpm range to develop their capability to burn residual or mixtures of residual and distillate fuels.(34,35,36)

The last trend observed in marine propulsion is the development of more efficient diesel engines. All diesel engine manufacturers are working to increase the fuel efficiency of their engines in response to rising fuel prices. The increases obtained are not breakthroughs, but rather careful engineering changes that generally result in fractional percent increases in fuel economy. When the changes are added together, some engines have improved fuel economy between five and ten percent.(37)

These trends in marine propulsion point to the increasing importance of the marine diesel emissions factor estimate. With declining importance of steam boiler propulsion systems, the boiler emission factors currently given in AP-42 are probably sufficient, but the diesel emission factors definitely require updating both to enlarge the data base and to account for the changes in diesel propulsion systems listed above.

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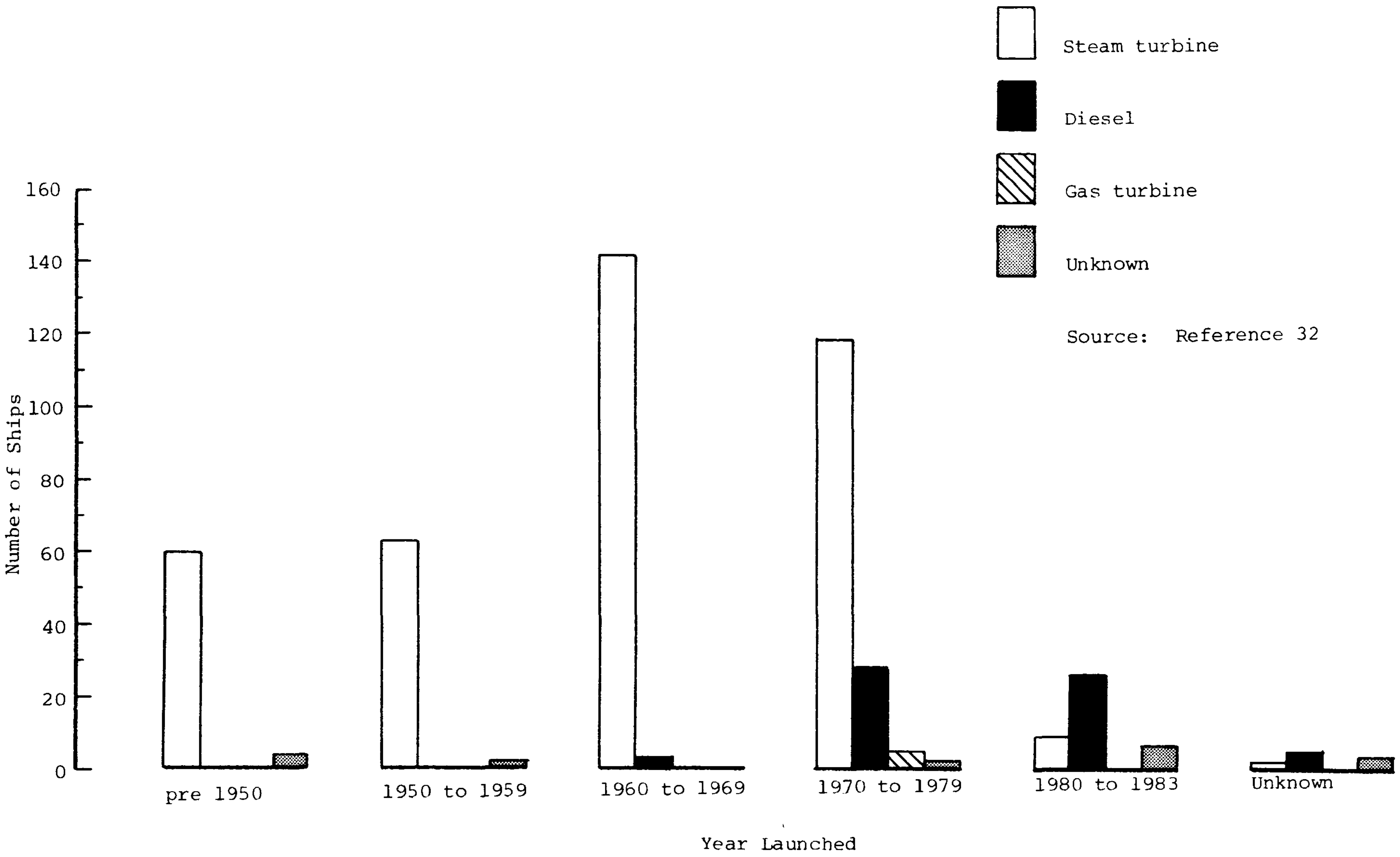
[a] Gross tons is a volume measurement. One gross ton = 100 ft$^3$ of enclosed space.

[b] Dead weight tons is a measure of the weight of a ship in long tons (2240 lbs) at maximum draft.



Source: Reference 32

Figure IV-2. Type of propulsion system in active U.S. flag vessels by year launched

## Review of OAQPS Report

During the search for information on marine vessel emissions, it was learned from EPA's Office of Air Quality Planning and Standards (OAQPS) that they had recently completed a study of marine vessel emissions. The study was conducted by Engineering-Science Corp. (E-S) for OAQPS. A draft of the final report entitled "Emission Factor Documentation for AP-42: Section 3.2.3, Inboard Powered Vessels" (EPA 450/4-84-001) was available.

Since the need for an update of the marine emission factors had been demonstrated, it was considered likely that this study would provide the needed update. The latest version of that draft final report was obtained and reviewed. The study did an excellent job of collecting the available data on marine vessel emissions. However, the methodology used to aggregate the data into emission factors appears flawed. For steam power plants, this methodology did not create a large problem. The boiler emission factors from the E-S study do not vary greatly from those currently in AP-42. In addition, except for the cities of San Diego and Norfolk, which are homeports for a large number of U.S. Navy ships, steam-powered vessels will not be a large fraction of marine traffic in the future.

The gasoline fueled pleasure craft emission factors are based on outboard engine studies done at SwRI during the early 1970's. Almost all outboard motors are two-stroke engines, whereas inboard gasoline engines are almost all four-stroke automotive derivative engines. Since two-stroke and four-stroke gasoline engines have greatly different emissions, the inboard gasoline emission factors in the E-S report are not recommended for use. The current AP-42 emission factors for inboard gasoline engines are based on precontrolled automotive engines. These AP-42 emission factors for gasoline inboard engines should be retained as the best available estimate, until some actual measurement studies are conducted. The diesel-powered pleasure boat emission factors in the E-S study are the same as those currently in AP-42.

As mentioned earlier in the section, the diesel engine emission factors for marine vessels have become the most important set of marine emission factors. The diesel propulsion engines for which measured emissions were obtained for the E-S report are shown in Table IV-2. Conspicuous by their absence are emission values from EMD engines, which constitute the bulk of towboat engines. Note however, that there are some engines in each category of speed, size, and usage.

While the data collection was excellent, analysis of the diesel emissions data presented in the report did not adequately consider a number of factors and did not combine individual engine data points in a useful manner. The greatest problem was the way the individual engine data were aggregated to produce emission factors for various horsepower classes. Because of the sparcity of data, large increments of percent power were combined (for example 0 to 15 percent power, and 15 to 45 percent). All data points available in a specific power interval were then averaged together. For example, if two engines A, and B, had data in the power internal between 0 and 15 percent, with engine A having 6 data points at idle and engine B having one data point at 10 percent power,all seven data points were averaged to give the emission levels in

## TABLE IV-2. DIESEL ENGINES HAVING MEASURED EMISSIONS IN DRAFT OF REPORT EPA 450/4-84-001

| Manufacturer | Engine Series | No. of Cylinders | Max RPM | HP Range | Typical Usage |
|---|---|---|---|---|---|
| Low Speed Engines (less than 600 rpm) | | | | | |
| M.A.N. | KSZ (2-stroke) | 4 to 12 | 110-145 | 7840 to 44,040 | large tankers and liners |
| M.A.N. | I&V 52/55 | 6 to 9 | 450 | 7200 to 21,600 | smaller tankers and liners |
| Pielstick | (4-stroke) | 12 to 18 | 520 | 6000 to 11,700 | smaller tankers and liners |
| Union (built in 1942) | 06 | -- | 350 | 300 | Coast Guard buoy tender |
| Medium Speed Engines (600 to 1300 rpm) | | | | | |
| Fairbanks-Morse | 38D8-1/8,<br>38TD8-1/8 (4-stroke) | 4 to 12<br>6, 9, 12 | 750/900<br>750/900 | 708 to 2760<br>1750 to 4200 | tow boats, work boats, etc. |
| Caterpillar | D379, D398, D399 (4-stroke) | 8, 12, 16 | 1300 | 640 to 1380 | fishing boats, pleasure craft |
| Waukesha | 6LRDCSM | -- | 1200 | 500 | Coast Guard Harbour tug |
| Ingersoll-Rand (built in 1943) | Type S | -- | 720 | 600 | Coast Guard Harbour tug |
| Cooper-Bessemer (built in 1942, 1944) | GN-8, GND-8 | -- | 600-700 | 600-700 | Coast Guard buoy tender |
| Cooper-Bessemer | FVBM-12-T | -- | 600 | 1580 | Coast Guard cutter |
| Alco | 16-251-B | -- | 1000 | 2500 | Coast Guard cutter |
| M.A.N. | L&V 20/27, 25/30 | 4 to 15 | 750-1000 | 545 to 9000 | tow boats, work boats, etc. |
| High Speed Engines (greater than 1300 rpm) | | | | | |
| Caterpillar | 3200, 3300 & 3400 (4-stroke) | 4 to 12 | 2100-2800 | 100 to 650 | fishing boats, pleasure craft |
| Cummins | (4-stroke) | 6, 8 | 1800-3000 | 195 to 520 | fishing boats, pleasure craft |
| Cummins | VT-12-900M | 12 | 2300 | 900 | Coast Guard patrol boat |
| G.M. | 6071-A | -- | 2000 | 200 | Coast Guard utility boats |

the 0 to 15 percent power range. Note that this gives the emissions from engine A six times the weight of the emissions from engine B. In the 15 to 40 percent power range, if engine A had one data point at 20 percent power and engine B had six data points at 40 percent power, all seven data points were again averaged to produce the average emission level in the 15 to 45 percent range. In this interval engine B emissions are given six times the weight of the engine A emissions.

This method makes the "average" emission factor in a given power interval a function of the emissions from the engine with the most data points in that interval. However, the engine with the most data points can change with power interval. The proper way to utilize the data would be to develop curves of emissions as functions of power for each engine. Then, based on the in-use population of each engine, population-weighted average emissions at specific percent power levels could be computed.

Another problem with the methodology is that while the emission factors are presented on both a fuel specific and a power specific basis, a different data base was used for the fuel specific emissions than was used for the power specific emissions. Thus, the two sets of emission factors are not really equivalent.

Other problems with the factors have to do with the data themselves. Almost all of the part-power data come from three sources: an in-use study of Coast Guard cutter and small boat emissions, an engine dynamometer study of Coast Guard small boat engines emissions, and part-power rated speed data from 13-mode emission tests of Cummins engines. The Cummins data as presented in the draft are not correct. A check with Cummins personnel revealed that Cummins inadvertently supplied E-S with the wrong values. Even if the data were correct, the Cummins data should not have been used because they do not represent the usual operating conditions for propulsion diesels. The Cummins 13 mode data are for various part power conditions at rated speed. Most marine propulsion engines in the Cummins size range run on an operating line through the speed-power map, so that part-power operation occurs at various speeds lower than rated speed. Thus, part power emissions at rated speed are not representative of emissions during the usual operation of these engines.

A review of the reports from which the in-use Coast Guard data were taken reveals that four of the 14 engine models tested were built during World War II, and are not representative of the majority of diesels now in service. These engines should not be included in the data base. In addition, a G.M. engine installed in a 40 foot launch was tested while tied to a pier. The resulting power points were at part speed, but several were at full throttle for that speed. Again this is not a usual engine operating condition. Diesel generator emissions from this Coast Guard study were also aggregated with propulsion engine emissions in the E-S study. Many engine models are used for both generators and main propulsion engines. However, generator rated power is generally less than main propulsion rated power for the same engine. All of the generators in the Coast Guard study were also constant speed units. Thus, their part power conditions are not representative of propulsion unit part power operation, as explained above.

An attempt was made to reanalyze the data contained in the E-S report to provide a more useful set of marine diesel emission factors. The diesel engines were divided by rated speed into slow speed (less than 600 rpm), medium speed (600 to 1300 rpm), and high speed (greater than 1300 rpm) engines. To some extent rated power is inversely proportional to speed; the slow speed engines in general have the highest rated power, while the high speed engines have the lowest rated power. It was decided to exclude the three Coast Guard cutter engines built in the 1940's as not representative of currently installed marine diesel engines.

For slow speed engines, data were available from three different engine series representing two manufacturers. The data consisted of two full-power points from one model M.A.N. four-stroke engine (L or V 52/55), two part power points from each of four different model M.A.N. two-stroke engines, a full power point from another model M.A.N. two-stroke engine, and a full power point from Colt-Pielstick four-stroke engine, for a total of 12 data points. The M.A.N. engines were tested on residual fuel, and the Pielstick engine on D2 diesel fuel. Obviously, there are hardly sufficient data to determine emission factors with any confidence. Nevertheless, they are all that is available, and they are plotted in Figure IV-3.

As can be seen from the figure, a trend with power from 60 to 100% can not be established. The only reasonable use of these data is to average all the data points separately for each emission to arrive at single factors for 60 to 100 percent power for each emission type. This process was done for all three emissions, except that the lowest $NO_x$ value at 100 percent power was omitted. The resulting emission factors are shown in Table IV-3. From data contained in the E-S report and our own experience, it appears that there is little difference in gaseous emission levels from diesel engines using different fuels, as long as the engine is running on the fuel for which it was designed. Therefore, the values in Table IV-3 can be used for engines designed for either distillate or residual fuel.

