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Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data

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Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data

Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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1. INTRODUCTION

The EPA is initiating a review of its guidance on developing emission inventories for ocean-going and harbor vessels operating at port areas. The current methodology, as defined in AP-42, is based on a three step calculation. The first step apportions the time spent by a vessel in a port area to different operating modes. The second calculates fuel consumption in each operating mode. The third step calculates emissions using fuel consumption specific emission factors, which is how marine engine emission factors have been historically specified. All of these calculations are by vessel type and class, with the type specifying whether the vessel is a tanker, passenger liner, etc, and the class specifying either the weight or horsepower range.

The time-in-mode is a function of the particular port area geography and is not considered in this report. The other factors used in the computation are examined, with particular focus on the emission factor, for all pollutants of concern. One reason for a detailed reconsideration of the emission factor is that a number of large marine diesels have been tested for emissions and their tests result have become available in the last few years. In addition, both the EPA and ARB have recently sponsored studies to calculate marine vessel emissions in the South Coast Air Basin and in some areas of Region IX, so that there is a body of new research available to update emission factors. Hence, the use of a larger and newer database on marine vessel emission is expected to substantially improve the quality of the derived emission factors.

In this work assignment, the EPA did not require a literature review, but instead provided with nine reports as the basis for this review. Due to the fact that data on emissions from gas turbines were restricted to two engines, most of the analysis presented in this report pertains only to diesel powered marine vessels and only an average emission rate for the gas turbines is presented. Section 2 of this report presents the findings of our literature review of the nine reports provided by EPA. Section 3 details our analysis of emissions data contained in reports, and the resultant derivation of emission factors. Section 4 provides an analysis of vessel classifications and

horsepower to vessel weight relationships. Section 5 summarizes the resultant emission factors by vessel type, and operating mode.

2. REVIEW OF RELEVANT DATA

2.1 INTRODUCTION

As noted, the U.S. EPA had identified nine reports in its work assignment for review. All of these were obtained by EEA from EPA and reviewed to assess the usefulness for this study. The reports can be classified into two groups of four reports. One group provides detailed tables on actual emissions data. The second group of four reports are studies that utilize one or more of the reports in the first group to estimate emission factors, and to estimate emission inventories for marine vessels operating in a specific region, like the South Coast Air Basin. One report simply provided data on gas turbines emissions and is not reviewed in this section, but the data is presented in Section 3.

The reports were reviewed to estimate the applicability of the data or the analysis to the EPA requirements to calculate emission factors by ship class, type and operating mode. EPA has also proposed rules for controlling marine engine emissions by defining three engine categories. The EPA categories are based on individual cylinder displacement and the categories are:

- less than five liters;
- five to 20 liters; and
- greater than 20 liters.

These categories approximately correspond to engines in the high speed, medium speed and slow speed categories used by IMO and Lloyds in previous analyses. However, the correspondence may or may not hold true for some specific engine designs.

2.2 FINDINGS ON REPORTS PROVIDING EMISSIONS DATA

The four reports that provide emissions data includes one from British Columbia Ferry Corporation, one from Environment Canada, one from Lloyd's (in three sections), and one from the U.S. Coast Guard. Each report is summarized in Appendix B.

The <u>Lloyd's</u> data[1,2,3] is the most detailed although there are some inconsistencies in the data. For example, the text and table do not agree on the actual number of engines tested, or the type. Data on engine tests are reported in Appendices, but engine make and displacement are not reported. In addition, the Lloyd's data also indicated large inconsistencies in the measured output at full load versus actual engine ratings. Ostensibly, all engines were tested at idle, 25, 50, 75, and 100 percent of full power; yet in a majority of cases, the 100 percent rated power as measured on the emissions test differs from the engine rated power by as much as ±50 percent. While reductions in power associated with a service derating is possible and production variations of ±10 percent may be reasonable, such large differences are cause for concern, especially as they are unexplained in the text.

However, it should be noted that for most engines, full output corresponded to 83 ±17% of rated power, while about ten engines have measured power either below 66 percent of rated or over 101 percent of rated power. Results indicate generally well behaved CO emission factors as a function of percent of rated power but HC and NO_x emissions dependence on load varies both in magnitude and direction across engines as a function of load. In general, absolute emission rates can vary across engines but the emissions profile for diesel engines as a function of load do not vary greatly. The variations as plotted in the Lloyds report are so large across engines that it raises questions on the data and test procedure.

The <u>BC Ferry Test Program</u> report[5] appears incomplete and has several inconsistencies that make the data difficult to use. The main issue is that the test procedure was conducted at two different, undefined conditions labeled "normal cruise" and "docking operation". Data on eight engines are presented, (the tables show nine engine tested at normal cruise), but the test conditions relative to the engine rated power are very inconsistent across engines. Engine data is inadequate to determine what EPA category they may fall into. Data presented indicates that five were medium speed diesels, while three are high speed engines (but the data on one high speed engine shows an improbably high RPM figure for a 4500 kW diesel). Only fuel specific emission rates are reported for the engines.

The Environment Canada report[6] provides data on 11 engines tested on three modes: maneuvering, low speed cruise and high speed cruise. The report does not describe how these modes are defined and whether the relative load on the engine (or load factor) was similar across the 11 engines. Only fuel specific emission indices are reported, and there are very large variations across engines in a similar category. Not enough data is provided to determine how these engines fit into the EPA categories. EEA attempted to obtain more detailed data on the test procedure and measured emissions from Environment Canada, but could not do so in the time available.

The tests conducted by the Coast Guard[4] were on six ships with two engines each (one ship also had two gas turbine engines in addition to the diesels). The test procedure was ostensibly conducted at idle, 25, 50, 75, and 100 percent of maximum power, although here again, there appear to be large differences in some instances between reported maximum power and engine ratings. In one instance, the observed power is 85 percent higher than the engine rating provided. Fuel specifications and engine type information (two-stroke/four-stroke) was not provided.

Across all of the four reports, emissions data is available on 20 slow speed engine, 51 medium speed engines and eight high speed engines, plus an additional ten auxiliary engines whose characteristics are not listed. It is not clear if these have been any QA/QC on the data, since the data appear to have certain inconsistencies.

Table 2-1 summarizes the data available and the test procedure used, to the extent it is documented.

2.3   SUMMARY OF REPORTS ANALYZING EMISSIONS DATA

Of the four reports in this category, three were reports that developed marine emissions, inventories for specific regions. The earliest (1991) report is by Booz-Allen and Hamilton[9] for the ARB that developed inventories for Los Angeles/Long Beach and San Francisco. The report computed emissions from Ocean-going, harbor, and fishing vessels. Ocean-going and harbor

TABLE 2-1
SUMMARY OF EMISSIONS DATA

Reference	BC Ferries	Environment Canada	Lloyds Register	Coast Guard
Vessels	8	13	40	6
Engines - Slow speed - Medium speed - High speed - Auxiliary	0 6 3 (?) 3	9 1 1 5	11 36 0 2	0 8 4 0
Test Cycle	• Normal cruise • Docking • Full Power for Auxiliary	• Maneuvering • Low Speed • Normal Cruise • Hoteling for Auxiliary engines	• 100% load • 75% load • 50% load • 25% load • Idle	• 100% load • 75% load • 50% load • 25% load • Idle
Data Reported	All except THC in kg/ton of fuel	All in Kg/ton of fuel	All except PM, as raw data	All in mass per kW-hr and per ton of fuel
Potential Problems	Test points undefined and varies by engine	Test points undefined. All engines not tested at all loads	Measured output at 100% load unrelated to rated power	Measured and rated power do not match for some engines.

vessels were further divided into four types and five weight or HP classes. Fishing vessels were subdivided into four HP categories. The operating profile in each port for the three vessel classes was obtained by surveys. Emissions were calculated using the DOT Port Vessel Emission Model, that calculates fuel consumption and resulting emissions using existing AP-42 emission factors. The methodology is relatively simplistic in that emissions are purely a function of fuel consumption, not load.

A very similar approach was used by Lloyds[8] to determine emissions from ferries operated in Vancouver by the British Columbia Ferry Corporation. The main difference appears to be the use of engine specific emission factors derived from the Lloyds's test program referenced in the previous section. The report is not clear how fuel consumption was translated to emissions, i.e., by mode or based on aggregate fuel consumption rates.

The two other reports, by Arcadis (previously Acurex), calculate emission inventories for marine vessels in the South Coast Air Basin. The 1996 report for the South Coast AQMD[10] differed from the 1991 Booz-Allen Report by including Navy and Coast Guard operations. The Acurex report also used actual data on the HP ratings and fuel consumption (obtained from Lloyds) and improved the characterization of operations in the South Coast. The Acurex report includes a very detailed classification of eight ship types, with each ship type subdivided into eight to ten weight categories. However emissions characterization again appear to be based on calculated fuel consumption, with the use of emission factors on a unit of fuel consumed as derived by Lloyds. These emissions appear to have been derived to represent a power setting of about 85 percent of maximum continuous rating (MCR), but there is no documentation of the methodology used.

The more recent (1999) report by Arcadis (Acurex) for EPA Region IX[8] provides an analysis of marine NO_x emissions for the South Coast. The characterization of ship types is quite detailed as in the 1996 report. This is the only report where emissions in units of work (g/kW-hr) were derived as a function of percent of MCR. The emission factors on this basis were constructed from the 'raw' data provided by Lloyds. Surprisingly, the report does not mention the large

discrepancy between rated and measured power and it is not obvious how the percent of MCR was derived. Regression analysis of individual data points was utilized to relate NO_x emissions to engine load factor (% of MCR). The regression analysis, however, suggested that NO_x emissions either decline slightly or are independent of MCR. If these results are correct, it would suggest little or no difference if NO_x was treated as a constant or as a function of load. Nevertheless, the methodology is conceptually superior to using aggregate fuel consumption data that is multiplied by an emission factor in units of fuel consumption.

2.4   RECOMMENDATIONS FOR ANALYSIS

The review of the emission data available indicated significant inconsistencies in engine power ratings versus measured power output that are too large to ascribe to engine-to-engine variability, or a 'service' derating. Moreover, the test procedures used by different organizations are inconsistent, while the reported results are incompatible with the results from a recommended IMO standard test cycles. In most cases, engine displacement is not available, so that the relationship to EPA engine categories cannot be exactly determined (but could be approximated). In addition, some reported changes in engine emissions with load are directionally inconsistent across engines. Hence, the data analysis focused on data cleaning techniques to identify and correct or reject data that are determined to be in error.

Reports by Booz-Allen, Acurex and Arcadis employ consistent classifications by ship type, but the Acurex and Arcadis reports have developed more detailed breakouts of each ship type by weight category. The use of Lloyd's data to determine the engine and auxiliary HP by these detailed type and weight categories is an improvement over earlier techniques. If engine power is linearly related to ship characteristics, it is not clear that models require the use of weight categories for ship types. A linear regression connecting horsepower to ship weight is preferable relative to analysis by weight categories.

The computation of emissions using fuel consumption as a surrogate load indicator appears to be both unnecessary and to introduce errors. Indeed, the 1999 Arcadis report has utilized emissions as a function of engine load factor to directly compute emission at every operating mode that is

represented in the operating profile. This direct method is preferable to linking emissions to fuel consumption since the computation of fuel consumption and the translations to emissions introduce multiplicative errors in emission estimations. EEA suggest a future marine emission model with four specified modes of operation (e.g., docking, low speed cruise, etc.) where each type of operation is associated with a single load factor. On the other hand, if emissions in g/kW-hr are approximately constant with load factors, (as indicated for NO_x in the Arcadis report) different approaches may not lead to significantly different answers.

In addition, time constraints did not allow us to resolve many of the data issues raised. In the future, EEA recommends that EPA focus on resolving some of the data issues and in expanding the database.

3. EMISSION FACTOR DEVELOPMENT

3.1   <u>INTRODUCTION</u>

Ostensibly, six of the reports provided to EEA for review present the results of marine engine
emissions testing.[1-6] However, three of these reports do not present the described emissions test
data in sufficient detail to support the fundamental analysis required for the development of
marine engine emission factors.[3,5,6] These reports essentially present the results of the author's
emission factor analysis, but not the underlying data that went into the analysis. Without this
underlying data, the utility of these reports is limited for several reasons. First, the presented
emission factors are expressed in units of emission mass per fuel mass consumed, a metric that
for real-world application requires either knowledge or estimation of fuel consumption rates.
However, fuel consumption rates are not usually measured, but rather estimated from engine
design and loading data, where engine loading itself can usually only be estimated. It seems
inappropriate to introduce additional uncertainty into the emissions estimation process through
the use of fuel mass-based emission factors in lieu of emission factors expressed in more
fundamental units of mass per unit engine work. Second, the presented emission factors
represent the aggregation of an unknown number of individual emission tests, such that the
statistical significance of the reported emission factors can be determined. Third, as
demonstrated below, considerable caution must be exercised in converting measured emission
concentrations into valid emission rates. Without access to the underlying test data, it is not
possible to either ensure that adequate caution has been exercised or that the generated emission
rates are comparable to those developed from other test programs.

Attempts were made to contact the authors of the three reports that do not present underlying
emission test data, but these attempts were not successful in the timeframe available to EEA for
analysis. As a result, the emission factors described below were developed through the statistical
analysis of fundamental test data presented in only three of the emission testing reports.[1,2,4] Two
of these reports were prepared by Lloyd's Register of Shipping and consider a wide range of
commercial engine sizes and configurations. The third report was prepared for the U.S. Coast

Guard (USCG) and considers a number of engines that are representative of marine engines in use in the USCG fleet. As described below, all three datasets required considerable quality assurance efforts to ensure that emission factors developed from the reported test data were both reasonable and accurate.

3.2 LLOYD'S EMISSION TEST DATA

Lloyd's Register of Shipping produced two reports that present the results of individual commercial marine emission tests.[1,2] Together, these reports present test data for a total of 46 main propulsion engines and 2 auxiliary engines as summarized in Table 3-1. Emission limits for marine engines have historically been established by engine size expressed in terms of engine rated speed, with nearly all commercial marine engines falling into the low and medium speed categories. The Lloyd's data are quite comprehensive, covering engines in both speed ranges, and the test program reports provide a listing of nearly all critical test data parameters, including:

- raw concentration-based emission measurements for nitrogen oxide (NO), sulfur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and hydrocarbons (HC),
- test engine load, speed, and volumetric fuel consumption,
- test engine specifications,
- test fuel density and carbon, hydrogen, nitrogen, and sulfur mass fractions, and
- ambient test conditions.

Nevertheless, it is important to recognize that exhaust mass flow rates are not measured, so the conversion of measured emission concentrations to emissions mass must be based on theoretical relationships. With the various parameters measured by Lloyd's, it is possible to estimate emissions mass (and thus mass emission rates) through the determination of the mass of intake air required to produce the observed (i.e., measured) combustion products. Ignoring the potential effects of exhaust non-homogeneity and emissions measurement error as well as the unaccounted influences of non-measured combustion products (e.g., particulate matter (PM) and nitrogen dioxide (NO_2)), there is only one specific mass of intake air that will produce a given quantity of combustion products for a given fuel. This specific mass can be calculated by chemically mass

TABLE 3-1
OVERVIEW OF THE LLOYD'S EMISSION TEST DATABASE

Ship Types Tested	Number of Ships Tested	No. of Main Engines Tested	No. of Main Engine Tests	Average Tests per Main Engine	No. of Auxiliary Engines Tested	No. of Auxiliary Engine Tests	Average Tests per Auxiliary Engine
Bulk Carrier	6	6	37	6.2	0	0	0
Container	2	2	11	5.5	1	5	5.0
Dredger	6	6	32	5.3	0	0	0
Roll-on/Roll-off	9	16	90	5.6	1	5	5.0
Tug	7*	7	71	10.1	0	0	0
Tanker	9	9	58	6.4	0	0	0
Total Tests	39	46	299	6.5	2	10	5.0

* For tugs, testing was performed both with (38 tests) and without (33 tests) another vessel being pushed. However, the net effect of this dual testing simply represents an increase in the number of engine loading scenarios tested for tugs.

balancing the input fuel characteristics with measured emission products (both of which are reported by Lloyd's). Such an approach is analogous to the carbon balance technique employed in motor vehicle emissions testing to estimate dilution air volumes in constant volume sampling (CVS) systems.

Given a complete and accurate characterization of: (1) emissions, (2) fuel, and (3) intake air, chemical mass balancing will produce an accurate determination of intake air mass. Ignoring any measurement error, the Lloyd's database does provide a complete characterization of the combustion fuel. Characterization of major emission species (i.e., CO_2 and O_2) as well as several minor emission species is also provided. While the widest possible scope of emission measurements is desirable for increased precision, relatively accurate mass balancing can be performed using emission measurements for CO_2 and O_2 alone, as these compounds account for the bulk of exhaust carbon and oxygen. For marine engines for example, emissions of either are one to two or more orders of magnitude higher than emissions of either CO or HC. However, no

measurements of intake air characteristics are provided by Lloyd's. Intake air containing significant concentrations of carbon or hydrogen can significantly influence chemical mass balance accuracy. In the absence of specific intake air characteristics, it is typical to assume an "average" air composition of 21 percent oxygen and 79 percent nitrogen (representing nitrogen plus other minor, relatively inert, air constituents). Such a presumption was employed in all mass balance analysis performed for this study.

Several additional issues should be considered in interpreting the Lloyd's emissions test data used in this study. No PM testing was performed and, therefore, the Lloyd's data are of no value in determining marine PM emission factors. Additionally, HC measurements are missing for 26 of the 309 emission tests performed. In instances where detailed chemical mass balancing, as described below, included measured HC, a value of zero was assumed for these 26 tests. This assumption is expected to result in only minor precision losses for calculated intake air mass as most combustion hydrogen is emitted as water (H_2O), not HC (emitted HC is typically two to three orders of magnitude lower than emitted H_2O). However, all 26 tests were excluded from the statistical analysis underlying the determination of HC emission factors.

Oxides of nitrogen (NO_x) emission factors are of particular interest in this study as NO_x represents a major pollutant emission species from diesel engines such as those used for marine propulsion. However, the Lloyd's database includes only NO measurements, omitting other NO_x components such as NO_2. To estimate total NO_x emissions from measured NO data, EEA relied on supplementary data presented in the text portion of the Lloyd's report[1] that summarized NO to NO_x ratios for a range of marine engine emission tests conducted prior to those reported. These tests reportedly cover a diverse range of fuels and test conditions, but the observed NO to NO_x ratio, as presented in Table 3-2, varies over a relatively narrow range of 0.86 to 0.98, with a mean and standard deviation of 0.94 and 0.03 respectively. Based on this data, EEA assumed for the purpose of this study, that emitted NO_x is equal to measured NO divided by 0.94.

TABLE 3-2
LLOYD'S NO TO NO$_x$ RATIO FOR MARINE ENGINES

Engine Type	Test Fuel	Idle	25% Load	50% Load	75% Load	Rated Load
Propeller Law	Fuel 1	0.93	0.93	0.95	0.96	0.96
	Fuel 2	0.96	0.89	0.91	0.93	0.93
	Fuel 3	0.91	0.91	0.92	0.92	0.96
	Fuel 4	0.86	0.87	0.89	0.92	0.94
Constant Speed	Fuel 1		0.97	0.98	0.97	0.96
	Fuel 2		0.92	0.93	0.92	0.93
	Fuel 3		0.96	0.94	0.97	0.96
	Fuel 4		0.95	0.94	0.94	0.94
Overall Average = 0.94, Standard Deviation = 0.03						

Even though Lloyd's reported ambient temperature, pressure, and humidity data, no ambient corrections have been applied to any of the emission estimates presented in this study. The decision to ignore ambient corrections was based on the fact that: (1) no generally accepted correction algorithms have been developed for marine engines, (2) ambient data is not available for the USCG data that were combined with the Lloyd's data to generate emission factors (see Section 3.3 below), and (3) the magnitude of ambient corrections are expected to be minor relative to the overall variability of the emissions data.

All emissions data for one of the tankers tested by Lloyd's (designated as ship TK7) have been excluded from statistical emission factor analysis because exhaust O_2 measurements are not reported. Unlike HC, O_2 is a major exhaust constituent and no reliable assumptions can be made regarding intake air mass (and thus exhaust and emissions mass) in the absence of reliable O_2 data. As a result, the seven emission tests conducted on tanker TK7 were excluded from the analysis database.

All Lloyd's test data not otherwise excluded as described above have been treated with equal weight in the emission factor analysis conducted for this study. This may result in some bias of analysis results toward engines with an above average number of associated emission tests, but there is no obvious means of weighting the data that would ensure less bias than simply treating all data with equal weight. Lloyd's stated test program design criteria was to conduct testing at idle and 25, 50, 75, and 100 percent of rated engine output. Therefore, ideally, each engine would be tested five times at five distinct operating modes. However, as indicated in Table 3-1, the number of actual tests per engine ranged from five to ten, with tug testing representing the upper bound due to testing in both "pushing" and "non-pushing" modes.

Because all testing was performed at variable load conditions, applying a weighting factor to all the test data for a given engine to equate that engine's overall statistical influence to that of a "five test" engine can result in an unintended bias at specific loads where the weighted engine's test data carries less influence than data from another engine, even though both represent equally valid test measurements at the given load. An alternative approach of simply discarding all but five test data points across the load range for any given test engine is less problematic, but requires some methodology to select those data points to either retain or exclude. Given the considerable variability in observed test data, it was concluded that the overall bias induced by simply retaining all data points was likely to be minor and thus no specific data weighting or selection/exclusion scheme was employed in this analysis. Follow-up analysis to quantify the potential magnitude of any bias can be conducted, but is beyond the scope of this analysis.

3.3   U.S. COAST GUARD EMISSION TEST DATA

Environmental Transportation Consultants produced a report for the Volpe National Transportation Systems Center and the USCG that presents the results of marine engine emission tests on six USCG vessels.[4] In total, the report presents comprehensive test data for 12 main diesel propulsion engines as summarized in Table 3-3. Summary data are also presented for two additional gas turbine propulsion engines, but supporting detailed test data are omitted from the report necessitating the exclusion of detailed gas turbine engine analysis from this study. In

general, the USCG data are less detailed that the Lloyd's data described in Section 3.2 above, but reported test data parameters include:

- raw concentration-based emission measurements for NO_x, SO_2, CO, CO_2, O_2, and HC,
- raw mass-based emission measurements for PM,
- test engine load, speed, and volumetric fuel consumption, and
- test engine specifications.

Data on fuel specifications, density, and composition was not included, representing the most critical omission for purposes of this study. Data on ambient test conditions was also omitted, but this omission is a lesser concern as any ambient adjustments to emissions are expected to be minor relative to overall data variability.

As described in Section 3.2, fuel characteristics are a necessary element in constructing an accurate chemical mass balance as required to estimate intake air mass and subsequently exhaust and emissions mass. Unfortunately, the USCG test data report only describes the combustion fuel as "diesel" and presents no supporting test data. Therefore, EEA undertook an alternative analysis approach in an attempt to estimate the characteristics of the unknown USCG diesel "fuel" as follows.[ ]

Using reported O_2 and CO_2 emission concentrations, the stoichiometric CO_2 concentration for the USCG fuel was derived through regression analysis as summarized in Figure 3-1. The derived stoichiometric CO_2 concentration (15.2 percent at zero percent O_2) can readily be translated through chemical mass balance to an implied fuel hydrogen to fuel carbon (H to C) ratio of 1.9127. Such a ratio is not typical for a diesel fuel, instead being more reflective of a lighter fuel such as gasoline and implying a bias toward a slight under-measurement of CO_2, O_2, or both. Although diesel fuels with H to C ratios above 1.9 have been reported, they generally represent upper bound H to C fuels and would be quite uncommon as an average fuel

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[ ] Certainly USCG test fuel specifications varied across test engines. However, fuel specifications can only be inferred from the aggregate USCG data and, therefore, derived specifications represent average, rather than specific fuel characteristics.

TABLE 3-3
OVERVIEW OF THE USCG EMISSION TEST DATABASE

Ship Types Tested	Number of Ships Tested	No. of Main Engines Tested	No. of Main Engine Tests	Average Tests per Main Engine	No. of Auxiliary Engines Tested
High Endurance Cutter (WHEC)	1	2*	30	15.0	0
Medium Endurance Cutter (WHEC)	2	4	60	15.0	0
Patrol Boat (WPB)	2	4	52	13.0	0
Utility Boat (UTB)	1	2	30	15.0	0
Total Tests	6	12*	172	14.3	0

* The report actually presents summary results for 2 WHEC diesel propulsion engines and 2 WHEC gas turbine propulsion engines, but only includes detailed test data for the two diesel engines. This "missing" data required that the two gas turbine engines be excluded from detailed statistical emission factor analysis in this study.

characteristic over the entire USCG emissions testing program. As a result, EEA elected to utilize the average fuel specifications for the various "diesel" fuels included in the Lloyd's marine engine test program as a better means of approximating the average unknown fuel characteristics associated with the USCG data. Table 3-4 presents the statistical specifications of the various Lloyd's test fuels. The average "all fuels" specifications were used for all USCG chemical mass balance analysis in this study.

Like the Lloyd's data, several additional assumptions are required in processing the USCG database. In general, however, required assumptions for the USCG data are more extensive than those associated with processing the Lloyd's database, but inclusion of the USCG data in this study is considered to be critical for two primary reasons. First, the USCG data serves as the only independent means of validating the basic trends observed through the Lloyd's test data. Second, the USCG database is the only database provided to EEA for review that includes PM

Derivation of USCG Fuel H to C Ratio

$O_2 = 20.956 - 1.375 \, (CO_2)$

(t=353)   (t=-135)

$r^2 = 0.99$, F = 18264, Obs = 142

Stoichiometric $CO_2 = 15.242\%$
Implied Fuel H to C Ratio = 1.9128

O2 (percent dry)

CO2 (percent dry)
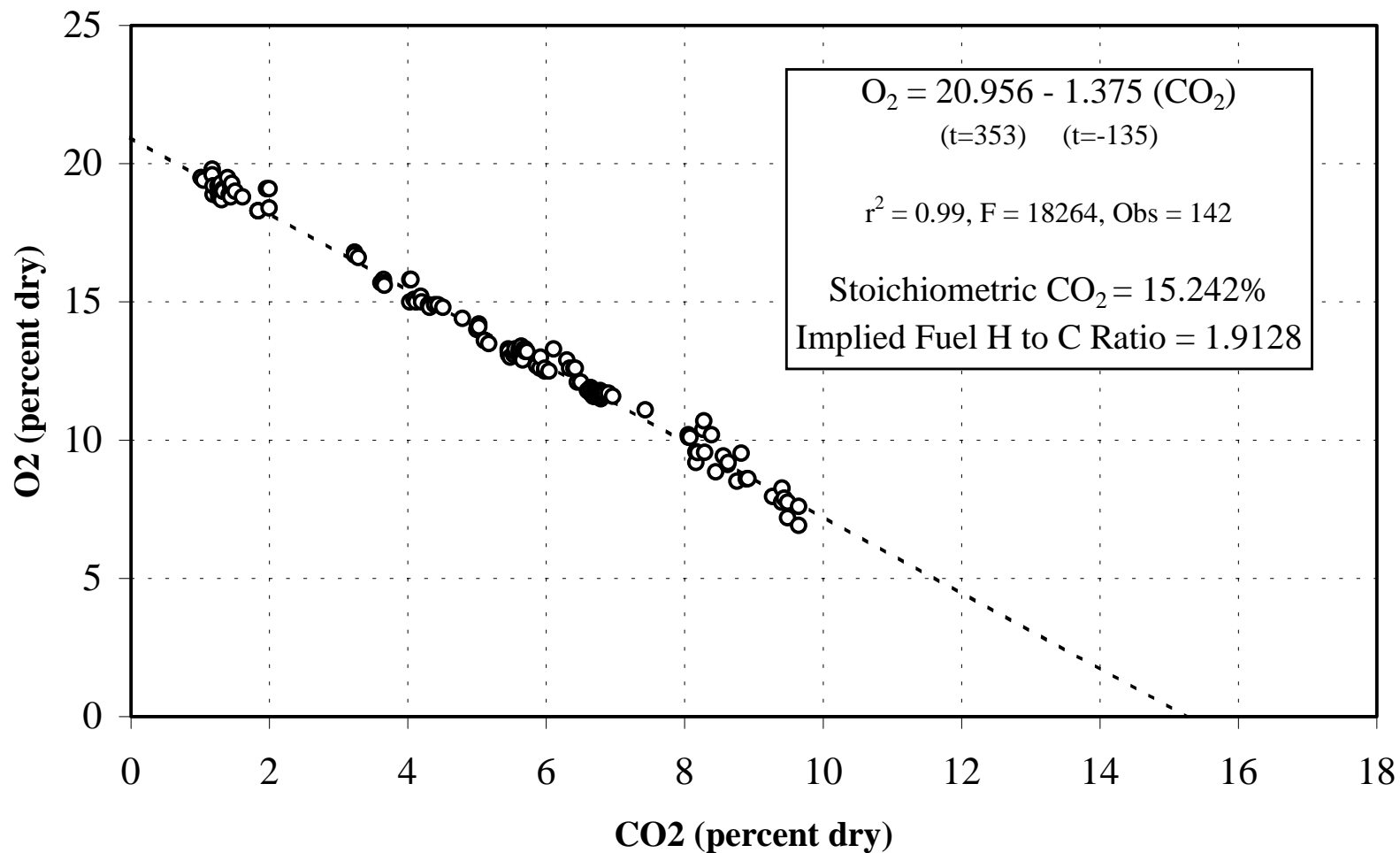
FIGURE 3-1

TABLE 3-4
LLOYD'S MARINE ENGINE FUEL SPECIFICATIONS

Parameter		Gas Oil	Heavy Fuel Oil	Intermediate Fuel Oil	Light Fuel Oil	All Fuels
Number of Observations		25	9	2	19	55
Density	Average	0.8553	0.9816	0.9900	0.9539	0.9149
	Standard Deviation	0.0056	0.0055	0.0000	0.0297	0.0587
Carbon Content	Average	0.8651	0.8606	0.8580	0.8601	0.8624
	Standard Deviation	0.0032	0.0078	0.0004	0.0047	0.0052
Hydrogen Content	Average	0.1293	0.1080	0.1042	0.1150	0.1200
	Standard Deviation	0.0030	0.0024	0.0001	0.0075	0.0103
Nitrogen Content	Average	0.0020	0.0040	0.0019	0.0033	0.0028
	Standard Deviation	0.0021	0.0024	0.0003	0.0005	0.0019
Sulfur Content	Average	0.0036	0.0274	0.0358	0.0215	0.0149
	Standard Deviation	0.0021	0.0077	0.0002	0.0094	0.0125
H to C Ratio	Average	1.7812	1.4954	1.4477	1.5937	1.6576
	Standard Deviation	0.0468	0.0338	0.0010	0.1029	0.1385
N to C Ratio	Average	0.0020	0.0040	0.0019	0.0033	0.0028
	Standard Deviation	0.0020	0.0024	0.0003	0.0005	0.0019
S to C Ratio	Average	0.0016	0.0120	0.0156	0.0094	0.0065
	Standard Deviation	0.0009	0.0034	0.0001	0.0041	0.0055

data. Nevertheless, the following issues should be considered in evaluating the USCG marine emissions data analysis.

Many of the HC measurements included in the USCG database are questionable and five of the 172 tests are missing HC measurements altogether. Additionally, about 17 percent of the reported HC measurements indicate concentrations below 0.001 ppmC, while nearly all of the remaining 83 percent exhibit concentrations over four orders of magnitude higher (often for the same engine at the same test conditions). For purposes of this analysis, these concentrations were assumed to equal 0.001 ppmC, but more in depth follow-up analysis beyond the scope of

this study may yield sufficient information to exclude these data as erroneous. As was the case with the Lloyd's data, in instances where detailed chemical mass balancing, as described below, included measured HC, a value of zero was assumed for all five tests where HC was unreported. This assumption will result in only minor precision losses for calculated intake air mass as most combustion hydrogen is emitted as H_2O, not HC. As with the Lloyd's data, all five tests were excluded from the statistical analysis underlying the determination of HC emission factors. At the same time, all HC measurements reported as being below 0.001 ppmC were retained throughout the entire analysis and could serve as a downward bias on estimated HC emission factors should such measurements ultimately be identified as erroneous.

USCG HC measurements were assumed to be reported as dry since they were based on bag sampling at a point apparently downstream of a sample line water trap. Since Lloyd's HC measurements are report as wet, a conversion factor was applied to the USCG HC data to convert the reported data to a wet measurement equivalent. This conversion factor was derived from analysis of the Lloyd's test data, through which it was determined that the average wet to dry exhaust concentration ratio was 0.9658, with a standard deviation of 0.0158 (based on 1215 data points associated with 302 individual test records evaluated over four mass balance techniques plus 7 individual test records evaluated over a single mass balance technique).