TABLE IV-3. RECOMMENDED EMISSION FACTORS FOR MARINE DIESEL ENGINES WITH DESIGN SPEEDS BELOW 600 RPM

Nominal Power Range: Above 3000 horsepower

Application: a) all foreign ships above 10,000 dead weight tons
b) Some newer U.S. registry ships above 10,000 dead weight tons
c) For both distillate and residual fuel

| | Emission Factor, g/kW-hr (g/hp-hr) | | |
|---|---|---|---|
| Percent Load | HC | CO | $NO_x$ |
| 60 to 100 | 0.48(0.35) | 1.6(1.2) | 13(9.4) |

As mentioned above, the marine diesel engine power range is generally inversely proportional to the rpm range. Thus, the slow speed engines tend to represent large power outputs. The M.A.N. and Pielstick engines in the data

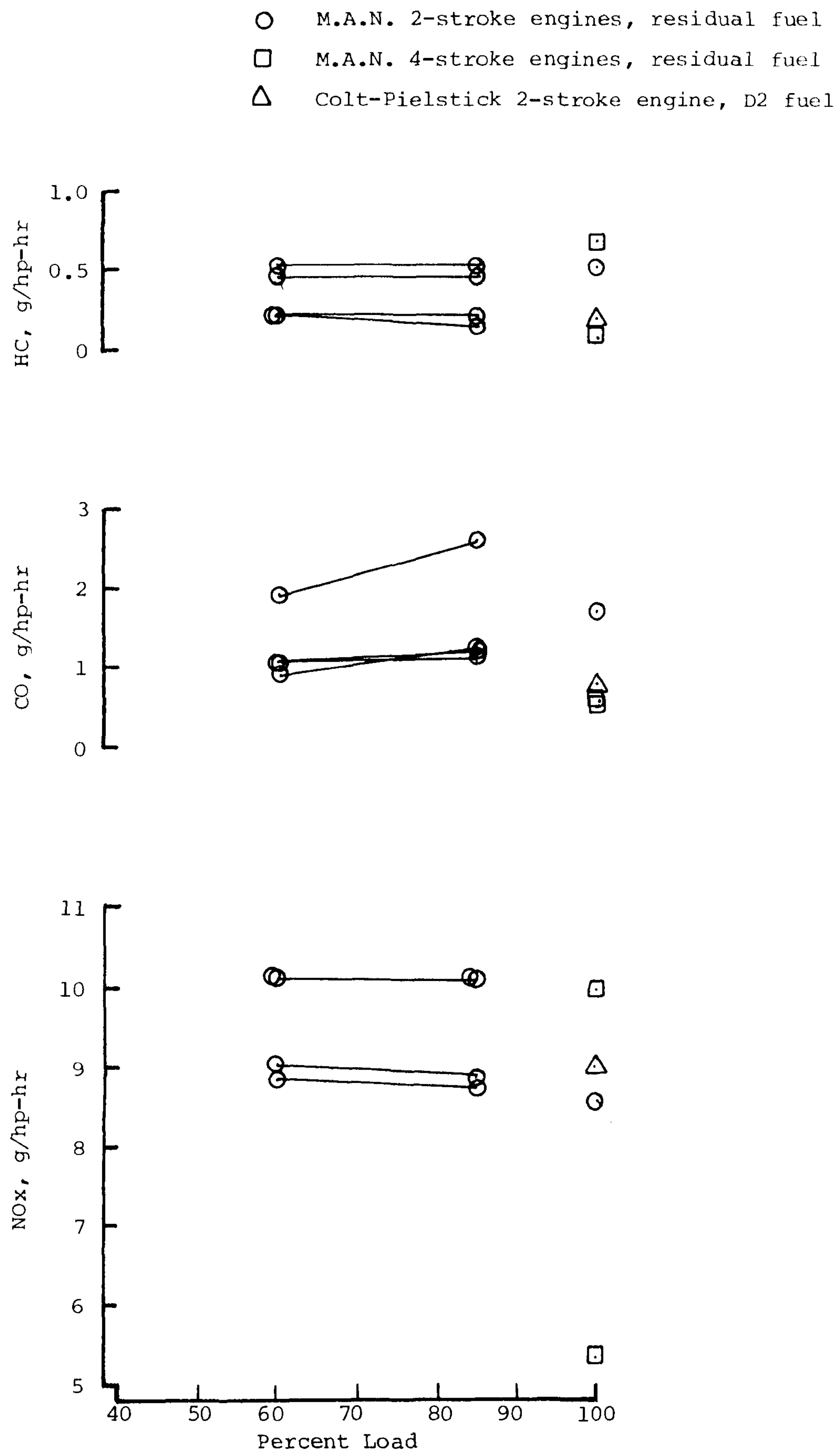


Figure IV-3. Emission levels from marine diesel engines with design speeds under 600 RPM base range from 7,200 to 44,000 horsepower. While several Japanese firms manufacture slow speed diesels with maximum output under 3,000 horsepower, most other slow speed diesel engines have design outputs above 3,000 horsepower.

The information in Table IV-4, taken from the E-S draft report, indicates that engines of greater than 3,000 horsepower are generally used in ships above 10,000 dead weight tons. This size vessel is normally used for ocean shipping. Recall that almost without exception, non-U.S. registry merchant ships use diesel engines for propulsive power, while only some of the newer U.S. registry ships use diesels. Thus, the emission factors given in Table V-3 could be used for all foreign ships in U.S. waters and for a fraction of the US. registry merchant ships, whether distillate or residual fueled.

Emissions from medium-speed engines were also investigated. Of the eight medium-speed engine types listed in Table IV-2 the Ingersoll-Rand and Cooper-Bessemer engines built in the 1940's were not used. Of the six remaining engine models with emissions data, four had data from the in-use study of Coast Guard vessels, and two had summary data from the manufacturer. In the course of investigating the emissions from the medium-speed engines, a number of errors were found in the Caterpillar data presented in the draft E-S report. In a phone conversation with Caterpillar it was learned that these errors apparently originated at the manufacturer. For this study, the corrected Caterpillar data for the D379, D398 and D399 were obtained from the manufacturer.

Of the six medium-speed engine models for which there were emissions data available, only four had part-power emissions. Engine power output was not available for all four of these engines, but fuel consumption was. Emission levels were therefore calculated in terms of grams per pound of fuel consumed. These emissions data were supplemented with EMD locomotive emissions data from SwRI studies. Plots of HC, CO, and $NO_X$ emissions as a function of percent power for these four engines are shown in Figure IV-4, IV-5 and IV-6. Percent power levels for the Waukesha engine were not available, so its emissions were not used.

As can be seen from examination of the figures, none of the engines has the same pattern of emissions with power level. There are many possible reasons for this difference. Except for the EMD engine, all part power engine data were from the in-use Coast Guard study, for which percent load was not measured, but rather assigned by vessel speed mode (slow, 1/3, 2/3, standard, full or flank). Thus it is probable that the percent load chosen for each engine was not exactly correct. In fact, for these curves the percent power values for Coast Guard data were adjusted slightly (up to 5 percent) to attempt to provide some pattern of emissions with power. This adjustment was still not sufficient to bring emission values from each engine into a common pattern. Apparently, variations in emissions at the same speed and load for various engine models, as well as variation in engine speed at the same percent load for various engine models, contributed to this lack of a common emissions pattern with percent power. In addition, for turbocharged engines, the turbocharger schedule varies with engine model. The use of variable pitch propellers on certain marine vessels can also cause operating point and emission differences from

TABLE IV-4. RELATIONSHIPS OF TYPICAL TONNAGE, VESSEL TYPE, AND PROPULSION UNIT CAPACITY[a]

| Vessel dead weight tonnage | General carrier $10^3$ kw($10^3$ HP) | Bulk carrier $10^3$ kw($10^3$ HP) | Tanker $10^3$ kw($10^3$ HP) |
|---|---|---|---|
| 5,000 | 1.8 - 3.2<br>(2.4 - 4.3) | 1.2 - 1.6<br>(1.6 - 2.2) | 0.8 - 1.6<br>(1.1 - 2.1) |
| 10,000 | 3.6 - 6.3<br>(4.8 - 8.5) | 2.4 - 3.3<br>(3.2 - 4.4) | 1.6 - 3.1<br>(2.2 - 4.2) |
| 20,000 | 7.2 - 12.7<br>(9.6 - 17.0) | 4.8 - 6.6<br>(6.4 - 8.8) | 3.3 - 6.4<br>(4.4 - 8.4) |
| 30,000 | 10.7 - 19.0<br>(14.4 - 25.5) | 7.2 - 9.8<br>(9.6 - 13.2) | 4.9 - 9.4<br>(6.6 - 12.6) |
| 40,000 | 14.3 - 25.4<br>(19.2 - 34.0) | 9.6 - 13.1<br>(12.8 - 17.6) | 6.6 - 12.5<br>(8.8 - 16.8) |
| 50,000 | 17.9 - 31.7<br>(24.0 - 42.5) | 11.9 - 16.4<br>(16.0 - 22.0) | 8.2 - 15.7<br>(11.0 - 21.0) |
| 75,000 | b | b | 12.3 - 23.5<br>(16.5 - 31.5) |
| 100,000 | b | b | 16.4 - 31.3<br>(22.0 - 42.0) |

[a] Typical for operating speeds of 10-18 knots. Specific vessel tonnage vs propulsion unit capacity may differ, especially at higher speeds. Ranges are a general guide to propulsion unit capacity, for use when actual capacities are not known. kw = kilowatt, HP = horsepower