In an analogous fashion, the USCG data reports NO_x while the Lloyd's data reports NO as a NO_x surrogate. As described in Section 3.2, Lloyd's claims an average NO to NO_x ratio of 0.94, a factor used by EEA to convert Lloyd's NO data to a NO_x equivalent. This same factor was also used to convert USCG reported NO_x data to an NO equivalent.

Unlike the Lloyd's data, which was treated without weighting individual data points, the USCG data was aggregated before statistical processing. This aggregation was necessary to address the fact that USCG data was reported individually for each of up to three tests performed on the same engine at the same load conditions. In effect, multiple data points were reported for identical test conditions, creating an inherent weighting factor of up to three for the USCG data versus the Lloyd's data. To reduce the weight of the USCG data to unity, all data points

applying to identical test conditions were collapsed into a single data point representative of the average reported test results for the component data.

Such an approach is generally consistent with the "average" test results for each unique set of test conditions as reported in the USCG test document.[4] Nevertheless, the USCG reported average test results will vary in some circumstances from those used in this study. This results from the fact that the average test results presented in the USCG report include the effects of partial tests, whereas those used in this study do not. For example, in the USCG report, results for three tests, two of which include measurement of HC, CO, NO_x, SO_2, O_2, CO_2, and PM and one of which only includes measurement of HC are averaged over two tests for CO, NO_x, SO_2, O_2, CO_2, and PM and over three tests for HC. In this study, all species are averaged over only the two comprehensive tests and the third, HC-only test is ignored. This is deemed a more appropriate aggregation methodology since there is no way of knowing how unmeasured emission species will have varied over the third test in accordance within any observed variation in HC. In addition, any individual tests for which inconsistent air/fuel ratios were calculated across the differing estimation methodologies described in Section 3.4 below, were also excluded from the aggregation process.

Finally, the USCG report also included specific fuel consumption estimates only for the average engine speed and output calculated for each unique set of test conditions. Since individual test results were re-aggregated for this study in accordance with the modified "acceptance" criteria described above, it was necessary to estimate fuel consumption for each individual test, instead of simply knowing the aggregate test average. In the absence of specific engine maps, EEA employed a simplifying assumption that fuel consumption varies linearly with engine speed for outputs "near" the specific engine output for which the USCG reported fuel consumption. Observed engine speed variations ranged from only –3 to +4 percent of reported average engine speed so that calculated fuel consumption adjustments averaged only 0.01 percent, with a maximum adjustment of 1.1 percent.

3.4   EMISSIONS DATA ANALYSIS

As described above, exhaust mass is not a measured component of either the Lloyd's or USCG databases. Nevertheless, an estimate of exhaust mass is necessary to covert concentration-based emission measurements into mass-based equivalents. To estimate exhaust flow for each emissions test included in the combined Lloyd's/USCG database, a chemical mass balance was employed using intake fuel characteristics and measured exhaust components to estimate the effective combustion air/fuel (A/F) ratio. This A/F ratio estimate can then be combined with fuel flow measurements reported for each emissions test to derive an estimate for intake air mass, that when added to intake fuel mass results in the required estimate of exhaust mass. In referring to intake air, it is worth noting that this includes both intake and scavenge air (as applicable, typically for two stroke engines) and that the estimated A/F ratio is the effective mass ratio of all air (regardless of the timing or location of its injection into the flow stream) to combustion fuel. While it is not possible to separate actual intake air from scavenge air based on exhaust measurements alone, such a separation is not required to estimate total exhaust mass, which is the critical analysis parameter for this study.

Figure 3-2 presents a summary of the A/F ratios calculated on the basis of Lloyd's and USCG reported exhaust components. Based on the calculated ratios, EEA has some concern over the integrity of the reported emissions data. This concern stems primarily from the magnitudes of the calculated A/F ratios over the entire engine load range, defined by EEA as the "fractional load" or the ratio of the reported engine output during the emissions test to the reported rated engine output. Even at 100 percent rated load, the Lloyd's database generally implies A/F ratios between 30:1 and 40:1. This is substantially higher than the 20:1 or so A/F ratios that would be expected from previous experience with on-road diesel engines. Moreover, while calculated A/F ratios approaching 80:1 are not unexpected at low load ranges, values of 1000:1 or, in one case, 4000:1 are certainly cause for concern. As noted above, scavenge airflow for two stroke engines could explain some of the excessive A/F ratios, but the generally apparent over-prediction is observed for both two and four stroke engines. Since EEA has no information on the number of engines employing secondary air scavenging or the mass of air flow associated with such
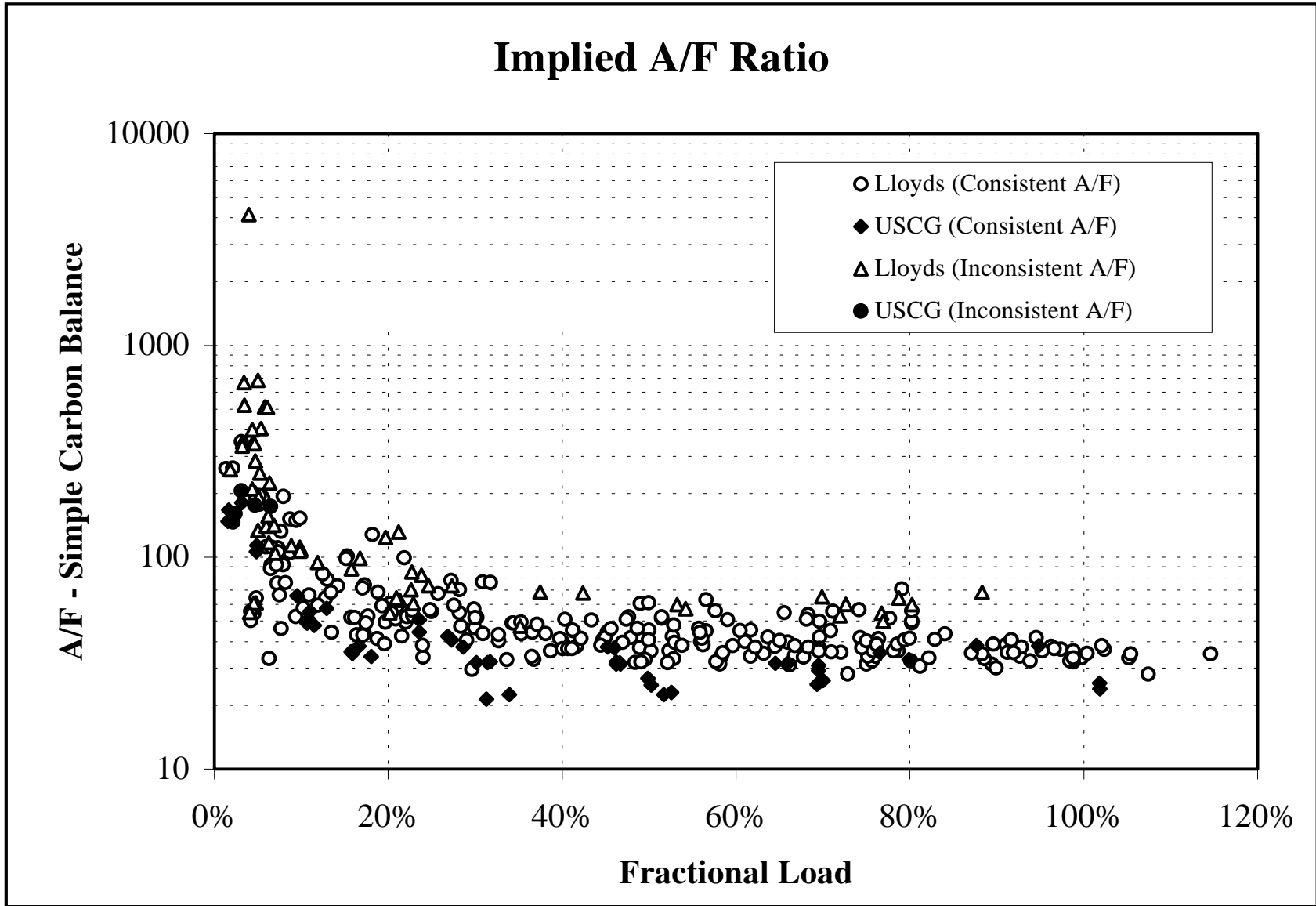
FIGURE 3-2

systems on marine engines, it is not possible to elaborate further (for this study) as to the role that secondary scavenging systems may have on apparent A/F ratio over-prediction.

In an attempt to isolate those data that are most highly suspect, EEA undertook a series of alternative chemical mass balance approaches to estimating effective A/F ratio. The first approach, designated for this study as the simple carbon balance approach, estimates A/F ratio on the basis of fuel H to C ratio and exhaust O_2 to CO_2 ratio alone. Without presenting the detailed mass balance derivation here, this method presumes that all intake fuel and air is fully represented in the exhaust as CO_2, H_2O, and unreacted air (represented as 21 percent O_2 and 79 percent molecular nitrogen (N_2)). Furthermore, this method represents a commonly employed mass balance approach in that it accounts for major exhaust constituents, providing a reasonably reliable A/F ratio estimate. However, in instances where exhaust constituents may not be measured accurately, there are more detailed alternative chemical mass balance methods that can be employed for validation purposes.

A more detailed carbon balance approach considers all measured exhaust constituents that contain either carbon or hydrogen (HC, CO, and CO_2 in the database available for this study). This approach can provide a considerably more accurate A/F ratio estimate when significant concentrations of either CO or HC are measured. A third A/F ratio estimation approach employing a detailed oxygen (rather than carbon) balance considers all measured oxygen, nitrogen, and hydrogen containing exhaust species (CO, CO_2, O_2, NO, SO_2, and HC in the database available for this study). Finally, a fourth A/F ratio estimation approach based solely on the amount of intake air required to completely combust the intake fuel and provide the measured quantity of "excess air" in the exhaust was also employed. This excess air approach uses only measured exhaust oxygen and measured fuel characteristics to satisfy the required chemical mass balance criteria.

Figures 3-3 through 3-5 present the results of the alternative A/F ratio evaluations. The three figures each present a plot of the estimated A/F ratio for one of the three alternative mass balance methods employed in this study versus the A/F ratio estimated using the simple carbon balance

approach. The considerable variation between three of the four approaches is easily observed. As might be expected, the simple carbon balance and detailed carbon balance approaches produce similar A/F estimates since both principally rely on a balance of intake and exhaust carbon. The excess air approach, which relies on the major exhaust oxygen containing component (i.e., air) as its primary mass balance criteria indicates significant deviation from the carbon-based approaches, but the greatest deviation is observed for the detailed oxygen balance, which relies on all exhaust oxygen containing compounds as its mass balance criteria. Moreover, the disagreement between the four approaches gets more pronounced as the estimated A/F ratio increases, with the oxygen-based approaches generally estimating lower A/F ratios than the carbon-based approaches. Given that exhaust mass and thus emissions mass are directly dependent on A/F ratio, there are clear concerns associated with the raw exhaust measurements reported in the marine engine database employed in this study.

Further evidence of the potential problems with the marine engine emissions databases can be observed by comparing measured CO_2 and O_2 concentrations. Figure 3-6 presents such a comparison, where the dashed lines represent the theoretical relationship between measured CO_2 and O_2 as implied by the measured characteristics of the Lloyd's test fuels. Deviations from these theoretical relationships are indicative of instances in which measurement error for either CO_2, O_2, or both are likely. Clearly, such deviations are quite common at low CO_2 concentrations, which correspond to high O_2 and thus high A/F ratios. More troubling, however, is the fact that significant deviations are observed across the full measured CO_2 spectrum.

Given the concerns associated with the reported exhaust emissions data, it would be advantageous to perform a more in depth analysis of the test programs underlying the reported data. However, such an analysis is beyond the scope of this study. As an alternative, EEA quantified the magnitude of the variation between the alternative A/F ratio estimation methodologies and retained for statistical analysis, only those tests for which consistent A/F ratios were observed across the alternative estimation approaches. For this study, consistent A/F ratios were defined as instances in which: (1) three of the four employed A/F ratio estimation

A/F Ratio Comparison

FIGURE 3-3

A/F Ratio Comparison

Legend:
- ○ Lloyds (Consistent A/F)
- ◆ USCG (Consistent A/F)
- △ Lloyds (Inconsistent A/F)
- ● USCG (Inconsistent A/F)
- - - - - One-to-One Line

Y-axis: A/F - Detailed Oxygen Balance (10 to 10000)

X-axis: A/F - Simple Carbon Balance (10 to 10000)

FIGURE 3-4

A/F Ratio Comparison

Legend:
- ○ Lloyds (Consistent A/F)
- ◆ USCG (Consistent A/F)
- △ Lloyds (Inconsistent A/F)
- ● USCG (Inconsistent A/F)
- - - - One-to-One Line

Y-axis: A/F - Excess Air Balance
X-axis: A/F - Simple Carbon Balance

FIGURE 3-5

CO₂ / O₂ Relationship

FIGURE 3-6

methodologies produced cumulative absolute estimate deviations of no more than 15 percent relative to the estimate produced by the simple carbon balance approach and (2) none of the three otherwise consistent A/F ratio estimates varied by more than 10 percent from the estimate produced by the simple carbon balance approach. The choice of these retention criteria are somewhat arbitrary, but deviations of this magnitude yield reasonably consistent mass emissions estimates, well within the overall uncertainty of the underlying test programs.

All figures presented in this section allow inspection of both consistent and inconsistent A/F ratio test data. Mass emission estimates presented in these figures and used for subsequent emission factor analysis represent the arithmetic average of the mass emission rates associated with the three most consistent A/F ratio estimation methodologies: the simple carbon balance, the detailed carbon balance, and the excess air approaches. Figure 3-7 presents a distribution of the cumulative absolute deviations associated with these same three A/F ratio estimation approaches for the combined Lloyd's and USCG database. As can be noted, approximately 18 percent of all reported emission tests do not meet the consistent A/F ratio criteria. Such records are excluded from all emission factor analysis in this study but have been included on all figures to allow the reader to evaluate the potential impact associated with this exclusion.

3.5   EMISSION FACTOR DEVELOPMENT

Based on the database development and acceptance criteria presented in the preceding sections, EEA compiled an overall emission factor analysis database consisting of 291 "consistent A/F ratio" emission tests spanning the full range of engine operating loads (i.e., from idle to 100 percent rated output). Figure 3-8 summarizes the overall test engine and operating loads represented in this database. As indicated, the bulk of the large engines tested by Lloyd's fail to meet the A/F ratio acceptance criteria, so that the overall database includes only a modest number of tests on engines rated above 10,000 kilowatts (kW). Given the under-representation of large marine engines in this database, further investigation of large engine performance relative to both emissions measurement accuracy and consistency with the emission factor algorithms presented below is recommended.

Consistency of A/F Ratio Estimates

FIGURE 3-7

Test Data Load Coverage

Legend:
- ○ Lloyds (Consistent A/F)
- ◆ USCG (Consistent A/F)
- △ Lloyds (Inconsistent A/F)
- ● USCG (Inconsistent A/F)

X-axis: Test Load (kW)
Y-axis: Rated Load (kW)
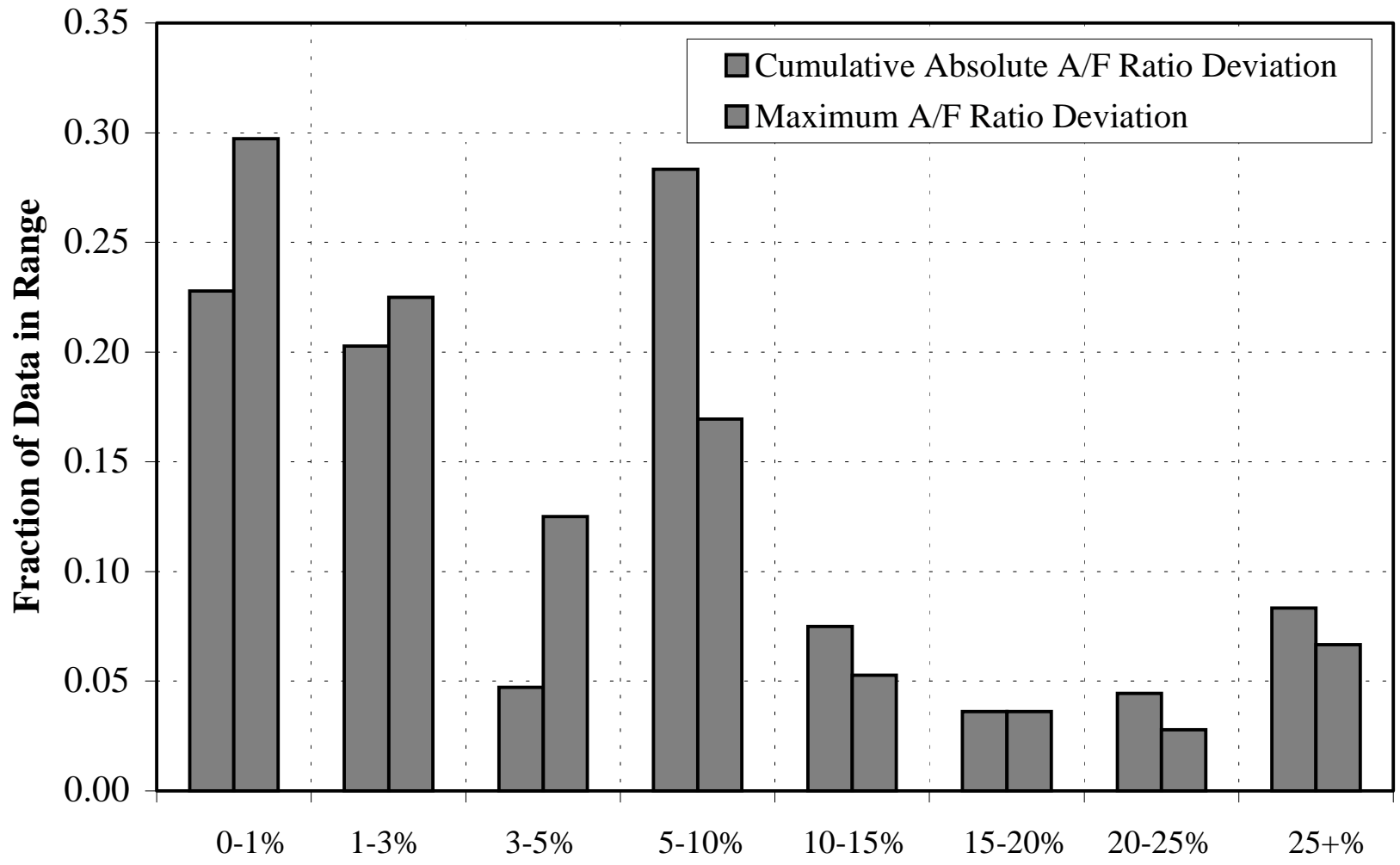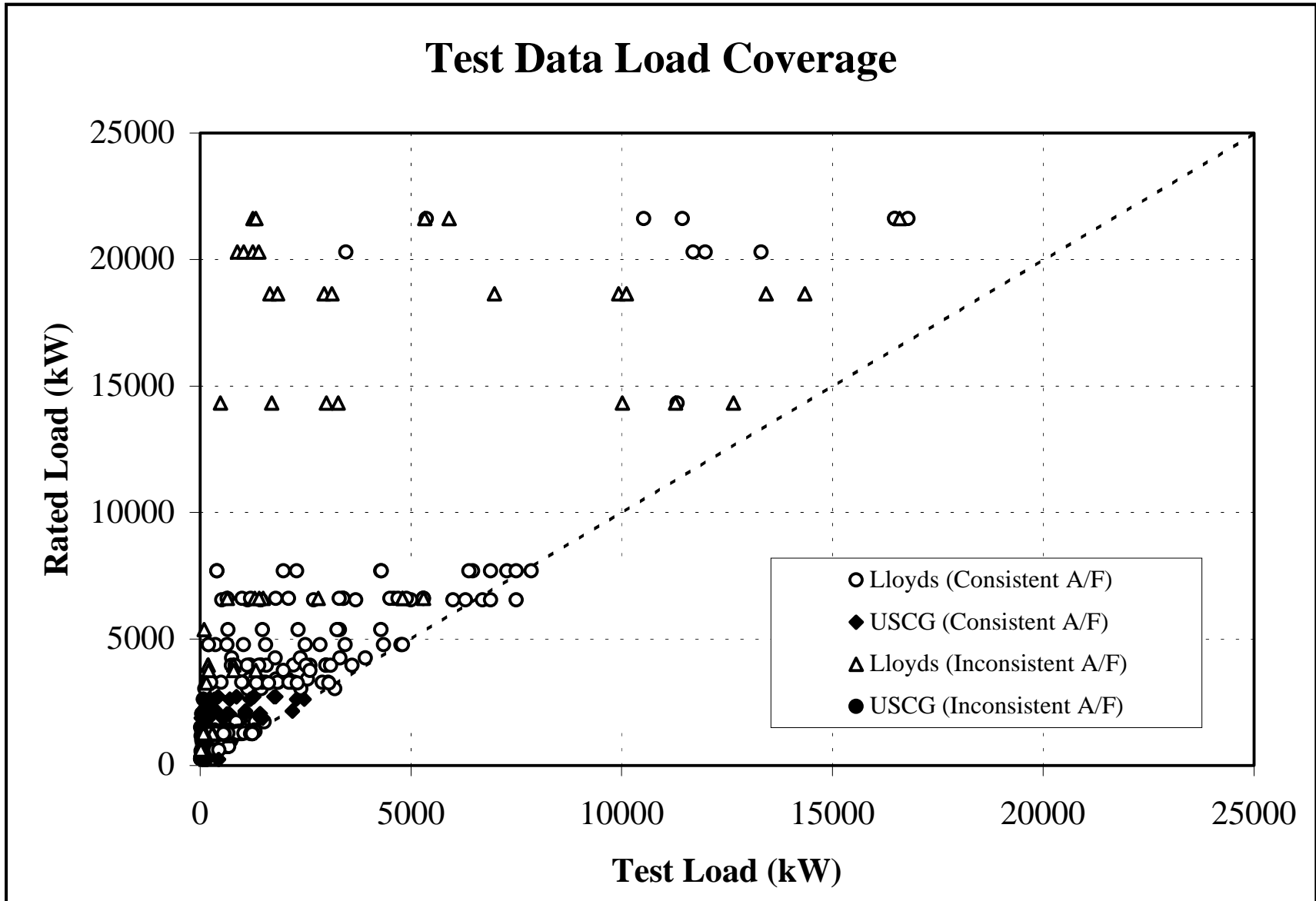
FIGURE 3-8

Figures 3-9 through 3-15 present measured (i.e., concentration-based) emissions by fractional engine load for each of the emission species represented in the analysis database. Although overall measurements for most species span several orders of magnitude, clear trends are observable for all species except CO, HC, and SO_2. The lack of a distinguishable trend in the raw CO and HC data is likely the result of the relatively low production of both species across the entire load range of diesel engines. The lack of a load-based trend for SO_2 is due to the direct relationship of SO_2 emissions to fuel sulfur content, which varies considerably across the emission test database.

Figures 3-16 and 3-17 present reported fuel consumption by absolute and fractional test load respectively. As indicated, the distribution of reported fuel consumption over fractional load space is quite "well behaved." Regression analysis indicates that fuel consumption is inversely related to fractional engine load as follows:

Fuel Consumption (g/kW-hr) = 14.1205 (1/Fractional Load) + 205.7169

$$(t = 22.75) \qquad\qquad (t = 32.88)$$

$$[r^2 = 0.64, F = 518, \text{Observations} = 291]$$

Based on this behavior, along with the previously illustrated (see Figure 3-2) well defined behavior of A/F ratio (and thus exhaust mass) with fractional load, statistical regression structures based on emissions mass by fractional load were investigated as the most promising basis for emission factor algorithms. It is worth noting that previous studies have investigated emission mass in terms of fuel consumption alone and while such an approach may yield reasonable emission estimates, fuel consumption is itself dependent on fractional load as illustrated in Figure 3-17 and, therefore, is not an appropriate independent regression parameter in instances where fuel consumption is not measured directly (with the exception of SO_2 emissions, which are directly dependent on highly variable fuel sulfur content). While a two step conversion from fractional load to fuel consumption to emissions mass is certainly feasible, the combined uncertainty associated with such a process is surely larger than the single step estimation of emissions mass from a given fractional load.

Measured CO$_2$

FIGURE 3-9

Measured O$_2$

FIGURE 3-10

Measured NO

FIGURE 3-11

Measured CO
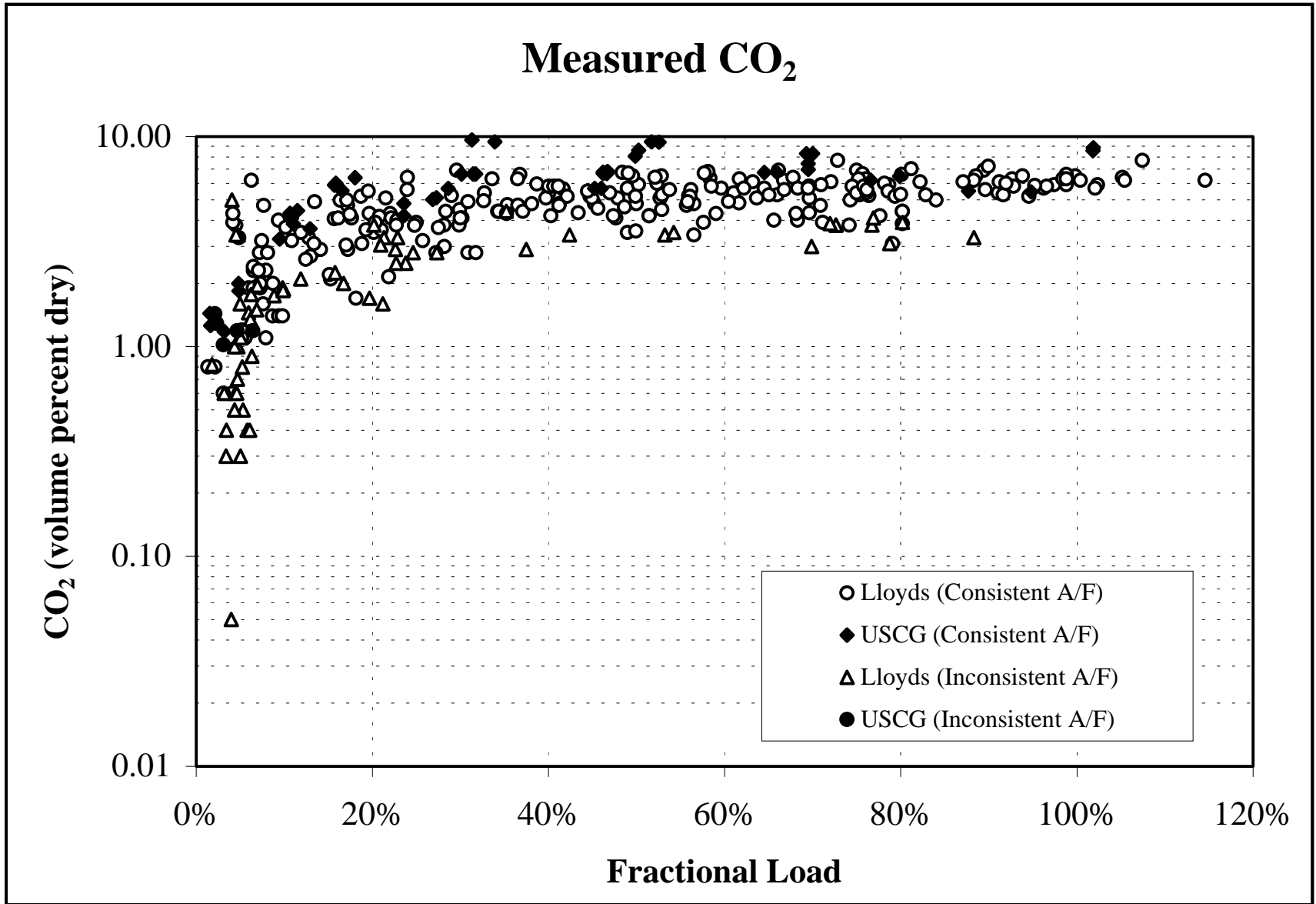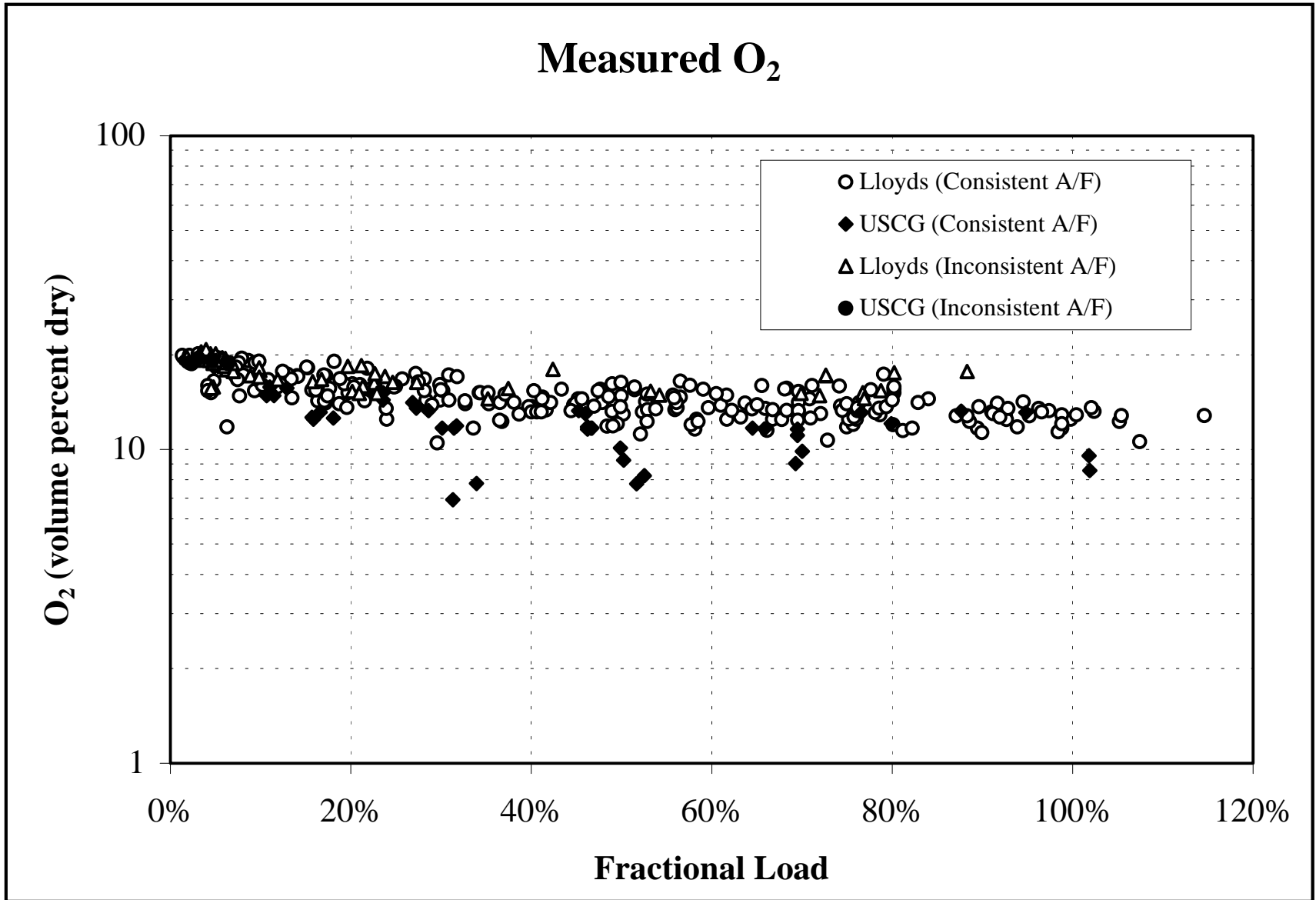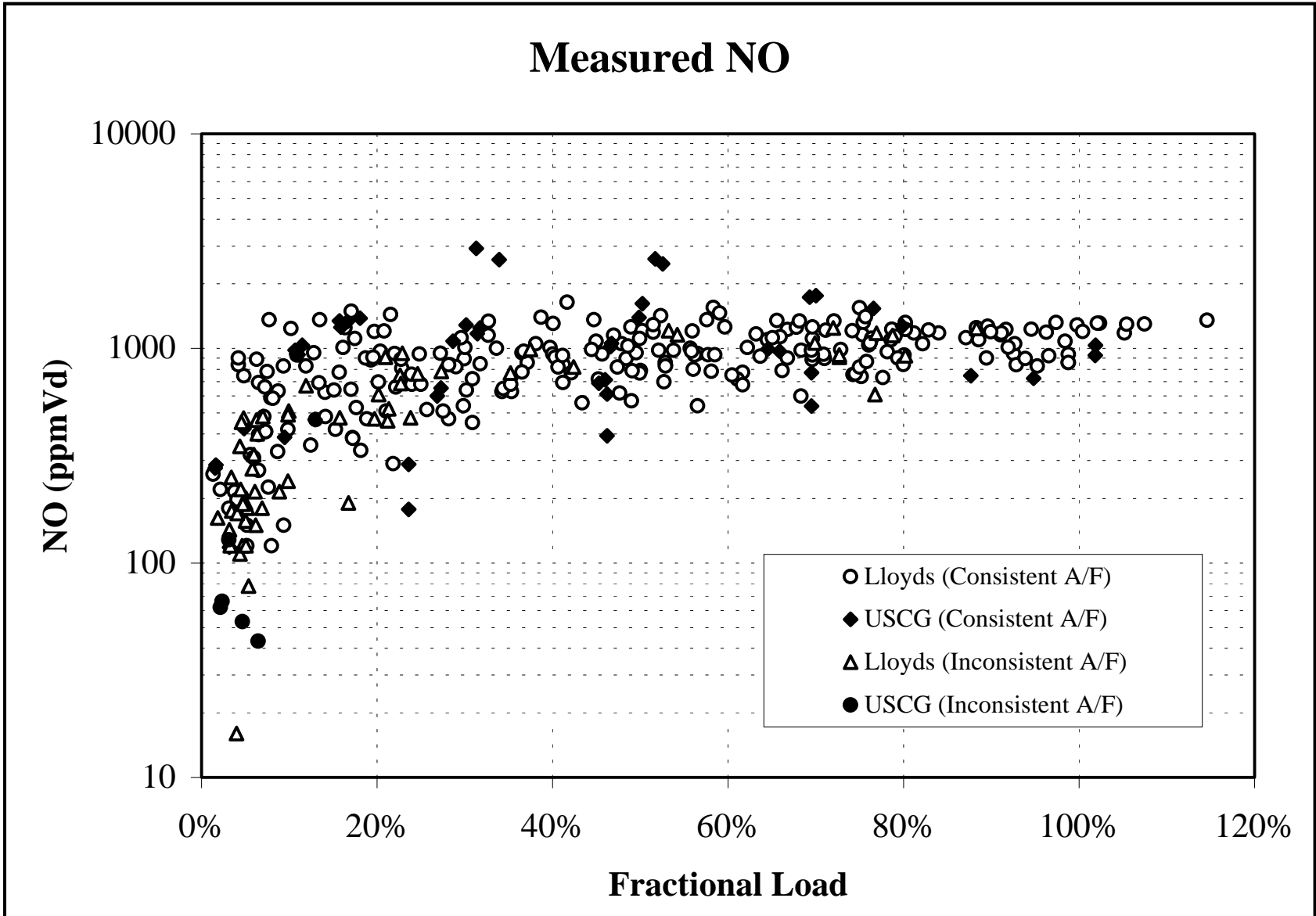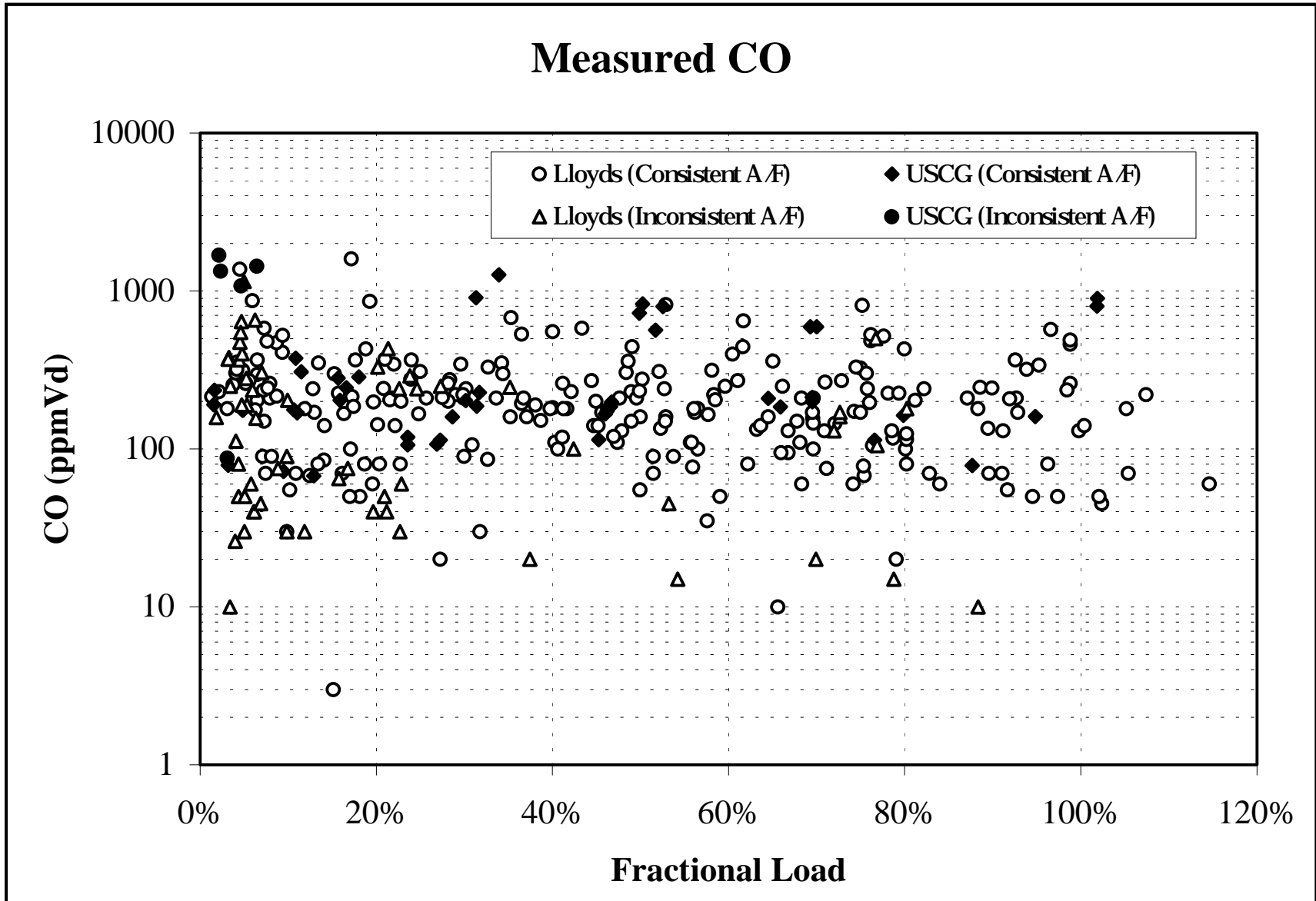
FIGURE 3-12

FIGURE 3-13

FIGURE 3-14

Measured PM

Legend:
- ○ Lloyds (Consistent A/F)
- ◆ USCG (Consistent A/F)
- △ Lloyds (Inconsistent A/F)
- ● USCG (Inconsistent A/F)

X-axis: Fractional Load (0% to 120%)
Y-axis: PM (lb per hour) (0.1 to 10.0)
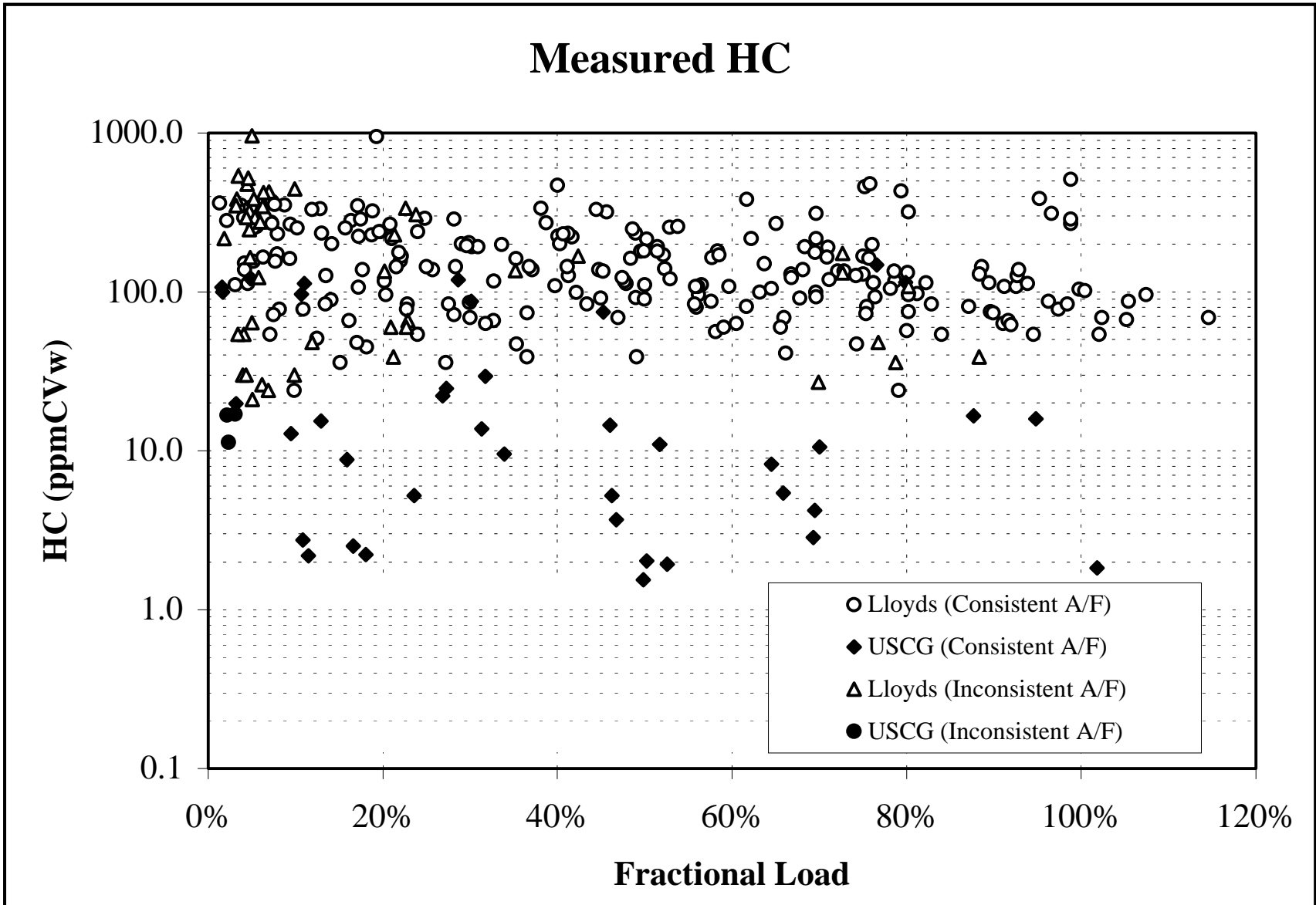
FIGURE 3-15
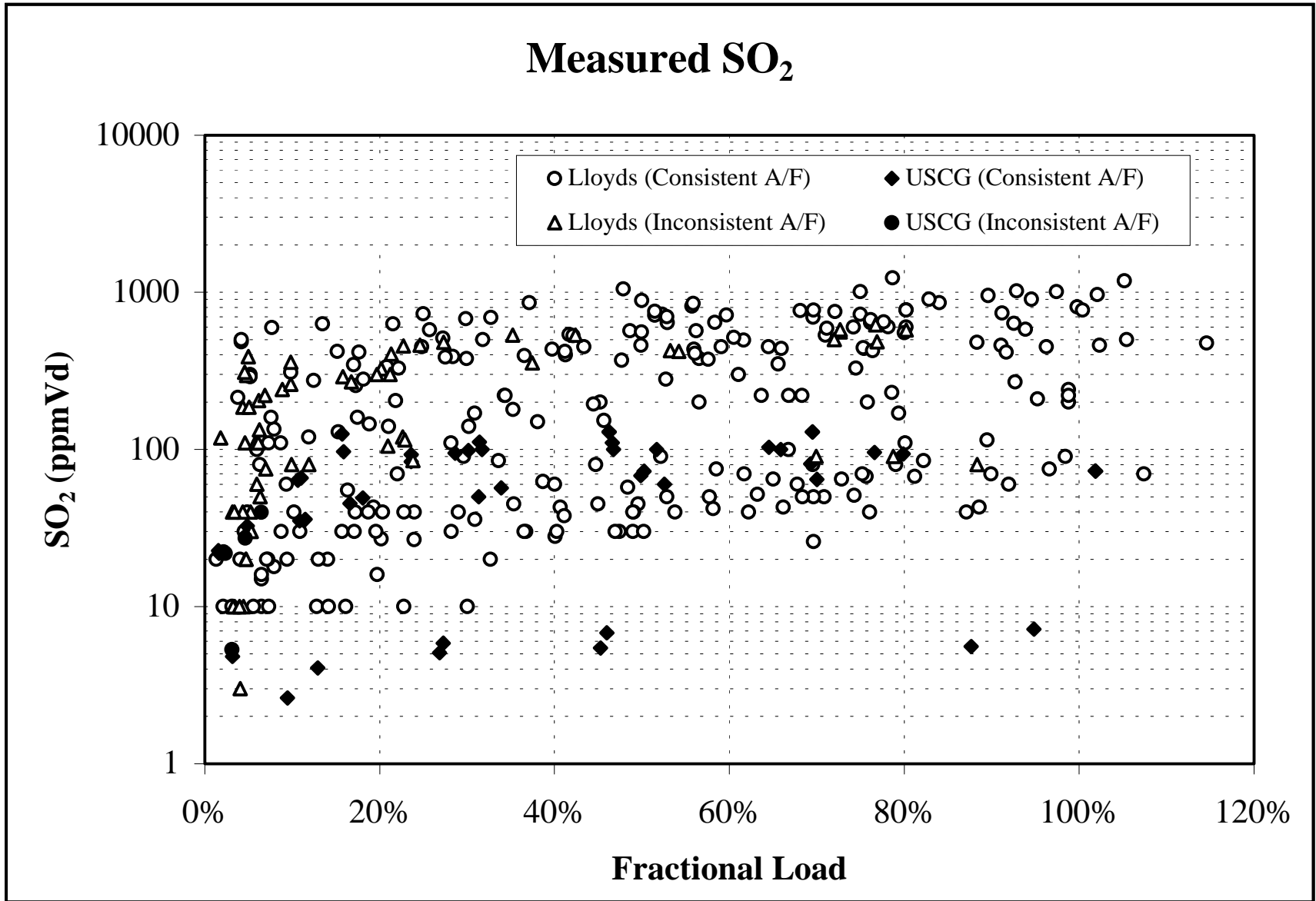
Fuel Consumption Data by Absolute Load
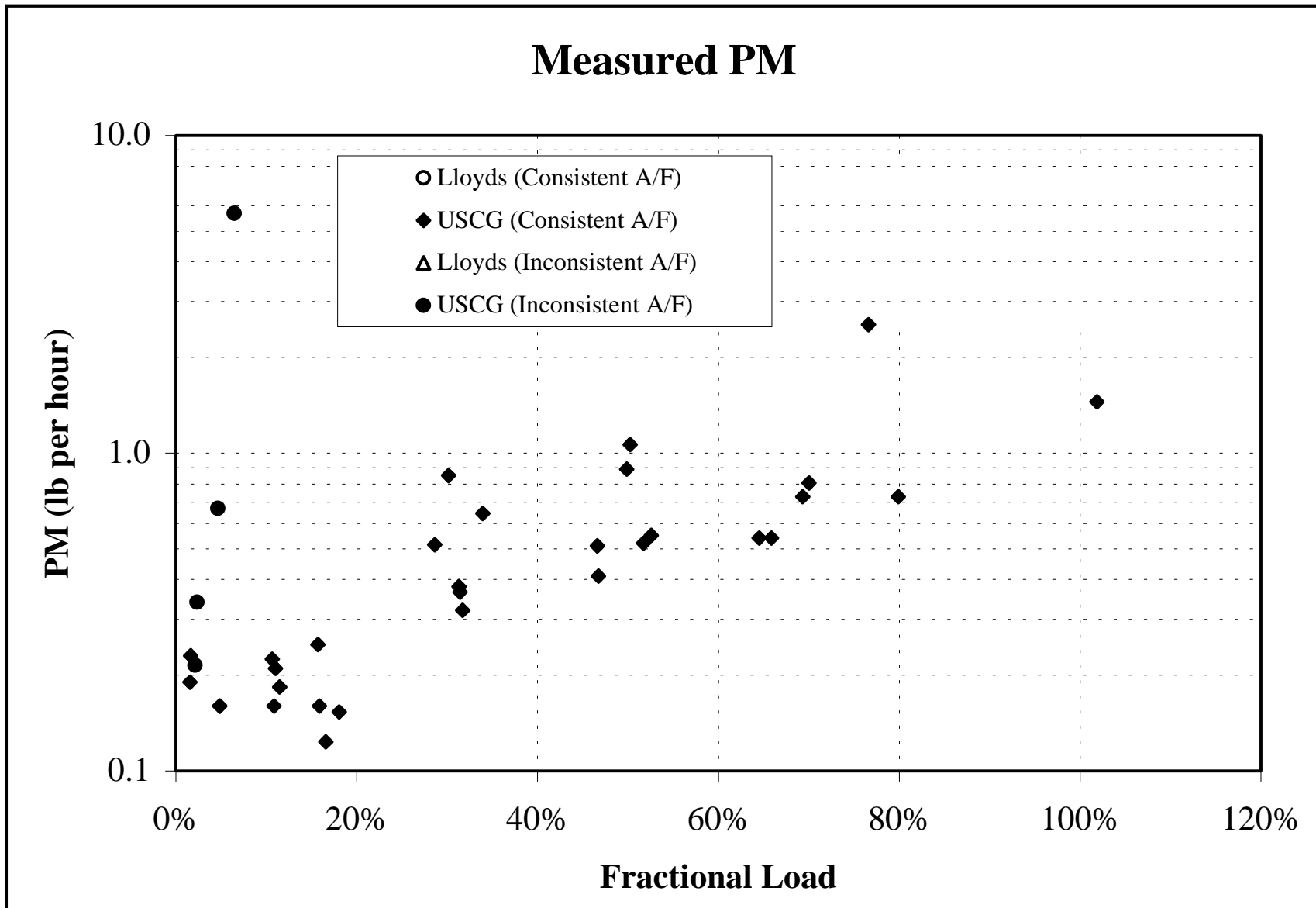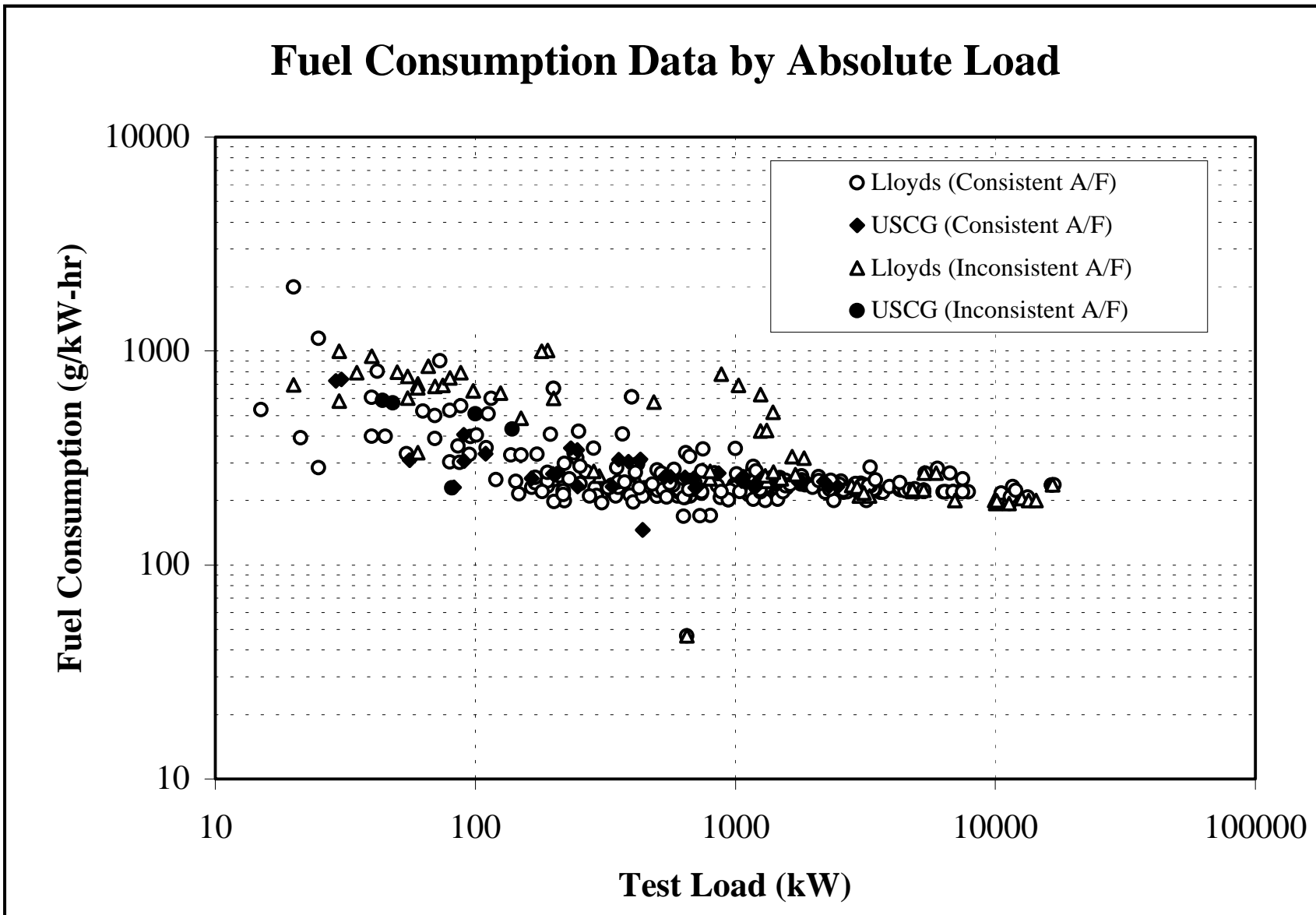
FIGURE 3-16

Fuel Consumption Data by Fractional Load

Legend:
- ○ Lloyds (Consistent A/F)
- ◆ USCG (Consistent A/F)
- △ Lloyds (Inconsistent A/F)
- ● USCG (Inconsistent A/F)
- —— Consistent Data Regression Line

X-axis: Fractional Load (0% to 120%)
Y-axis: Fuel Consumption (g/kW-hr) (10 to 10000)
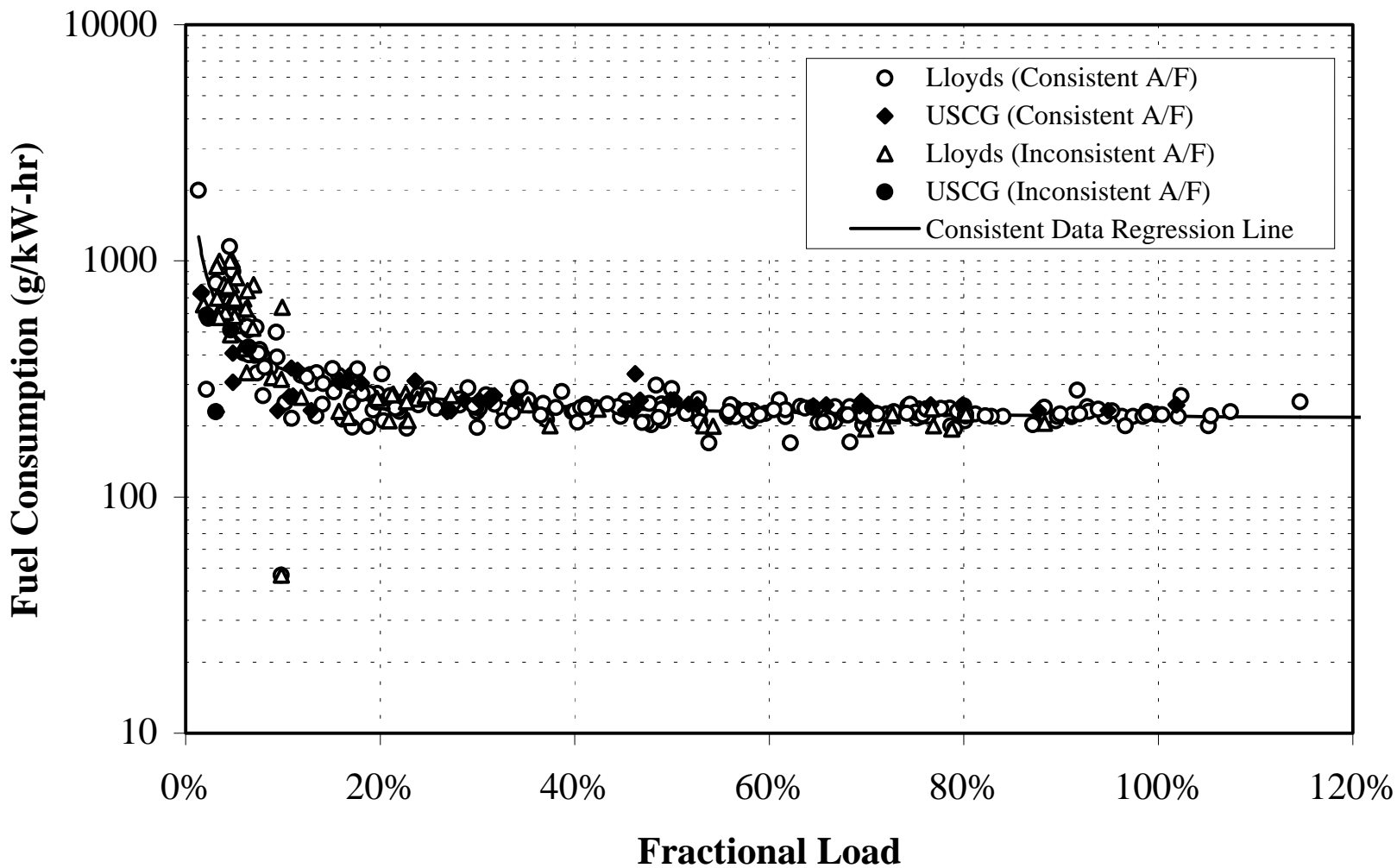
FIGURE 3-17

Figures 3-18 through 3-26 summarize work-specific mass emission rates by species based on the chemical mass balance of parameters reported in the combined Lloyd's and USCG database. In general, all species display an inverse exponential distribution with fractional load. Although the behavior of the work-specific emission rate data is at least as good as expected given the wide range of engines tested, an expected upturn in the work-specific emission rate for NO_x at high fractional loads is not readily apparent. Nevertheless, to check for the potential existence of such a trend, both full and partial load range regression structures were evaluated.

To confirm the validity of an inverse exponential relationship between mass emissions and fractional load as opposed to a simple linear relation, EEA regressed the emissions/load data over both linear and inverse exponential structures. In all cases, excepting SO_2 as discussed below, the inverse exponential relations exhibited substantially better statistics (i.e., higher correlation coefficients and more significant regression parameter statistics). Restricted load range regressions evaluated to determine whether the inverse exponential relations were most appropriate over the entire fractional load range or whether specific fractional load ranges were better represented with alternative linear algorithms, revealed similar results. Specifically, separate regressions over the 0-20 percent and 20-100 percent fractional load ranges were constructed to determine if a better inverse exponential fit over the lower load range or an alternative linear fit over the upper load range might be more appropriate than an inverse exponential fit over the full fractional load range. For all emission species (again excepting SO_2), it was evident that the best statistical fit of the reported emissions data was obtained with the inverse exponential relations over the full fractional load range. In no case did any linear relation over the full or upper load range (20-100 percent) yield better statistics. After determining the superiority of the inverse exponential approach, the most appropriate values for the fractional load exponents were evaluated, although all regressions yielded surprisingly good fits for an initially evaluated exponent of negative unity. Alternative exponent value regressions were selected as the basis for the best fit regression only in cases where such values produced significantly improved statistics relative to a unity exponent. Table 3-5 presents the results of this regression analysis for each emission species evaluated.