[b] Not available

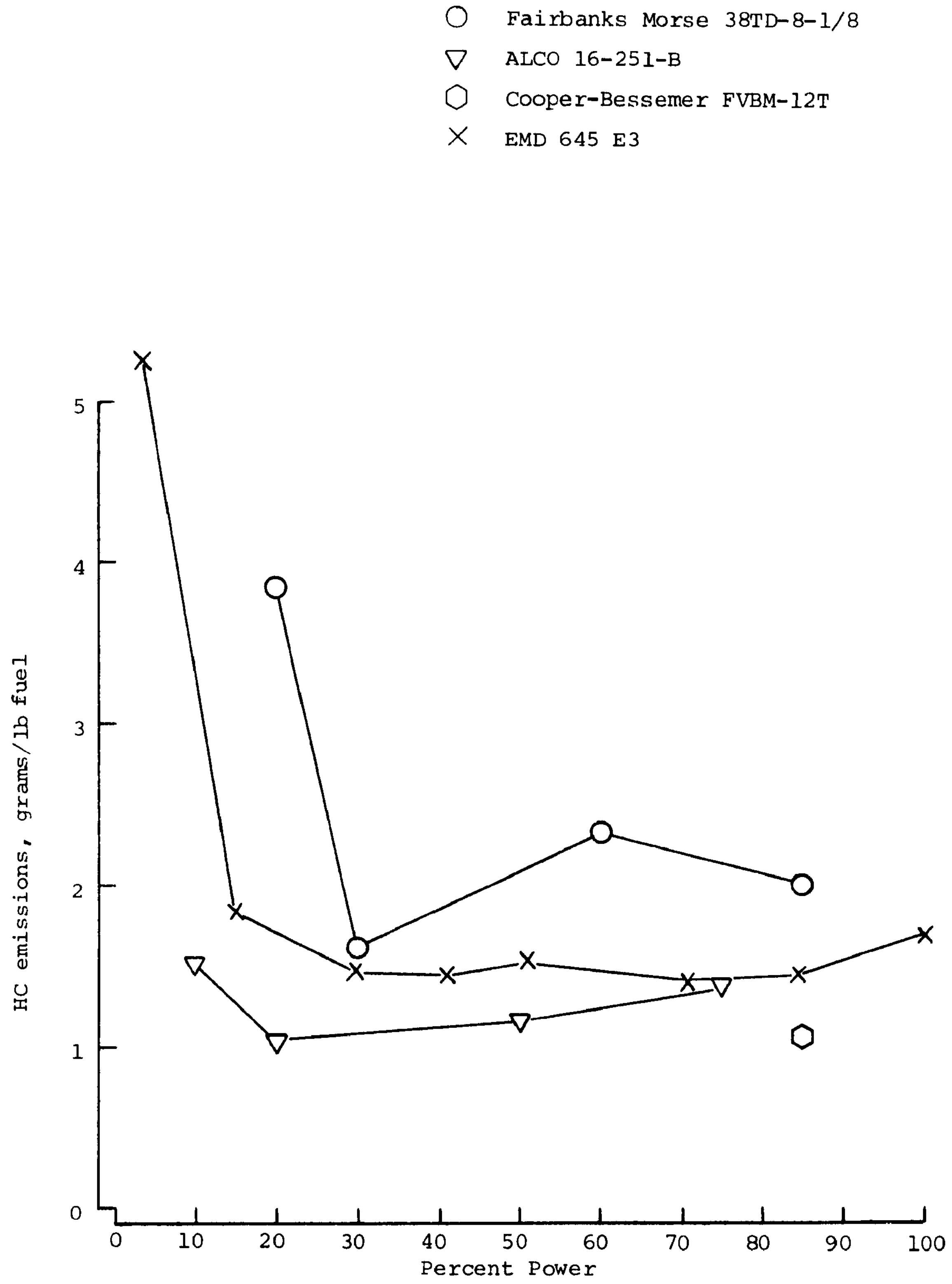


Figure IV-4. HC emissions from four medium-speed marine diesel engines

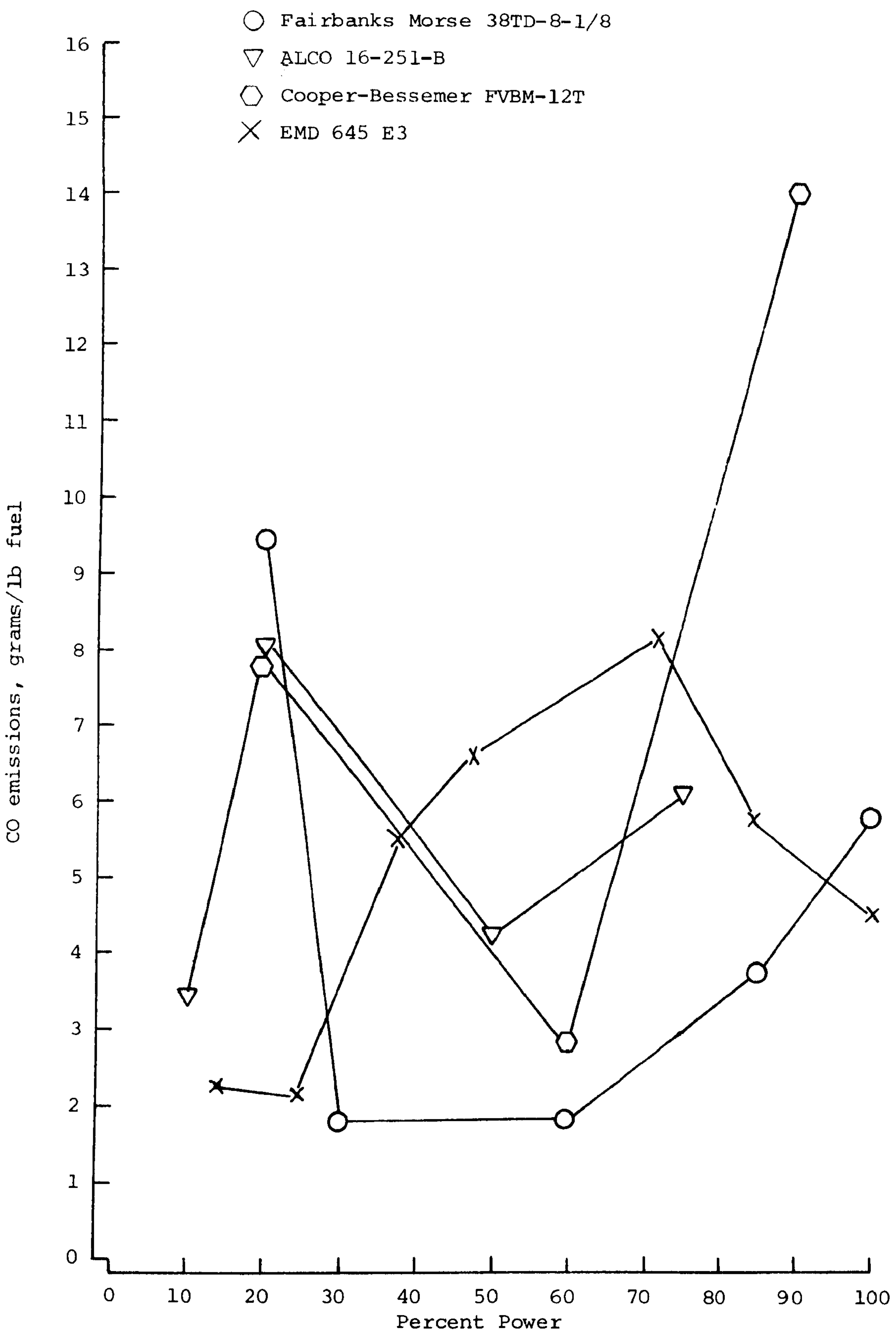


Figure IV-5. CO emissions from four medium-speed marine diesel engines

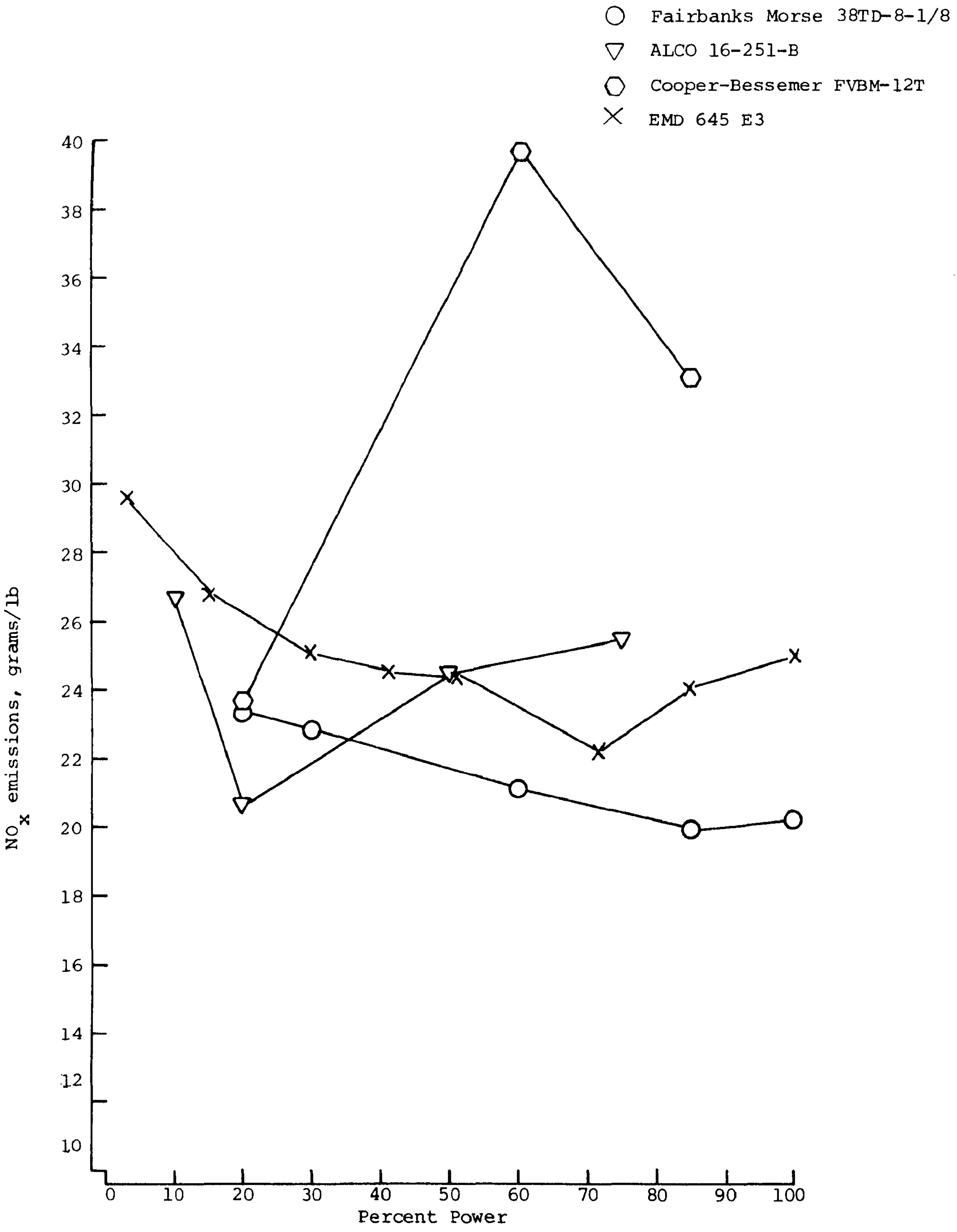


Figure IV-6. $NO_x$ emissions from four medium-speed marine diesel engines installation-to-installation for the same engine model. The result of these considerations is that marine engines may operate at very different points on the engine performance map, with very different emissions, and still be at the same percentage of rated power.

These considerations also indicate that useful marine emission factors require a more detailed analysis than available information allows. Without additional information on the duty cycles of the various classes of shipping, information on the percentage of total engines in service by manufacturer, and additional emission data for the more popular engines, adequate marine vessel emission factors can not be developed.

The diesel emission factors presented in the E-S report are based heavily on the same study of in-use Coast Guard vessels on which the current AP-42 diesel emission factors are based. In addition, as explained above, there are a number of methodology and analytical problems in the E-S study. Therefore it is recommended that the present AP-42 diesel emission factors continue to be used with two changes. The first change is the deletion of the 1550 horsepower entry (this entry is really for a steam boiler, not a diesel engine). The second change is the addition of the high horsepower engine emission factors given in Table IV-3 of this section.

## Information Needed for Marine Diesel Emission Factors

Since it was determined that more information was needed to determine useful marine diesel emission factors, an attempt was made to obtain that information; or if the information was not available, to define what is needed for the benefit of future studies. Information is first required on the kinds of vessels in service by vessel usage, together with the numbers of vessels in each usage category. Typical or average operating cycles of each usage category are needed. Then a determination of propulsion system type and the in-use population of the various engine models is required. Finally, emission measurements on the more popular engine propulsion systems are needed to complete the calculation of the marine diesel emission factors.

In this discussion, as in AP-42, a distinction is made between marine propulsion engines and marine electrical generator engines. For a variety of reasons, these two uses of diesel engines can be expected to have somewhat different emission factors. Only marine diesel propulsion engines will be discussed here.

Sources for statistics on marine vessels in the United States are diverse and generally not in a form that is usable for environmental impact determinations. A number of published sources were consulted.(38-40) In addition, telephone contact was made with a number of persons in shipping, shipbuilding and marine industry associations.(41-44)

United States marine traffic can be defined by location (great lakes, river, coastal, or transocean) or by type of vessel (bulk carrier, liner, towboat, workboat, fishing boat. etc). Some locations have predominately one type of vessel traffic. For instance, river traffic is predominantly towboats pushing barges. However, most locations will have a large variety of types of vessels. Because of this diversity of vessels in most locations, the emission factor needs are best served by considering vessels by type, regardless of where they are located.

For this project, marine vessels were divided in 10 types, as shown in Table IV-5. This table does not show outboard motor-powered boats, since they have traditionally been considered separately in AP-42. The vessels have been separated into various categories because their different use results in different main propulsion systems, different design power to displacement ratios and different operating cycles. Consequently, the different types can be expected to have different emission rates. Note that many of the column entries are blank, indicating that the information was not available in the sources located.

Estimates of the number of vessels have been obtained from a number of sources. For consideration of air pollution impact, the important population estimate is the number of vessels in U.S. waters per day. While the definition of the water area where vessel emissions would affect regional air pollution varies from region to region, a suggested starting point for coastal areas would be the waters where U.S. inland rules-of-the-road apply. The estimated number of vessels in the U.S. waters for each type of vessel is also shown in Table IV-5. Except where all vessels are always within U.S. waters, little information was available on which to base an estimate. For foreign shipping, the number was based on yearly foreign ships visiting New York, Los Angeles, and Houston(45) then extended to the whole country. For the U.S. flag vessels, including Navy ships, it was assumed that one-third of the fleet was in U.S. waters at any one time. For U.S. Coast Guard and fishing boats, it was assumed that 90 percent were within U.S. water each day. The total estimated inboard-powered marine vessels, excluding pleasure boats, in U.S. waters on an average day is approximately 29,000 vessels.

In Table IV-5 the main propulsion units are listed as either steam or diesel. Except for U.S. flag merchant ships and the U.S. Navy, diesel propulsion is used almost exclusively. The diesel engines for the vessels listed in Table IV-5 range from under 100 horsepower to greater than 30,000 horsepower per engine. The smallest engines are marine versions of truck engines, and have design speeds up to 2,800 rpm. The largest engines have design speeds of 100 rpm or less. Within these limits, engine rpm is somewhat inversely proportional to design horsepower. An article in Marine Engineering/Log(46) indicated that for ships built in 1976 with diesel engines over 10,000 horsepower, approximately 79 percent had slow-speed, two stroke engines.

Marine diesel powerplants are produced by a large number of companies worldwide. The share of installations for each manufacturer is not known. It appears that worldwide Burmeister and Wain (B&W), M.A.N. and Sultzer account for a large portion of the two-stroke slow-speed installations, and that M.A.N., Sultzer, and Pielstick are popular four-stroke engines.(47,48) In the U.S., EMD is apparently the most popular diesel engine manufacturer for river towboat engines.(49)

A possible source has been found for most of the missing marine diesel information needed; however, the information could be costly. The American

## TABLE IV-5. MARINE VESSELS IN U.S. WATERS CLASSED FOR AIR POLLUTION STUDIES

| Type of Vessel | Total Number(a) | No. Within U.S. Waters(h) Per Day | Type of Main Propulsion | Average HP (Range) |
|---|---|---|---|---|
| U.S. Flag Tankers and bulk carriers | 333(c) | 111 | 80% steam, 20% diesel | 14380 |
| U.S. Flag Liners | | | | |
| a. ocean | 840(c) | 277 | 80% steam, 20% diesel | 6806 |
| b. river | 1226(c) | 1226 | diesel | 1556 |
| c. Great Lakes | 261(c) | 261 | 80% steam, 20% diesel | 3070 |
| Oceangoing Foreign Tankers and bulk carriers | 23,000(b) | 1000 | diesel | -- |
| Foreign Liners | | | diesel | -- |
| Towboats | 4890(c) | 4890 | diesel | 1554 |
| Oceangoing Workboats and tugs | 2833(d) | 2833 | diesel | (100-18,000) |
| Ferries | | | | |
| a. general | | | | |
| b. railroad | 78(c) | 78 | -- | -- |
| U.S. Navy & Coast Guard | | | | |
| a. combatant | 405(e) | 134 | 70% steam, 25% nuclear, 5% other | |
| b. auxiliary | 169(e) | 56 | | |
| c. Coast Guard | 252(e) | 226 | 98% diesel, 2% steam | -- |
| Fishing Vessels | 19,500(f) | 17,550 | diesel | -- |
| Inboard Pleasure Craft | 700,000(g) | 700,000 | diesel, gasoline | -- |

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(a) unless otherwise noted, this is the number of vessels homeported in the U.S.
(b) total number of ships worldwide. Source: World Almanac
(c) Source: "Summary of U.S. Flag Passenger and Cargo Vessels." Corps of Engineers, Waterborne Commerce Statistics Center, New Orleans, LA.
(d) Source: "Marine Engineering/Log." June 15, 1983
(e) Source: <u>Jane's Fighting Ships 1982-1983</u>
(f) Source: Telecon with M. Kinter, American Waterway Operators
(g) Source: AP-42
(h) Estimated. See test for explanation.

Bureau of Shipping (ABS) publishes a ship registry that includes information on over 50,000 vessels (apparently most of the ships in the world above 500 gross tons). Part of the information includes main propulsion type, horsepower and manufacturer. This information is on a computerized data base. Custom searches of the data base are available through ABS Computers, Inc., a subsidiary of ABS. In theory it should be possible to obtain statistical descriptions (mean, mode, median, standard deviation and range) for vessel size and horsepower as well as number of engine installations by engine manufacturer for the types of vessels listed in Table IV-5. The cost of this information would probably be on the order of several thousand dollars.(50) Since this expenditure was not planned for this project, funds are not available for such a data base search. Nevertheless, the service offers an opportunity to obtain information which is absolutely necessary before reliable marine diesel emission factors can be developed. It is mentioned here for consideration in future work concerning marine vessels.

The only information on vessel operating cycles found was for Coast Guard vessels.(51) Operating cycles are required if emission factors are to be expressed in terms most useful to air quality planners, such as grams of emissions per mile or hour of operation, or grams of emissions per ton mile or ton-hour of operation. This area also requires a great deal more research, but it is necessary if realistic marine diesel emission factors are to be developed.

As was pointed out in the review of the E-S report on marine emission factors, usable diesel emission factors require much more than the compilation of a few part-power points. There is likely to be a wide variation in emissions when all marine vessels are considered. Some of the emissions variation is due to vessel type and operating cycle as mentioned above. Even within a given vessel type, however, there are likely to be wide variations in diesel emissions because of differences in propulsion systems.

To understand why knowledge of the vessel propulsion system is important, it is necessary to understand how the total propulsion system can affect emissions. First of all, there are two different systems for using diesel engines in marine propulsion. One system is the direct-drive system, in which the engine is coupled directly to the propeller (either with or without reduction gears). With this system, the engine operates at various speeds and loads. The second system is a diesel-electric system in which the diesel engine drives a generator and the propeller is driven by an electric motor. With this system, the diesel engine most often operates at one speed and varying loads. While the installed percentage of the two system types are not known, the direct drive appears to be more popular.(32)

Typical engine performance maps for a four-stroke, turbocharged, medium-speed marine diesel engine and a comparable two-stroke turbocharged engine are presented in Figure IV-7 and IV-8, respectively. Shown on the maps are lines of constant $BSNO_x$ and typical operating curves for a direct drive application of each engine. These maps are taken from a SwRI study conducted for the U.S. Coast Guard.(52) As can bee seen from the figures, each engine type produces a different pattern of $BSNO_x$ with power level. These maps are considered typical, but emission patterns and levels can vary considerably from

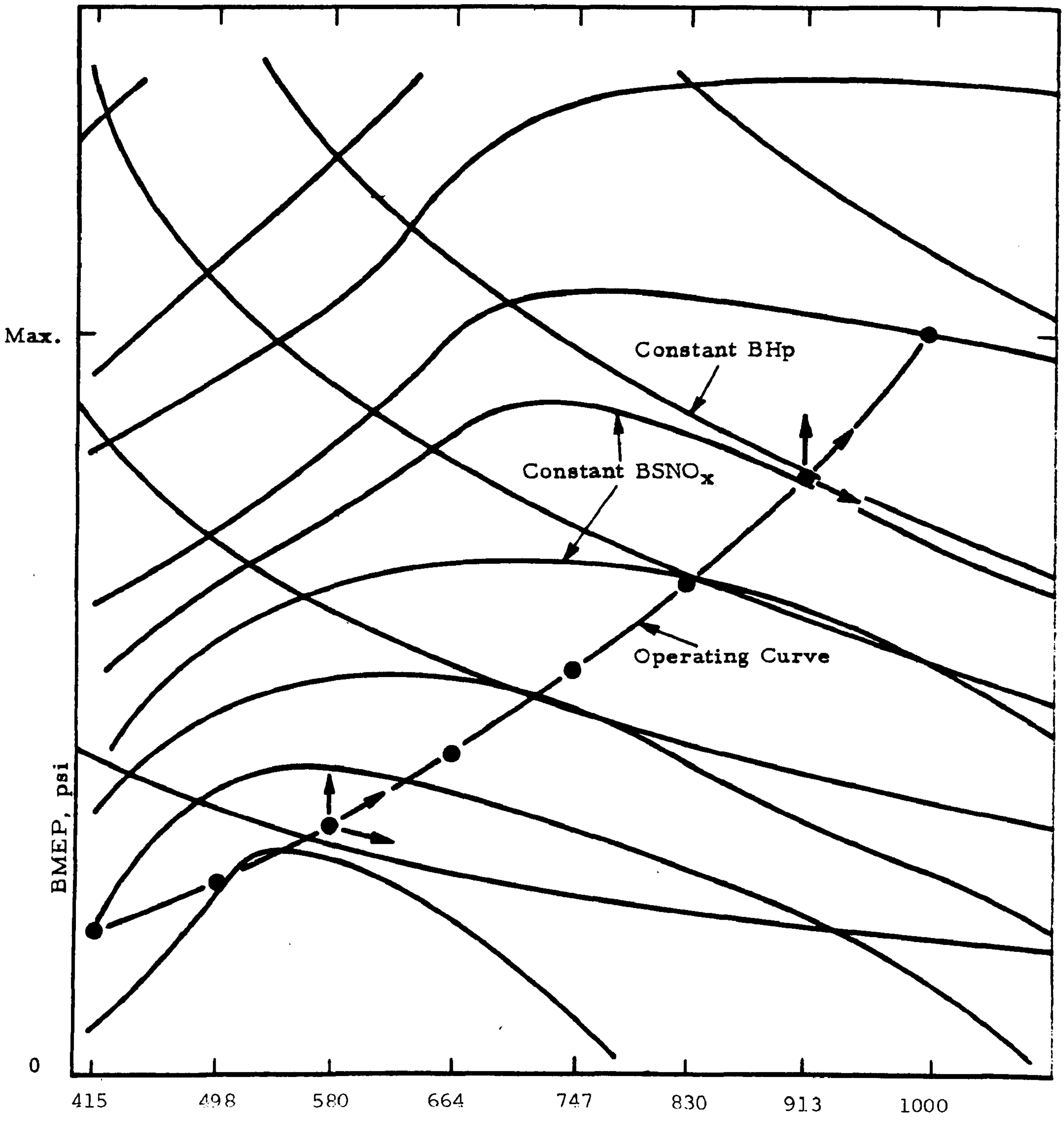

Figure IV-/. Typical brake specific $NO_x$ map -- four-stroke cycle turbocharged marine engine