PM Emission Rate Data

FIGURE 3-18
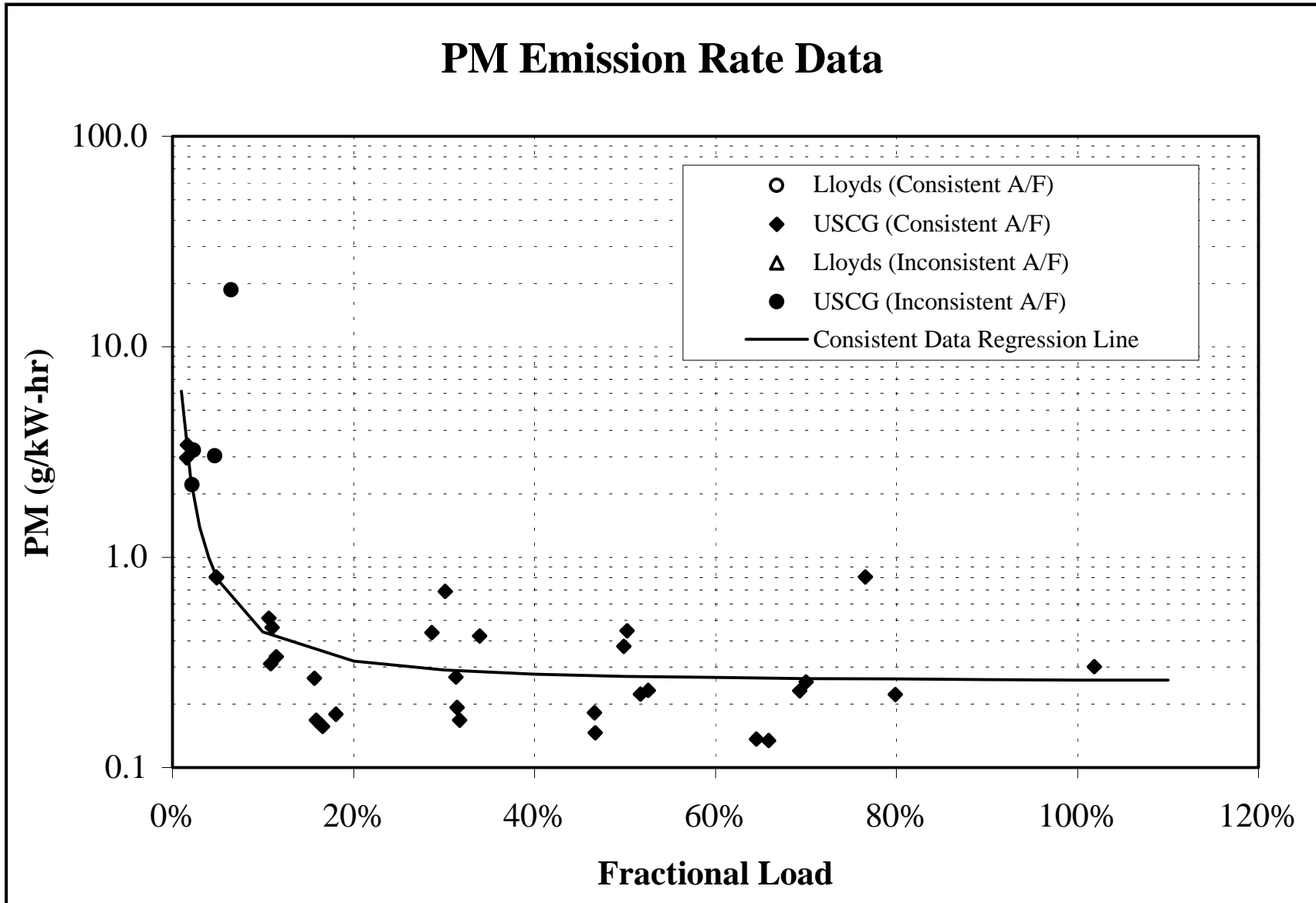
NO Emission Rate Data
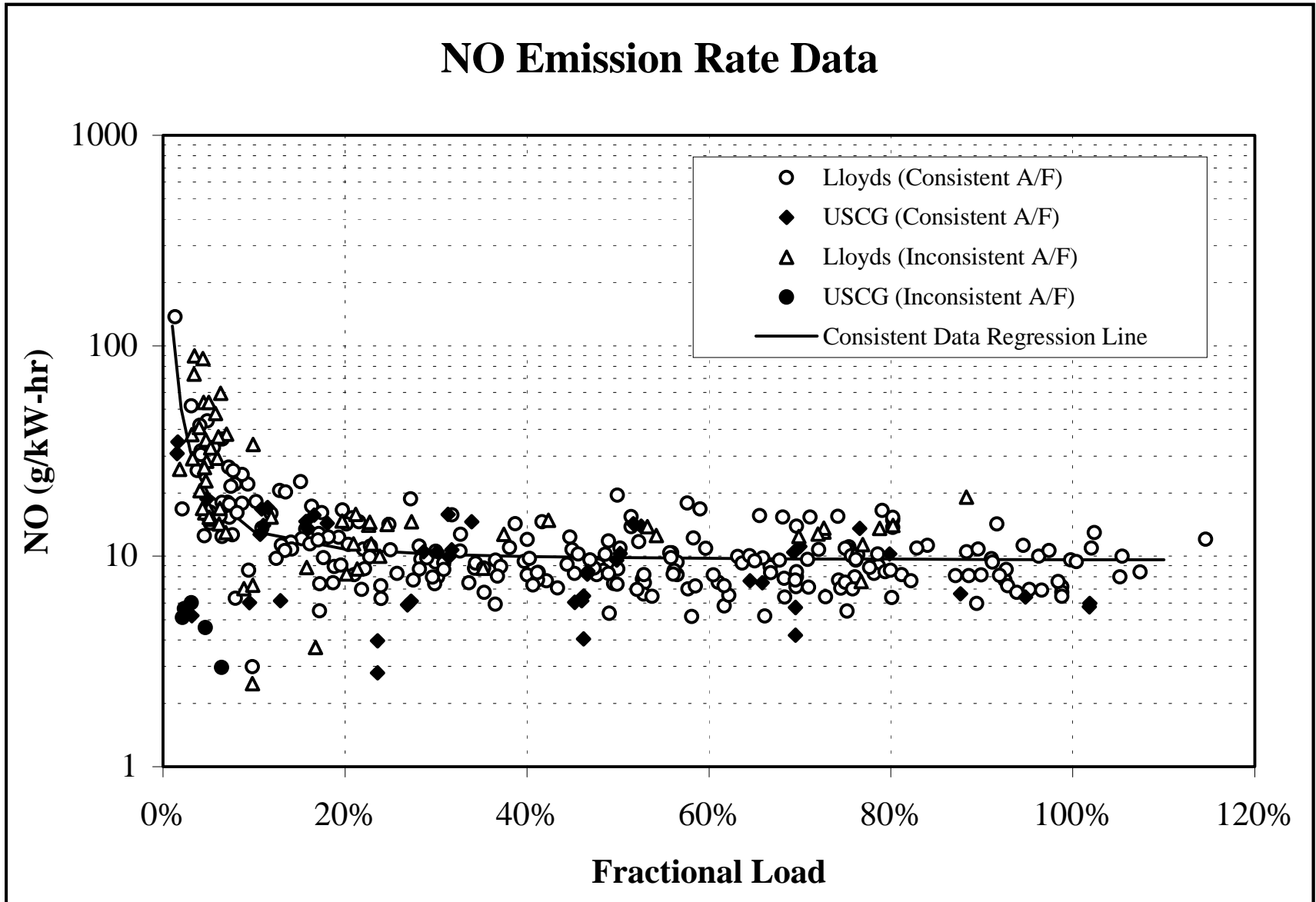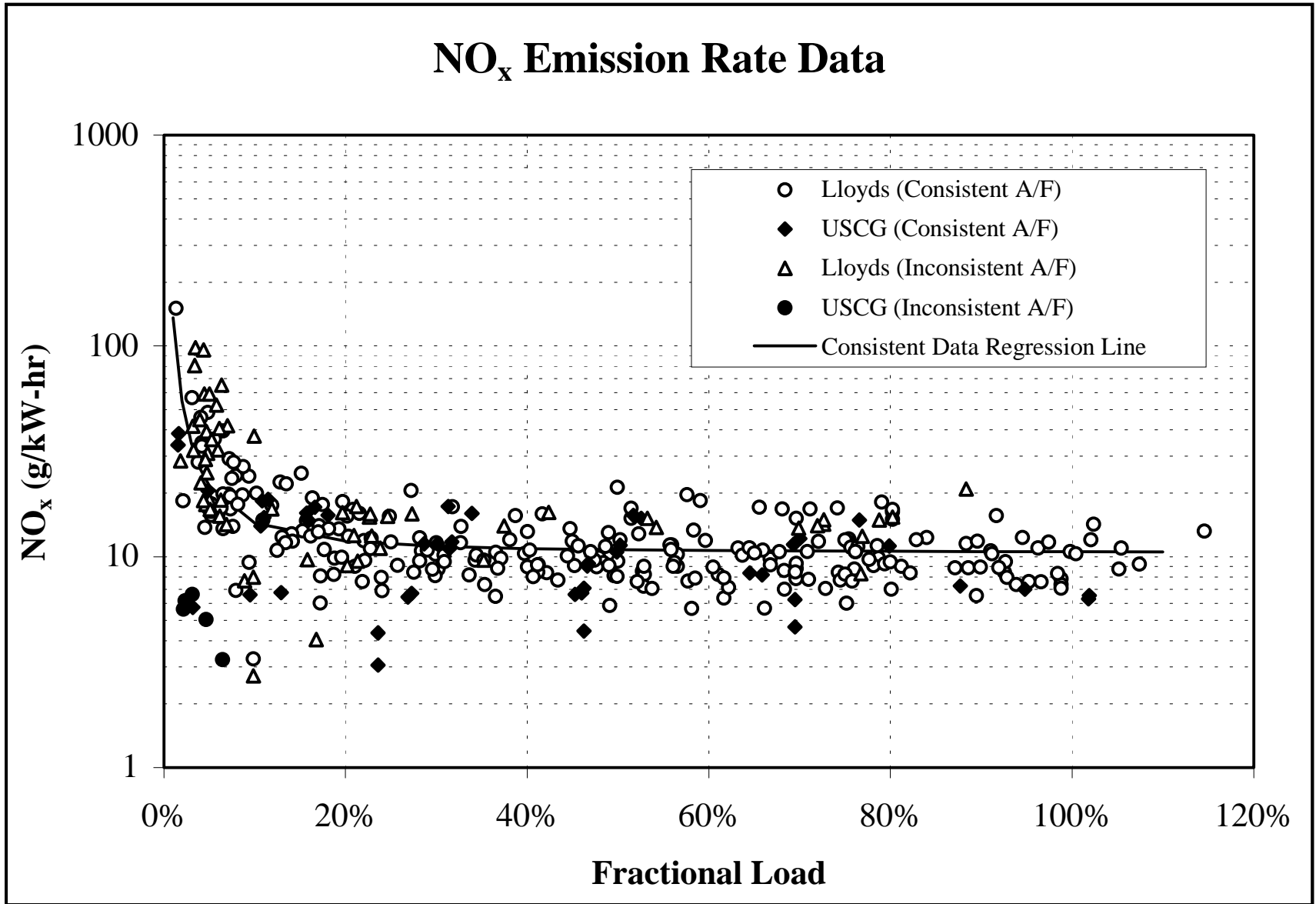
FIGURE 3-19

FIGURE 3-20

NO$_2$ Equivalent NO$_x$ Emission Rate Data

FIGURE 3-21

SO$_2$ Emission Rate Data

FIGURE 3-22

CO Emission Rate Data

FIGURE 3-23

CO₂ Emission Rate Data

FIGURE 3-24

FIGURE 3-25

HC Emission Rate Data

Legend:
- ○ Lloyds (Consistent A/F)
- ◆ USCG (Consistent A/F)
- △ Lloyds (Inconsistent A/F)
- ● USCG (Inconsistent A/F)
- — Consistent Data Regression Line

X-axis: Fractional Load

Y-axis: HC (g/kW-hr)
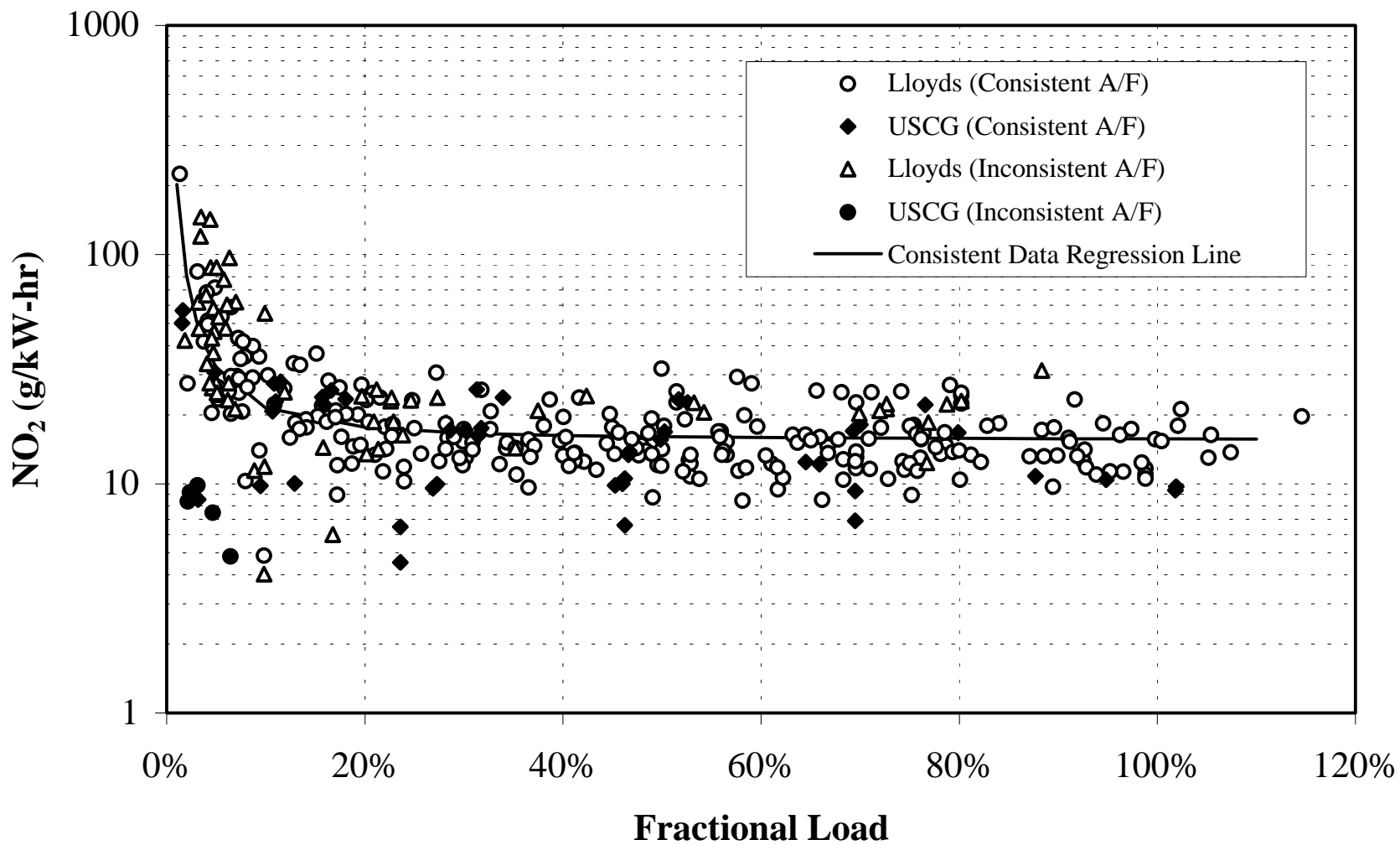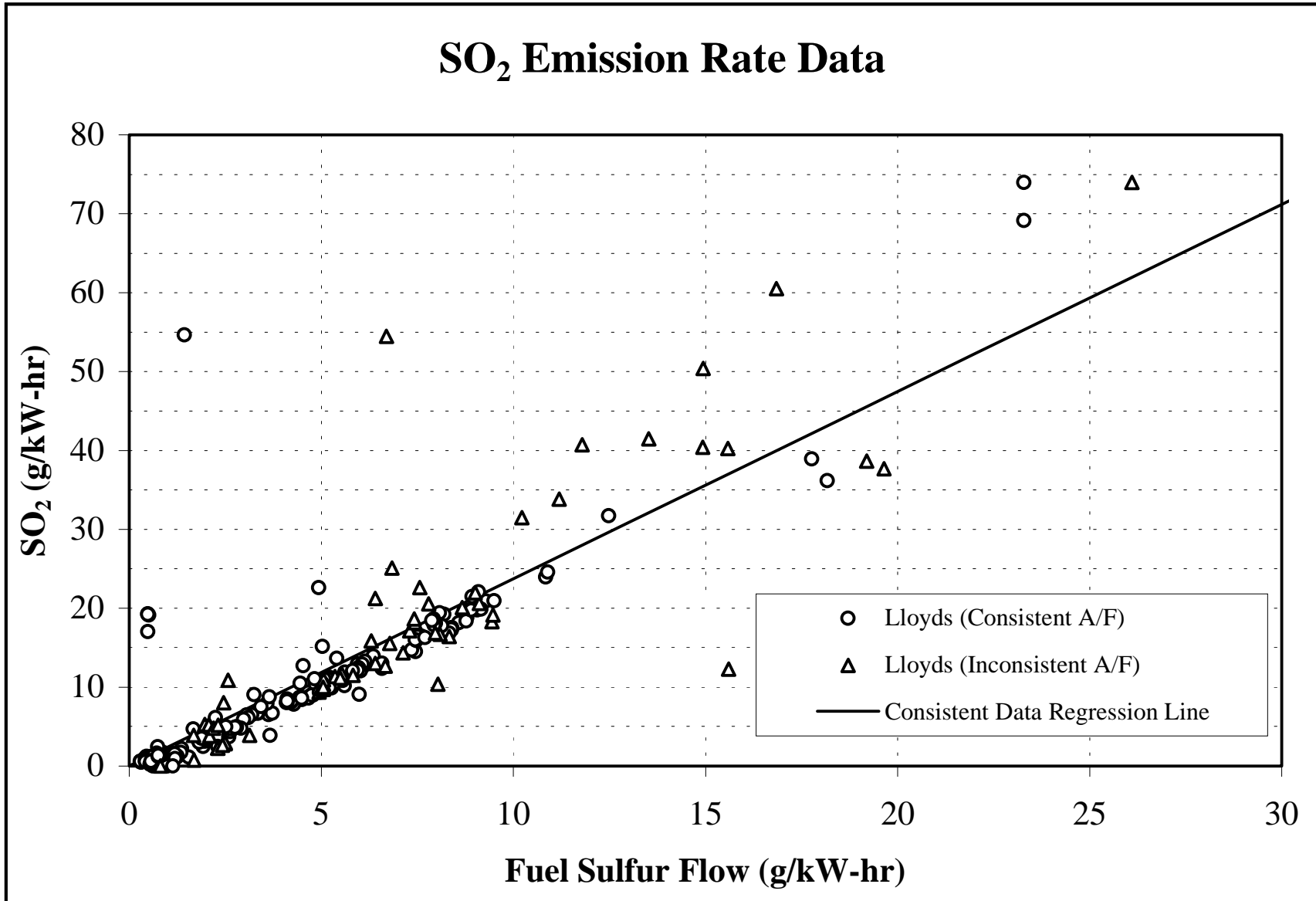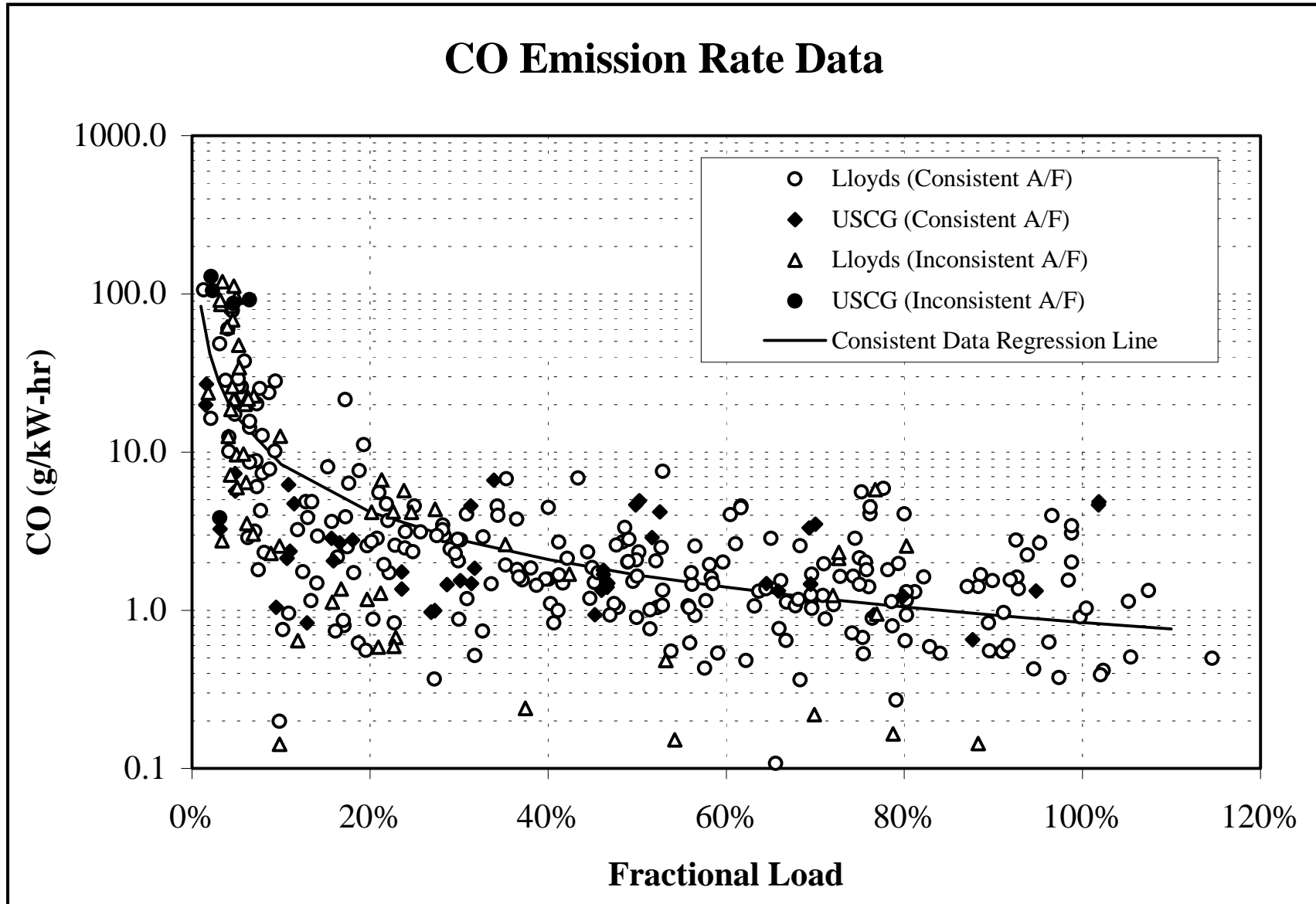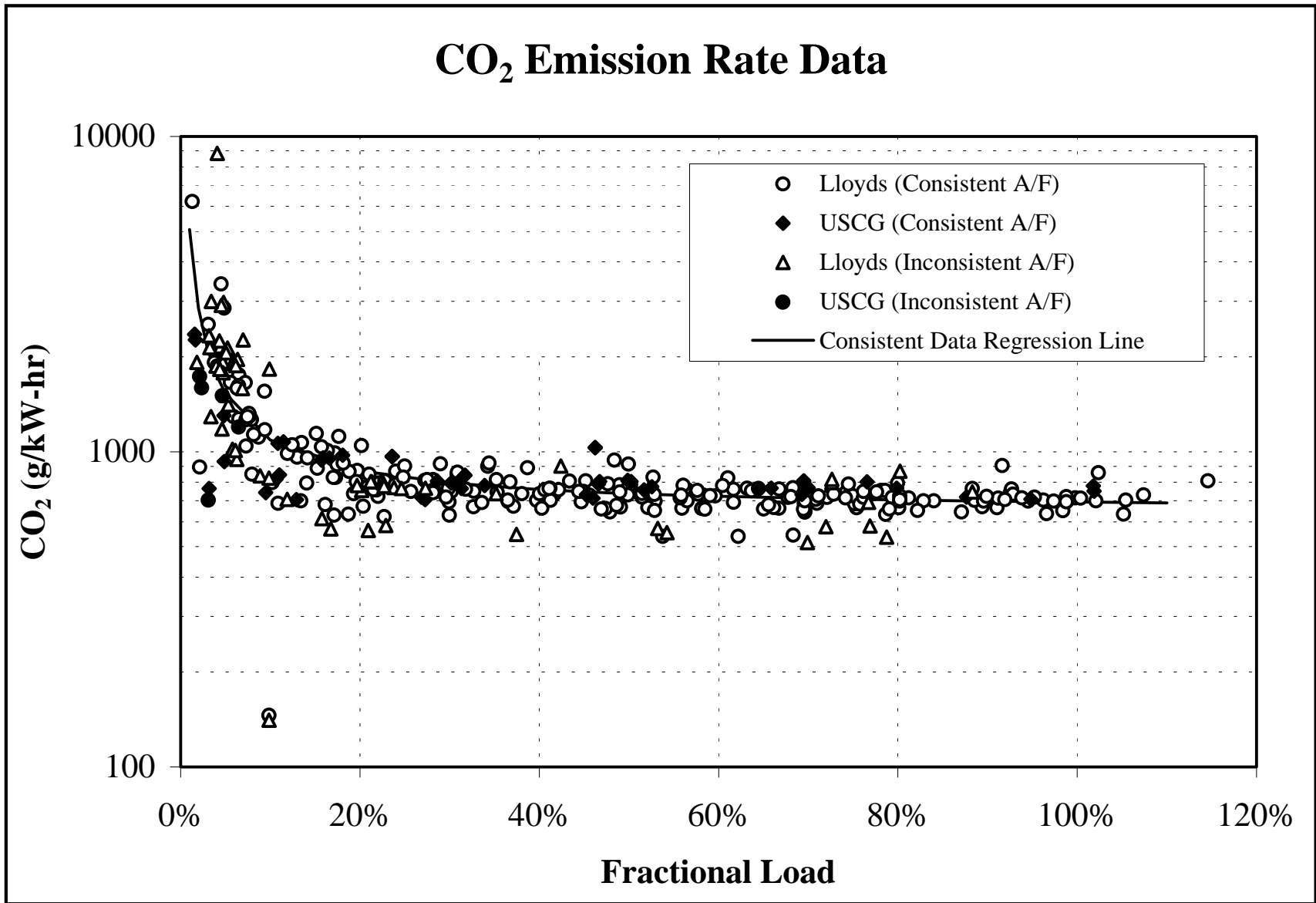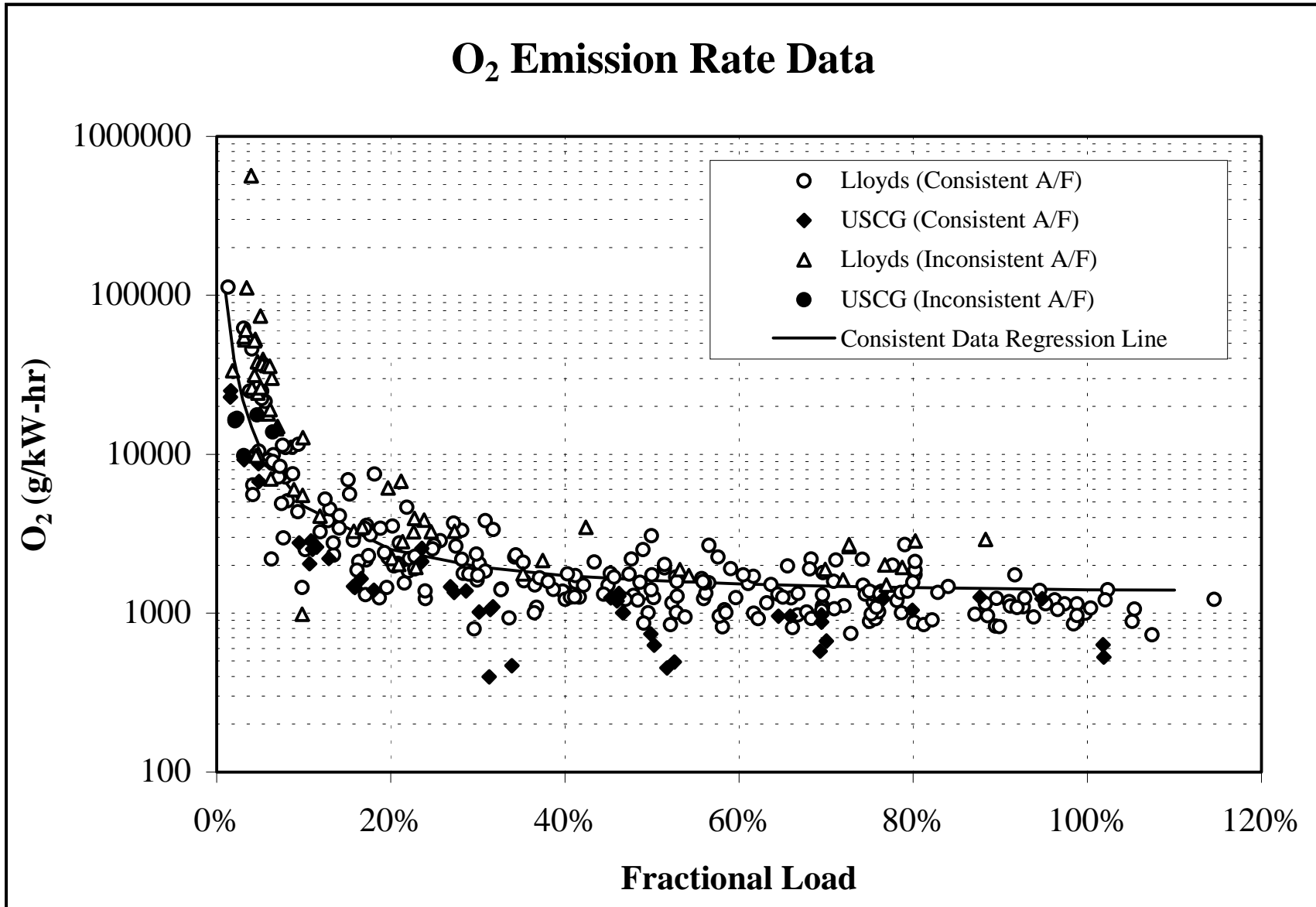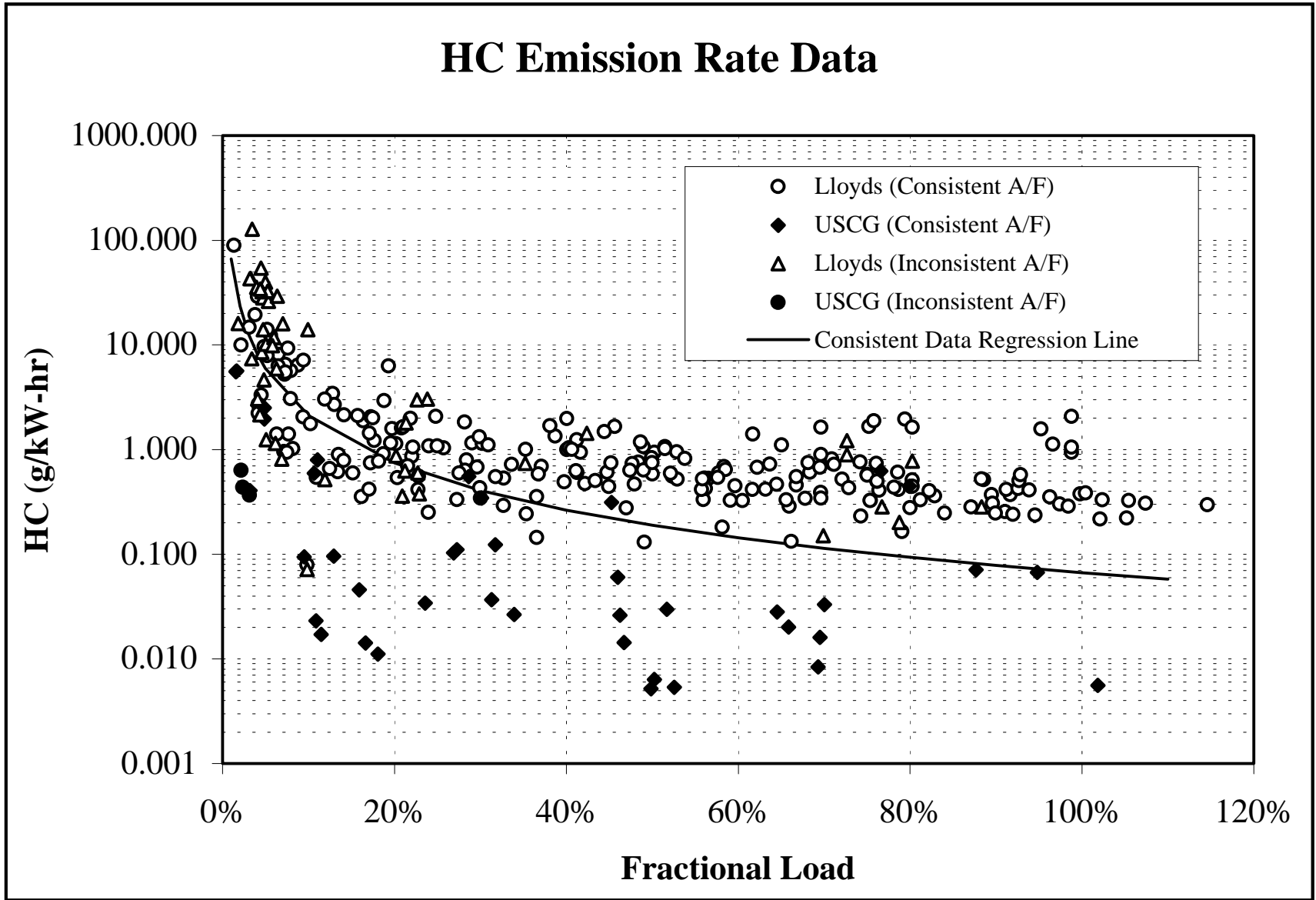
FIGURE 3-26

TABLE 3-5
MARINE ENGINE EMISSION FACTOR ALGORITHMS

Statistical Parameter	PM	NO	NO$_x$	NO$_2$	SO$_2$	CO	CO$_2$	O$_2$	HC	Dry Exhaust	H$_2$O	Wet Exhaust
Exponent (x)	1.5	1.5	1.5	1.5	n/a	1	1	1.5	1.5	1.5	1	1.5
Intercept (b)	0.2551	9.5181	10.4496	15.5247	-0.4792	0.1548	648.6	1298.1	0.3859	8982	220.09	9243
Intercept t-stat	7.780	24.154	24.154	24.154	-1.124	0.323	33.957	4.101	1.429	6.390	29.806	6.557
Significant intercept t?	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes
Coefficient (a)	0.0059	0.1146	0.1255	0.1865	2.3735	0.8378	44.1	107.9	0.0667	489	15.92	491
Coefficient t-stat	23.143	19.391	19.391	19.391	28.924	17.700	23.374	22.769	17.064	23.239	21.839	23.271
Significant coefficient t?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
r^2	.95	.57	.57	.57	.78	.52	.65	.64	.52	.65	.62	.65
F-stat	536	376	376	376	837	313	546	512	291	540	477	541
Significant F-stat?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	31	291	291	291	239	291	291	291	271	291	291	291

3-44

1. All regressions but SO$_2$ are in the form of: Emission Rate (g/kW-hr) = a (Fractional Load)$^{-x}$ + b
2. Fractional load is equal to actual engine output divided by rated engine output.
3. The SO$_2$ regression is in the form of: Emission Rate (g/kW-hr) = a (Fuel Sulfur Flow in g/kW-hr) + b

SO$_2$, due to its obvious dependence on fuel sulfur content,[ ] is treated in a different fashion than the remainder of the emission species. Theoretically, work-specific SO$_2$ emissions should approach two times work-specific fuel sulfur consumption (i.e., the ratio of the molecular weight of SO$_2$ to elemental sulfur is 64.0628/32.064, or 1.998), depending on the relative insignificance of other sulfur sources (e.g., sulfur compounds in intake air) and sinks (e.g., sulfate emissions). Since a direct linear relationship (with a zero intercept and a coefficient of about two) should be evidenced, such a regression structure was evaluated for SO$_2$ in lieu of the load-based regression structures described above for other emission species.

The resulting regression statistics are presented in Table 3-5, where it is evident that the proper zero intercept was derived, but that the derived fuel sulfur coefficient (2.37) is about 20 percent too high. While this lends further support to an overestimation bias in the implied effective A/F ratio of the underlying emission test data (i.e., A/F overestimation implies exhaust mass overestimation, thereby implying emission species overestimation) and further investigation into this phenomenon is recommended, it is not possible within the time or resource constraints of this study to elaborate further. Certainly, a 20 percent error in emissions estimates in not unreasonable given the overall variability of emission rates across engines. Nevertheless, the apparent overestimation of SO$_2$ implies a directional bias that should be addressed. In the interim, EEA recommends using the theoretical coefficient for SO$_2$ production (i.e., 1.998) in place of that presented in Table 3-5.