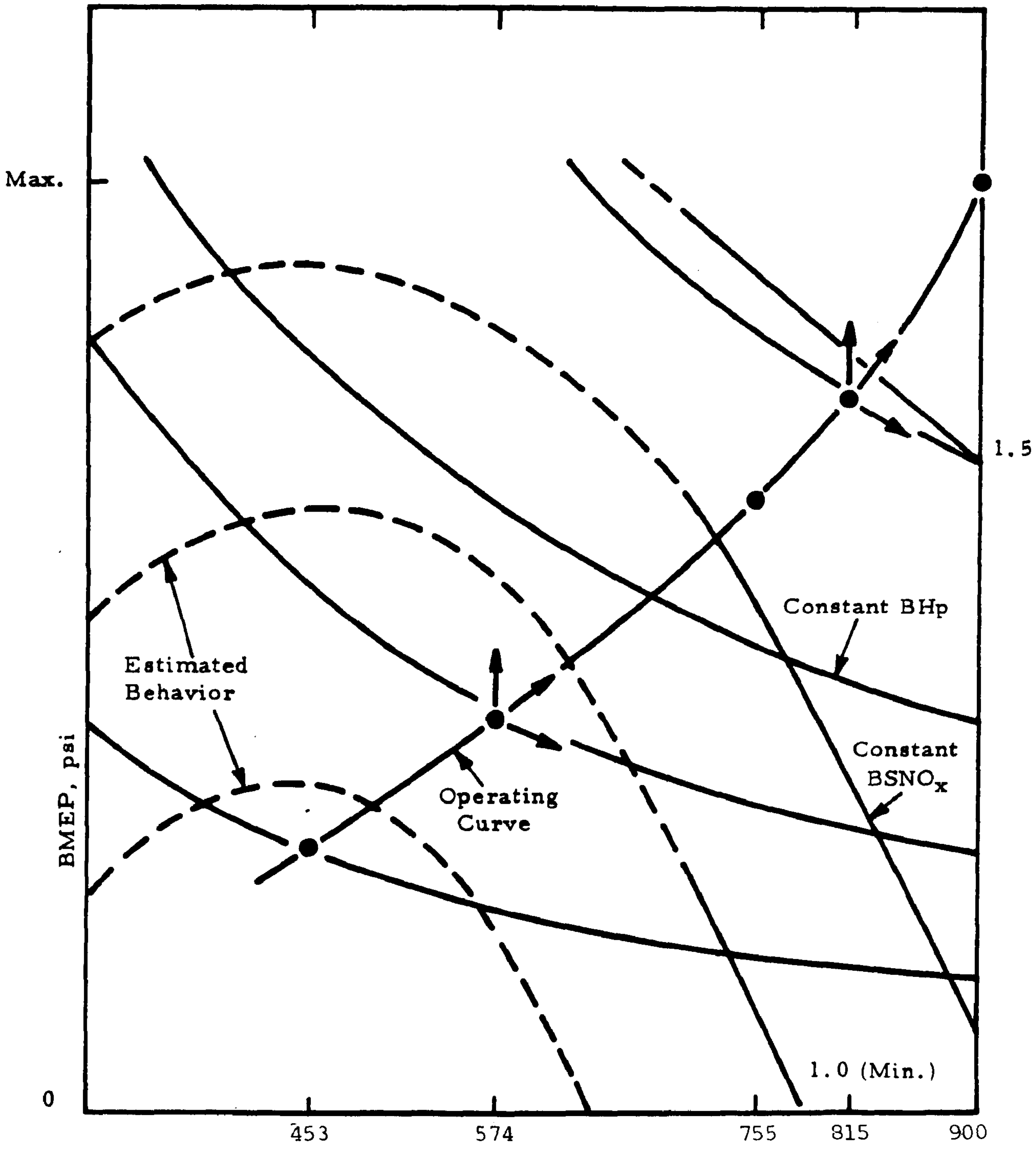

Figure IV-8. Typical brake specific NO$_x$ map -- two-stroke cycle turbocharged marine engine one engine model to another. In addition, if the operating line changes, the pattern and magnitude of the $BSNO_X$ values can change.

The two main parameters that can change the operating curve are: the reduction gear ratio (if reduction gears are used) and the propellers pitch. For a given vessel, it takes a certain amount of power to move the vessel through the water at a given speed. Reduction gear ratios are fixed for each installation; but if the reduction gear ratio were changed, the engine speed at which a given vessel speed is achieved would change, just as shifting gears in an automobile changes the engine speed for a given vehicle speed. Since there is no transmission in a maine vessel propulsion system, different reduction gear ratios in different installations will produce different engine operating curves for a given engine or engine type.

The propeller pitch will also affect the shaft speed at which a given horsepower is attained. Some propellers are fixed (or constant) pitch. Other propellers are equipped to change pitch while in operation. To show the effects of propeller pitch, a variable pitch propeller map is shown in Figure IV-9. This map is for a Coast Guard WHEC type cutter, and is taken from the recently completed study by SwRI for the Coast Guard.(51) The figure shows the relationships between propeller speed, horsepower, propeller pitch, and vessel speed. For this discussion, the important observation is that for a given vessel speed, the propeller rpm, and hence, the engine speed, changes as the propeller pitch (proportional to the pitch ratio "P/D" in the figure) is changed.

The object of this discussion is to demonstrate the importance of having a good compilation of the in-use marine diesel propulsion systems before attempting to determine emission factors for marine diesel engines. Once the population percentages of the various in-use systems have been ascertained, emission measurements on representative systems can be made along the engine operating curve to produce truly representative emission factors. While such an undertaking is beyond the scope of this project, it is recommended for a future study.

## Regional and National Impact

Only a few studies of the regional impact of marine vessels were found in the literature.(23,53-56) The three most recent studies(23,55,56), all completed in 1976 to 1978 time period, were reviewed. Each study examined a different region. The regions examined were: St. Louis, The Port of New York, and Houston. Somewhat similar methods were used in the New York and the St. Louis studies, while a different methodology was used in the Houston study. In the process of comparing the results from these studies, it was discovered that there were errors in the calculation of diesel emission factors in both the Port of New York and Houston studies. These errors were corrected, and the annual marine emissions recomputed for both studies.

The recalculated emissions (in tons per year) from non-military vessels determined by each of the studies shown in Table IV-6. Also listed in the table are the percentage contributions of marine vessels to total regional emissions of each pollutant. To enable a comparison between regions, the 1970 commerce in tons of cargo for each port (from reference 58) is presented in the table.

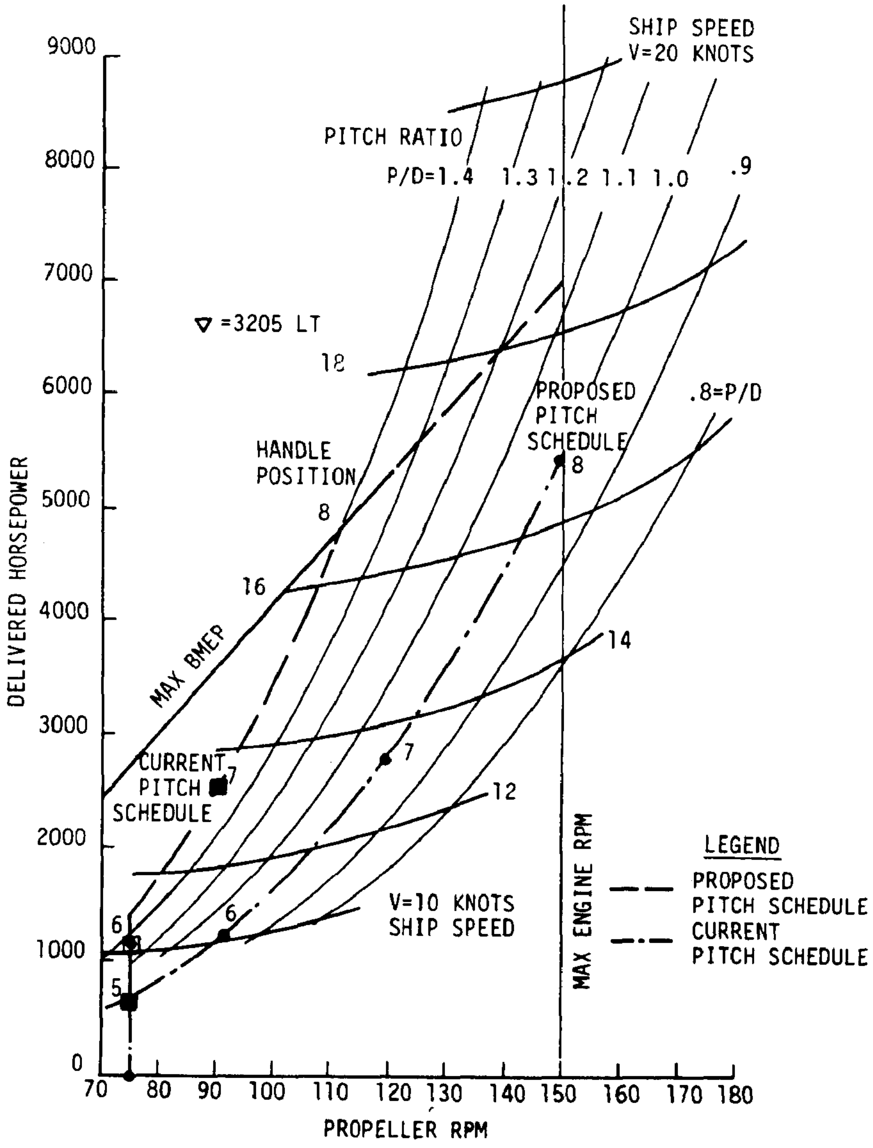

Figure IV-9. Hypothetical WHEC pitch schedule, Propulsion Systems, Inc., ® Propeller

Since St. Louis is a river port, the cargo figure includes not only cargo with origin or destination in St. Louis, but also cargo that "passes by" on the river. The cargo tonnage estimate for St. Louis was obtained from reference 55.

TABLE IV-6. MARINE EMISSIONS IMPACT OF THREE AREAS

| | Value by Port Location | | |
|---|---|---|---|
| Data Item | St. Louis | Port of New York New Jersey | Houston |
| Emissions, tons/year | | | |
| HC | 939 | 3289 | 364 |
| CO | 2103 | 7683 | 782 |
| $NO_x$ | 3292 | 15694 | 2664 |
| Percent of Total Area Emissions | | | |
| HC | 0.32 | 0.31 | 0.10 |
| CO | 0.06 | 0.18 | 0.09 |
| $NO_x$ | 0.76 | 1.56 | 1.10 |
| Cargo, millions of tons per year | 50.00 | 174.01 | 64.65 |
| Cargo specific emissions, tons/million tons of cargo | | | |
| HC | 18.78 | 18.90 | 6.61 |
| CO | 42.06 | 44.15 | 18.40 |
| $NO_x$ | 65.84 | 90.19 | 56.59 |

While the vessel emissions from each region should not necessarily be exactly proportional to the cargo level, the cargo specific emissions in terms of tons of emissions per million tons of cargo could all be expected to be of the same order of magnitude. This comparison holds for New York and St. Louis, whose cargo specific emissions are in good agreement, but not when comparing Houston with either New York or St. Louis. Part of the reason for these differences appears to be due to the propulsion system mix in the various ports. St. Louis was assumed to be all diesels, as would be expected in an area where almost all waterborne vessels are towboats. The New York Harbor study concluded that 95 percent of the operational hours in New York Harbor were accounted for by diesel-powered vessels. The Houston study indicated that only 65 percent of the cargo tonnage in the part of Houston was carried by diesel-powered vessels. This difference in percent of diesel vessels accounts for some of the difference between New York and Houston marine emissions on a cargo specific basis.

After a review of the calculational methods used in both the Houston study and the New York study, it is considered likely that the Houston study probably underestimates the marine emissions. The key parameter of the methodology used in the Houston study is the fuel consumption per thousand tons of cargo carried for various classes of vessels. The variables used to calculate this parameter appear to be more suited to open water cruising than maneuvering in a harbor. Therefore, the values of fuel consumption per thousand tons of cargo used in the Houston study were probably too low, causing the total marine emissions per year to be too low. If the New York emissions per million tons of cargo are used for Houston, the annual Houston marine emissions would be:

| | HC | CO | $NO_x$ |
|---|---|---|---|
| Estimated Houston emission (tons/year) | 1,222 | 2,854 | 5,819 |
| Percent of total Houston emissions | 0.33 | 0.32 | 2.5 |

Even with these revised emissions, the marine contribution in the Houston area is less than one percent for HC and CO, and less than 3 percent for $NO_x$. Thus for all three regions investigated, marine emissions were less than one percent of the total HC and CO emissions, and less than three percent of the total $NO_x$ emissions.

As with all determination of total emissions in an area, this analysis does not address the effect of marine vessel emissions on microscale situations. There are likely to be areas around docks and marine terminals where marine vessels are the predominate sources of ambient air pollution. However, no situations have been found in the literature in which marine vessel emissions have caused an area to exceed ambient air standards.

Emissions estimates for the South Coast Air Basin (SCAB) have been obtained for both locomotives and construction equipment. It was therefore decided to also estimate the marine vessel $NO_x$ emission in the SCAB to provide one region with the $NO_x$ emissions impact from all three off-highway emission sources studied in this project. Marine vessel $NO_x$ emissions in the SCAB were estimated using the total cargo tons handled in the ports of Los Angeles and Long Beach in 1981 (75.06 million tons, from reference 58) together with the cargo specific $NO_x$ emission factor from the Port of New York (see Table IV-6). Using these figures, and the total SCAB $NO_x$ emissions from reference 26, it is estimated that marine vessel emissions contributed 6771 tons of $NO_x$, or 1.5 percent of the total SCAB annual $NO_x$ emissions.

Estimate of emissions based on cargo specific emission factors can only be made in areas where the majority of the ships are being loaded or unloaded since it is based on cargo handled. To obtain a nationwide estimate of marine vessel emissions another method is required, since a large quantity of the emissions will occur in the river networks. The method used was to estimate the national marine emission percentages from the railroad percentages using the fact that inland waterway traffic carries about 42 percent of the freight railroads carry, but requires only approximately 81 percent of the fuel per revenue ton-mile. The detailed calculations for this estimate are shown in Appendix C. The resulting estimate of marine vessel contributions to nationwide emissions are shown on the following page.

| | National Annual Marine Vessel Emissions As: | |
|---|---|---|
| | Percent of All Sources | Percent of Mobile Sources |
| HC | 0.2 | 0.6 |
| CO | 0.2 | 0.2 |
| $NO_x$ | 2.1 | 5.0 |

## V. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

This study has examined emissions from three off-highway mobile source categories. New emission factors were recommended for two of the categories, and national and regional emissions were estimated for each category individually. The study indicated that for the sources investigated, the largest air pollution impact was from $NO_x$ emissions. On a nationwide basis, it is estimated that in 1981 there were 19.5 million tons of $NO_x$ emitted into the atmosphere(21). Mobile sources were estimated to contribute 8.2 million tons of this $NO_x$, or about 42 percent of the total(21). The contribution to nationwide $NO_x$ emissions from the three sources investigated in this study are shown below.

| Source Category | Percent of 1981 $NO_x$ Emissions from All Sources | Percent of 1981 $NO_x$ Emissions from Mobile Source |
|---|---|---|
| Railroads | 4.6 | 11.0 |
| Construction/equipment | 2.0 | 4.7 |
| Marine vessels | 2.1 | 5.0 |
| Total of 3 categories | 8.7 | 20.7 |

Since on-highway mobile source $NO_x$ emissions standards will tend to reduce mobile source $NO_x$ emissions as a whole, and because of projected increases in the off-highway $NO_x$ due to increased economic activity (more goods shipped by rail and water, and more construction activity), the percentages shown above are likely to increase somewhat in the future.