It is also important to note that statistics presented for NO$_2$ do not represent direct nitrogen dioxide emissions, but rather the NO$_2$ equivalent mass of emitted NO$_x$. In effect, NO$_2$ emission rates reflect the net emission rate of NO$_x$ assuming all NO$_x$ is converted to NO$_2$ (through oxidation from a source not accounted for in the intake/exhaust stream, such as post-exhaust atmospheric oxidation). This emission rate was produced as requested by the EPA, but should be recognized as the maximum potential post-exhaust contribution to atmospheric NO$_2$ and not

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[ ] Of course, carbon containing emission species are equally dependent on fuel carbon content. However, while total fuel consumption is an acceptable surrogate for fuel carbon consumption due to the fact that carbon comprises the bulk of the total fuel, the considerable variability of sulfur content across fuels makes SO$_2$ emissions dependent not on just fuel consumption per se (and thus co-dependent on load), but on fuel sulfur consumption in particular.

an indication of directly emitted NO_2.

Statistics associated with each of the various regression structures evaluated by EEA are presented in Appendix A. This includes both the full and partial load range regression structures evaluated as well as separate regressions for: (1) all database records and (2) only those database records satisfying the A/F ratio acceptance criteria discussed above. The improvement in regression statistics for consistent A/F ratio records (designated in Appendix A as the "Yes Data" regressions under the column labeled "A/F Criteria") relative to those of the "All Data" regressions across emission species is obvious and further illustrates the need to address any remaining uncertainty in A/F ratios (and thus exhaust and emission species mass) to minimize emission factor uncertainty.

The regression statistics presented in Table 3-5 apply to the aggregate emissions test database and do not distinguish between the various engine types (e.g., two stroke versus four stoke) or diesel fuels (e.g., distillate, light residual, etc.) encountered in marine vessel operations. Study time and resource constraints as well as underlying test program structure prohibit an in-depth evaluation of whether a finer resolution of marine vessel emission rates is appropriate. For example, more two stroke engine data for which consistent A/F ratio estimates can be developed, more larger engine emission data in general, more data using less common fuels, and data collected from the same engine while operating on different fuels is critical to isolating and quantifying distinctions between any or all of these elements. Given the current size and construction of the underlying emissions test database, it is not possible to separate simple engine-to-engine variability from potential engine or fuel type influences.

Nevertheless, to investigate the potential for such distinctions and provide an indication of the need for further database enhancement, regression statistics for both two versus four stroke engines and the various fuel types identified in the Lloyd's database were generated. Regression statistics for these various data sets are included in Appendix A. Figures A-1 through A-11 plot all consistent A/F ratio test data by engine type and emission species, while Figures A-12

through A-21 plot the same data by test fuel type.[*]

A review of Figures A-1 through A-21 and the regression statistics presented in Appendix A reveals that it is certainly possible that both engine configuration and fuel type could be significant influences on marine engine emission rates for one or more emission species. Unfortunately, it is not possible given existing database structure and available time and resource constraints to determine whether the apparent influences are attributable to simple variability across engines or to specific engine or fuel characteristics. However, it is also apparent that the scatter for most, if not all, of the separated engine type and fuel specific data is sufficiently wide to support the general usage of the regression statistics presented in Table 3-5 until such time as supplemental test data can be collected and supporting analysis performed. Nevertheless, EEA certainly recommends that such evaluation be performed as soon as possible to validate the general applicability of the presented regressions.

An initial investigation of the dependence of exhaust NO_x on fuel nitrogen content was also conducted. As shown in Figures 3-27 through 3-29, the scatter of estimated NO_x emissions at any given fuel nitrogen content is considerably wider than any trend in NO_x with increasing fuel nitrogen content. In fact, the only trend across fuel nitrogen content appears to be flat. Given the overwhelming significance of intake air nitrogen on overall NO_x formation, such a trend is not surprising.

Lastly, all presented emission factors and emission factor analysis in this study apply solely to marine internal combustion engines operating on diesel fuel (either distillate or residual). Moreover, no distinction has been made between main propulsion engines and auxiliary engines. This lack of distinction is based on two major factors, one technical and one logistical. Technically, no significant differences are expected between the emission profiles of marine engines used for propulsion versus auxiliary operations as the same engine makes and models are

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[*] The USCG database does not identify the two versus four stroke configuration of several of its component test engines and does not distinguish the various test fuels employed during testing, except to indicate that all fuels were "diesel." Therefore, all engine type statistics for "not indicated" engines and "diesel" fuel are based on USCG data only. Conversely, all statistics for specific types of diesel fuel are based on Lloyd's data only.

used to satisfy both applications. Logistically, the entire marine engine database used for this study contains test data for only two auxiliary engines, prohibiting any detailed independent assessment of auxiliary engines alone. Similarly, no emissions data for steam engines was provided to EEA for review. For gas turbines, EPA provided a summary data sheet for only a single oil tanker engine tested at two loads,[11] while the USCG report[4] cites summary test results for two additional gas turbines, but provides no supporting data such as that included for all diesel engines tested. Therefore, the ability to develop detailed emission factors for gas turbines is also quite limited.

Table 3-6 and Figure 3-30 summarize the available gas turbine emissions data and present several arithmetic averages of reported mass emission rate data. Regressions were not performed over the full load range of these turbines as no emissions rate data was provided at loads below about 50 percent of rated output. While both NO_x and CO may exhibit trends (NO_x increasing with load, CO decreasing with load), there simply is no data available to indicate whether these trends hold true over the lower load ranges and, if so, what the general shape of the emissions curve might be. Therefore, at this time, the use of simple arithmetic averages over the entire range of test data or at each individual test data load point (50, 75, and 100 percent of rated output) represents the only viable emission factor estimation technique. The resulting emission factors for either approach are presented in Table 3-6. With appropriate qualifications given the gas turbine database size, gas turbine emissions would, in general, appear to be about half those of diesel marine engines for NO_x and similar to diesel marine engine emissions for HC, CO, and PM.
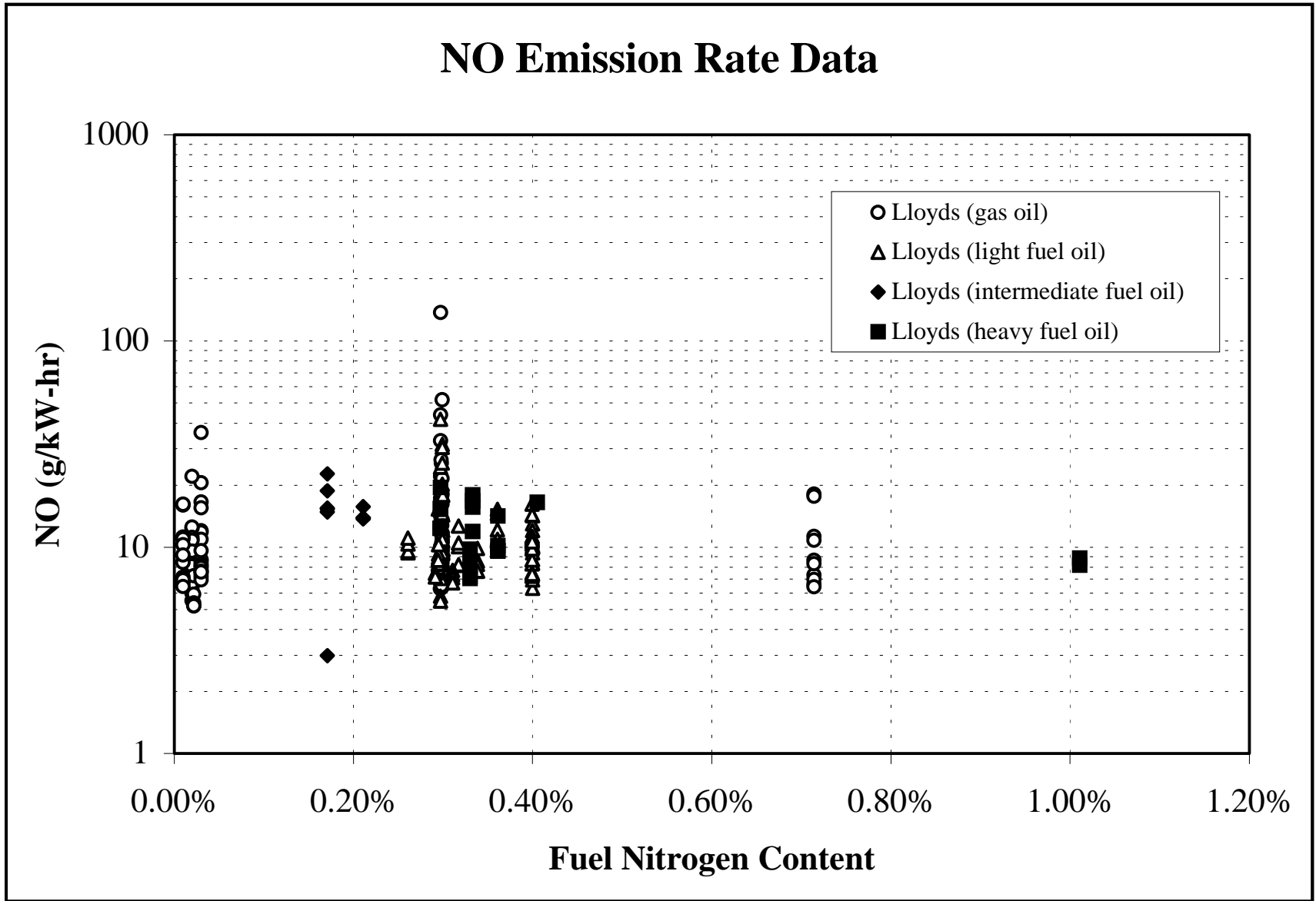
FIGURE 3-27
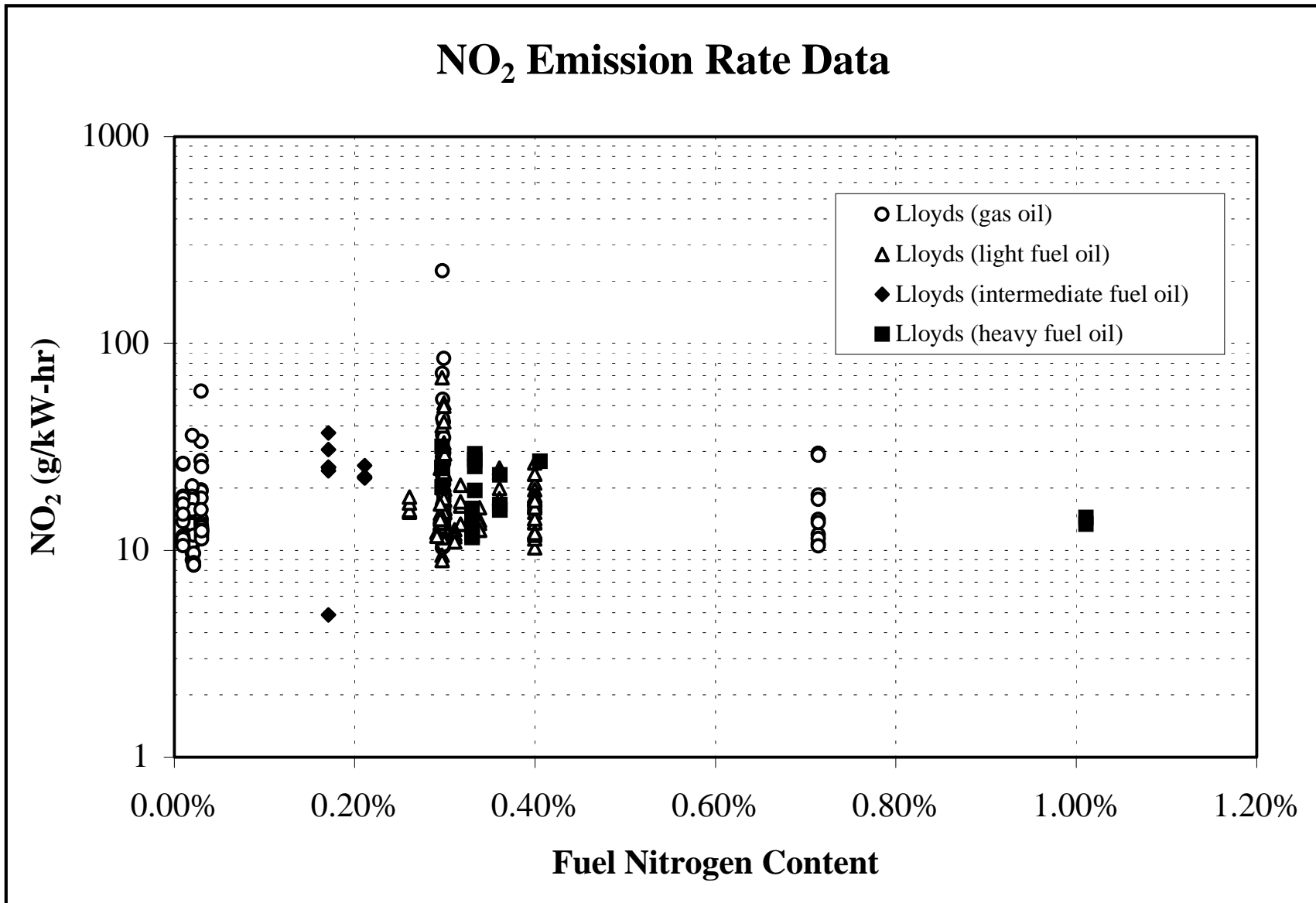
FIGURE 3-28

FIGURE 3-29

TABLE 3-6
MARINE GAS TURBINE EMISSION RATE DATA

Parameter	Chevron "Louisiana"		USCG "Sherman"						Overall Average	50% Load Average	75% Load Average	Full Load Average
			Starboard			Port						
Test Load (mW)	6.30	4.60	13.42	9.84	6.71	13.42	9.84	6.71				
Rated Load (mW)	8.05	8.05	13.42	13.42	13.42	13.42	13.42	13.42				
Fractional Load	0.78	0.57	1.00	0.73	0.50	1.00	0.73	0.50				
Reported Emission Rate (pounds per hour)												
PM	2.21	4.31										
SO_2	12.35	12.64	10.50	3.87	4.10	8.54	2.89	3.68				
NO_x	62.50	33.60	177.00	80.40	50.60	205.00	87.10	53.60				
CO	-1.17	0.31	2.98	27.40	39.50	31.60	26.90	43.50				
HC			2.67	16.00	3.41	0.50	7.23	1.47				
Reported Emission Rate (g/kW-hr)												
PM	0.16	0.42							0.29	0.42	0.16	
SO_2	0.89	1.25	0.35	0.18	0.28	0.29	0.13	0.25	0.45	0.59	0.40	0.32
NO_x	4.50	3.31	5.98	3.71	3.42	6.93	4.01	3.62	4.44	3.45	4.07	6.45
CO	-0.08	0.03	0.10	1.26	2.67	1.07	1.24	2.94	1.15	1.88	0.81	0.58
HC			0.09	0.74	0.23	0.02	0.33	0.10	0.25	0.16	0.54	0.05

Gas Turbine Emission Rates
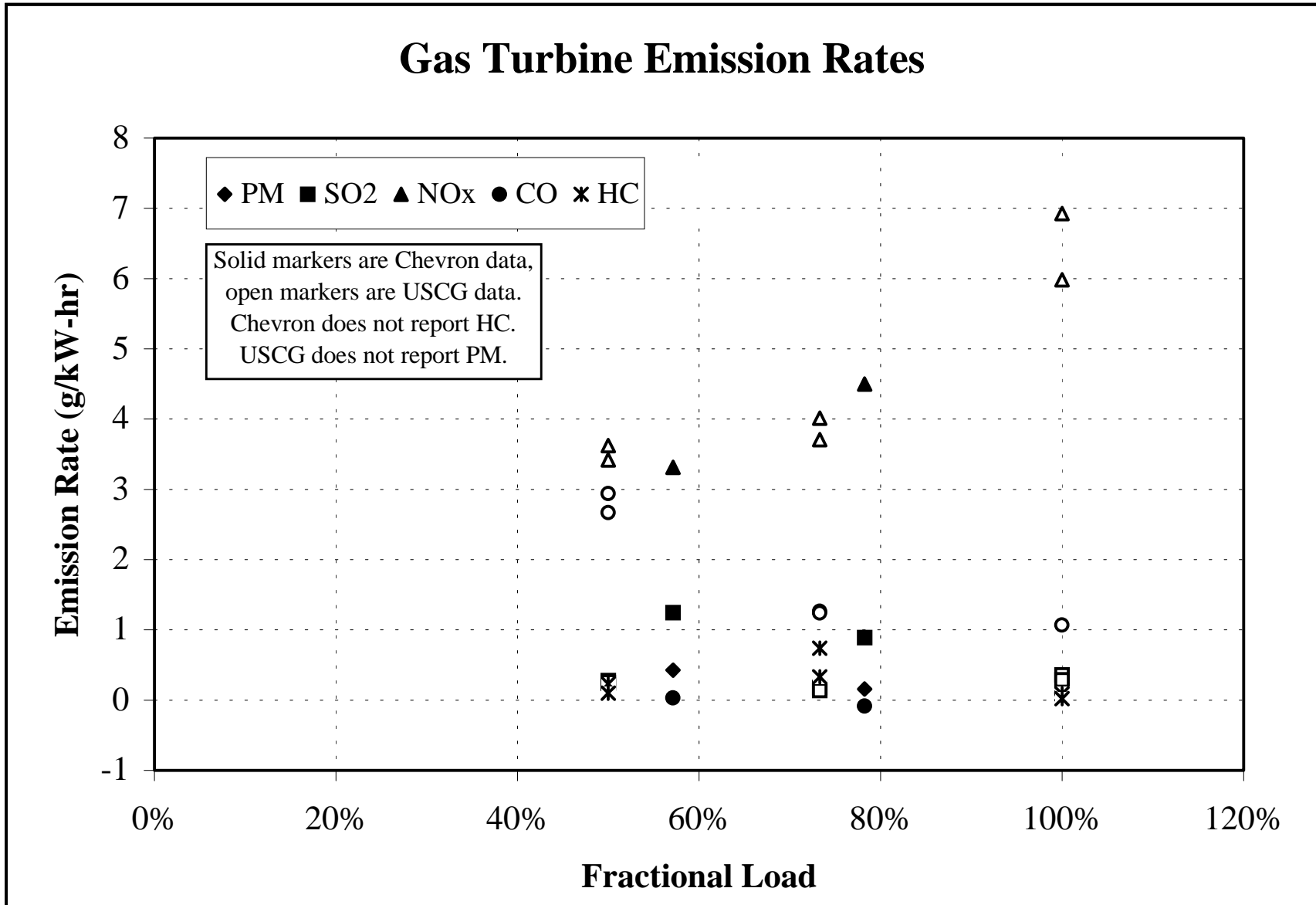
FIGURE 3-30

4. MARINE VESSEL CLASSIFICATIONS AND POWER RATINGS

4.1 CLASSIFICATIONS EMPLOYED IN LITERATURE

Three of the reports provided by EPA had utilized specific classifications of marine vessels that varied both in detail and grouping, and these groupings are reviewed below.

The 1991 report by Booz-Allen[9] categorizes oceangoing vessels into four types:

- container ships;
- tankers and bulk carriers;
- general cargo/vehicle carriers/RORO/and ocean-going tugs; and
- passenger liners and cruise ships.

Each particular category is then divided into weight classes in 25,000 ton deadweight ton (DWT) steps (0 to 25, 25 to 50, etc) and an average horsepower is associated with each weight class for every ship type. However, the horsepower data is identical across all ship types, except for tankers and bulk carriers. The report also identifies horsepower for tankers and bulk carriers as being <u>higher</u> than the horsepower (see Table 4-1) for other types within each weight class. The Booz-Allen data is potentially incorrect, since tankers and bulk carriers cruise relatively slowly (their cargo is not perishable or high cost), and typically have the <u>lowest</u> horsepower for a given deadweight.

The Acurex report[10] for SCAQMD also has a categorization scheme by deadweight and ship type. The analysis relied on data from Lloyds, from the ships visiting San Pedro Bay. Acurex classified ships by type and 'design category' where:

$$\text{Design Category} = (\text{DWT})^{0.667} * (\text{Service Speed})^3/10^4$$

TABLE 4-1
BOOZ-ALLEN CLASSIFICATION OF VESSELS

Type	DWT (x1000) Range	Horsepower
(1) Tankers & Bulk Carriers	0-25	16862
	25-50	35742
	50-75	59342
	75-100	80582
	100+	104182
(2) All Others*	0-25	8560
	25-50	11920
	50-75	16120
	75-100	19900
	100+	24100

* Booz-Allen has three categories for vessels: (a) container ships, (b) general cargo/vehicle carriers/RORO/ ocean-going tugs, and (c) passenger and cruise ships. However, all use the same HP to DWT relationship.

This equation is based on the well-known relationship between power to overcome drag, which varies as the surface area in the water and the cube of speed. From the Lloyds registration data, Acurex developed eight ship type categories namely:

- auto carriers;
- bulk carriers;
- container ships;
- general cargo ships;
- passenger ships;
- refrigerated cargo (reefer) ships;
- 'roll-on, roll-off,' or RORO; and
- tankers.

Each of the eight ship types is then further subdivided into design categories (up to eight) in step of 200. These classifications are provided in Appendix C. However, it is not clear how many ships were available in the sample for each combination of design category and ship type. An examination of the data suggests significant sample variation since, in several instances, horsepower declines with increasing design category range. The Acurex analysis showed that the design category approach reduced the dispersion in horsepower within a ship type, but also showed the dispersion reduction relative to using deadweight as an indicator was not large. In addition, these are large variations in the percentage increase in horsepower for every 200 step in design category range, indicating significant unexplained variation in horsepower.

The Arcadis (1999) report[8] for the EPA utilizes the same ship types as the Acurex study cited above, but also provided cruise speeds by ship type. Bulk carriers, tankers and general cargo ships had cruise speeds in the range of 15 to 16 knots, while reefers, RORO and container ships had speeds of 20 to 22 knots. Auto carriers had an average speed of 18.3 knots while passenger liner had an average speed of 19.9 knots. These estimates appear reasonable except for passenger liners, where the relatively low average speed may have been influenced by the sample selected; many passenger liners have speeds of 30 knots or higher. In addition, the Arcadis report stated that there was considerable dispersion of speeds within ship type, but a

majority of ships were within ± 2 knots of the averages cited. This would suggest that bulk carriers and tankers would have similar relationships between deadweight and horsepower, while reefers, container ships and RORO may also have similar relationships.

Non-oceangoing vessels are typically more simply classified by type and horsepower. The Booz-Allen report classifies these vessels into the following:

- fishing vessels;
- tugs;
- passenger ferries;
- dredging and construction ships;
- work/crew boats.

The Acurex report uses a virtually identical classification for non-oceangoing vessels as the Booz-Allen classification, but further groups all vessels except for tugs and fishing vessels into a single category called 'other' for emission estimation.

4.2   OPERATING MODE CLASSIFICATIONS IN LITERATURE

In general, ocean-going ships approach a port area at cruise speed, but reduce speed when they are positioned within a few miles of the port (known as a precautionary area) to a speed of about 10 to 12 knots. Much closer to the docking area (about one mile), the ships slow to about five knots and, assisted by tugboats, maneuver into the harbor and dock at the pier. Once at the pier, only the auxiliary engines are used to provide electrical and accessory power, in a mode called "hoteling." The literature reviewed uniformly cites these four modes, through not all four modes are used in all reports reviewed.

The Booz-Allen report cites these four modes, called full, half, slow and moored. The power ratings, as a function of rated maximum power are 80, 40, 10, and zero for the four modes respectively with regard to main engines. It was also assumed that for all ocean-going vessels, the auxiliary power engines were operated at 500 kW. For harbor and fishing vessels, three modes are utilized: full at 80 percent power, cruise at 50 percent power and slow at 20 percent

power. No hoteling emissions appear to be included from these classes of vessels.

The Acurex report assumed that at cruise, engines are operated at 80 percent of the maximum continuous rating (MCR). Slow cruise was estimated as 12 knots, and the percent of power required was calculated based on the cube of the ratio of 12 knots to actual cruise speed. Hence, the percent of power used varies according to ship type, since for example, RORO and container ship cruse much faster than bulk carriers and tankers. As a result, the percent of power used varies from a little as 14 percent of MCR for container ships to 40 percent of MCR for bulk carriers. For maneuvering, container ships were estimated to use only 10 percent of MCR, while at the other extreme, bulk carriers were assumed to use 20 percent of MCR, based on 'engineering judgement."

The Acurex report also attempted to estimate auxiliary power loads under all modes including hoteling. A survey based method was used, but no good relationships were found between auxiliary loads and ship size or weight. Acurex recommend the following auxiliary power loads independent of ship type (except for passenger ships) or weight:

- slow/fast cruise   -   750 kW
- maneuvering   -   1250 kW
- hoteling   -   1000 kW

For passenger ships only, auxiliary power loads of 5000 kW were estimated under all conditions.

Acurex did not develop mode specific emission rates for harbor and fishing vessels, but simply used annual fuel consumption average per horsepower to estimate emissions for tugs. Harbor vessel activity was characterized at three modes representing 80, 50, and 20 percent of MCR. Fishing vessel activity was characterized at 80 and 25 percent of MCR and at idle. (Fishing vessels do not have large "hoteling" loads).

The newer Arcadis report[8] does not vary significantly in its assessment of loads and operating modes relative to the Acurex report. Table 4-2 shows the loads by vessel type and mode for ocean going vessels, as provided in this report.

The Environment Canada report[6] also cites four modes, but does not have specific values for percent of power used by ship type on these modes.

4.3   ANALYSIS OF SHIP TYPE AND WEIGHT CATEGORIES

Under this work assignment, EPA provided a data base on ships operating at the West Coast that contained information on ship type, weight, cruise speed and engine horsepower, obtained from Lloyds. The database was similar in content to the one used by Arcadis in earlier analyses, and has been provided to Arcadis for some current (ongoing) analyses.

While the date base contained about 5000 records, it included some data with incomplete records for ship horsepower, type or weight. It also included data on non-oceangoing vessels such as tugs, construction vessels and fishing vessels. Oceangoing vessels were classified in the scheme cited in the Acurex report and included eight broad classifications by ship type as listed in Section 4-1. The total sample of oceangoing ships with all necessary data was about 4100 vessels.

Ideally, rated horsepower would be more closely related to the maximum loaded weight of the ship (i.e., empty weight + payload) but data on empty weight was not available for a large fraction of the data records, and only deadweight (DWT) data is constantly available. EEA attempted two sets of regressions that link horsepower to ship characteristics. The first is between horsepower and DWT by ship type for each of the eight types. The second has horsepower as the independent variable and uses $(DWT)^{0.667}$ and $(speed)^3$ as the independent variables. In addition, a regression across all ship types was performed using both regression specifications.

TABLE 4-2
ENGINE LOADS BY SHIP TYPE FOR EACH OPERATING MODE

Ship Type	Cruise	Slow Cruise	Maneuvering
Auto Carrier	80	20	15
Bulk Carrier	80	40	20
Container	80	10	10
General Cargo	80	35	20
Passenger	80	20	15
Reefer	80	20	15
RORO	80	15	10
Tanker	80	40	20

Source: Reference 8.

Table 4-3 shows the regressions for the eight types and across all ship types using (DWT) as the independent variable. The regression has poor explanatory power when all ship types are combined, but has reasonable explanatory power when each ship type is considered separately. Most of the regressions by ship type have r^2 values in excess of 0.55.

Table 4-4 shows the regressions for the same ship types when $(DWT)^{0.667}$ and $(speed)^3$ are the independent variables. These regressions have better explanatory power than the regressions using DWT alone, but the improvements are not very large, except for the case when all ship types are considered as one group. This is consistent with the observation that cruise speeds within a ship type do not vary much, but vary significantly across ship types.

Our contacts with a few ports established that its is easier to obtain information on a ship's deadweight tonnage that to obtain cruise speed or horsepower (which would require purchase of Lloyd's data). Hence, the use of the (DWT) based regressions may be preferable to determine horsepower. In examining the regression and the related scatter plots (not included in this report), it was obvious that certain ship type categories could be combined

The regression coefficient for bulk carriers and tankers are very similar, and Arcadis also reports a very similar top speed, so that combining these categories is appropriate. In addition, Table 4-4 also shows that the DWT coefficient for auto carriers, RORO, container ship and reefers are quite similar (between 15 and 20) and could be combined. Plots of horsepower against (DWT) for these ship types show that RORO reefers and auto carriers are distributed in the 5000 to 20,000 ton DWT range while most of the container ships are the 20,000 to 70,000 ton DWT range. Because of their relatively high horsepower to weight ratio in comparison to general cargo ships and tankers, and because of the fact that the sample size for these ship types was (individually) only about 100 to 160, they were combined with container ships. Regression coefficients for the combined categories are shown in Table 4-5.

TABLE 4-3
RESULTS OF REGRESSIONS BETWEEN HORSEPOWER
AND DEADWEIGHT TONNAGE

SHIP TYPE	INTERCEPT	DWT COEFF	R-SQUARE
ALL (N= 4103)	9070 (42.05)	0.1097 (26.01)	0.14
AUTO CARRIER (N= 157)	7602 (7.33)	0.4172 (5.75)	0.176
BULK CARRIER (N= 1644)	6726 (54.54)	0.0985 (26.01)	0.55
CONTAINER (N=489)	-749.4 (-0.61)	0.800 (26.29)	0.59
GENERAL CARGO (N=641)	3046 (15.67)	0.288 (28.43)	0.56
PASSENGER (N= 40)	-4877 (-1.24)	6.81 (9.97)	0.72
REEFER (N=160)	1364 (2.23)	1.007 (14.93)	0.58
RORO (N= 110)	4358 (6.70)	0.5364 (18.34)	0.76
TANKER (N=861)	6579 (34.61)	0.1083 (41.16)	0.66

T-statistics in parentheses under coefficients.

TABLE 4-4
REGRESSIONS OF HORSE POWER vs DEADWEIGHT AND CRUISE SPEED

SHIP TYPE	INTERCEPT	DWT COEFF	SPEED COEFF	R-SQUARED
ALL (N= 4103)	-4585 (23.18)	6.711 (51.95)	2.662 (92.66)	0.73
AUTOCARRIER (N=157)	2956 (1.947)	14.41 (5.788)	0.381 (3.38)	0.25
BULK CARRIER (N=1644)	1586 (6.514)	5.901 (48.55)	0.791 (13.11)	0.61
CONTAINER (N=489)	-13924 (-10.36)	20.06 (12.60)	2.342 (16.63)	0.73
GENERAL CARGO (N=839)	-1307 (-7.73)	8.819 (34.94)	1.202 (34.84)	0.80
PASSENGER (N= 40)	-25305 (-4.43)	118.45 (5.228)	2,612 (3.498)	0.73
REEFER (N= 160)	-2357 (-3.68)	17.00 (8.749)	0.861 (10.98)	0.77
RORO (N= 110)	-3664 (-5.02)	16.18 (15.68)	1.386 (9.040)	0.88
TANKER (N= 861)	156.6 (0.544)	6.271 (49.32)	1.291 (16.40)	0.78

T-statistics in parentheses. Equation uses $(DWT)^{0.667}$ and $(SPEED)^3$ as independent variables.

TABLE 4-5
RECCOMENDED SHIP TYPES AND REGRESSIONS
OF HORESEPOWER TO DEADWEIGHT

SHIP TYPE	INTERCEPT	DWT COEFF.	R-SQUARE
BULK CARRIERS +TANKERS (N=2505)	9070 (48.52)	0.101 (49.55)	0.67
PASSENGER (N= 40)	-4877 (-1.24)	6.81 (9.97)	0.72
GENERAL CARGO (N= 641)	3046 (15.67)	0.288 (28.43)	0.56
CONTAINER/RORO AUTO CARRIER/REEFER (N= 917)	2581 (5.50)	0.719 (47.27)	0.71

T-statistics in parentheses under coefficients.

Passenger ships posed a dilemma since there are only 40 ships in the database. The regression show extremely high horsepower per DWT, and it implies that a 15,000 DWT ship would have engines whose output is about 100,000 HP. In contrast, the Arcadis report estimates a similar ship would have engines rated at 33,000 HP. It should be noted that the passenger ships in the Arcadis report had relatively low top speeds of about 20 knots. If typical speeds are closer to 30 knots, the cubic relationship with speed would explain the differences in horsepower, since $(30/20)^3$ is 3.375, i.e., passenger ships capable of 30 knots cruise would require 3.375 times the power of ships capable of 20 knot cruise. Nevertheless, the regressions should be treated with caution because of the very small sample.