Since emissions from the three categories are not uniform over the whole country, it is more useful to examine emission impact by region. The $NO_x$ emissions in tons per year from all three off-highway categories were determined for the South Coast Air Basin (SCAB) in California. The SCAB includes a major part of Los Angeles County, all of Orange County, and parts of Riverside and San Bernardino Counties. As of early 1983, this area exceeded the ambient air quality standard for ozone,(57) having the highest ozone readings in the country(21). There were only 11 counties in the whole U.S. that exceeded the $NO_x$ air quality standard(57). This area contains all or part of four of those counties. The contributions from the three off-highway sources to the 1979 (1977 for railroads) SCAB $NO_x$ emissions are shown below.

| Category | Percent of Total SCAB $NO_x$ Emissions Low Estimate | Percent of Total SCAB $NO_x$ Emissions High Estimate |
|---|---|---|
| Railroads | 1.7 | 6.1 |
| Construction equipment | 0.9 | 2.4 |
| Marine vessels | 1.5 | 1.5 |
| Total | 4.1 | 10.0 |

A low and a high estimate are shown because different methods and sources produced different estimates. The railroad percentage estimates are for the entire four counties, not just the portions of the counties in the SCAB. There are other regions where the contributions for railroad emissions were higher. In Kansas City and Chicago, for example, the high estimates of railroad contributions $NO_x$ emissions in 1977 were approximately 9 and 8 percent, respectively.

## Conclusions

The following conclusions were derived from this study of emissions from locomotives, construction equipment, and marine vessels.

Locomotives:

1. Over the past 10 years, a number of changes have occurred in railroad operating practices and in locomotive engines themselves, due to rapidly increasing fuel cost. These changes, together with the availability of additional locomotive emissions data, all indicated that new locomotive emission factors were required.

2. The locomotive emission factors developed in this study in general have lower HC and higher CO and $NO_x$ values than those in AP-42. As an example, for the national average emission factors, HC is 44 percent, CO is 138 percent and $NO_x$ is 143 percent of the AP-42 values. The revised factors can be used to provide improved estimates of the contribution of locomotives to local, regional, and national air pollution totals.

3. A recently completed AAR study of 40 locomotives should provide a far superior locomotive emissions data base, when the study results are released.

4. There is a need for additional information on current locomotive operating cycles.

5. Locomotive contributions to HC and CO levels, both on a national and regional basis, are under two percent of total HC or CO Emissions. Locomotive contributions to $NO_x$ emissions in 1981 were approximately 4.6 percent of the national total. In the future, in some regions, the locomotive contribution may exceed 10 percent of total regional $NO_x$ emissions.

Construction Equipment:

1. A recent study, called the CAL/ERT study, sponsored by a consortium of industry groups, has produced the most comprehensive investigation of construction equipment emissions done to date.

2. The CAL/ERT study emission factors are recommended as replacements for the current construction equipment emission factors in AP-42. These new factors do not differ greatly from those currently in AP-42. The average of all new HC emission factors is eight percent higher, CO is 41 percent higher and $NO_x$ is 12 percent lower, than the AP-42 averages.

3. A deficiency in the CAL/ERT report is that the emissions factors are not necessarily based on in-service units.

4. Construction equipment HC and CO are less than one percent of total national HC and CO emissions. Construction equipment contributed approximately two percent of the national $NO_x$ emissions for 1981, and about 4.7 percent of the 1981 national mobile source $NO_x$ emissions. As an example of regional impact, construction equipment in the South Coast Air Basin of California may contribute as much as 2.4 percent of the total $NO_x$ emissions in the region.

Marine Vessels:

1. Over the past ten years, rising fuel costs have caused several changes in marine vessel powerplants. One of the most significant is the increased use of diesel engines in the U.S. merchant fleet. In addition, marine diesel engine manufacturers are striving to increase the efficiency of the engine while permitting operation with poorer grades of fuel.

2. The data available to calculate marine vessel emissions and emissions impact are extremely scarce.

3. Marine boiler emissions from either AP-42 or the draft report of EPA-450/4-84-001 are adequate for present use.

4. Extending previous regional studies to a national estimate on the basis of cargo tonnage, it appears that marine vessels contribute approximately two percent of the total national $NO_x$ emissions, and approximately five percent of the national mobile source $NO_x$ emissions. Regionally, marine vessels can contribute as much as two and one half percent of the $NO_x$ emissions. The fact that the marine vessel contribution is higher at the national level than at the regional level runs counter to the intuitive notion that the regional impact should be higher. A possible reason for this difference is that the majority of the ton-miles of cargo for this estimate are accumulated on the U.S. river systems outside of urban areas.

## Recommendations

The off-highway mobile emission sources investigated in this study are not major sources of air pollution at this time. However, as more on-highway vehicles meeting current and future emission regulations are put in service, off-highway mobile sources will increase in importance, with air quality planners becoming increasingly interested in them. At the present time, much of the information required to accurately assess the contribution of these off-highway mobile sources is not available. To provide this information, a list of recommended research work, in order of the priority perceived from this study, is presented below.

1. A survey of marine vessels is required to determine how vessels should be classed for emissions studies, and the population of each class in U.S. waters. In addition, diesel engine population by manufacturer and design horsepower is required. This latter information should be obtainable from the computer data base of the American Bureau of Shipping.

2. Once the popular makes and models of marine diesel engines and the classes of vessels are defined, cycles for typical in-harbor operation of each class of vessel and the more popular engines should be defined.

3. A project is required to measure actual marine diesel engine exhaust emissions and fuel consumption at engine operating conditions defined by the duty cycles. These measurements should be made on a number of the most popular engine makers and models.

4. It is recommended that a study be conducted to define locomotive duty cycles representing current operational practices. The duty cycles should be based on a twenty-four hour day, and include the time the engine is shut down.

5. While locomotive emission factor estimates are considered to be better than those for construction equipment or marine vessels, the emission results of the AAR 40-locomotive study just completed would no doubt add greatly to the accuracy of locomotive emission factors. It is recommended that these data from the AAR study, when they become available, be incorporated into the locomotive emissions data base, and new emission factors calculated.

6. The AAR should soon have a computer data base of locomotives in service. It is recommended that this data base be used as soon as available, to update information on number of engines by manufacturer, model, and horsepower, as well as information on number of line-haul and switch engines.

7. The construction equipment emission factors recommended in this report are assumed to be for new engines. It is recommended that a selection of in-use construction equipment be tested for emissions to define the relationships between new and in-use emissions.

8. The negotiations between the state of California and the construction industry group should be followed to determine what construction equipment impact estimate is finally agreed upon for the California regions.

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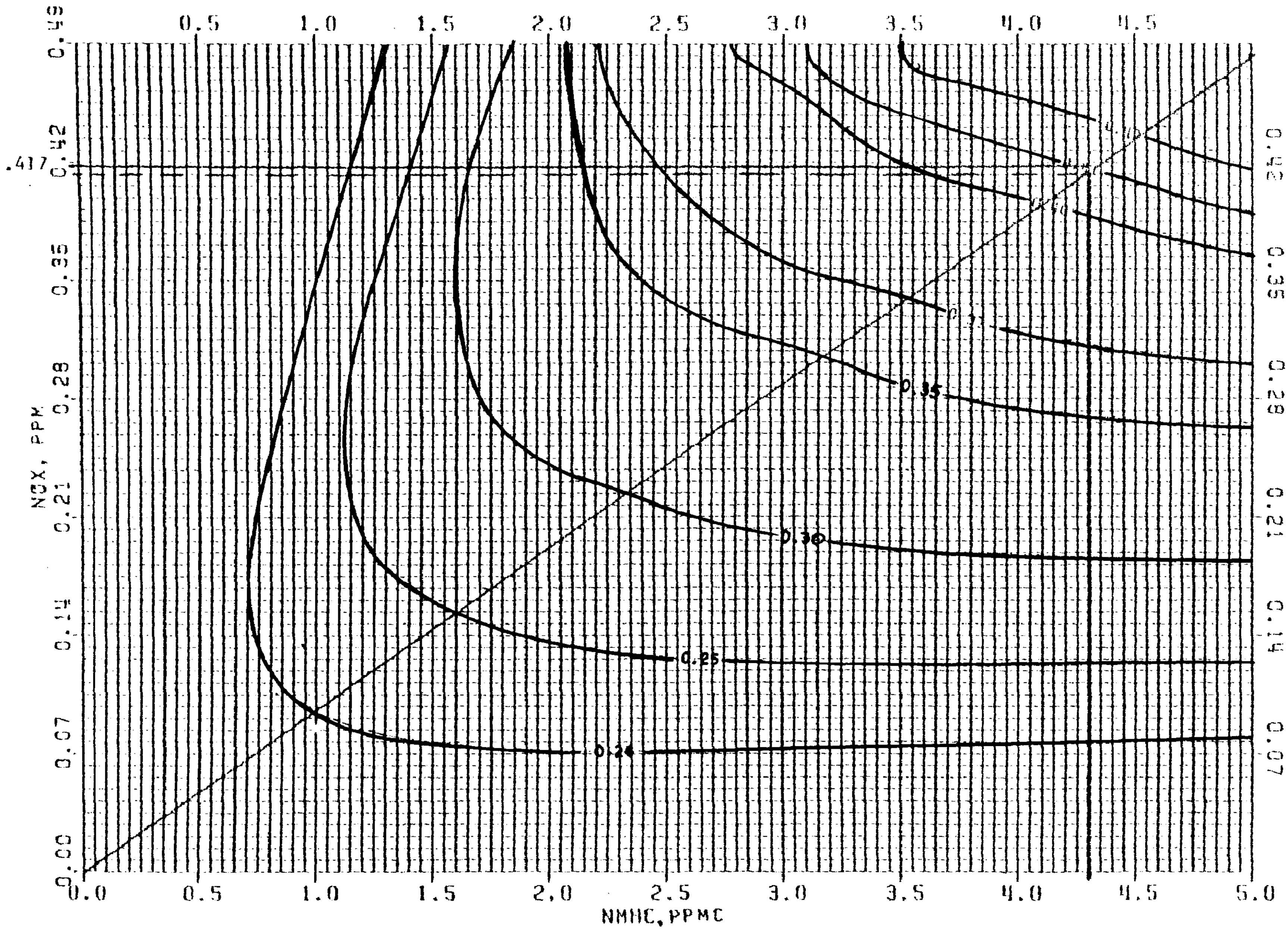
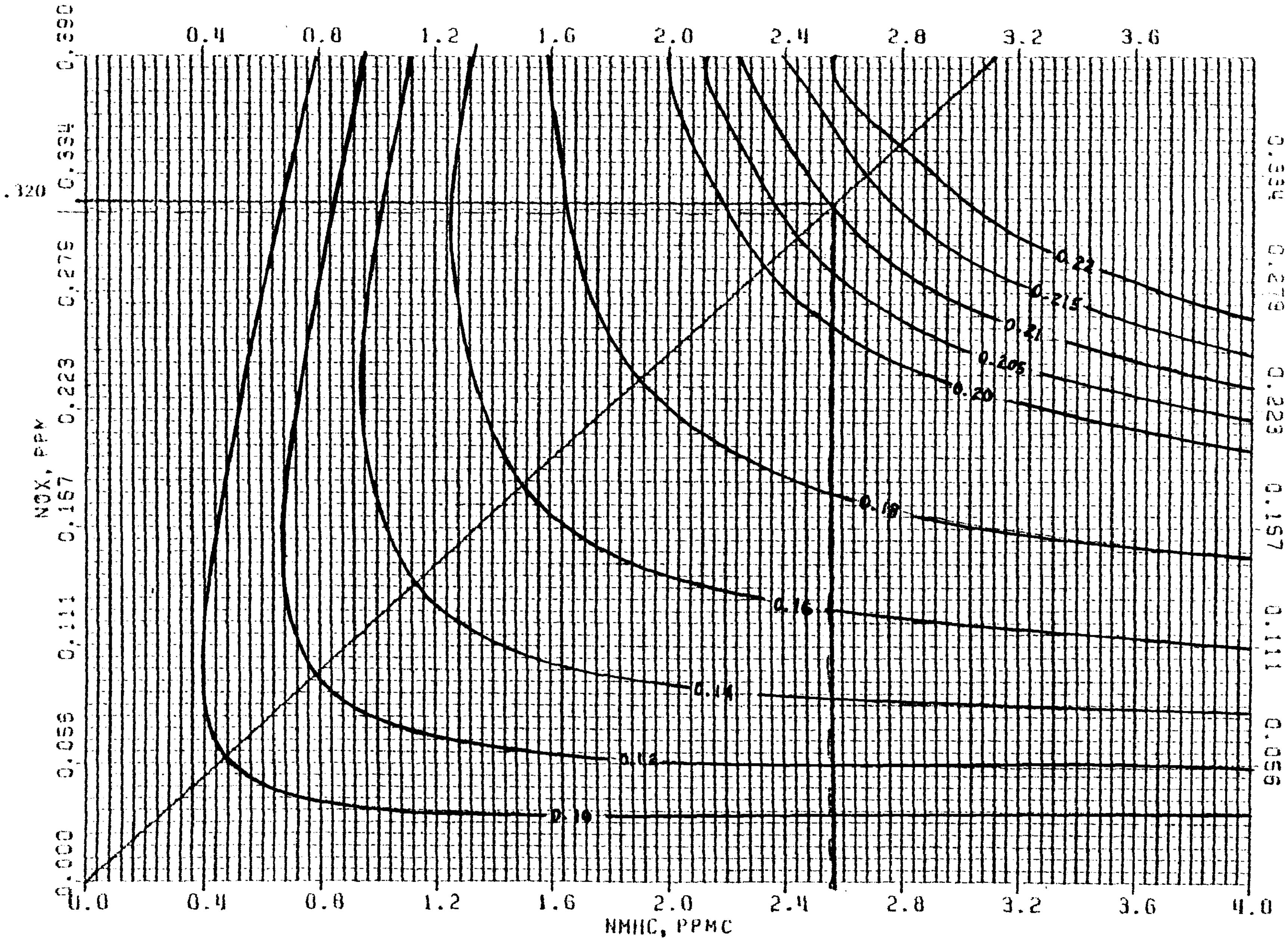
# APPENDIX A

## EXAMPLES OF PLOTS FROM THE EKMA COMPUTER PROGRAM SHOWING THE RELATIONSHIP BETWEEN HC, $NO_X$ AND $O_3$



** SCAB ** JULY 13, 1978



** SACRAMENTO ** JULY 21, 1978

# APPENDIX B

# SUPPORTING MATERIAL FOR LOCOMOTIVE EMISSION FACTOR DEVELOPMENT AND IMPACT DETERMINATION

## Calculation of Average Daily Locomotive Operating Hours[a]

A. Freight Locomotives:

annual diesel locomotive miles = $1.316 \times 10^9$

diesel locomotive average speed = 18.2 miles/hour

annual diesel locomotive hours = $(1.316 \times 10^9)/(18.2) = 72320384$

number of diesel locomotives in freight service = 21592

annual operating hours per locomotive = 72320384/21592 = 3349

daily operating hours per locomotive = 3344/365 = 9.2

B. Passenger Locomotives:

annual diesel locomotive miles = $48.423 \times 10^6$

diesel locomotive average speed = 31.3 miles/hour

C. Switching Locomotives:

total annual diesel yard switching miles = $167.734 \times 10^6$

number of diesel switching locomotive = 5511

annual diesel yard switching miles per locomotive = $(167{,}734 \times 10^6)/5511$
= 30436

daily switching miles per locomotive = 30436/365 = 83.387

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(a) Based on 1980 Statistics as given in Statistical Summary Numbers 66.