No independent data on the possible modes of operation and load factors was received. The Arcadis report utilizing estimates of load factor derived from speeds appears more defensible than using constant load factors across ship types for each mode. However, the load factor for slow cruise (in the precautionary area) derived by Arcadis is based on an assumption that all ships slow to 12 knots. It is entirely possible that larger ships such as bulk carriers and tankers may operate slower as they cannot be maneuvered or stopped as easily as small ships, so that using 12 knots for all ships may be incorrect. Due to the cubic relationship of power to speed, slowing to ten knots would imply a load factor almost <u>half</u> that of slowing to 12 knots. The cubic relationship also assumes that propeller and drivetrain efficiency remains constant over the speed range which is likely incorrect. Due to the grouping of vessel types, and due to modest changes to speed assumptions, EEA suggests load factors that are slightly different from the Arcadis factors by mode, and these are listed in Table 4-6.

No alternatives to hoteling loads other than Arcadis survey based data are available. Hence, we suggest these be utilized until more extensive survey based data becomes available.

TABLE 4-6
SUGGESTED LOADS BY MODE
(as percent of maximum continuous rating)

	Cruise	Slow Cruise	Maneuvering
Bulk Carrier & Tankers	80	40	20
General Cargo	80	35	20
Passenger*	80	20	10
Container/RORO/Reefer/Auto Carrier	80	30	15
Auxiliary Loads in kW			
	Fast/Slow Cruise	**Maneuvering**	**Hoteling**
Passenger Ships	5000	5000	5000
All Others	750	1250	1000

* All values except main engine load categories marked are from Reference 8.

Data on the horsepower and operating modes of all non-oceangoing hips is much more sparse. Based on the data provided by EPA, EEA calculated the following average rated horsepower by vessel type:

- Fishing Vessels   -   1106
- Tug   -   4268
- Ferries   -   2415
- Yachts   -   1863
- Harbor Operations   -   5046

No data is available to compare these estimates, but these estimates are based on samples of about 100 vessels in each class.

Operating mode data on non-oceangoing vessels is not easy to characterize. Typical estimates have been based on power factors of 80 percent, 40 percent, 20 percent and idle, for cruise, slow cruise, maneuvering, and trawling or waiting. No estimates of auxiliary loads for such vessels are available.

The operating mode data on both oceangoing and non-oceangoing vessels appears to be derived from numerous assumptions that have not been subjected to any validation by EEA. However, this is the best available data within the time and resource constraints of this project.

5. EMISSION FACTOR SUMMARY

The analysis presented in this report derives new emission factors for marine vessels, based on data from the Lloyds Marine Exhaust Emissions Research Program, and the Coast Guard Test Program. Unlike marine emission factors that were historically specified in units of fuel consumption, the emission factors are specified in units of work (kW-hr) and are dependent on engine load factor, which is the ratio of actual output to rated output based on the maximum continuous rating.

The computation of emissions (and fuel consumption, if required) can be performed by ship type for a given port and requires the following inputs:

- The number of calls to the port by vessel class and deadweight tonnage.
- The time spent, by ship type, in each of four operating modes defined as: normal cruise, slow cruise, maneuvering and hoteling.

Alternatively, if ship horsepower is directly available for each ship, classification by deadweight tonnage is not required. In addition, the user may define alternative modes of operation and typical engine load factors by mode.

The basic equations used for the calculation are:

$$\text{TIME}_{\text{VCC, DWT, MODE}} = \text{CALLS}_{\text{VCC, DWT}} \times \text{LENGTH}_{\text{VCC,DWT}} \times \%\text{TIME}_{\text{VCC, DWT, MODE}}/100$$

$$\text{EMISSIONS}_{\text{VCC,DWT,MODE}} = (\text{EF})(\text{LF}_{\text{MODE}}) \times (\text{HP})(\text{DWT}) \times \text{LF}_{\text{MODE}} \times \text{TIME}_{\text{VCC, DWT, MODE}}$$

where:

VCC is the vessel class (tanker, RORO, etc.)
DWT is the deadweight tons
EF is the emissions factor
LF is the mode specific load factor

For the calculation, the TIME equation requires port specific inputs, while this report provides the EF and HP relationships.

The emission factors and fuel consumption rates are derived from substantially more data than earlier emission factors, and represent an improvement over the current fuel based emission factors. However, the emission factors derived are subject to the following cautions:

- A significant portion of the database had measurements that yielded inconsistent values of air-fuel ratio depending on the calculation methodology employed. These records were excluded from the analysis, but the remaining database was still adequate for analysis.

- Some of the data reported suspiciously low values of HC concentrations (below one ppb), but these data were retained in the analysis. However, the number of records with low HC values is small.

- There are concerns regarding the determination of output power at each test mode, for about ten percent of the records.

- Most of the data analyzed is on engines rated at less than 8000 kW. Most of the data points eliminated from analysis due to errors are from higher output engines, which are mostly two-stroke engines. Hence, the applicability of the derived emission factors to all engine sizes is not firmly established.

The emissions factor algorithms derived are of the form:

$$E \text{ (g/kW-hr)} = a \text{ (Fractional Load)}^{-x} + b$$

where E is the emissions rate per unit of work. The data analysis showed no statistically significant differences in emissions rates by engine size or output range, or by two-stroke/four-stoke, subject to the caveats detailed above. Emissions rates for SO_2 are based on (fuel consumption x sulfur content of fuel) since all SO_2 emissions are fuel derived. Table 5-1 provides a summary of HC, CO, NO_x, NO_2, PM, CO_2, and SO_2 emission factors and fuel consumption as a function of load. The fuel consumption factor algorithm (derived from the same database as the emission factors) is also in the same equation form as emission factor algorithms. These emissions factor and fuel consumption rate algorithms are applicable to all engine sizes since the emissions data showed no statistically significant difference across engine sizes. In all cases (including fuel consumption), the algorithms provide the rates per unit of work, i.e. per kW-hr. In order to obtain the absolute emission or fuel consumption level in grams, it is

TABLE 5-1
MARINE ENGINE EMISSION FACTOR
AND FUEL CONSUMPTION ALGORITHMS
(in g/kW-hr, for all marine engines)

Pollutant	Exponent (x)	Intercept (b)	Coefficient (a)
PM	1.5	0.2551	0.0059
NO_x	1.5	10.4496	0.1255
NO_2	1.5	15.5247	0.18865
SO_2	n/a	n/s	2.3735
CO	1	n/s	0.8378
HC	1.5	n/s	0.0667
CO_2	1	648.6	44.1

1. All regressions but SO_2 are in the form of:

   Emissions Rate (g/kW-hr) = a (Fractional Load)$^{-x}$ + b

2. Fractional load is equal to actual engine output divided by rated engine output.

3. The SO_2 regression is the form of:

   Emissions Rate (g/kW-hr) = a (Fuel Sulfur Flow in g/kW-hr) + b

4. **Fuel Consumption (g/kW-hr) = 14.12/(Fractional Load) + 205.717**

5. n/a is not applicable, n/s is not statistically significant.

necessary to multiply the rates per unit of work by the work in kilowatts and the time in hours, as indicated by the equation listed on page 5-1 for emissions.

While the rederivation of emission factors and fuel consumption rate are central to this report, the relationship of engine rated horsepower to ship type and deadweight tonnage was also investigated. Oceangoing ships were classified into four types and their horsepower was related to deadweight (DWT) using linear regressions. The results are:

(1) Bulk Carriers and Tankers: HP = 9070 + 0.101 (DWT)
(2) General Cargo Ships: HP = 3046 + 0.288 (DWT)
(3) Container/RORO/Auto Carriers/Refrigerated Ships: HP = 2581 + 0.719 (DWT)
(4) Passenger Ships: HP = -4877 + 6.81 (DWT)

The relationship for the passenger ship category is the most uncertain since the sample of ships in this category was very small (40).

For all non-ocean going vessels, the empty weight or deadweight is generally not available in the Lloyd's registration data, so that for these classes of vessels, only an average horsepower across the class was computed. The values are based on a sample of about 100 vessels in each category and the results are:

- fishing vessels   -   1106 HP;
- tugs   -   4268 HP;
- ferries   -   2415 HP;
- yachts   -   1863 HP;
- harbor operations   -   5046 HP;

The values could be used as default values in the absence of actual HP data on the vessels operating at a specific port.

Operating modes were divided into four types:

- normal cruise;
- slow cruise;
- maneuvering;
- docking (hoteling).

No independent data analysis was performed on the load factors for the engines (main and auxiliary) at these operating modes. Results from literature are summarized, and the best source of load factor data is from a recent report by Arcadis. Nevertheless, this data relies on a number of assumptions that may not be true, especially for a specific port. The auxiliary engine loads (in absolute kilowatts) may be the most arbitrary as they are specified <u>independent of ship size </u>or weight.

Computation of emissions from auxiliary engines require the use of the same emission factors specified in Table 5-1, and are evaluated at a load factor equal to one (i.e., at full load). Hence, the equation for emission from auxiliary engines is given by

$$\text{Emissions} = (EF)(LF=1) \times \text{Auxiliary Power (kW)} \times \text{Time}_{VCC,DWT,HOTEL}$$

Table 5-2 shows the suggested load factors for both ocean-going vessels and non-ocean-going vessels. While these values could be reasonable default values, the use of port specific load factors is preferable, if available.

TABLE 5-2
SUGGESTED LOAD FACTORS
(as percent of maximum continuous rating)

Vessel Type	Cruise	Slow Cruise	Maneuvering
Bulk Carriers & Tankers	80	40	20
General Cargo	80	35	20
Passenger	80	20	10
Container/RORO/Reefer/Auto Carrier	80	30	15
All non-oceangoing	80	40	20

SUGGESTED AUXILIARY LOADS IN KW
(ocean-going vessels only)*

	Slow Cruise	Maneuvering	Hoteling
Passenger Ships	5000	5000	5000
All others	750	1250	1000

* Non-oceangoing vessels do not have separate auxiliary loads of significance.

6. REFERENCES

1. *Marine Exhaust Emissions Research Programme: Steady State Operation*, Lloyd's Register of Shipping, London, United Kingdom, 1990.

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4. *Shipboard Marine Engines Emission Testing for the United States Coast Guard*, Delivery Order Number 31, Final Report, prepared by Environmental Transportation Consultants for the Volpe National Transportation Systems Center and the United States Coast Guard Headquarters Naval Engineering Division, undated (emissions testing conducted in 1995).

5. *BC Ferries Emissions Test Program, Report for the BC Ferry Corporation*, ERMD #98-26711, Environment Canada, Ottawa, Ontario, Canada, 1998

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7. *Marine Emissions Quantification – BCFC Ferries operating in Greater Vancouver Regional District Airshed*, 97/EE/7002, Final Report, prepared by Lloyd's Register of Shipping for the British Columbia Ferry Corporation, London, United Kingdom, 1997.

8. *Analysis of Marine Emissions in the South Coast Air Basin*, Draft Report, EPA Contract Number 68-C6-0068, Work Assignment Number 0-02, prepared by Acurex Environmental Corporation for the U.S. Environmental Protection Agency, 1999.

9. *Inventory of Air Pollutant Emissions from Marine Vessels*, Final Report, prepared by Booz-Allen & Hamilton for the California Air Resources Board, Revised March 1991

10. *Marine Vessel Emission Inventory and Control Strategies*, Final Report, prepared by Acurex Environmental Corp., for the South Coast Air Quality Management District, 1996

11. Facsimile transmittal on gas turbine emission rates from the Chevron "Louisiana," Brian Shafritz of the Santa Barbara County (California) Air Pollution Control District to Gregg Jansen [sic] of the U.S. Environmental Protection Agency, June 1, 1999.

APPENDIX A

EMISSION FACTOR REGRESSION SUMMARIES

KEY TO APPENDIX TERMS:

1. All regressions are of the form:

    Emission rate (g/kW-hr) = (Coefficient × Independent Variable) + Intercept

    where: Coefficient = Value in column labeled "Coeff,"
    Intercept = Value in column labeled "Intercept," and
    Independent Variable = Parameter indicated in column labeled "Param" as follows:

    "FL" = Fractional Load,
    "1/(FL^e)" = Fractional Load to the negative "e" power, and
    "Fuel S" = Fuel sulfur flow in g/kW-hr.

2. Where applicable, the exponent "e" is indicated in the upper center of each regression summary.

3. Entries in the column labeled "A/F Criteria" have the following meanings:

    "All Data" indicates that no data was excluded from the regression analysis due to inconsistencies in estimated A/F ratio.

    "Yes Data" indicates that only data meeting the consistent A/F ratio criteria described in Section 3 is included in the regression analysis.

4. Entries in the column labeled "Loads Covered" have the following meanings:

    "FL ge 0" means all data with an indicated fractional load greater than or equal to zero.

    "FL ge 20" means all data with an indicated fractional load greater than or equal to 20 percent.

    "FL lt 20" means all data with an indicated fractional load of less than 20 percent.

5. Entries in the column labeled "Cycles Covered" have the following meanings:

> "All" means all reported engine types are included in the regression analysis.

> "2 Stroke" means only data for reported two stroke engines are included in the regression analysis.

> "4 Stroke" means only data for reported four stroke engines are included in the regression analysis.

> "Not Ind." (not indicated) means only data for USCG engines not reported as either two or four stroke are included in the regression analysis.

6. Entries in the column labeled "Fuels Covered" have the following meanings:

> "All" means all reported fuel types are included in the regression analysis.

> "Diesel" means only USCG fuel types (all identified simply as "diesel") are included in the regression analysis.

> "Gas Oil" means only data for reported gas oil fuel are included in the regression analysis.

> "Gas Oil" means only data for reported gas oil fuel are included in the regression analysis.

> "Hvy FO" means only data for reported heavy fuel oil fuel are included in the regression analysis.

> "Int FO" means only data for reported intermediate fuel oil fuel are included in the regression analysis.

> "Light FO" means only data for reported light fuel oil fuel are included in the regression analysis.

7. Entries in the columns labeled "Int-T" and "Coeff-T" indicate the regression t statistics for the intercept and coefficient respectively.

8. Entries in the column labeled "r2" indicate the regression correlation coefficient.

9. Entries in the column labeled "F" indicate the regression model variance F statistic.

10. Entries in the three columns labeled "Sig?" indicate, from left to right, whether ("Yes") or not ("No") the indicated intercept t statistic, coefficient t statistic, and variance F statistic are significant at the 99 percent confidence level.

11. Entries in the column labeled "Obs" indicate the number of observations used in the regression analysis.

REGRESSION SUMMARY FOR: PM   Exponent = 1.5

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load …				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	2.4352	2.981	Yes	-3.6383	-1.892	No	FL	0.10	3.58	No	35	2.435	2.435	2.435	2.435	2.435
All Data	FL ge 0	All	All	0.8332	1.430	No	0.0066	1.593	No	1/(FL^e)	0.07	2.54	No	35					
All Data	FL ge 20	All	All	0.3344	2.696	No	-0.0482	-0.221	No	FL	0.00	0.05	No	19					
All Data	FL lt 20	All	All	4.5556	2.245	No	-25.4900	-1.300	No	FL	0.11	1.69	No	16					
All Data	FL lt 20	All	All	1.8897	1.272	No	0.0035	0.486	No	1/(FL^e)	0.02	0.24	No	16					
Yes Data	FL ge 0	All	All	0.9289	4.369	Yes	-1.1052	-2.346	No	FL	0.16	5.50	No	31	0.929	0.929	0.929	0.929	0.929
Yes Data	FL ge 0	All	All	0.2551	7.780	Yes	0.0059	23.143	Yes	1/(FL^e)	0.95	535.58	Yes	31	0.784	0.442	0.279	0.263	0.261
Yes Data	FL ge 20	All	All	0.3344	2.696	No	-0.0482	-0.221	No	FL	0.00	0.05	No	19					
Yes Data	FL lt 20	All	All	2.4562	6.000	Yes	-15.5027	-4.426	No	FL	0.66	19.59	Yes	12	2.456	2.456	2.456	2.456	2.456
Yes Data	FL lt 20	All	All	0.1797	3.921	Yes	0.0061	27.472	Yes	1/(FL^e)	0.99	754.73	Yes	12	0.726	0.373	0.204	0.188	0.186
Yes Data	FL ge 0	Not Ind.	All	0.9533	3.927	Yes	-1.1154	-1.967	No	FL	0.14	3.87	No	25	0.953	0.953	0.953	0.953	0.953
Yes Data	FL ge 0	2 Stroke	All	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	4 Stroke	All	0.4088	4.140	Yes	-0.2656	-1.443	No	FL	0.34	2.08	No	6	0.409	0.409	0.409	0.409	0.409
Yes Data	FL ge 0	Not Ind.	All	0.2558	6.235	Yes	0.0059	20.590	Yes	1/(FL^e)	0.95	423.95	Yes	25	0.785	0.443	0.279	0.264	0.262
Yes Data	FL ge 0	2 Stroke	All	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	4 Stroke	All	0.1828	2.955	No	0.0274	1.602	No	1/(FL^e)	0.39	2.57	No	6					
Yes Data	FL ge 0	All	Diesel	0.9289	4.369	Yes	-1.1052	-2.346	No	FL	0.16	5.50	No	31	0.929	0.929	0.929	0.929	0.929
Yes Data	FL ge 0	All	Gas Oil	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	All	Hvy FO	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	All	Int FO	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	All	Light FO	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	All	Diesel	0.2551	7.780	Yes	0.0059	23.143	Yes	1/(FL^e)	0.95	535.58	Yes	31	0.784	0.442	0.279	0.263	0.261
Yes Data	FL ge 0	All	Gas Oil	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	All	Hvy FO	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	All	Int FO	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	All	Light FO	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	Not Ind.	Diesel	0.9533	3.927	Yes	-1.1154	-1.967	No	FL	0.14	3.87	No	25	0.953	0.953	0.953	0.953	0.953
Yes Data	FL ge 0	2 Stroke	Diesel	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	2 Stroke	Gas Oil	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	2 Stroke	Hvy FO	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	2 Stroke	Int FO	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	4 Stroke	Diesel	0.4088	4.140	Yes	-0.2656	-1.443	No	FL	0.34	2.08	No	6	0.409	0.409	0.409	0.409	0.409
Yes Data	FL ge 0	4 Stroke	Gas Oil	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	4 Stroke	Light FO	0.0000	0.000		0.0000	0.000		FL	0.00	0.00		0					
Yes Data	FL ge 0	Not Ind.	Diesel	0.2558	6.235	Yes	0.0059	20.590	Yes	1/(FL^e)	0.95	423.95	Yes	25	0.785	0.443	0.279	0.264	0.262
Yes Data	FL ge 0	2 Stroke	Diesel	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	2 Stroke	Gas Oil	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	2 Stroke	Hvy FO	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	2 Stroke	Int FO	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	4 Stroke	Diesel	0.1828	2.955	No	0.0274	1.602	No	1/(FL^e)	0.39	2.57	No	6					
Yes Data	FL ge 0	4 Stroke	Gas Oil	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					
Yes Data	FL ge 0	4 Stroke	Light FO	0.0000	0.000		0.0000	0.000		1/(FL^e)	0.00	0.00		0					

REGRESSION SUMMARY FOR: NO   Exponent = 1.5

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load …				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	20.0268	19.658	Yes	-14.9792	-7.862	No	FL	0.15	61.81	Yes	356	20.027	20.027	20.027	20.027	20.027
All Data	FL ge 0	All	All	10.4583	18.481	Yes	0.1110	14.647	Yes	1/(FL^e)	0.38	214.54	Yes	356	20.386	13.968	10.897	10.613	10.569
All Data	FL ge 20	All	All	10.7756	22.772	Yes	-1.7939	-2.449	No	FL	0.02	6.00	No	241	10.776	10.776	10.776	10.776	10.776
All Data	FL lt 20	All	All	36.0476	11.209	Yes	-158.9668	-5.124	No	FL	0.19	26.25	Yes	115	36.048	36.048	36.048	36.048	36.048
All Data	FL lt 20	All	All	14.1805	7.215	Yes	0.0939	6.270	Yes	1/(FL^e)	0.26	39.31	Yes	115	22.577	17.149	14.552	14.312	14.274
Yes Data	FL ge 0	All	All	16.9497	17.580	Yes	-10.8279	-6.407	No	FL	0.12	41.06	Yes	291	16.950	16.950	16.950	16.950	16.950
Yes Data	FL ge 0	All	All	9.5181	24.154	Yes	0.1143	19.391	Yes	1/(FL^e)	0.57	376.02	Yes	291	19.746	13.134	9.970	9.678	9.632
Yes Data	FL ge 20	All	All	10.3842	21.257	Yes	-1.6405	-2.207	No	FL	0.02	4.87	No	217	10.384	10.384	10.384	10.384	10.384
Yes Data	FL lt 20	All	All	33.9582	8.753	Yes	-144.4380	-4.358	No	FL	0.21	18.99	Yes	74	33.958	33.958	33.958	33.958	33.958
Yes Data	FL lt 20	All	All	11.4486	7.186	Yes	0.1070	8.884	Yes	1/(FL^e)	0.52	78.93	Yes	74	21.015	14.831	11.871	11.598	11.556
Yes Data	FL ge 0	Not Ind.	All	18.6862	11.938	Yes	-14.8995	-4.426	No	FL	0.45	19.59	Yes	26	18.686	18.686	18.686	18.686	18.686
Yes Data	FL ge 0	2 Stroke	All	9.5052	6.425	Yes	3.3223	1.239	No	FL	0.03	1.54	No	45	9.505	9.505	9.505	9.505	9.505
Yes Data	FL ge 0	4 Stroke	All	17.7374	14.654	Yes	-12.2715	-5.936	No	FL	0.14	35.23	Yes	220	17.737	17.737	17.737	17.737	17.737
Yes Data	FL ge 0	Not Ind.	All	10.8992	17.308	Yes	0.0461	10.252	Yes	1/(FL^e)	0.81	105.10	Yes	26	15.022	12.357	11.081	10.964	10.945
Yes Data	FL ge 0	2 Stroke	All	11.5228	15.199	Yes	-0.0331	-1.394	No	1/(FL^e)	0.04	1.94	No	45	11.523	11.523	11.523	11.523	11.523
Yes Data	FL ge 0	4 Stroke	All	8.7618	24.437	Yes	0.1701	27.588	Yes	1/(FL^e)	0.78	761.12	Yes	220	23.980	14.142	9.434	9.000	8.932
Yes Data	FL ge 0	All	Diesel	13.8772	11.302	Yes	-7.2368	-3.571	No	FL	0.21	12.76	Yes	49	13.877	13.877	13.877	13.877	13.877
Yes Data	FL ge 0	All	Gas Oil	20.6879	9.899	Yes	-18.7851	-4.675	No	FL	0.16	21.86	Yes	114	20.688	20.688	20.688	20.688	20.688
Yes Data	FL ge 0	All	Hvy FO	10.7749	4.684	Yes	2.3879	0.616	No	FL	0.02	0.38	No	22	10.775	10.775	10.775	10.775	10.775
Yes Data	FL ge 0	All	Int FO	14.3115	3.934	Yes	0.8539	0.128	No	FL	0.00	0.02	No	10	14.311	14.311	14.311	14.311	14.311
Yes Data	FL ge 0	All	Light FO	14.9135	14.592	Yes	-7.4032	-4.384	No	FL	0.17	19.22	Yes	96	14.913	14.913	14.913	14.913	14.913
Yes Data	FL ge 0	All	Diesel	8.9596	13.947	Yes	0.0466	7.634	Yes	1/(FL^e)	0.55	58.29	Yes	49	13.129	10.434	9.144	9.025	9.006
Yes Data	FL ge 0	All	Gas Oil	8.5884	13.755	Yes	0.1679	20.753	Yes	1/(FL^e)	0.79	430.69	Yes	114	23.604	13.897	9.252	8.823	8.756
Yes Data	FL ge 0	All	Hvy FO	12.5316	11.263	Yes	-0.0974	-0.611	No	1/(FL^e)	0.02	0.37	No	22	12.532	12.532	12.532	12.532	12.532
Yes Data	FL ge 0	All	Int FO	16.4739	8.921	Yes	-0.2364	-1.546	No	1/(FL^e)	0.23	2.39	No	10	16.474	16.474	16.474	16.474	16.474
Yes Data	FL ge 0	All	Light FO	8.8753	23.720	Yes	0.1754	13.124	Yes	1/(FL^e)	0.65	172.25	Yes	96	24.562	14.421	9.569	9.120	9.051
Yes Data	FL ge 0	Not Ind.	Diesel	18.6862	11.938	Yes	-14.8995	-4.426	No	FL	0.45	19.59	Yes	26	18.686	18.686	18.686	18.686	18.686
Yes Data	FL ge 0	2 Stroke	Diesel	5.7116	39.867	Yes	0.8915	3.117	No	FL	0.58	9.72	No	9	5.712	5.712	5.712	5.712	5.712
Yes Data	FL ge 0	2 Stroke	Gas Oil	9.3553	3.353	No	-3.7954	-0.572	No	FL	0.14	0.33	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	10.7749	4.684	Yes	2.3879	0.616	No	FL	0.02	0.38	No	22	10.775	10.775	10.775	10.775	10.775
Yes Data	FL ge 0	2 Stroke	Int FO	14.3115	3.934	Yes	0.8539	0.128	No	FL	0.00	0.02	No	10	14.311	14.311	14.311	14.311	14.311
Yes Data	FL ge 0	4 Stroke	Diesel	10.3081	4.813	Yes	-2.9725	-1.180	No	FL	0.10	1.39	No	14	10.308	10.308	10.308	10.308	10.308
Yes Data	FL ge 0	4 Stroke	Gas Oil	21.2210	9.822	Yes	-19.4814	-4.720	No	FL	0.17	22.28	Yes	110	21.221	21.221	21.221	21.221	21.221
Yes Data	FL ge 0	4 Stroke	Light FO	14.9135	14.592	Yes	-7.4032	-4.384	No	FL	0.17	19.22	Yes	96	14.913	14.913	14.913	14.913	14.913
Yes Data	FL ge 0	Not Ind.	Diesel	10.8992	17.308	Yes	0.0461	10.252	Yes	1/(FL^e)	0.81	105.10	Yes	26	15.022	12.357	11.081	10.964	10.945
Yes Data	FL ge 0	2 Stroke	Diesel	6.2249	74.161	Yes	-0.0058	-4.130	No	1/(FL^e)	0.71	17.06	Yes	9	6.225	6.225	6.225	6.225	6.225
Yes Data	FL ge 0	2 Stroke	Gas Oil	6.3121	6.932	No	0.0575	3.339	No	1/(FL^e)	0.85	11.15	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	12.5316	11.263	Yes	-0.0974	-0.611	No	1/(FL^e)	0.02	0.37	No	22	12.532	12.532	12.532	12.532	12.532
Yes Data	FL ge 0	2 Stroke	Int FO	16.4739	8.921	Yes	-0.2364	-1.546	No	1/(FL^e)	0.23	2.39	No	10	16.474	16.474	16.474	16.474	16.474
Yes Data	FL ge 0	4 Stroke	Diesel	8.4415	3.834	Yes	-0.0495	-0.096	No	1/(FL^e)	0.00	0.01	No	14	8.441	8.441	8.441	8.441	8.441
Yes Data	FL ge 0	4 Stroke	Gas Oil	8.7582	13.922	Yes	0.1695	20.995	Yes	1/(FL^e)	0.80	440.78	Yes	110	23.917	14.118	9.428	8.995	8.928
Yes Data	FL ge 0	4 Stroke	Light FO	8.8753	23.720	Yes	0.1754	13.124	Yes	1/(FL^e)	0.65	172.25	Yes	96	24.562	14.421	9.569	9.120	9.051

REGRESSION SUMMARY FOR: NOx   Exponent = 1.5

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load …				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	21.9867	19.658	Yes	-16.4451	-7.862	No	FL	0.15	61.81	Yes	356	21.987	21.987	21.987	21.987	21.987
All Data	FL ge 0	All	All	11.4817	18.481	Yes	0.1219	14.647	Yes	1/(FL^e)	0.38	214.54	Yes	356	22.381	15.335	11.963	11.652	11.604
All Data	FL ge 20	All	All	11.8301	22.772	Yes	-1.9694	-2.449	No	FL	0.02	6.00	No	241	11.830	11.830	11.830	11.830	11.830
All Data	FL lt 20	All	All	39.5753	11.209	Yes	-174.5233	-5.124	No	FL	0.19	26.25	Yes	115	39.575	39.575	39.575	39.575	39.575
All Data	FL lt 20	All	All	15.5683	7.215	Yes	0.1031	6.270	Yes	1/(FL^e)	0.26	39.31	Yes	115	24.787	18.828	15.976	15.712	15.671
Yes Data	FL ge 0	All	All	18.6084	17.580	Yes	-11.8876	-6.407	No	FL	0.12	41.06	Yes	291	18.608	18.608	18.608	18.608	18.608
Yes Data	FL ge 0	All	All	10.4496	24.154	Yes	0.1255	19.391	Yes	1/(FL^e)	0.57	376.02	Yes	291	21.678	14.419	10.946	10.625	10.575
Yes Data	FL ge 20	All	All	11.4004	21.257	Yes	-1.8011	-2.207	No	FL	0.02	4.87	No	217	11.400	11.400	11.400	11.400	11.400
Yes Data	FL lt 20	All	All	37.2814	8.753	Yes	-158.5718	-4.358	No	FL	0.21	18.99	Yes	74	37.281	37.281	37.281	37.281	37.281
Yes Data	FL lt 20	All	All	12.5690	7.186	Yes	0.1174	8.884	Yes	1/(FL^e)	0.52	78.93	Yes	74	23.071	16.282	13.033	12.733	12.686
Yes Data	FL ge 0	Not Ind.	All	20.5149	11.938	Yes	-16.3577	-4.426	No	FL	0.45	19.59	Yes	26	20.515	20.515	20.515	20.515	20.515
Yes Data	FL ge 0	2 Stroke	All	10.4352	6.425	Yes	3.6475	1.239	No	FL	0.03	1.54	No	45	10.435	10.435	10.435	10.435	10.435
Yes Data	FL ge 0	4 Stroke	All	19.4732	14.654	Yes	-13.4724	-5.936	No	FL	0.14	35.23	Yes	220	19.473	19.473	19.473	19.473	19.473
Yes Data	FL ge 0	Not Ind.	All	11.9658	17.308	Yes	0.0506	10.252	Yes	1/(FL^e)	0.81	105.10	Yes	26	16.492	13.566	12.166	12.037	12.016
Yes Data	FL ge 0	2 Stroke	All	12.6504	15.198	Yes	-0.0363	-1.394	No	1/(FL^e)	0.04	1.94	No	45	12.650	12.650	12.650	12.650	12.650
Yes Data	FL ge 0	4 Stroke	All	9.6193	24.437	Yes	0.1868	27.588	Yes	1/(FL^e)	0.78	761.12	Yes	220	26.327	15.526	10.358	9.880	9.806
Yes Data	FL ge 0	All	Diesel	15.2353	11.302	Yes	-7.9452	-3.572	No	FL	0.21	12.76	Yes	49	15.235	15.235	15.235	15.235	15.235
Yes Data	FL ge 0	All	Gas Oil	22.7124	9.899	Yes	-20.6235	-4.675	No	FL	0.16	21.86	Yes	114	22.712	22.712	22.712	22.712	22.712
Yes Data	FL ge 0	All	Hvy FO	11.8293	4.684	Yes	2.6216	0.616	No	FL	0.02	0.38	No	22	11.829	11.829	11.829	11.829	11.829
Yes Data	FL ge 0	All	Int FO	15.7119	3.934	Yes	0.9377	0.128	No	FL	0.00	0.02	No	10	15.712	15.712	15.712	15.712	15.712
Yes Data	FL ge 0	All	Light FO	16.3730	14.592	Yes	-8.1277	-4.384	No	FL	0.17	19.22	Yes	96	16.373	16.373	16.373	16.373	16.373
Yes Data	FL ge 0	All	Diesel	9.8363	13.947	Yes	0.0512	7.634	Yes	1/(FL^e)	0.55	58.28	Yes	49	14.413	11.454	10.039	9.908	9.887
Yes Data	FL ge 0	All	Gas Oil	9.4289	13.755	Yes	0.1843	20.753	Yes	1/(FL^e)	0.79	430.69	Yes	114	25.913	15.257	10.157	9.686	9.613
Yes Data	FL ge 0	All	Hvy FO	13.7580	11.263	Yes	-0.1069	-0.611	No	1/(FL^e)	0.02	0.37	No	22	13.758	13.758	13.758	13.758	13.758
Yes Data	FL ge 0	All	Int FO	18.0862	8.921	Yes	-0.2595	-1.546	No	1/(FL^e)	0.23	2.39	No	10	18.086	18.086	18.086	18.086	18.086
Yes Data	FL ge 0	All	Light FO	9.7439	23.720	Yes	0.1925	13.124	Yes	1/(FL^e)	0.65	172.24	Yes	96	26.966	15.833	10.505	10.013	9.936
Yes Data	FL ge 0	Not Ind.	Diesel	20.5149	11.938	Yes	-16.3577	-4.426	No	FL	0.45	19.59	Yes	26	20.515	20.515	20.515	20.515	20.515
Yes Data	FL ge 0	2 Stroke	Diesel	6.2705	39.887	Yes	0.9784	3.118	No	FL	0.58	9.72	No	9	6.270	6.270	6.270	6.270	6.270
Yes Data	FL ge 0	2 Stroke	Gas Oil	10.2705	3.354	No	-4.1654	-0.572	No	FL	0.14	0.33	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	11.8293	4.684	Yes	2.6216	0.616	No	FL	0.02	0.38	No	22	11.829	11.829	11.829	11.829	11.829
Yes Data	FL ge 0	2 Stroke	Int FO	15.7119	3.934	Yes	0.9377	0.128	No	FL	0.00	0.02	No	10	15.712	15.712	15.712	15.712	15.712
Yes Data	FL ge 0	4 Stroke	Diesel	11.3168	4.813	Yes	-3.2635	-1.180	No	FL	0.10	1.39	No	14	11.317	11.317	11.317	11.317	11.317
Yes Data	FL ge 0	4 Stroke	Gas Oil	23.2977	9.822	Yes	-21.3880	-4.720	No	FL	0.17	22.28	Yes	110	23.298	23.298	23.298	23.298	23.298
Yes Data	FL ge 0	4 Stroke	Light FO	16.3730	14.592	Yes	-8.1277	-4.384	No	FL	0.17	19.22	Yes	96	16.373	16.373	16.373	16.373	16.373
Yes Data	FL ge 0	Not Ind.	Diesel	11.9658	17.308	Yes	0.0506	10.252	Yes	1/(FL^e)	0.81	105.10	Yes	26	16.492	13.566	12.166	12.037	12.016
Yes Data	FL ge 0	2 Stroke	Diesel	6.8337	74.147	Yes	-0.0064	-4.127	No	1/(FL^e)	0.71	17.03	Yes	9	6.834	6.834	6.834	6.834	6.834
Yes Data	FL ge 0	2 Stroke	Gas Oil	6.9302	6.932	No	0.0631	3.339	No	1/(FL^e)	0.85	11.15	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	13.7580	11.263	Yes	-0.1069	-0.611	No	1/(FL^e)	0.02	0.37	No	22	13.758	13.758	13.758	13.758	13.758
Yes Data	FL ge 0	2 Stroke	Int FO	18.0862	8.921	Yes	-0.2595	-1.546	No	1/(FL^e)	0.23	2.39	No	10	18.086	18.086	18.086	18.086	18.086
Yes Data	FL ge 0	4 Stroke	Diesel	9.2673	3.834	Yes	-0.0543	-0.096	No	1/(FL^e)	0.00	0.01	No	14	9.267	9.267	9.267	9.267	9.267
Yes Data	FL ge 0	4 Stroke	Gas Oil	9.6153	13.922	Yes	0.1861	20.995	Yes	1/(FL^e)	0.80	440.78	Yes	110	26.257	15.499	10.351	9.875	9.801
Yes Data	FL ge 0	4 Stroke	Light FO	9.7439	23.720	Yes	0.1925	13.124	Yes	1/(FL^e)	0.65	172.24	Yes	96	26.966	15.833	10.505	10.013	9.936