## ESTIMATE OF PERCENT OF OPERATING TIME THAT AMBIENT TEMPERATURE IS ABOVE 50 F

1. From "Climatic Atlas of the United States" the areas of the country where the average minimum temperature is above 50 F by month.

| Month | Areas Where Avg. Minimum Temp. is 50°F |
|---|---|
| January | All of Florida; Brownsville, TX. |
| February | All of Florida; Brownsville, TX. |
| March | Florida, South Texas, Louisiana |
| April | FL, GA, SC, AL, MS, LA, AR, TX, Desert Southwest, Southern California |
| May | All states east of Colorado and South of Missouri, California, most of Arizona and Northwest |
| June | All of country except high Rockies |
| July | All of country except high Rockies |
| August | All of country except high Rockies |
| September | All of country east of Colorado and South of Minnesota and Vermont. Also CA, AZ, southern New Mexico. |
| October | Same as April |
| November | Same as March |
| December | Same as January |

2. Calculation of Fraction of Time Available

| Months | Area | Fraction of Annual hr | Fraction of County[a] | Product |
|---|---|---|---|---|
| November through February | Florida and Brownsville, TX | 0.330 | 0.02 | 0.0066 |
| March | FL, South TX, LA | 0.083 | 0.05 | 0.0042 |
| April and May | Southern U.S. | 0.167 | 0.50 | 0.0835 |
| June through August | All of U.S. | 0.250 | 1.00 | 0.2500 |
| September | 2/3 of U.S. | 0.083 | 0.67 | 0.1680 |
| October | Southern U.S. | 0.083 | 0.50 | 0.0420 |
| | | | Total | 0.5500 |

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[a] Fraction of railroad miles used with small area for November through February and for March

3. Thus, approximately 55 percent of the time weather conditions will permit engine shut down.

# APPENDIX C

# SUPPORTING MATERIAL FOR MARINE EMISSION FACTORS DEVELOPMENT AND IMPACT DETERMINATION

## Calculation of National Marine Vessel Emissions Impact

1. The marine vessel emissions are divided into two parts: the river contribution and the ocean harbor contribution. The river contribution is calculated by comparison to the railroad contribution. The ocean harbor contribution directly from cargo specific emission factor and total tons of coastal cargo.

2. River Contribution

(a) From "Railroad Facts, 1983(1) in 1981, Great Lakes and river traffic accounted for 16 percent of the total freight shipped in the U.S. Railroads accounted for 37.9 percent. Therefore, inland waterborne traffic accounted for:

inland water = 16/37.9 = 0.422

(b) Inland vessels use 3.3 gal/1000 ton-miles(2). Railroads in 1981 used 4.08 gal/1000 revenue ton-miles(1) Thus inland vessels would use 3.3/4.08 = 0.81 of fuel railroads use to carry the same ton-miles of cargo

(c) Inland vessels in 1981 use the following percent of railroad fuel:

0.81 x .422 = 0.34 or 34 percent of the fuel used by the railroads

(d) Assuming inland vessels (which are mostly powered by EMD engines) have the same fuel specific emissions as railroads the inland vessel contribution to national emissions is 34 percent of the railroads contribution.

| | Railroad | | Inland Vessels ( RRx.34) | |
|---|---|---|---|---|
| | Percent of All Sources | Percent of Mobile Sources | Percent of All Sources | Percent of Mobile Sources |
| HC | 0.34 | 0.94 | 0.12 | 0.32 |
| CO | 0.35 | 0.46 | 0.12 | 0.16 |
| $NO_x$ | 4.6 | 11 | 1.6 | 3.7 |

3. Coastal Contribution

(a) In 1981 foreign and coastal cargo handled amounted to $1179.1 \times 10^6$ tons(2)

(b) From text cargo specific emission factors for coastal areas are represented by the New York harbor cargo specific emission factors. The tons of emissions per year are:

$HC = (19\ \text{tons}/10^6\ \text{tons})\text{x}1179.1\text{x}10^6\ \text{tons} = 22{,}403\ \text{tons/year}$

$CO = (44\ \text{tons}/10^6\ \text{tons})\text{x}1179.1\text{x}10^6\ \text{tons} = 51{,}880\ \text{tons/year}$

$NO_x = (90\ \text{tons}/10^6\ \text{tons})\text{x}1179.1\text{x}10^6\ \text{tons} = 106{,}119\ \text{tons/year}$

(c) As a percent of total nationwide emissions using the 1981 Emissions Report(3):

| | Percent of All Sources | Percent of Mobile Sources |
|---|---|---|
| HC | $(22{,}403/21.0\text{x}10^6)\text{x}100 = 0.11$ | $(22{,}403/7.5\ \text{x}\ 10^6) = 0.30$ |
| CO | $(51{,}880/91\text{x}10^6)\text{x}100 = 0.06$ | $(51{,}880/70\text{x}10^6\text{x}100) = 0.07$ |
| $NO_x$ | $(106{,}119/19.5\text{x}10^6)\text{x}100 = 0.54$ | $(106{,}119/8.2\text{x}10^6)\text{x}100 = 1.29$ |

4. Total Marine Impact

| | Emissions Percent of Total | | | | | |
|---|---|---|---|---|---|---|
| | HC | | CO | | $NO_x$ | |
| | All Sources | Mobile Sources | Oil Sources | Mobile Sources | All Sources | Mobile Sources |
| River | 0.12 | 0.32 | 0.12 | 0.16 | 1.6 | 3.7 |
| Coastal | 0.11 | 0.30 | 0.06 | 0.07 | 0.5 | 1.3 |
| Total | 0.23 | 0.62 | 0.18 | 0.23 | 2.1 | 5.0 |

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References

1. "Yearbook of Railroad Facts - 1982." Association of American Railroads, Washington, D.C.

2. Dattner, S.L., Ledbetter, J. O., and Miksod, R. W., "A Method for Rapid Calculation of Merchant Vessel Combustion Emissions," Journal of the Air Pollution Control Assoc., Vol. 30, No. 3, March, 1980, pages 305 to 309.

3. "National Air Quality and Emissions Trends Report, 1981, "Report No. EPA 450/4-83-011, U.S. Environmental Protection Agency, Office Air Quality Planning and Standards, Research Triangle Park, NC.

# APPENDIX D

## AP-42 SECTIONS CONTAINING EMISSION FACTORS FOR LOCOMOTIVES, CONSTRUCTION EQUIPMENT AND MARINE VESSELS

## 3.2.2 Locomotives

*by David S. Kircher*

3.2.2.1 General – Railroad locomotives generally follow one of two use patterns: railyard switching or road-haul service. Locomotives can be classified on the basis of engine configuration and use pattern into five categories: 2-stroke switch locomotive (supercharged), 4-stroke switch locomotive, 2-stroke road service locomotive (supercharged), 2-stroke road service locomotive (turbocharged), and 4-stroke road service locomotive.

The engine duty cycle of locomotives is much simpler than many other applications involving diesel internal combustion engines because locomotives usually have only eight throttle positions in addition to idle and dynamic brake. Emission testing is made easier and the results are probably quite accurate because of the simplicity of the locomotive duty cycle.

3.2.2.2 Emissions – Emissions from railroad locomotives are presented two ways in this section. Table 3.2.2-1 contains average factors based on the nationwide locomotive population breakdown by category. Table 3.2.2-2 gives emission factors by locomotive category on the basis of fuel consumption and on the basis of work output (horsepower hour).

The calculation of emissions using fuel-based emission factors is straightforward. Emissions are simply the product of the fuel usage and the emission factor. In order to apply the work output emission factor, however, an

Table 3.2.2-1. AVERAGE LOCOMOTIVE EMISSION FACTORS BASED ON NATIONWIDE STATISTICS[a]

| Pollutant | Average emissions[b] | |
|---|---|---|
| | lb/$10^3$ gal | kg/$10^3$ liter |
| Particulates[c] | 25 | 3.0 |
| Sulfur oxides[d] ($SO_x$ as $SO_2$) | 57 | 6.8 |
| Carbon monoxide | 130 | 16 |
| Hydrocarbons | 94 | 11 |
| Nitrogen oxides ($NO_x$ as $NO_2$) | 370 | 44 |
| Aldehydes (as HCHO) | 5.5 | 0.66 |
| Organic acids[c] | 7 | 0.84 |

[a] Reference 1.

[b] Based on emission data contained in Table 3.2.2-2 and the breakdown of locomotive use by engine category in the United States in Reference 1.

[c] Data based on highway diesel data from Reference 2. No actual locomotive particulate test data are available.

[d] Based on a fuel sulfur content of 0.4 percent from Reference 3.

## Table 3.2.2-2. EMISSION FACTORS BY LOCOMOTIVE ENGINE CATEGORY[a]
## EMISSION FACTOR RATING: B

| | Engine category | | | | |
|---|---|---|---|---|---|
| Pollutant | 2-Stroke supercharged switch | 4-Stroke switch | 2-Stroke supercharged road | 2-Stroke turbocharged road | 4-Stroke road |
| Carbon monoxide | | | | | |
| lb/$10^3$ gal | 84 | 380 | 66 | 160 | 180 |
| kg/$10^3$ liter | 10 | 46 | 7.9 | 19 | 22 |
| g/hphr | 3.9 | 13 | 1.8 | 4.0 | 4.1 |
| g/metric hphr | 3.9 | 13 | 1.8 | 4.0 | 4.1 |
| Hydrocarbon | | | | | |
| lb/$10^3$ gal | 190 | 146 | 148 | 28 | 99 |
| kg/$10^3$ liter | 23 | 17 | 18 | 3.4 | 12 |
| g/hphr | 8.9 | 5.0 | 4.0 | 0.70 | 2.2 |
| g/metric hphr | 8.9 | 5.0 | 4.0 | 0.70 | 2.2 |
| Nitrogen oxides ($NO_x$ as $NO_2$) | | | | | |
| lb/$10^3$ gal | 250 | 490 | 350 | 330 | 470 |
| kg/$10^3$ liter | 30 | 59 | 42 | 40 | 56 |
| g/hphr | 11 | 17 | 9.4 | 8.2 | 10 |
| g/metric hphr | 11 | 17 | 9.4 | 8.2 | 10 |

[a] Use average factors (Table 3.2.2-1) for pollutants not listed in this table.

additional calculation is necessary. Horsepower hours can be obtained using the following equation:

$$w = lph$$

where: w = Work output (horsepower hour)

l = Load factor (average power produced during operation divided by available power)

p = Available horsepower

h = Hours of usage at load factor (l)

After the work output has been determined, emissions are simply the product of the work output and the emission factor. An approximate load factor for a line-haul locomotive (road service) is 0.4; a typical switch engine load factor is approximately 0.06.[1]

## References for Section 3.2.2

1. Hare, C.T. and K.J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Part 1. Locomotive Diesel Engines and Marine Counterparts. Final Report. Southwest Research Institute. San Antonio, Texas Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number EHA 70-108. October 1972.

2. Young, T.C. Unpublished Data from the Engine Manufacturers Association. Chicago, Ill. May 1970.

3. Hanley, G.P. Exhaust Emission Information on Electro-Motive Railroad Locomotives and Diesel Engines. General Motors Corp. Warren, Mich. October 1971.

## 3.2.7 Heavy-Duty Construction Equipment

*by David S. Kircher*

3.2.7.1 General – Because few sales, population, or usage data are available for construction equipment, a number of assumptions were necessary in formulating the emission factors presented in this section.[1] The useful life of construction equipment is fairly short because of the frequent and severe usage it must endure. The annual usage of the various categories of equipment considered here ranges from 740 hours (wheeled tractors and rollers) to 2000 hours (scrapers and off-highway trucks). This high level of use results in average vehicle lifetimes of only 6 to 16 years. The equipment categories in this section include: tracklaying tractors, tracklaying shovel loaders, motor graders, scrapers, off-highway trucks, wheeled loaders, wheeled tractors, rollers, wheeled dozers, and miscellaneous machines. The latter category contains a vast array of less numerous mobile and semi-mobile machines used in construction, such as, belt loaders, cranes, pumps, mixers, and generators. With the exception of rollers, the majority of the equipment within each category is diesel-powered.

3.2.7.2 Emissions – Emission factors for heavy-duty construction equipment are reported in Table 3.2.7-1 for diesel engines and in Table 3.2.7-2 for gasoline engines. The factors are reported in three different forms—on the basis of running time, fuel consumed, and power consumed. In order to estimate emissions from time-based emission factors, annual equipment usage in hours must be estimated. The following estimates of use for the equipment listed in the tables should permit reasonable emission calculations.

| Category | Annual operation, hours/year |
|---|---|
| Tracklaying tractors | 1050 |
| Tracklaying shovel loaders | 1100 |
| Motor graders | 830 |
| Scrapers | 2000 |
| Off-highway trucks | 2000 |
| Wheeled loaders | 1140 |
| Wheeled tractors | 740 |
| Rollers | 740 |
| Wheeled dozers | 2000 |
| Miscellaneous | 1000 |

The best method for calculating emissions, however, is on the basis of "brake specific" emission factors (g/kWh or g/hphr). Emissions are calculated by taking the product of the brake specific emission factor, the usage in hours, the power available (that is, rated power), and the load factor (the power actually used divided by the power available).

## References for Section 3.2.7

1. Hare, C. T. and K. J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines – Final Report. Part 5: Heavy-Duty Farm, Construction, and Industrial Engines. Southwest Research Institute, San Antonio, Tex. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. October 1973. 105 p.

2. Hare, C. T. Letter to C. C. Masser of Environmental Protection Agency, Research Triangle Park, N.C., concerning fuel-based emission rates for farm, construction, and industrial engines. San Antonio, Tex. January 14, 1974. 4 p.