REGRESSION SUMMARY FOR: NO2 Equivalent NOx Exponent = 1.5

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load …				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	32.6651	19.659	Yes	-24.4322	-7.862	No	FL	0.15	61.81	Yes	356	32.665	32.665	32.665	32.665	32.665
All Data	FL ge 0	All	All	17.0581	18.481	Yes	0.1810	14.647	Yes	1/(FL^e)	0.38	214.54	Yes	356	33.250	22.783	17.774	17.311	17.239
All Data	FL ge 20	All	All	17.5759	22.772	Yes	-2.9262	-2.449	No	FL	0.02	6.00	No	241	17.576	17.576	17.576	17.576	17.576
All Data	FL lt 20	All	All	58.7960	11.209	Yes	-259.2844	-5.124	No	FL	0.19	26.25	Yes	115	58.796	58.796	58.796	58.796	58.796
All Data	FL lt 20	All	All	23.1294	7.215	Yes	0.1531	6.270	Yes	1/(FL^e)	0.26	39.31	Yes	115	36.825	27.972	23.735	23.343	23.283
Yes Data	FL ge 0	All	All	27.6461	17.580	Yes	-17.6612	-6.408	No	FL	0.12	41.06	Yes	291	27.646	27.646	27.646	27.646	27.646
Yes Data	FL ge 0	All	All	15.5247	24.154	Yes	0.1865	19.391	Yes	1/(FL^e)	0.57	376.02	Yes	291	32.207	21.423	16.262	15.785	15.711
Yes Data	FL ge 20	All	All	16.9374	21.257	Yes	-2.6760	-2.207	No	FL	0.02	4.87	No	217	16.937	16.937	16.937	16.937	16.937
Yes Data	FL lt 20	All	All	55.3881	8.753	Yes	-235.5868	-4.358	No	FL	0.21	18.99	Yes	74	55.388	55.388	55.388	55.388	55.388
Yes Data	FL lt 20	All	All	18.6734	7.186	Yes	0.1744	8.884	Yes	1/(FL^e)	0.52	78.93	Yes	74	34.277	24.190	19.363	18.917	18.848
Yes Data	FL ge 0	Not Ind.	All	30.4786	11.938	Yes	-24.3023	-4.426	No	FL	0.45	19.59	Yes	26	30.479	30.479	30.479	30.479	30.479
Yes Data	FL ge 0	2 Stroke	All	15.5034	6.425	Yes	5.4192	1.239	No	FL	0.03	1.54	No	45	15.503	15.503	15.503	15.503	15.503
Yes Data	FL ge 0	4 Stroke	All	28.9309	14.654	Yes	-20.0158	-5.936	No	FL	0.14	35.23	Yes	220	28.931	28.931	28.931	28.931	28.931
Yes Data	FL ge 0	Not Ind.	All	17.7773	17.308	Yes	0.0752	10.252	Yes	1/(FL^e)	0.81	105.10	Yes	26	24.502	20.155	18.074	17.882	17.852
Yes Data	FL ge 0	2 Stroke	All	18.7945	15.199	Yes	-0.0539	-1.394	No	1/(FL^e)	0.04	1.94	No	45	18.794	18.794	18.794	18.794	18.794
Yes Data	FL ge 0	4 Stroke	All	14.2911	24.437	Yes	0.2775	27.588	Yes	1/(FL^e)	0.78	761.12	Yes	220	39.113	23.067	15.388	14.679	14.569
Yes Data	FL ge 0	All	Diesel	22.6347	11.302	Yes	-11.8040	-3.572	No	FL	0.21	12.76	Yes	49	22.635	22.635	22.635	22.635	22.635
Yes Data	FL ge 0	All	Gas Oil	33.7434	9.899	Yes	-30.6400	-4.675	No	FL	0.16	21.86	Yes	114	33.743	33.743	33.743	33.743	33.743
Yes Data	FL ge 0	All	Hvy FO	17.5747	4.684	Yes	3.8949	0.616	No	FL	0.02	0.38	No	22	17.575	17.575	17.575	17.575	17.575
Yes Data	FL ge 0	All	Int FO	23.3426	3.934	Yes	1.3935	0.128	No	FL	0.00	0.02	No	10	23.343	23.343	23.343	23.343	23.343
Yes Data	FL ge 0	All	Light FO	24.3249	14.592	Yes	-12.0752	-4.384	No	FL	0.17	19.22	Yes	96	24.325	24.325	24.325	24.325	24.325
Yes Data	FL ge 0	All	Diesel	14.6136	13.947	Yes	0.0760	7.634	Yes	1/(FL^e)	0.55	58.28	Yes	49	21.414	17.018	14.914	14.720	14.690
Yes Data	FL ge 0	All	Gas Oil	14.0083	13.755	Yes	0.2738	20.753	Yes	1/(FL^e)	0.79	430.69	Yes	114	38.499	22.667	15.091	14.391	14.282
Yes Data	FL ge 0	All	Hvy FO	20.4401	11.263	Yes	-0.1589	-0.611	No	1/(FL^e)	0.02	0.37	No	22	20.440	20.440	20.440	20.440	20.440
Yes Data	FL ge 0	All	Int FO	26.8702	8.922	Yes	-0.3856	-1.546	No	1/(FL^e)	0.23	2.39	No	10	26.870	26.870	26.870	26.870	26.870
Yes Data	FL ge 0	All	Light FO	14.4763	23.720	Yes	0.2861	13.124	Yes	1/(FL^e)	0.65	172.24	Yes	96	40.062	23.522	15.607	14.876	14.762
Yes Data	FL ge 0	Not Ind.	Diesel	30.4786	11.938	Yes	-24.3023	-4.426	No	FL	0.45	19.59	Yes	26	30.479	30.479	30.479	30.479	30.479
Yes Data	FL ge 0	2 Stroke	Diesel	9.3158	39.863	Yes	1.4542	3.117	No	FL	0.58	9.72	No	9	9.316	9.316	9.316	9.316	9.316
Yes Data	FL ge 0	2 Stroke	Gas Oil	15.2591	3.353	No	-6.1893	-0.572	No	FL	0.14	0.33	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	17.5747	4.684	Yes	3.8949	0.616	No	FL	0.02	0.38	No	22	17.575	17.575	17.575	17.575	17.575
Yes Data	FL ge 0	2 Stroke	Int FO	23.3426	3.934	Yes	1.3935	0.128	No	FL	0.00	0.02	No	10	23.343	23.343	23.343	23.343	23.343
Yes Data	FL ge 0	4 Stroke	Diesel	16.8134	4.813	Yes	-4.8488	-1.180	No	FL	0.10	1.39	No	14	16.813	16.813	16.813	16.813	16.813
Yes Data	FL ge 0	4 Stroke	Gas Oil	34.6129	9.822	Yes	-31.7759	-4.720	No	FL	0.17	22.28	Yes	110	34.613	34.613	34.613	34.613	34.613
Yes Data	FL ge 0	4 Stroke	Light FO	24.3249	14.592	Yes	-12.0752	-4.384	No	FL	0.17	19.22	Yes	96	24.325	24.325	24.325	24.325	24.325
Yes Data	FL ge 0	Not Ind.	Diesel	17.7773	17.308	Yes	0.0752	10.252	Yes	1/(FL^e)	0.81	105.10	Yes	26	24.502	20.155	18.074	17.882	17.852
Yes Data	FL ge 0	2 Stroke	Diesel	10.1530	74.148	Yes	-0.0094	-4.129	No	1/(FL^e)	0.71	17.05	Yes	9	10.153	10.153	10.153	10.153	10.153
Yes Data	FL ge 0	2 Stroke	Gas Oil	10.2959	6.932	No	0.0937	3.339	No	1/(FL^e)	0.85	11.15	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	20.4401	11.263	Yes	-0.1589	-0.611	No	1/(FL^e)	0.02	0.37	No	22	20.440	20.440	20.440	20.440	20.440
Yes Data	FL ge 0	2 Stroke	Int FO	26.8702	8.922	Yes	-0.3856	-1.546	No	1/(FL^e)	0.23	2.39	No	10	26.870	26.870	26.870	26.870	26.870
Yes Data	FL ge 0	4 Stroke	Diesel	13.7683	3.834	Yes	-0.0807	-0.096	No	1/(FL^e)	0.00	0.01	No	14	13.768	13.768	13.768	13.768	13.768
Yes Data	FL ge 0	4 Stroke	Gas Oil	14.2852	13.922	Yes	0.2764	20.995	Yes	1/(FL^e)	0.80	440.78	Yes	110	39.010	23.027	15.378	14.672	14.562
Yes Data	FL ge 0	4 Stroke	Light FO	14.4763	23.720	Yes	0.2861	13.124	Yes	1/(FL^e)	0.65	172.24	Yes	96	40.062	23.522	15.607	14.876	14.762

REGRESSION SUMMARY FOR: CO   Exponent = 1

<div style="margin-left:-30px;">A-6</div>

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load …				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	17.9327	11.404	Yes	-23.1061	-7.856	No	FL	0.15	61.72	Yes	356	17.933	17.933	17.933	17.933	17.933
All Data	FL ge 0	All	All	-0.7044	-0.757	No	1.2802	16.633	Yes	1/(FL^e)	0.44	276.67	Yes	356	25.603	12.802	3.200	1.600	1.280
All Data	FL ge 20	All	All	2.8330	12.807	Yes	-1.4384	-4.200	No	FL	0.07	17.64	Yes	241	2.833	2.833	2.833	2.833	2.833
All Data	FL lt 20	All	All	47.6066	9.888	Yes	-299.4701	-6.447	No	FL	0.27	41.57	Yes	115	47.607	47.607	47.607	47.607	47.607
All Data	FL lt 20	All	All	-0.8009	-0.203	No	1.2891	6.867	Yes	1/(FL^e)	0.29	47.15	Yes	115	25.782	12.891	3.223	1.611	1.289
Yes Data	FL ge 0	All	All	9.9821	9.983	Yes	-11.4844	-6.553	No	FL	0.13	42.94	Yes	291	9.982	9.982	9.982	9.982	9.982
Yes Data	FL ge 0	All	All	0.1548	0.323	No	0.8378	17.700	Yes	1/(FL^e)	0.52	313.29	Yes	291	16.756	8.378	2.094	1.047	0.838
Yes Data	FL ge 20	All	All	2.7465	12.135	Yes	-1.3058	-3.791	No	FL	0.06	14.38	Yes	217	2.746	2.746	2.746	2.746	2.746
Yes Data	FL lt 20	All	All	30.8036	7.784	Yes	-179.5074	-5.309	No	FL	0.28	28.19	Yes	74	30.804	30.804	30.804	30.804	30.804
Yes Data	FL lt 20	All	All	-0.5190	-0.218	No	0.8653	7.175	Yes	1/(FL^e)	0.42	51.48	Yes	74	17.306	8.653	2.163	1.082	0.865
Yes Data	FL ge 0	Not Ind.	All	7.1043	4.138	Yes	-7.1069	-1.925	No	FL	0.13	3.71	No	26	7.104	7.104	7.104	7.104	7.104
Yes Data	FL ge 0	2 Stroke	All	10.0714	2.787	Yes	-12.2131	-1.865	No	FL	0.07	3.48	No	45	10.071	10.071	10.071	10.071	10.071
Yes Data	FL ge 0	4 Stroke	All	10.4487	9.169	Yes	-12.0126	-6.172	No	FL	0.15	38.09	Yes	220	10.449	10.449	10.449	10.449	10.449
Yes Data	FL ge 0	Not Ind.	All	1.2052	2.717	No	0.3414	14.485	Yes	1/(FL^e)	0.90	209.81	Yes	26	6.828	3.414	0.853	0.427	0.341
Yes Data	FL ge 0	2 Stroke	All	-0.0311	-0.016	No	1.0290	3.637	Yes	1/(FL^e)	0.24	13.23	Yes	45	20.580	10.290	2.572	1.286	1.029
Yes Data	FL ge 0	4 Stroke	All	-0.8389	-1.956	No	1.1081	23.705	Yes	1/(FL^e)	0.72	561.94	Yes	220	22.161	11.081	2.770	1.385	1.108
Yes Data	FL ge 0	All	Diesel	4.9827	5.218	Yes	-3.4791	-2.208	No	FL	0.09	4.88	No	49	4.983	4.983	4.983	4.983	4.983
Yes Data	FL ge 0	All	Gas Oil	12.3421	5.885	Yes	-16.0776	-3.988	No	FL	0.12	15.90	Yes	114	12.342	12.342	12.342	12.342	12.342
Yes Data	FL ge 0	All	Hvy FO	2.2926	1.739	No	0.7222	0.325	No	FL	0.01	0.11	No	22					
Yes Data	FL ge 0	All	Int FO	-0.0250	-0.338	No	1.6230	11.935	Yes	FL	0.95	142.44	Yes	10	0.081	0.162	0.649	1.298	1.623
Yes Data	FL ge 0	All	Light FO	12.9905	8.795	Yes	-15.6928	-6.429	No	FL	0.31	41.34	Yes	96	12.991	12.991	12.991	12.991	12.991
Yes Data	FL ge 0	All	Diesel	1.1761	3.294	Yes	0.3111	12.743	Yes	1/(FL^e)	0.78	162.38	Yes	49	7.398	4.287	1.954	1.565	1.487
Yes Data	FL ge 0	All	Gas Oil	-1.5152	-1.755	No	1.1578	15.205	Yes	1/(FL^e)	0.67	231.19	Yes	114	23.156	11.578	2.894	1.447	1.158
Yes Data	FL ge 0	All	Hvy FO	3.1895	3.905	Yes	-0.2032	-0.755	No	1/(FL^e)	0.03	0.57	No	22	3.189	3.189	3.189	3.189	3.189
Yes Data	FL ge 0	All	Int FO	1.1732	9.474	Yes	-0.1249	-4.351	No	1/(FL^e)	0.70	18.93	Yes	10	1.173	1.173	1.173	1.173	1.173
Yes Data	FL ge 0	All	Light FO	-0.6867	-1.058	No	1.3344	13.786	Yes	1/(FL^e)	0.67	190.05	Yes	96	26.687	13.344	3.336	1.668	1.334
Yes Data	FL ge 0	Not Ind.	Diesel	7.1043	4.138	Yes	-7.1069	-1.925	No	FL	0.13	3.71	No	26	7.104	7.104	7.104	7.104	7.104
Yes Data	FL ge 0	2 Stroke	Diesel	1.6026	3.847	Yes	-0.8657	-1.041	No	FL	0.13	1.08	No	9	1.603	1.603	1.603	1.603	1.603
Yes Data	FL ge 0	2 Stroke	Gas Oil	56.3283	2.555	No	-89.1275	-1.701	No	FL	0.59	2.89	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	2.2926	1.739	No	0.7222	0.325	No	FL	0.01	0.11	No	22					
Yes Data	FL ge 0	2 Stroke	Int FO	-0.0250	-0.338	No	1.6230	11.935	Yes	FL	0.95	142.44	Yes	10	0.081	0.162	0.649	1.298	1.623
Yes Data	FL ge 0	4 Stroke	Diesel	3.6282	5.165	Yes	-1.5295	-1.851	No	FL	0.22	3.43	No	14	3.628	3.628	3.628	3.628	3.628
Yes Data	FL ge 0	4 Stroke	Gas Oil	10.3567	5.510	Yes	-13.1566	-3.664	No	FL	0.11	13.42	Yes	110	10.357	10.357	10.357	10.357	10.357
Yes Data	FL ge 0	4 Stroke	Light FO	12.9905	8.795	Yes	-15.6928	-6.429	No	FL	0.31	41.34	Yes	96	12.991	12.991	12.991	12.991	12.991
Yes Data	FL ge 0	Not Ind.	Diesel	1.2052	2.717	No	0.3414	14.485	Yes	1/(FL^e)	0.90	209.81	Yes	26	6.828	3.414	0.853	0.427	0.341
Yes Data	FL ge 0	2 Stroke	Diesel	0.7511	4.762	Yes	0.0725	5.278	Yes	1/(FL^e)	0.80	27.86	Yes	9	2.201	1.476	0.932	0.842	0.824
Yes Data	FL ge 0	2 Stroke	Gas Oil	-2.3730	-1.597	No	3.6561	28.520	Yes	1/(FL^e)	1.00	813.41	Yes	4	73.122	36.561	9.140	4.570	3.656
Yes Data	FL ge 0	2 Stroke	Hvy FO	3.1895	3.905	Yes	-0.2032	-0.755	No	1/(FL^e)	0.03	0.57	No	22	3.189	3.189	3.189	3.189	3.189
Yes Data	FL ge 0	2 Stroke	Int FO	1.1732	9.474	Yes	-0.1249	-4.351	No	1/(FL^e)	0.70	18.93	Yes	10	1.173	1.173	1.173	1.173	1.173
Yes Data	FL ge 0	4 Stroke	Diesel	1.7660	1.824	No	0.3854	0.954	No	1/(FL^e)	0.07	0.91	No	14					
Yes Data	FL ge 0	4 Stroke	Gas Oil	-1.7160	-2.700	No	1.0740	19.151	Yes	1/(FL^e)	0.77	366.75	Yes	110	21.480	10.740	2.685	1.343	1.074
Yes Data	FL ge 0	4 Stroke	Light FO	-0.6867	-1.058	No	1.3344	13.786	Yes	1/(FL^e)	0.67	190.05	Yes	96	26.687	13.344	3.336	1.668	1.334

REGRESSION SUMMARY FOR: CO2   Exponent = 1

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load …				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	1361.0	24.928	Yes	-911.9	-8.931	No	FL	0.18	79.76	Yes	356	1361.0	1361.0	1361.0	1361.0	1361.0
All Data	FL ge 0	All	All	653.1	20.189	Yes	46.5	17.363	Yes	1/(FL^e)	0.46	301.48	Yes	356	1582.8	1117.9	769.3	711.2	699.5
All Data	FL ge 20	All	All	807.0	64.326	Yes	-120.6	-6.210	No	FL	0.14	38.56	Yes	241	807.0	807.0	807.0	807.0	807.0
All Data	FL lt 20	All	All	2361.5	14.126	Yes	-10017.0	-6.211	No	FL	0.25	38.57	Yes	115	2361.5	2361.5	2361.5	2361.5	2361.5
All Data	FL lt 20	All	All	731.2	5.373	Yes	43.8	6.749	Yes	1/(FL^e)	0.29	45.55	Yes	115	1606.9	1169.0	840.6	785.9	775.0
Yes Data	FL ge 0	All	All	1186.3	26.161	Yes	-647.5	-8.148	No	FL	0.19	66.38	Yes	291	1186.3	1186.3	1186.3	1186.3	1186.3
Yes Data	FL ge 0	All	All	648.6	33.957	Yes	44.1	23.374	Yes	1/(FL^e)	0.65	546.34	Yes	291	1530.3	1089.4	758.8	703.7	692.7
Yes Data	FL ge 20	All	All	819.5	66.563	Yes	-132.5	-7.072	No	FL	0.19	50.02	Yes	217	819.5	819.5	819.5	819.5	819.5
Yes Data	FL lt 20	All	All	2207.6	12.978	Yes	8823.5	-6.072	No	FL	0.34	36.86	Yes	74	2207.6	2207.6	2207.6	2207.6	2207.6
Yes Data	FL lt 20	All	All	639.4	6.831	Yes	44.5	9.365	Yes	1/(FL^e)	0.55	87.71	Yes	74	1529.4	1084.4	750.7	695.0	683.9
Yes Data	FL ge 0	Not Ind.	All	1228.3	11.111	Yes	-684.5	-2.879	No	FL	0.26	8.29	Yes	26	1228.3	1228.3	1228.3	1228.3	1228.3
Yes Data	FL ge 0	2 Stroke	All	1045.2	8.284	Yes	-479.9	-2.099	No	FL	0.09	4.40	No	45	1045.2	1045.2	1045.2	1045.2	1045.2
Yes Data	FL ge 0	4 Stroke	All	1202.2	22.388	Yes	-662.2	-7.220	No	FL	0.19	52.13	Yes	220	1202.2	1202.2	1202.2	1202.2	1202.2
Yes Data	FL ge 0	Not Ind.	All	742.8	36.310	Yes	24.5	22.528	Yes	1/(FL^e)	0.95	507.49	Yes	26	1232.4	987.6	804.0	773.4	767.2
Yes Data	FL ge 0	2 Stroke	All	667.1	9.719	Yes	35.8	3.571	Yes	1/(FL^e)	0.23	12.75	Yes	45	1382.6	1024.8	756.5	711.8	702.9
Yes Data	FL ge 0	4 Stroke	All	606.0	32.861	Yes	55.8	27.754	Yes	1/(FL^e)	0.78	770.29	Yes	220	1721.6	1163.8	745.5	675.7	661.8
Yes Data	FL ge 0	All	Diesel	1060.2	16.674	Yes	-389.8	-3.715	No	FL	0.23	13.80	Yes	49	1060.2	1060.2	1060.2	1060.2	1060.2
Yes Data	FL ge 0	All	Gas Oil	1355.3	13.847	Yes	-986.7	-5.244	No	FL	0.20	27.50	Yes	114	1355.3	1355.3	1355.3	1355.3	1355.3
Yes Data	FL ge 0	All	Hvy FO	939.8	23.391	Yes	-302.1	-4.464	No	FL	0.50	19.93	Yes	22	939.8	939.8	939.8	939.8	939.8
Yes Data	FL ge 0	All	Int FO	680.3	3.872	Yes	72.7	0.225	No	FL	0.01	0.05	No	10	680.3	680.3	680.3	680.3	680.3
Yes Data	FL ge 0	All	Light FO	1142.9	22.495	Yes	-556.0	-6.622	No	FL	0.32	43.85	Yes	96	1142.9	1142.9	1142.9	1142.9	1142.9
Yes Data	FL ge 0	All	Diesel	721.3	28.580	Yes	22.5	13.065	Yes	1/(FL^e)	0.78	170.71	Yes	49	1172.3	946.8	777.7	749.5	743.9
Yes Data	FL ge 0	All	Gas Oil	574.8	15.544	Yes	59.5	18.240	Yes	1/(FL^e)	0.75	332.68	Yes	114	1764.2	1169.5	723.5	649.1	634.3
Yes Data	FL ge 0	All	Hvy FO	670.6	31.198	Yes	41.8	5.900	Yes	1/(FL^e)	0.64	34.81	Yes	22	1506.5	1088.6	775.1	722.9	712.4
Yes Data	FL ge 0	All	Int FO	820.3	7.151	Yes	-31.8	-1.197	No	1/(FL^e)	0.15	1.43	No	10	820.3	820.3	820.3	820.3	820.3
Yes Data	FL ge 0	All	Light FO	634.8	46.184	Yes	53.0	25.879	Yes	1/(FL^e)	0.88	669.74	Yes	96	1695.4	1165.1	767.3	701.1	687.8
Yes Data	FL ge 0	Not Ind.	Diesel	1228.3	11.111	Yes	-684.5	-2.879	No	FL	0.26	8.29	Yes	26	1228.3	1228.3	1228.3	1228.3	1228.3
Yes Data	FL ge 0	2 Stroke	Diesel	733.4	73.288	Yes	-28.2	-1.413	No	FL	0.22	2.00	No	9	733.4	733.4	733.4	733.4	733.4
Yes Data	FL ge 0	2 Stroke	Gas Oil	2407.9	2.562	No	2852.9	-1.277	No	FL	0.45	1.63	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	939.8	23.391	Yes	-302.1	-4.464	No	FL	0.50	19.93	Yes	22	939.8	939.8	939.8	939.8	939.8
Yes Data	FL ge 0	2 Stroke	Int FO	680.3	3.872	Yes	72.7	0.225	No	FL	0.01	0.05	No	10	680.3	680.3	680.3	680.3	680.3
Yes Data	FL ge 0	4 Stroke	Diesel	982.6	22.744	Yes	-273.4	-5.378	No	FL	0.71	28.92	Yes	14	982.6	982.6	982.6	982.6	982.6
Yes Data	FL ge 0	4 Stroke	Gas Oil	1308.4	13.646	Yes	-915.1	-4.995	No	FL	0.19	24.95	Yes	110	1308.4	1308.4	1308.4	1308.4	1308.4
Yes Data	FL ge 0	4 Stroke	Light FO	1142.9	22.495	Yes	-556.0	-6.622	No	FL	0.32	43.85	Yes	96	1142.9	1142.9	1142.9	1142.9	1142.9
Yes Data	FL ge 0	Not Ind.	Diesel	742.8	36.310	Yes	24.5	22.528	Yes	1/(FL^e)	0.95	507.49	Yes	26	1232.4	987.6	804.0	773.4	767.2
Yes Data	FL ge 0	2 Stroke	Diesel	710.3	143.907	Yes	1.7	3.983	Yes	1/(FL^e)	0.69	15.86	Yes	9	744.5	727.4	714.5	712.4	712.0
Yes Data	FL ge 0	2 Stroke	Gas Oil	395.8	3.159	No	133.6	12.357	Yes	1/(FL^e)	0.99	152.70	Yes	4	2671.0	1335.5	333.9	166.9	133.6
Yes Data	FL ge 0	2 Stroke	Hvy FO	670.6	31.198	Yes	41.8	5.900	Yes	1/(FL^e)	0.64	34.81	Yes	22	1506.5	1088.6	775.1	722.9	712.4
Yes Data	FL ge 0	2 Stroke	Int FO	820.3	7.151	Yes	-31.8	-1.197	No	1/(FL^e)	0.15	1.43	No	10	820.3	820.3	820.3	820.3	820.3
Yes Data	FL ge 0	4 Stroke	Diesel	586.2	7.950	Yes	98.9	3.215	Yes	1/(FL^e)	0.46	10.34	Yes	14	2565.0	1575.6	833.6	709.9	685.2
Yes Data	FL ge 0	4 Stroke	Gas Oil	573.7	16.696	Yes	57.1	18.836	Yes	1/(FL^e)	0.77	354.79	Yes	110	1715.9	1144.8	716.5	645.1	630.8
Yes Data	FL ge 0	4 Stroke	Light FO	634.8	46.184	Yes	53.0	25.879	Yes	1/(FL^e)	0.88	669.74	Yes	96	1695.4	1165.1	767.3	701.1	687.8