### Table 3.2.7-1. EMISSION FACTORS FOR HEAVY-DUTY, DIESEL-POWERED CONSTRUCTION EQUIPMENT[a]
### EMISSION FACTOR RATING: C

| Pollutant | Tracklaying tractor | Wheeled tractor | Wheeled dozer | Scraper | Motor grader |
|---|---|---|---|---|---|
| Carbon monoxide | | | | | |
| g/hr | 175. | 973. | 335. | 660. | 97.7 |
| lb/hr | 0.386 | 2.15 | 0.739 | 1.46 | 0.215 |
| g/kWh | 3.21 | 5.90 | 2.45 | 3.81 | 2.94 |
| g/hphr | 2.39 | 4.40 | 1.83 | 2.84 | 2.19 |
| kg/10$^3$ liter | 10.5 | 19.3 | 7.90 | 11.8 | 9.35 |
| lb/10$^3$ gal | 87.5 | 161. | 65.9 | 98.3 | 78.0 |
| Exhaust hydrocarbons | | | | | |
| g/hr | 50.1 | 67.2 | 106. | 284. | 24.7 |
| lb/hr | 0.110 | 0.148 | 0.234 | 0.626 | 0.054 |
| g/kWh | 0.919 | 1.86 | 0.772 | 1.64 | 0.656 |
| g/hphr | 0.685 | 1.39 | 0.576 | 1.22 | 0.489 |
| kg/10$^3$ liter | 3.01 | 6.10 | 2.48 | 5.06 | 2.09 |
| lb/10$^3$ gal | 25.1 | 50.9 | 20.7 | 42.2 | 17.4 |
| Nitrogen oxides ($NO_x$ as $NO_2$) | | | | | |
| g/hr | 665. | 451. | 2290. | 2820. | 478. |
| lb/hr | 1.47 | 0.994 | 5.05 | 6.22 | 1.05 |
| g/kWh | 12.2 | 12.5 | 16.8 | 16.2 | 14.1 |
| g/hphr | 9.08 | 9.35 | 12.5 | 12.1 | 10.5 |
| kg/10$^3$ liter | 39.8 | 41.0 | 53.9 | 50.2 | 44.8 |
| lb/10$^3$ gal | 332. | 342. | 450. | 419. | 374. |
| Aldehydes (RCHO as HCHO) | | | | | |
| g/hr | 12.4 | 13.5 | 29.5 | 65. | 5.54 |
| lb/hr | 0.027 | 0.030 | 0.065 | 0.143 | 0.012 |
| g/kWh | 0.228 | 0.378 | 0.215 | 0.375 | 0.162 |
| g/hphr | 0.170 | 0.282 | 0.160 | 0.280 | 0.121 |
| kg/10$^3$ liter | 0.745 | 1.23 | 0.690 | 1.16 | 0.517 |
| lb/10$^3$ gal | 6.22 | 10.3 | 5.76 | 9.69 | 4.31 |
| Sulfur oxides ($SO_x$ as $SO_2$) | | | | | |
| g/hr | 62.3 | 40.9 | 158. | 210. | 39.0 |
| lb/hr | 0.137 | 0.090 | 0.348 | 0.463 | 0.086 |
| g/kWh | 1.14 | 1.14 | 1.16 | 1.21 | 1.17 |
| g/hphr | 0.851 | 0.851 | 0.867 | 0.901 | 0.874 |
| kg/10$^3$ liter | 3.73 | 3.73 | 3.74 | 3.74 | 3.73 |
| lb/10$^3$ gal | 31.1 | 31.1 | 31.2 | 31.2 | 31.1 |
| Particulate | | | | | |
| g/hr | 50.7 | 61.5 | 75. | 184. | 27.7 |
| lb/hr | 0.112 | 0.136 | 0.165 | 0.406 | 0.061 |
| g/kWh | 0.928 | 1.70 | 0.551 | 1.06 | 0.838 |
| g/hphr | 0.692 | 1.27 | 0.411 | 0.789 | 0.625 |
| kg/10$^3$ liter | 3.03 | 5.57 | 1.77 | 3.27 | 2.66 |
| lb/10$^3$ gal | 25.3 | 46.5 | 14.8 | 27.3 | 22.2 |

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[a] References 1 and 2.

Table 3.2.7-1 (continued). EMISSION FACTORS FOR HEAVY-DUTY, DIESEL-POWERED CONSTRUCTION EQUIPMENT[a]
EMISSION FACTOR RATING: C

| Pollutant | Wheeled loader | Tracklaying loader | Off-Highway truck | Roller | Miscel-laneous |
|---|---|---|---|---|---|
| Carbon monoxide | | | | | |
| g/hr | 251. | 72.5 | 610. | 83.5 | 188. |
| lb/hr | 0.553 | 0.160 | 1.34 | 0.184 | 0.414 |
| g/kWh | 3.51 | 2.41 | 3.51 | 4.89 | 3.78 |
| g/hphr | 2.62 | 1.80 | 2.62 | 3.65 | 2.82 |
| kg/$10^3$ liter | 11.4 | 7.90 | 11.0 | 13.7 | 11.3 |
| lb/$10^3$ gal | 95.4 | 65.9 | 92.2 | 114. | 94.2 |
| Exhaust hydrocarbons | | | | | |
| g/hr | 84.7 | 14.5 | 198. | 24.7 | 71.4 |
| lb/hr | 0.187 | 0.032 | 0.437 | 0.054 | 0.157 |
| g/kWh | 1.19 | 0.485 | 1.14 | 1.05 | 1.39 |
| g/hphr | 0.888 | 0.362 | 0.853 | 0.781 | 1.04 |
| kg/$10^3$ liter | 3.87 | 1.58 | 3.60 | 2.91 | 4.16 |
| lb/$10^3$ gal | 32.3 | 13.2 | 30.0 | 24.3 | 34.7 |
| Nitrogen oxides ($NO_x$ as $NO_2$) | | | | | |
| g/hr | 1090. | 265. | 3460. | 474. | 1030. |
| lb/hr | 2.40 | 0.584 | 7.63 | 1.04 | 2.27 |
| g/kWh | 15.0 | 8.80 | 20.0 | 21.1 | 19.8 |
| g/hphr | 11.2 | 6.56 | 14.9 | 15.7 | 14.8 |
| kg/$10^3$ liter | 48.9 | 28.8 | 62.8 | 58.5 | 59.2 |
| lb/$10^3$ gal | 408. | 240. | 524. | 488. | 494. |
| Aldehydes (RCHO as HCHO) | | | | | |
| g/hr | 18.8 | 4.00 | 51.0 | 7.43 | 13.9 |
| lb/hr | 0.041 | 0.009 | 0.112 | 0.016 | 0.031 |
| g/kWh | 0.264 | 0.134 | 0.295 | 0.263 | 0.272 |
| g/hphr | 0.197 | 0.100 | 0.220 | 0.196 | 0.203 |
| kg/$10^3$ liter | 0.859 | 0.439 | 0.928 | 0.731 | 0.813 |
| lb/$10^3$ gal | 7.17 | 3.66 | 7.74 | 6.10 | 6.78 |
| Sulfur oxides ($SO_x$ as $SO_2$) | | | | | |
| g/hr | 82.5 | 34.4 | 206. | 30.5 | 64.7 |
| lb/hr | 0.182 | 0.076 | 0.454 | 0.067 | 0.143 |
| g/kWh | 1.15 | 1.14 | 1.19 | 1.34 | 1.25 |
| g/hphr | 0.857 | 0.853 | 0.887 | 1.00 | 0.932 |
| kg/$10^3$ liter | 3.74 | 3.74 | 3.74 | 3.73 | 3.73 |
| lb/$10^3$ gal | 31.2 | 31.2 | 31.2 | 31.1 | 31.1 |
| Particulate | | | | | |
| g/hr | 77.9 | 26.4 | 116. | 22.7 | 63.2 |
| lb/hr | 0.172 | 0.058 | 0.256 | 0.050 | 0.139 |
| g/kWh | 1.08 | 0.878 | 0.673 | 1.04 | 1.21 |
| g/hphr | 0.805 | 0.655 | 0.502 | 0.778 | 0.902 |
| kg/$10^3$ liter | 3.51 | 2.88 | 2.12 | 2.90 | 3.61 |
| lb/$10^3$ gal | 29.3 | 24.0 | 17.7 | 24.2 | 30.1 |

[a] References 1 and 2.

## Table 3.2.7-2. EMISSION FACTORS FOR HEAVY-DUTY GASOLINE-POWERED CONSTRUCTION EQUIPMENT[a]

EMISSION FACTOR RATING: C

| Pollutant | Wheeled tractor | Motor grader | Wheeled loader | Roller | Miscel-laneous |
|---|---|---|---|---|---|
| Carbon monoxide | | | | | |
| g/hr | 4320. | 5490. | 7060. | 6080. | 7720. |
| lb/hr | 9.52 | 12.1 | 15.6 | 13.4 | 17.0 |
| g/kWh | 190. | 251. | 219. | 271. | 266. |
| g/hphr | 142. | 187. | 163. | 202. | 198. |
| kg/$10^3$ liter | 389. | 469. | 435. | 460. | 475. |
| lb/$10^3$ gal | 3250. | 3910. | 3630. | 3840. | 3960. |
| Exhaust hydrocarbons | | | | | |
| g/hr | 164. | 186. | 241. | 277. | 254. |
| lb/hr | 0.362 | 0.410 | 0.531 | 0.611 | 0.560 |
| g/kWh | 7.16 | 8.48 | 7.46 | 12.40 | 8.70 |
| g/hphr | 5.34 | 6.32 | 5.56 | 9.25 | 6.49 |
| kg/$10^3$ liter | 14.6 | 15.8 | 14.9 | 21.1 | 15.6 |
| lb/$10^3$ gal | 122. | 132. | 124. | 176. | 130. |
| Evaporative hydrocarbons[b] | | | | | |
| g/hr | 30.9 | 30.0 | 29.7 | 28.2 | 25.4 |
| lb/hr | 0.0681 | 0.0661 | 0.0655 | 0.0622 | 0.0560 |
| Crankcase hydrocarbons[b] | | | | | |
| g/hr | 32.6 | 37.1 | 48.2 | 55.5 | 50.7 |
| lb/hr | 0.0719 | 0.0818 | 0.106 | 0.122 | 0.112 |
| Nitrogen oxides ($NO_x$ as $NO_2$) | | | | | |
| g/hr | 195. | 145. | 235. | 164. | 187. |
| lb/hr | 0.430 | 0.320 | 0.518 | 0.362 | 0.412 |
| g/kWh | 8.54 | 6.57 | 7.27 | 7.08 | 6.42 |
| g/hphr | 6.37 | 4.90 | 5.42 | 5.28 | 4.79 |
| kg/$10^3$ liter | 17.5 | 12.2 | 14.5 | 12.0 | 11.5 |
| lb/$10^3$ gal | 146. | 102. | 121. | 100. | 95.8 |
| Aldehydes (RCHO as HCHO) | | | | | |
| g/hr | 7.97 | 8.80 | 9.65 | 7.57 | 9.00 |
| lb/hr | 0.0176 | 0.0194 | 0.0213 | 0.0167 | 0.0198 |
| g/kWh | 0.341 | 0.386 | 0.298 | 0.343 | 0.298 |
| g/hphr | 0.254 | 0.288 | 0.222 | 0.256 | 0.222 |
| kg/$10^3$ liter | 0.697 | 0.721 | 0.593 | 0.582 | 0.532 |
| lb/$10^3$ gal | 5.82 | 6.02 | 4.95 | 4.86 | 4.44 |
| Sulfur oxides ($SO_x$ as $SO_2$) | | | | | |
| g/hr | 7.03 | 7.59 | 10.6 | 8.38 | 10.6 |
| lb/hr | 0.0155 | 0.0167 | 0.0234 | 0.0185 | 0.0234 |
| g/kWh | 0.304 | 0.341 | 0.319 | 0.373 | 0.354 |
| g/hphr | 0.227 | 0.254 | 0.238 | 0.278 | 0.264 |
| kg/$10^3$ liter | 0.623 | 0.636 | 0.636 | 0.633 | 0.633 |
| lb/$10^3$ gal | 5.20 | 5.31 | 5.31 | 5.28 | 5.28 |

Table 3.2.7-2. (continued). EMISSION FACTORS FOR HEAVY-DUTY GASOLINE-POWERED CONSTRUCTION EQUIPMENT[a]
EMISSION FACTOR RATING: C

| Pollutant | Wheeled tractor | Motor grader | Wheeled loader | Roller | Miscel-laneous |
|---|---|---|---|---|---|
| Particulate | | | | | |
| g/hr | 10.9 | 9.40 | 13.5 | 11.8 | 11.7 |
| lb/hr | 0.0240 | 0.0207 | 0.0298 | 0.0260 | 0.0258 |
| g/kWh | 0.484 | 0.440 | 0.421 | 0.527 | 0.406 |
| g/hphr | 0.361 | 0.328 | 0.314 | 0.393 | 0.303 |
| kg/$10^3$ liter | 0.991 | 0.822 | 0.839 | 0.895 | 0.726 |
| lb/$10^3$ gal | 8.27 | 6.86 | 7.00 | 7.47 | 6.06 |

[a] References 1 and 2.

[b] Evaporative and crankcase hydrocarbons based on operating time only (Reference 1).

## 3.2.3 Inboard-Powered Vessels

*Revised by David S. Kircher*

3.2.3.1 General – Vessels classified on the basis of use will generally fall into one of three categories: commercial, pleasure, or military. Although usage and population data on vessels are, as a rule, relatively scarce, information on commercial and military vessels is more readily available than data on pleasure craft. Information on military vessels is available in several study reports,[1-5] but data on pleasure craft are limited to sales-related facts and figures.[6-10]

Commercial vessel population and usage data have been further subdivided by a number of industrial and governmental researchers into waterway classifications[11-16] (for example, Great Lakes vessels, river vessels, and coastal vessels). The vessels operating in each of these waterway classes have similar characteristics such as size, weight, speed, commodities transported, engine design (external or internal combustion), fuel used, and distance traveled. The wide variation between classes, however, necessitates the separate assessment of each of the waterway classes with respect to air pollution.

Information on military vessels is available from both the U.S. Navy and the U.S. Coast Guard as a result of studies completed recently. The U.S. Navy has released several reports that summarize its air pollution assessment work.[3-5] Emission data have been collected in addition to vessel population and usage information. Extensive study of the air pollutant emissions from U.S. Coast Guard watercraft has been completed by the U.S. Department of Transportation. The results of this study are summarized in two reports.[1-2] The first report takes an in-depth look at population/usage of Coast Guard vessels. The second report, dealing with emission test results, forms the basis for the emission factors presented in this section for Coast Guard vessels as well as for non-military diesel vessels.

Although a large portion of the pleasure craft in the U.S. are powered by gasoline outboard motors (see section 3.2.4 of this document), there are numerous larger pleasure craft that use inboard power either with or without "out-drive" (an outboard-like lower unit). Vessels falling into the inboard pleasure craft category utilize either Otto cycle (gasoline) or diesel cycle internal combustion engines. Engine horsepower varies appreciably from the small "auxiliary" engine used in sailboats to the larger diesels used in yachts.

### 3.2.3.2 Emissions

*Commercial vessels.* Commercial vessels may emit air pollutants under two major modes of operation: underway and at dockside (auxiliary power).

Emissions underway are influenced by a great variety of factors including power source (steam or diesel), engine size (in kilowatts or horsepower), fuel used (coal, residual oil, or diesel oil), and operating speed and load. Commercial vessels operating within or near the geographic boundaries of the United States fall into one of the three categories of use discussed above (Great Lakes, rivers, coastline). Tables 3.2.3-1 and 3.2.3-2 contain emission information on commercial vessels falling into these three categories. Table 3.2.3-3 presents emission factors for diesel marine engines at various operating modes on the basis of horsepower. These data are applicable to any vessel having a similar size engine, not just to commercial vessels.

Unless a ship receives auxiliary steam from dockside facilities, goes immediately into drydock, or is out of operation after arrival in port, she continues her emissions at dockside. Power must be made available for the ship's lighting, heating, pumps, refrigeration, ventilation, etc. A few steam ships use auxiliary engines (diesel) to supply power, but they generally operate one or more main boilers under reduced draft and lowered fuel rates–a very inefficient process. Motorships (ships powered by internal combustion engines) normally use diesel-powered generators to furnish auxiliary power.[17] Emissions from these diesel-powered generators may also be a source of underway emissions if they are used away from port. Emissions from auxiliary power systems, in terms of the

## Table 3.2.3-1. AVERAGE EMISSION FACTORS FOR COMMERCIAL MOTORSHIPS BY WATERWAY CLASSIFICATION

### EMISSION FACTOR RATING: C

| Emissions[a] | Class[c] River | Great Lakes | Coastal |
|---|---|---|---|
| Sulfur oxides[b] | | | |
| ($SO_x$ as $SO_2$) | | | |
| kg/$10^3$ liter | 3.2 | 3.2 | 3.2 |
| lb/$10^3$ gal | 27 | 27 | 27 |
| Carbon monoxide | | | |
| kg/$10^3$ liter | 12 | 13 | 13 |
| lb/$10^3$ gal | 100 | 110 | 110 |
| Hydrocarbons | | | |
| kg/$10^3$ liter | 6.0 | 7.0 | 6.0 |
| lb/$10^3$ gal | 50 | 59 | 50 |
| Nitrogen oxides | | | |
| ($NO_x$ as $NO_2$) | | | |
| kg/$10^3$ liter | 33 | 31 | 32 |
| lb/$10^3$ gal | 280 | 260 | 270 |

[a] Expressed as function of fuel consumed (based on emission data from Reference 2 and population/usage data from References 11 through 16.

[b] Calculated, not measured. Based on 0.20 percent sulfur content fuel and density of 0.854 kg/liter (7.12 lb/gal) from Reference 17.

[c] Very approximate particulate emission factors from Reference 2 are 470 g/hr (1.04 lb/hr). The reference does not contain suffieient information to calculate fuel-based factors.

quantity of fuel consumed, are presented in Table 3.2.3-4. In some instances, fuel quantities used may not be available, so calculation of emissions based on kilowatt hours (kWh ) produced may be necessary. For operating loads in excess of zero percent, the mass emissions ($e_l$) in kilograms per hour (pounds per hour) are given by:

$$e_l = kle_f \qquad (1)$$

where: $k$ = a constant that relates fuel consumption to kilowatt hours,[2]

that is, $3.63 \times 10^{-4}$ 1000 liters fuel/kWh

or

$9.59 \times 10^{-5}$ 1000 gal fuel/kWh

$l$ = the load, kW

$e_f$ = the fuel-specific emission factor from Table 3.2.3-4, kg/$10^3$ liter (lb/$10^3$ gal)

### Table 3.2.3-2. EMISSION FACTORS FOR COMMERCIAL STEAMSHIPS–ALL GEOGRAPHIC AREAS
### EMISSION FACTOR RATING: D

| Pollutant | Fuel and operating mode[a] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Residual oil[b] | | | | | | Distillate oil[b] | | | | | |
| | Hoteling | | Cruise | | Full | | Hoteling | | Cruise | | Full | |
| | kg/$10^3$ liter | lb/$10^3$ gal | kg/$10^3$ liter | lb/$10^3$ gal | kg/$10^3$ liter | lb/$10^3$ gal | kg/$10^3$ liter | lb/$10^3$ gal | kg/$10^3$ liter | lb/$10^3$ gal | kg/$10^3$ liter | lb/$10^3$ gal |
| Particulates[c] | 1.20[d] | 10.0[d] | 2.40 | 20.0 | 6.78 | 56.5 | 1.8 | 15 | 1.78 | 15 | 1.78 | 15 |
| Sulfur oxides ($SO_x$ as $SO_2$)[e] | 19.1S | 159S | 19.1S | 159S | 19.1S | 159S | 17.0S | 142S | 17.0S | 142S | 17.0S | 142S |
| Carbon monoxide[c] | Neg[d] | Neg[d] | 0.414 | 3.45 | 0.872 | 7.27 | 0.5 | 4 | 0.5 | 4 | 0.5 | 4 |
| Hydrocarbons[c] | 0.38[d] | 3.2[d] | 0.082 | 0.682 | 0.206 | 1.72 | 0.4 | 3 | 0.4 | 3 | 0.4 | 3 |
| Nitrogen oxides ($NO_x$ as $NO_2$) | 4.37 | 36.4 | 6.70 | 55.8 | 7.63 | 63.6 | 2.66 | 22.2 | 2.83 | 23.6 | 5.34 | 44.5 |

[a] The operating modes are based on the percentage of maximum available power: "hoteling" is 10 to 11 percent of available power, "full" is 100 percent of available power, and "cruise" is an intermediate power (35 to 75 percent, depending on the test organization and vessel tested).

[b] Test organizations used "Navy Special" fuel oil, which is not a true residual oil. No vessel test data were available for residual oil combustion. "Residual" oil results are from References 2, 3, and 5. "Distillate" oil results are from References 3 and 5 only. Exceptions are noted. "Navy Distillate" was used as distillate test fuel.

[c] Particulate, carbon monoxide, and hydrocarbon emission factors for distillate oil combustion are based on stationary boilers (see Section 1.3 of this document).

[d] Reference 18 indicates that carbon monoxide emitted during hoteling is small enough to be considered negligible. This reference also places hydrocarbons at 0.38 kg/$10^3$ liter (3.2 lb/$10^3$ gal) and particulate at 1.20 kg/$10^3$ liter (10.0 lb/$10^3$ gal). These data are included for completeness only and are not necessarily comparable with other tabulated data.

[e] Emission factors listed are theoretical in that they are based on all the sulfur in the fuel converting to sulfur dioxide. Actual test data from References 3 and 5 confirm the validity of these theoretical factors. "S" is fuel sulfur content in percent.

### Table 3.2.3-3. DIESEL VESSEL EMISSION FACTORS BY OPERATING MODE[a]
### EMISSION FACTOR RATING: C

| | | Emissions[b] | | | | | |
|---|---|---|---|---|---|---|---|
| | | Carbon monoxide | | Hydrocarbons | | Nitrogen oxides ($NO_x$ as $NO_2$) | |
| Horsepower | Mode | lb/$10^3$ gal | kg/$10^3$ liter | lb/$10^3$ gal | kg/$10^3$ liter | lb/$10^3$ gal | kg/$10^3$ liter |
| 200 | Idle | 210.3 | 25.2 | 391.2 | 46.9 | 6.4 | 0.8 |
| | Slow | 145.4 | 17.4 | 103.2 | 12.4 | 207.8 | 25.0 |
| | Cruise | 126.3 | 15.1 | 170.2 | 20.4 | 422.9 | 50.7 |
| | Full | 142.1 | 17.0 | 60.0 | 7.2 | 255.0 | 30.6 |
| 300 | Slow | 59.0 | 7.1 | 56.7 | 6.8 | 337.5 | 40.4 |
| | Cruise | 47.3 | 5.7 | 51.1 | 6.1 | 389.3 | 46.7 |
| | Full | 58.5 | 7.0 | 21.0 | 2.5 | 275.1 | 33.0 |
| 500 | Idle | 282.5 | 33.8 | 118.1 | 14.1 | 99.4 | 11.9 |
| | Cruise | 99.7 | 11.9 | 44.5 | 5.3 | 338.6 | 40.6 |
| | Full | 84.2 | 10.1 | 22.8 | 2.7 | 269.2 | 32.3 |
| 600 | Idle | 171.7 | 20.6 | 68.0 | 8.2 | 307.1 | 36.8 |
| | Slow | 50.8 | 6.1 | 16.6 | 2.0 | 251.5 | 30.1 |
| | Cruise | 77.6 | 9.3 | 24.1 | 2.9 | 349.2 | 41.8 |
| 700 | Idle | 293.2 | 35.1 | 95.8 | 11.5 | 246.0 | 29.5 |
| | Cruise | 36.0 | 4.3 | 8.8 | 1.1 | 452.8 | 54.2 |
| 900 | Idle | 223.7 | 26.8 | 249.1 | 29.8 | 107.5 | 12.9 |
| | 2/3 | 62.2 | 7.5 | 16.8 | 2.0 | 167.2 | 20.0 |
| | Cruise | 80.9 | 9.7 | 17.1 | 2.1 | 360.0 | 43.1 |
| 1550 | Idle | 12.2 | 1.5 | – | – | 39.9 | 4.8 |
| | Cruise | 3.3 | 0.4 | 0.64 | 0.1 | 36.2 | 4.3 |
| | Full | 7.0 | 0.8 | 1.64 | 0.2 | 37.4 | 4.5 |
| 1580 | Slow | 122.4 | 14.7 | – | – | 371.3 | 44.5 |
| | Cruise | 44.6 | 5.3 | – | – | 623.1 | 74.6 |
| | Full | 237.7 | 28.5 | 16.8 | 2.0 | 472.0 | 5.7 |
| 2500 | Slow | 59.8 | 7.2 | 22.6 | 2.7 | 419.6 | 50.3 |
| | 2/3 | 126.5 | 15.2 | 14.7 | 1.8 | 326.2 | 39.1 |
| | Cruise | 78.3 | 9.4 | 16.8 | 2.0 | 391.7 | 46.9 |
| | Full | 95.9 | 11.5 | 21.3 | 2.6 | 399.6 | 47.9 |
| 3600 | Slow | 148.5 | 17.8 | 60.0 | 7.2 | 367.0 | 44.0 |
| | 2/3 | 28.1 | 3.4 | 25.4 | 3.0 | 358.6 | 43.0 |
| | Cruise | 41.4 | 5.0 | 32.8 | 4.0 | 339.6 | 40.7 |
| | Full | 62.4 | 7.5 | 29.5 | 3.5 | 307.0 | 36.8 |

[a] Reference 2.

[b] Particulate and sulfur oxides data are not available.

## Table 3.2.3-4. AVERAGE EMISSION FACTORS FOR DIESEL-POWERED ELECTRICAL GENERATORS IN VESSELS[a]
## EMISSION FACTOR RATING: C

| Rated output,[b] kW | Load,[c] % rated output | Emissions | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Sulfur oxides ($SO_x$ as $SO_2$)[d] | | Carbon monoxide | | Hydro-carbons | | Nitrogen oxides ($NO_x$ as $NO_2$) | |
| | | $lb/10^3$ gal | $kg/10^3$ liter | $lb/10^3$ gal | $kg/10^3$ liter | $lb/10^3$ gal | $kg/10^3$ liter | $lb/10^3$ gal | $kg/10^3$ liter |
| 20 | 0 | 27 | 3.2 | 150 | 18.0 | 263 | 31.5 | 434 | 52.0 |
| | 25 | 27 | 3.2 | 79.7 | 9.55 | 204 | 24.4 | 444 | 53.2 |
| | 50 | 27 | 3.2 | 53.4 | 6.40 | 144 | 17.3 | 477 | 57.2 |
| | 75 | 27 | 3.2 | 28.5 | 3.42 | 84.7 | 10.2 | 495 | 59.3 |
| 40 | 0 | 27 | 3.2 | 153 | 18.3 | 584 | 70.0 | 214 | 25.6 |
| | 25 | 27 | 3.2 | 89.0 | 10.7 | 370 | 44.3 | 219 | 26.2 |
| | 50 | 27 | 3.2 | 67.6 | 8.10 | 285 | 34.2 | 226 | 27.1 |
| | 75 | 27 | 3.2 | 64.1 | 7.68 | 231 | 27.7 | 233 | 27.9 |
| 200 | 0 | 27 | 3.2 | 134 | 16.1 | 135 | 16.2 | 142 | 17.0 |
| | 25 | 27 | 3.2 | 97.9 | 11.7 | 33.5 | 4.01 | 141 | 16.9 |
| | 50 | 27 | 3.2 | 62.3 | 7.47 | 17.8 | 2.13 | 140 | 16.8 |
| | 75 | 27 | 3.2 | 26.7 | 3.20 | 17.5 | 2.10 | 137 | 16.4 |
| 500 | 0 | 27 | 3.2 | 58.4 | 7.00 | 209 | 25.0 | 153 | 18.3 |
| | 25 | 27 | 3.2 | 53.4 | 6.40 | 109 | 13.0 | 222 | 26.6 |
| | 50 | 27 | 3.2 | 48.1 | 5.76 | 81.9 | 9.8 | 293 | 35.1 |
| | 75 | 27 | 3.2 | 43.7 | 5.24 | 59.1 | 7.08 | 364 | 43.6 |

[a] Reference 2.

[b] Maximum rated output of the diesel-powered generator.

[c] Generator electrical output (for example, a 20 kW generator at 50 percent load equals 10 kW output).

[d] Calculated, not measured, based on 0.20 percent fuel sulfur content and density of 0.854 kg/liter (7.12 lb/gal) from Reference 17.

At zero load conditions, mass emission rates ($e_l$) may be approximated in terms of kg/hr (lb/hr) using the following relationship:

$$e_l = k l_{rated} e_f \tag{2}$$

where: k = a constant that relates rated output and fuel consumption,

that is, $6.93 \times 10^{-5}$ 1000 liters fuel/kW

or

$1.83 \times 10^{-5}$ 1000 gal fuel/kW

$l_{rated}$ = the rated output, kW

$e_f$ = the fuel-specific emission factor from Table 3.2.3-4, $kg/10^3$ liter ($lb/10^3$ gal)

*Pleasure craft.* Many of the engine designs used in inboard pleasure craft are also used either in military vessels (diesel) or in highway vehicles (gasoline). Out of a total of 700,000 inboard pleasure craft registered in the United States in 1972, nearly 300,000 were inboard/outdrive. According to sales data, 60 to 70 percent of these inboard/outdrive craft used gasoline-powered automotive engines rated at more than 130 horsepower.[6] The remaining 400,000 pleasure craft used conventional inboard drives that were powered by a variety of powerplants, both gasoline and diesel. Because emission data are not available for pleasure craft, Coast Guard and automotive data[2,19] are used to characterize emission factors for this class of vessels in Table 3.2.3-5.

*Military vessels.* Military vessels are powered by a wide variety of both diesel and steam power plants. Many of the emission data used in this section are the result of emission testing programs conducted by the U.S. Navy and the U.S. Coast Guard.[1-3,5] A separate table containing data on military vessels is not provided here, but the included tables should be sufficient to calculate approximate military vessel emissions.

TABLE 3.2.3.-5. AVERAGE EMISSION FACTORS FOR INBOARD PLEASURE CRAFT[a]

EMISSION FACTOR RATING: D

| | Based on fuel consumption | | | | Based on operating time | | | |
|---|---|---|---|---|---|---|---|---|
| | Diesel engine[b] | | Gasoline engine[c] | | Diesel engine[b] | | Gasoline engine[c] | |
| Pollutant | $kg/10^3$ liter | $lb/10^3$ gal | $kg/10^3$ liter | $lb/10^3$ gal | kg/hr | lb/hr | kg/hr | lb/hr |
| Sulfur oxides[d] ($SO_x$ as $SO_2$) | 3.2 | 27 | 0.77 | 6.4 | – | – | 0.008 | 0.019 |
| Carbon monoxide | 17 | 140 | 149 | 1240 | – | – | 1.69 | 3.73 |
| Hydrocarbons | 22 | 180 | 10.3 | 86 | – | – | 0.117 | 0.258 |
| Nitrogen oxides ($NO_x$ as $NO_2$) | 41 | 340 | 15.7 | 131 | – | – | 0.179 | 0.394 |

[a] Average emission factors are based on the duty cycle developed for large outboards (≥ 48 kilowatts or ≥ 65 horsepower) from Reference 7. The above factors take into account the impact of water scrubbing of underwater gasoline engine exhaust, also from Reference 7. All values given are for single engine craft and must be modified for multiple engine vessels.

[b] Based on tests of diesel engines in Coast Guard vessels, Reference 2.

[c] Based on tests of automotive engines, Reference 19. Fuel consumption of 11.4 liter/hr (3 gal/hr) assumed. The resulting factors are only *rough* estimates.

[d] Based on fuel sulfur content of 0.20 percent for diesel fuel and 0.043 percent for gasoline from References 7 and 17. Calculated using fuel density of 0.740 kg/liter (6.17 lb/gal) for gasoline and 0.854 kg/liter (7.12 lb/gal) for diesel fuel.

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# APPENDIX E

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# PERSONS CONTACTED

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16. ABSTRACT

This study examined three categories of off-highway mobile emission sources to determine current emission factors of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen ($NO_x$). The three categories examined were locomotives, marine vessels, and farm and construction equipment. National and regional impact of these emission sources were also examined. For locomotives, it was found that rising fuel prices had led to engine improvements as well as changes in locomotive operation. Additional measured emission data were also found in the literature. Using new duty cycles and the additional emissions test data, new locomotive emission factors were developed. In U.S. waters, marine emissions are changing as diesel engines are used in a larger portion of the U.S. Merchant Fleet. None of the literature surveyed provided sufficient valid information to determine new marine diesel engine emission factors. New farm and construction equipment emission factors were recommended based on a recent study found in the literature.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Air Pollution<br>Exhaust Emissions<br>Diesel Locomotives<br>Marine Engines<br>Agricultural Equipment<br>Construction Equipment | Locomotive Emissions<br>Marine Emissions<br>Off-Highway Emissions<br>Farm Equipment Emissions<br>Construction Equipment Emissions | |

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