REGRESSION SUMMARY FOR: O2   Exponent = 1.5

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load ...				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	17437.0	6.247	Yes	-22996.0	-4.405	No	FL	0.05	19.40	Yes	356	17437.0	17437.0	17437.0	17437.0	17437.0
All Data	FL ge 0	All	All	3007.9	1.720	No	161.2	6.886	Yes	1/(FL^e)	0.12	47.41	Yes	356	14421.9	5098.9	637.4	225.3	161.2
All Data	FL ge 20	All	All	2378.7	21.528	Yes	1375.3	-8.040	No	FL	0.21	64.64	Yes	241	2378.7	2378.7	2378.7	2378.7	2378.7
All Data	FL lt 20	All	All	47341.0	4.810	Yes	-302256.0	-3.183	No	FL	0.08	10.13	Yes	115	47341.0	47341.0	47341.0	47341.0	47341.0
All Data	FL lt 20	All	All	9630.8	1.513	No	130.8	2.698	No	1/(FL^e)	0.06	7.28	No	115					
Yes Data	FL ge 0	All	All	7798.3	9.080	Yes	9141.2	-6.072	No	FL	0.11	36.87	Yes	291	7798.3	7798.3	7798.3	7798.3	7798.3
Yes Data	FL ge 0	All	All	1298.1	4.101	Yes	107.9	22.769	Yes	1/(FL^e)	0.64	518.42	Yes	291	10945.2	4708.8	1724.4	1448.8	1405.9
Yes Data	FL ge 20	All	All	2130.4	22.334	Yes	1137.9	-7.839	No	FL	0.22	61.45	Yes	217	2130.4	2130.4	2130.4	2130.4	2130.4
Yes Data	FL lt 20	All	All	25276.0	7.256	Yes	-152436.0	-5.122	No	FL	0.27	26.24	Yes	74	25276.0	25276.0	25276.0	25276.0	25276.0
Yes Data	FL lt 20	All	All	2076.7	1.484	No	104.8	9.917	Yes	1/(FL^e)	0.58	98.34	Yes	74	9377.5	3315.5	414.4	146.5	104.8
Yes Data	FL ge 0	Not Ind.	All	7018.9	4.036	Yes	9675.1	-2.587	No	FL	0.22	6.69	No	26	7018.9	7018.9	7018.9	7018.9	7018.9
Yes Data	FL ge 0	2 Stroke	All	4761.9	9.196	Yes	4395.3	-4.683	No	FL	0.34	21.93	Yes	45	4761.9	4761.9	4761.9	4761.9	4761.9
Yes Data	FL ge 0	4 Stroke	All	8415.0	7.630	Yes	9864.1	-5.236	No	FL	0.11	27.42	Yes	220	8415.0	8415.0	8415.0	8415.0	8415.0
Yes Data	FL ge 0	Not Ind.	All	1038.3	5.831	Yes	47.2	37.143	Yes	1/(FL^e)	0.98	1379.57	Yes	26	5262.3	2531.7	1225.0	1104.3	1085.5
Yes Data	FL ge 0	2 Stroke	All	1999.4	9.461	Yes	51.3	7.767	Yes	1/(FL^e)	0.58	60.33	Yes	45	6591.4	3622.9	2202.3	2071.1	2050.7
Yes Data	FL ge 0	4 Stroke	All	877.2	2.897	Yes	155.1	29.779	Yes	1/(FL^e)	0.80	886.80	Yes	220	14749.4	5781.8	1490.3	1094.0	1032.3
Yes Data	FL ge 0	All	Diesel	4711.8	4.819	Yes	4607.4	-2.856	No	FL	0.15	8.16	Yes	49	4711.8	4711.8	4711.8	4711.8	4711.8
Yes Data	FL ge 0	All	Gas Oil	10081.0	5.295	Yes	-13574.0	-3.709	No	FL	0.11	13.76	Yes	114	10081.0	10081.0	10081.0	10081.0	10081.0
Yes Data	FL ge 0	All	Hvy FO	4830.9	7.861	Yes	4262.3	-4.118	No	FL	0.46	16.96	Yes	22	4830.9	4830.9	4830.9	4830.9	4830.9
Yes Data	FL ge 0	All	Int FO	4385.2	4.346	Yes	3544.2	-1.915	No	FL	0.31	3.67	No	10	4385.2	4385.2	4385.2	4385.2	4385.2
Yes Data	FL ge 0	All	Light FO	7885.8	7.613	Yes	8944.3	-5.225	No	FL	0.23	27.31	Yes	96	7885.8	7885.8	7885.8	7885.8	7885.8
Yes Data	FL ge 0	All	Diesel	968.0	9.310	Yes	47.4	48.006	Yes	1/(FL^e)	0.98	2304.57	Yes	49	5211.2	2468.2	1155.6	1034.3	1015.5
Yes Data	FL ge 0	All	Gas Oil	580.4	1.196	No	152.5	24.247	Yes	1/(FL^e)	0.84	587.90	Yes	114	13638.7	4822.0	602.7	213.1	152.5
Yes Data	FL ge 0	All	Hvy FO	1578.6	6.138	Yes	199.7	5.418	Yes	1/(FL^e)	0.59	29.36	Yes	22	19441.7	7894.2	2368.0	1857.7	1778.3
Yes Data	FL ge 0	All	Int FO	2385.1	3.481	No	38.0	0.670	No	1/(FL^e)	0.05	0.45	No	10					
Yes Data	FL ge 0	All	Light FO	1016.8	2.438	No	177.4	11.914	Yes	1/(FL^e)	0.60	141.94	Yes	96	15869.4	5610.7	701.3	248.0	177.4
Yes Data	FL ge 0	Not Ind.	Diesel	7018.9	4.036	Yes	9675.1	-2.587	No	FL	0.22	6.69	No	26	7018.9	7018.9	7018.9	7018.9	7018.9
Yes Data	FL ge 0	2 Stroke	Diesel	4082.7	3.220	No	4183.2	-1.653	No	FL	0.28	2.73	No	9					
Yes Data	FL ge 0	2 Stroke	Gas Oil	6724.9	2.253	No	8951.3	-1.262	No	FL	0.44	1.59	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	4830.9	7.861	Yes	4262.3	-4.118	No	FL	0.46	16.96	Yes	22	4830.9	4830.9	4830.9	4830.9	4830.9
Yes Data	FL ge 0	2 Stroke	Int FO	4385.2	4.346	Yes	3544.2	-1.915	No	FL	0.31	3.67	No	10	4385.2	4385.2	4385.2	4385.2	4385.2
Yes Data	FL ge 0	4 Stroke	Diesel	1329.9	4.721	Yes	-579.7	-1.749	No	FL	0.20	3.06	No	14	1329.9	1329.9	1329.9	1329.9	1329.9
Yes Data	FL ge 0	4 Stroke	Gas Oil	10238.0	5.173	Yes	-13783.0	-3.645	No	FL	0.11	13.29	Yes	110	10238.0	10238.0	10238.0	10238.0	10238.0
Yes Data	FL ge 0	4 Stroke	Light FO	7885.8	7.613	Yes	8944.3	-5.225	No	FL	0.23	27.31	Yes	96	7885.8	7885.8	7885.8	7885.8	7885.8
Yes Data	FL ge 0	Not Ind.	Diesel	1038.3	5.831	Yes	47.2	37.143	Yes	1/(FL^e)	0.98	1379.57	Yes	26	5262.3	2531.7	1225.0	1104.3	1085.5
Yes Data	FL ge 0	2 Stroke	Diesel	1132.5	41.841	Yes	46.4	102.674	Yes	1/(FL^e)	1.00	10542.03	Yes	9	5283.6	2600.2	1316.0	1197.4	1179.0
Yes Data	FL ge 0	2 Stroke	Gas Oil	1194.0	10.283	Yes	82.9	37.767	Yes	1/(FL^e)	1.00	1426.33	Yes	4	8608.3	3815.4	1521.7	1309.9	1276.9
Yes Data	FL ge 0	2 Stroke	Hvy FO	1578.6	6.138	Yes	199.7	5.418	Yes	1/(FL^e)	0.59	29.36	Yes	22	19441.7	7894.2	2368.0	1857.7	1778.3
Yes Data	FL ge 0	2 Stroke	Int FO	2385.1	3.481	No	38.0	0.670	No	1/(FL^e)	0.05	0.45	No	10					
Yes Data	FL ge 0	4 Stroke	Diesel	312.8	1.501	No	182.5	3.752	Yes	1/(FL^e)	0.54	14.08	Yes	14	16320.5	5770.2	721.3	255.0	182.5
Yes Data	FL ge 0	4 Stroke	Gas Oil	615.3	1.236	No	153.4	24.010	Yes	1/(FL^e)	0.84	576.47	Yes	110	13720.3	4850.9	606.4	214.4	153.4
Yes Data	FL ge 0	4 Stroke	Light FO	1016.8	2.438	No	177.4	11.914	Yes	1/(FL^e)	0.60	141.94	Yes	96	15869.4	5610.7	701.3	248.0	177.4

REGRESSION SUMMARY FOR:　　　HC　　　　　　　　　　　　　Exponent = 1.5

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load …				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	8.3003	8.497	Yes	-10.9026	-6.050	No	FL	0.10	36.60	Yes	321	8.300	8.300	8.300	8.300	8.300
All Data	FL ge 0	All	All	1.1654	2.036	No	0.0810	11.057	Yes	1/(FL^e)	0.28	122.26	Yes	321	7.249	2.563	0.320	0.113	0.081
All Data	FL ge 20	All	All	0.9744	12.004	Yes	-0.5558	-4.478	No	FL	0.09	20.06	Yes	218	0.974	0.974	0.974	0.974	0.974
All Data	FL lt 20	All	All	22.1000	6.861	Yes	-141.1223	-4.437	No	FL	0.16	19.69	Yes	103	22.100	22.100	22.100	22.100	22.100
All Data	FL lt 20	All	All	3.8756	1.846	No	0.0691	4.530	Yes	1/(FL^e)	0.17	20.52	Yes	103	6.178	2.184	0.273	0.097	0.069
Yes Data	FL ge 0	All	All	4.1802	6.502	Yes	-5.0538	-4.513	No	FL	0.07	20.37	Yes	271	4.180	4.180	4.180	4.180	4.180
Yes Data	FL ge 0	All	All	0.3859	1.429	No	0.0667	17.064	Yes	1/(FL^e)	0.52	291.17	Yes	271	5.970	2.111	0.264	0.093	0.067
Yes Data	FL ge 20	All	All	0.8851	11.272	Yes	-0.4455	-3.762	No	FL	0.07	14.16	Yes	201	0.885	0.885	0.885	0.885	0.885
Yes Data	FL lt 20	All	All	14.0632	5.101	Yes	-86.3093	-3.656	No	FL	0.16	13.37	Yes	70	14.063	14.063	14.063	14.063	14.063
Yes Data	FL lt 20	All	All	0.3131	0.265	No	0.0670	7.710	Yes	1/(FL^e)	0.47	59.45	Yes	70	5.995	2.120	0.265	0.094	0.067
Yes Data	FL ge 0	Not Ind.	All	1.7494	3.541	Yes	-2.6120	-2.321	No	FL	0.21	5.39	No	22	1.749	1.749	1.749	1.749	1.749
Yes Data	FL ge 0	2 Stroke	All	0.7667	3.957	Yes	-0.3210	-0.904	No	FL	0.02	0.82	No	43	0.767	0.767	0.767	0.767	0.767
Yes Data	FL ge 0	4 Stroke	All	5.1403	6.175	Yes	-6.1653	-4.388	No	FL	0.09	19.25	Yes	206	5.140	5.140	5.140	5.140	5.140
Yes Data	FL ge 0	Not Ind.	All	0.1789	1.807	No	0.0113	17.361	Yes	1/(FL^e)	0.94	301.40	Yes	22	1.010	0.357	0.045	0.016	0.011
Yes Data	FL ge 0	2 Stroke	All	0.5473	5.503	Yes	0.0052	1.705	No	1/(FL^e)	0.07	2.91	No	43	0.547	0.547	0.547	0.547	0.547
Yes Data	FL ge 0	4 Stroke	All	0.1150	0.543	No	0.1106	31.223	Yes	1/(FL^e)	0.83	974.85	Yes	206	9.890	3.497	0.437	0.155	0.111
Yes Data	FL ge 0	All	Diesel	0.9475	3.450	Yes	-0.9892	-2.214	No	FL	0.11	4.90	No	42	0.947	0.947	0.947	0.947	0.947
Yes Data	FL ge 0	All	Gas Oil	6.0535	4.370	Yes	-8.1345	-3.055	No	FL	0.08	9.33	Yes	114	6.054	6.054	6.054	6.054	6.054
Yes Data	FL ge 0	All	Hvy FO	1.0406	4.630	Yes	-0.7845	-2.046	No	FL	0.19	4.19	No	20	1.041	1.041	1.041	1.041	1.041
Yes Data	FL ge 0	All	Int FO	0.1605	0.575	No	1.3609	2.658	No	FL	0.47	7.06	No	10					
Yes Data	FL ge 0	All	Light FO	4.7410	6.578	Yes	-5.6510	-4.871	No	FL	0.22	23.73	Yes	85	4.741	4.741	4.741	4.741	4.741
Yes Data	FL ge 0	All	Diesel	0.0657	0.969	No	0.0110	18.455	Yes	1/(FL^e)	0.89	340.58	Yes	42	0.985	0.348	0.044	0.015	0.011
Yes Data	FL ge 0	All	Gas Oil	-0.0980	-0.301	No	0.1102	26.184	Yes	1/(FL^e)	0.86	685.59	Yes	114	9.860	3.486	0.436	0.154	0.110
Yes Data	FL ge 0	All	Hvy FO	0.5361	4.376	Yes	0.0167	0.995	No	1/(FL^e)	0.05	0.99	No	20	0.536	0.536	0.536	0.536	0.536
Yes Data	FL ge 0	All	Int FO	1.0607	6.147	Yes	-0.0325	-2.273	No	1/(FL^e)	0.39	5.17	No	10	1.061	1.061	1.061	1.061	1.061
Yes Data	FL ge 0	All	Light FO	0.4183	1.347	No	0.1051	9.612	Yes	1/(FL^e)	0.53	92.40	Yes	85	9.404	3.325	0.416	0.147	0.105
Yes Data	FL ge 0	Not Ind.	Diesel	1.7494	3.541	Yes	-2.6120	-2.321	No	FL	0.21	5.39	No	22	1.749	1.749	1.749	1.749	1.749
Yes Data	FL ge 0	2 Stroke	Diesel	0.2060	3.164	No	-0.1509	-1.162	No	FL	0.16	1.35	No	9					
Yes Data	FL ge 0	2 Stroke	Gas Oil	2.2633	2.224	No	-3.4396	-1.422	No	FL	0.50	2.02	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	1.0406	4.630	Yes	-0.7845	-2.046	No	FL	0.19	4.19	No	20	1.041	1.041	1.041	1.041	1.041
Yes Data	FL ge 0	2 Stroke	Int FO	0.1605	0.575	No	1.3609	2.658	No	FL	0.47	7.06	No	10					
Yes Data	FL ge 0	4 Stroke	Diesel	0.0218	2.350	No	0.0059	0.589	No	FL	0.04	0.35	No	11					
Yes Data	FL ge 0	4 Stroke	Gas Oil	6.2336	4.330	Yes	-8.3627	-3.041	No	FL	0.08	9.25	Yes	110	6.234	6.234	6.234	6.234	6.234
Yes Data	FL ge 0	4 Stroke	Light FO	4.7410	6.578	Yes	-5.6510	-4.871	No	FL	0.22	23.73	Yes	85	4.741	4.741	4.741	4.741	4.741
Yes Data	FL ge 0	Not Ind.	Diesel	0.1789	1.807	No	0.0113	17.361	Yes	1/(FL^e)	0.94	301.40	Yes	22	1.010	0.357	0.045	0.016	0.011
Yes Data	FL ge 0	2 Stroke	Diesel	0.0999	3.036	No	0.0017	3.023	No	1/(FL^e)	0.57	9.14	No	9					
Yes Data	FL ge 0	2 Stroke	Gas Oil	0.2000	2.820	No	0.0299	22.278	Yes	1/(FL^e)	1.00	496.29	Yes	4	2.672	0.945	0.118	0.042	0.030
Yes Data	FL ge 0	2 Stroke	Hvy FO	0.5361	4.376	Yes	0.0167	0.995	No	1/(FL^e)	0.05	0.99	No	20	0.536	0.536	0.536	0.536	0.536
Yes Data	FL ge 0	2 Stroke	Int FO	1.0607	6.147	Yes	-0.0325	-2.273	No	1/(FL^e)	0.39	5.17	No	10	1.061	1.061	1.061	1.061	1.061
Yes Data	FL ge 0	4 Stroke	Diesel	0.0235	2.608	No	0.0009	0.370	No	1/(FL^e)	0.02	0.14	No	11					
Yes Data	FL ge 0	4 Stroke	Gas Oil	-0.0432	-0.132	No	0.1113	26.559	Yes	1/(FL^e)	0.87	705.36	Yes	110	9.956	3.520	0.440	0.156	0.111
Yes Data	FL ge 0	4 Stroke	Light FO	0.4183	1.347	No	0.1051	9.612	Yes	1/(FL^e)	0.53	92.40	Yes	85	9.404	3.325	0.416	0.147	0.105

REGRESSION SUMMARY FOR:　　　Dry Exhaust Mass　　　　　　Exponent = 1.5

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load …				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	81773	6.739	Yes	-103985	-4.582	No	FL	0.06	21.00	Yes	356	81773.0	81773.0	81773.0	81773.0	81773.0
All Data	FL ge 0	All	All	16654	2.196	No	725	7.136	Yes	1/(FL^e)	0.13	50.92	Yes	356	64821.6	22917.9	2864.7	1012.8	724.7
All Data	FL ge 20	All	All	13974	29.048	Yes	6660	-8.942	No	FL	0.25	79.96	Yes	241	13974.0	13974.0	13974.0	13974.0	13974.0
All Data	FL lt 20	All	All	215837	5.064	Yes	-1354570	-3.294	No	FL	0.09	10.85	Yes	115	215837.0	215837.0	215837.0	215837.0	215837.0
All Data	FL lt 20	All	All	46871	1.699	No	586	2.788	Yes	1/(FL^e)	0.06	7.77	Yes	115	52414.7	18531.4	2316.4	819.0	586.0
Yes Data	FL ge 0	All	All	38787	10.070	Yes	-42156	-6.244	No	FL	0.12	38.99	Yes	291	38787.0	38787.0	38787.0	38787.0	38787.0
Yes Data	FL ge 0	All	All	8982	6.390	Yes	489	23.239	Yes	1/(FL^e)	0.65	540.03	Yes	291	52701.8	24439.3	10914.2	9665.2	9470.9
Yes Data	FL ge 20	All	All	12856	30.853	Yes	5551	-8.754	No	FL	0.26	76.63	Yes	217	12856.0	12856.0	12856.0	12856.0	12856.0
Yes Data	FL lt 20	All	All	118345	7.628	Yes	-693710	-5.234	No	FL	0.28	27.39	Yes	74	118345.0	118345.0	118345.0	118345.0	118345.0
Yes Data	FL lt 20	All	All	13054	2.103	No	473	10.086	Yes	1/(FL^e)	0.59	101.73	Yes	74	42309.6	14958.7	1869.8	661.1	473.0
Yes Data	FL ge 0	Not Ind.	All	35710	4.504	Yes	-44675	-2.620	No	FL	0.22	6.86	No	26	35710.0	35710.0	35710.0	35710.0	35710.0
Yes Data	FL ge 0	2 Stroke	All	25164	9.547	Yes	-21223	-4.442	No	FL	0.31	19.73	Yes	45	25164.0	25164.0	25164.0	25164.0	25164.0
Yes Data	FL ge 0	4 Stroke	All	41490	8.401	Yes	-45285	-5.368	No	FL	0.12	28.82	Yes	220	41490.0	41490.0	41490.0	41490.0	41490.0
Yes Data	FL ge 0	Not Ind.	All	8207	10.211	Yes	216	37.625	Yes	1/(FL^e)	0.98	1415.64	Yes	26	27522.5	15036.4	9061.1	8509.3	8423.4
Yes Data	FL ge 0	2 Stroke	All	11780	10.838	Yes	252	7.401	Yes	1/(FL^e)	0.56	54.77	Yes	45	34284.1	19736.4	12774.5	12131.6	12031.6
Yes Data	FL ge 0	4 Stroke	All	7100	5.325	Yes	700	30.514	Yes	1/(FL^e)	0.81	931.13	Yes	220	69690.4	29229.0	9866.1	8078.0	7799.8
Yes Data	FL ge 0	All	Diesel	25056	5.642	Yes	-21595	-2.946	No	FL	0.16	8.68	Yes	49	25056.0	25056.0	25056.0	25056.0	25056.0
Yes Data	FL ge 0	All	Gas Oil	49392	5.783	Yes	-62686	-3.818	No	FL	0.12	14.57	Yes	114	49392.0	49392.0	49392.0	49392.0	49392.0
Yes Data	FL ge 0	All	Hvy FO	24582	9.202	Yes	-19331	-4.297	No	FL	0.48	18.47	Yes	22	24582.0	24582.0	24582.0	24582.0	24582.0
Yes Data	FL ge 0	All	Int FO	21717	4.339	Yes	-14896	-1.623	No	FL	0.25	2.63	No	10	21717.0	21717.0	21717.0	21717.0	21717.0
Yes Data	FL ge 0	All	Light FO	38883	8.479	Yes	-40817	-5.386	No	FL	0.24	29.01	Yes	96	38883.0	38883.0	38883.0	38883.0	38883.0
Yes Data	FL ge 0	All	Diesel	7715	15.764	Yes	216	46.522	Yes	1/(FL^e)	0.98	2164.33	Yes	49	27070.0	14558.1	8570.5	8017.5	7931.5
Yes Data	FL ge 0	All	Gas Oil	5900	2.745	No	688	24.725	Yes	1/(FL^e)	0.85	611.34	Yes	114	61579.4	21771.6	2721.5	962.2	688.5
Yes Data	FL ge 0	All	Hvy FO	9835	8.921	Yes	905	5.729	Yes	1/(FL^e)	0.62	32.82	Yes	22	90791.8	38457.2	13412.3	11099.5	10739.6
Yes Data	FL ge 0	All	Int FO	13652	4.138	Yes	114	0.416	No	1/(FL^e)	0.02	0.17	No	10	13652.0	13652.0	13652.0	13652.0	13652.0
Yes Data	FL ge 0	All	Light FO	7526	4.210	Yes	811	12.697	Yes	1/(FL^e)	0.63	161.23	Yes	96	80024.7	33158.1	10729.9	8658.6	8336.4
Yes Data	FL ge 0	Not Ind.	Diesel	35710	4.504	Yes	-44675	-2.620	No	FL	0.22	6.86	No	26	35710.0	35710.0	35710.0	35710.0	35710.0
Yes Data	FL ge 0	2 Stroke	Diesel	20751	3.847	Yes	-17801	-1.653	No	FL	0.28	2.73	No	9	20751.0	20751.0	20751.0	20751.0	20751.0
Yes Data	FL ge 0	2 Stroke	Gas Oil	40881	2.327	No	-52924	-1.268	No	FL	0.45	1.61	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	24582	9.202	Yes	-19331	-4.297	No	FL	0.48	18.47	Yes	22	24582.0	24582.0	24582.0	24582.0	24582.0
Yes Data	FL ge 0	2 Stroke	Int FO	21717	4.339	Yes	-14896	-1.623	No	FL	0.25	2.63	No	10	21717.0	21717.0	21717.0	21717.0	21717.0
Yes Data	FL ge 0	4 Stroke	Diesel	10269	7.703	Yes	3880	-2.474	No	FL	0.34	6.12	No	14	10269.0	10269.0	10269.0	10269.0	10269.0
Yes Data	FL ge 0	4 Stroke	Gas Oil	49800	5.609	Yes	-63187	-3.725	No	FL	0.11	13.88	Yes	110	49800.0	49800.0	49800.0	49800.0	49800.0
Yes Data	FL ge 0	4 Stroke	Light FO	38883	8.479	Yes	-40817	-5.386	No	FL	0.24	29.01	Yes	96	38883.0	38883.0	38883.0	38883.0	38883.0
Yes Data	FL ge 0	Not Ind.	Diesel	8207	10.211	Yes	216	37.625	Yes	1/(FL^e)	0.98	1415.64	Yes	26	27522.5	15036.4	9061.1	8509.3	8423.4
Yes Data	FL ge 0	2 Stroke	Diesel	8199	67.122	Yes	197	96.782	Yes	1/(FL^e)	1.00	9366.66	Yes	9	25857.0	14442.2	8979.6	8475.1	8396.6
Yes Data	FL ge 0	2 Stroke	Gas Oil	8215	13.124	Yes	489	41.328	Yes	1/(FL^e)	1.00	1707.97	Yes	4	51952.0	23678.6	10148.3	8898.7	8704.3
Yes Data	FL ge 0	2 Stroke	Hvy FO	9835	8.921	Yes	905	5.729	Yes	1/(FL^e)	0.62	32.82	Yes	22	90791.8	38457.2	13412.3	11099.5	10739.6
Yes Data	FL ge 0	2 Stroke	Int FO	13652	4.138	Yes	114	0.416	No	1/(FL^e)	0.02	0.17	No	10	13652.0	13652.0	13652.0	13652.0	13652.0
Yes Data	FL ge 0	4 Stroke	Diesel	4285	4.130	Yes	979	4.044	Yes	1/(FL^e)	0.58	16.36	Yes	14	91857.6	35246.4	8154.9	5653.0	5263.8
Yes Data	FL ge 0	4 Stroke	Gas Oil	5980	2.699	No	691	24.304	Yes	1/(FL^e)	0.85	590.69	Yes	110	61811.2	21853.6	2731.7	965.8	691.1
Yes Data	FL ge 0	4 Stroke	Light FO	7526	4.210	Yes	811	12.697	Yes	1/(FL^e)	0.63	161.23	Yes	96	80024.7	33158.1	10729.9	8658.6	8336.4

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REGRESSION SUMMARY FOR: H2O   Exponent = 1

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load … 0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	477.17	29.543	Yes	-331.90	-10.987	No	FL	0.25	120.72	Yes	356	477.17	477.17	477.17	477.17	477.17
All Data	FL ge 0	All	All	222.44	25.956	Yes	16.49	23.250	Yes	1/(FL^e)	0.60	540.55	Yes	356	552.25	387.35	263.67	243.05	238.93
All Data	FL ge 20	All	All	280.42	57.875	Yes	-51.20	-6.824	No	FL	0.16	46.57	Yes	241	280.42	280.42	280.42	280.42	280.42
All Data	FL lt 20	All	All	825.06	18.584	Yes	3478.26	-8.121	No	FL	0.37	65.94	Yes	115	825.06	825.06	825.06	825.06	825.06
All Data	FL lt 20	All	All	259.05	7.286	Yes	15.20	8.966	Yes	1/(FL^e)	0.42	80.40	Yes	115	563.00	411.03	297.04	278.05	274.25
Yes Data	FL ge 0	All	All	416.44	24.781	Yes	-238.44	-8.095	No	FL	0.18	65.53	Yes	291	416.44	416.44	416.44	416.44	416.44
Yes Data	FL ge 0	All	All	220.09	29.806	Yes	15.92	21.839	Yes	1/(FL^e)	0.62	476.93	Yes	291	538.52	379.31	259.89	239.99	236.01
Yes Data	FL ge 20	All	All	284.37	56.590	Yes	-53.02	-6.933	No	FL	0.18	48.07	Yes	217	284.37	284.37	284.37	284.37	284.37
Yes Data	FL lt 20	All	All	782.36	12.204	Yes	3163.97	-5.777	No	FL	0.32	33.38	Yes	74	782.36	782.36	782.36	782.36	782.36
Yes Data	FL lt 20	All	All	220.34	6.104	Yes	15.94	8.698	Yes	1/(FL^e)	0.51	75.65	Yes	74	539.05	379.69	260.18	240.26	236.27
Yes Data	FL ge 0	Not Ind.	All	423.18	11.379	Yes	-236.35	-2.955	No	FL	0.27	8.73	Yes	26	423.18	423.18	423.18	423.18	423.18
Yes Data	FL ge 0	2 Stroke	All	366.65	6.640	Yes	-210.79	-2.106	No	FL	0.09	4.44	No	45	366.65	366.65	366.65	366.65	366.65
Yes Data	FL ge 0	4 Stroke	All	424.42	21.963	Yes	-241.36	-7.312	No	FL	0.20	53.47	Yes	220	424.42	424.42	424.42	424.42	424.42
Yes Data	FL ge 0	Not Ind.	All	257.01	38.289	Yes	8.30	23.289	Yes	1/(FL^e)	0.96	542.37	Yes	26	423.10	340.05	277.77	267.39	265.31
Yes Data	FL ge 0	2 Stroke	All	198.53	6.678	Yes	16.22	3.739	Yes	1/(FL^e)	0.25	13.98	Yes	45	522.93	360.73	239.08	218.81	214.75
Yes Data	FL ge 0	4 Stroke	All	208.46	30.979	Yes	20.06	27.350	Yes	1/(FL^e)	0.77	748.01	Yes	220	609.57	409.02	258.60	233.53	228.52
Yes Data	FL ge 0	All	Diesel	366.09	17.044	Yes	-136.04	-3.838	No	FL	0.24	14.73	Yes	49	366.09	366.09	366.09	366.09	366.09
Yes Data	FL ge 0	All	Gas Oil	498.35	13.593	Yes	-362.12	-5.138	No	FL	0.19	26.40	Yes	114	498.35	498.35	498.35	498.35	498.35
Yes Data	FL ge 0	All	Hvy FO	275.59	23.913	Yes	-78.35	-4.037	No	FL	0.45	16.30	Yes	22	275.59	275.59	275.59	275.59	275.59
Yes Data	FL ge 0	All	Int FO	200.29	3.937	Yes	21.87	0.234	No	FL	0.01	0.06	No	10	200.29	200.29	200.29	200.29	200.29
Yes Data	FL ge 0	All	Light FO	380.12	23.514	Yes	-190.68	-7.138	No	FL	0.35	50.95	Yes	96	380.12	380.12	380.12	380.12	380.12
Yes Data	FL ge 0	All	Diesel	249.71	28.157	Yes	7.61	12.542	Yes	1/(FL^e)	0.77	157.31	Yes	49	401.83	325.77	268.72	259.21	257.31
Yes Data	FL ge 0	All	Gas Oil	212.09	14.629	Yes	21.80	17.051	Yes	1/(FL^e)	0.72	290.73	Yes	114	648.02	430.06	266.58	239.34	233.89
Yes Data	FL ge 0	All	Hvy FO	205.72	32.352	Yes	10.86	5.181	Yes	1/(FL^e)	0.57	26.84	Yes	22	422.87	314.30	232.86	219.29	216.58
Yes Data	FL ge 0	All	Int FO	242.25	7.336	Yes	-9.52	-1.244	No	1/(FL^e)	0.16	1.55	No	10	242.25	242.25	242.25	242.25	242.25
Yes Data	FL ge 0	All	Light FO	209.17	48.104	Yes	17.37	26.800	Yes	1/(FL^e)	0.88	718.24	Yes	96	556.66	382.92	252.60	230.88	226.54
Yes Data	FL ge 0	Not Ind.	Diesel	423.18	11.379	Yes	-236.35	-2.955	No	FL	0.27	8.73	Yes	26	423.18	423.18	423.18	423.18	423.18
Yes Data	FL ge 0	2 Stroke	Diesel	248.95	415.284	Yes	0.06	0.053	No	FL	0.00	0.00	No	9	248.95	248.95	248.95	248.95	248.95
Yes Data	FL ge 0	2 Stroke	Gas Oil	1003.21	2.547	No	1202.47	-1.285	No	FL	0.45	1.65	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	275.59	23.913	Yes	-78.35	-4.037	No	FL	0.45	16.30	Yes	22	275.59	275.59	275.59	275.59	275.59
Yes Data	FL ge 0	2 Stroke	Int FO	200.29	3.937	Yes	21.87	0.234	No	FL	0.01	0.06	No	10	200.29	200.29	200.29	200.29	200.29
Yes Data	FL ge 0	4 Stroke	Diesel	343.21	24.260	Yes	-100.48	-6.036	No	FL	0.75	36.44	Yes	14	343.21	343.21	343.21	343.21	343.21
Yes Data	FL ge 0	4 Stroke	Gas Oil	475.58	13.613	Yes	-328.57	-4.923	No	FL	0.18	24.23	Yes	110	475.58	475.58	475.58	475.58	475.58
Yes Data	FL ge 0	4 Stroke	Light FO	380.12	23.514	Yes	-190.68	-7.138	No	FL	0.35	50.95	Yes	96	380.12	380.12	380.12	380.12	380.12
Yes Data	FL ge 0	Not Ind.	Diesel	257.01	38.289	Yes	8.30	23.289	Yes	1/(FL^e)	0.96	542.37	Yes	26	423.10	340.05	277.77	267.39	265.31
Yes Data	FL ge 0	2 Stroke	Diesel	248.92	529.531	Yes	0.01	0.196	No	1/(FL^e)	0.01	0.04	No	9	248.92	248.92	248.92	248.92	248.92
Yes Data	FL ge 0	2 Stroke	Gas Oil	156.49	3.046	No	56.12	12.662	Yes	1/(FL^e)	0.99	160.34	Yes	4	1122.49	561.24	140.31	70.16	56.12
Yes Data	FL ge 0	2 Stroke	Hvy FO	205.72	32.352	Yes	10.86	5.181	Yes	1/(FL^e)	0.57	26.84	Yes	22	422.87	314.30	232.86	219.29	216.58
Yes Data	FL ge 0	2 Stroke	Int FO	242.25	7.336	Yes	-9.52	-1.244	No	1/(FL^e)	0.16	1.55	No	10	242.25	242.25	242.25	242.25	242.25
Yes Data	FL ge 0	4 Stroke	Diesel	197.86	7.716	Yes	36.20	3.383	Yes	1/(FL^e)	0.49	11.44	Yes	14	921.87	559.86	288.36	243.11	234.06
Yes Data	FL ge 0	4 Stroke	Gas Oil	210.71	16.687	Yes	20.68	18.560	Yes	1/(FL^e)	0.76	344.46	Yes	110	624.33	417.52	262.42	236.56	231.39
Yes Data	FL ge 0	4 Stroke	Light FO	209.17	48.104	Yes	17.37	26.800	Yes	1/(FL^e)	0.88	718.24	Yes	96	556.66	382.92	252.60	230.88	226.54

REGRESSION SUMMARY FOR: Wet Exhaust Mass   Exponent = 1.5

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fractional Load …				
															0.05	0.10	0.40	0.80	1.00
All Data	FL ge 0	All	All	82250	6.775	Yes	-104317	-4.594	No	FL	0.06	21.11	Yes	356	82250.0	82250.0	82250.0	82250.0	82250.0
All Data	FL ge 0	All	All	16926	2.231	No	727	7.155	Yes	1/(FL^e)	0.13	51.20	Yes	356	65019.9	22988.0	2873.5	1015.9	726.9
All Data	FL ge 20	All	All	14254	29.641	Yes	6711	-9.014	No	FL	0.25	81.25	Yes	241	14254.0	14254.0	14254.0	14254.0	14254.0
All Data	FL lt 20	All	All	216662	5.082	Yes	-1358048	-3.302	No	FL	0.09	10.90	Yes	115	216662.0	216662.0	216662.0	216662.0	216662.0
All Data	FL lt 20	All	All	47241	1.712	No	588	2.796	Yes	1/(FL^e)	0.06	7.82	Yes	115	52572.6	18587.2	2323.4	821.4	587.8
Yes Data	FL ge 0	All	All	39204	10.141	Yes	-42395	-6.257	No	FL	0.12	39.15	Yes	291	39204.0	39204.0	39204.0	39204.0	39204.0
Yes Data	FL ge 0	All	All	9243	6.557	Yes	491	23.271	Yes	1/(FL^e)	0.65	541.52	Yes	291	53151.2	24767.0	11183.6	9929.2	9734.0
Yes Data	FL ge 20	All	All	13140	31.522	Yes	5604	-8.834	No	FL	0.27	78.04	Yes	217	13140.0	13140.0	13140.0	13140.0	13140.0
Yes Data	FL lt 20	All	All	119128	7.655	Yes	-696874	-5.242	No	FL	0.28	27.47	Yes	74	119128.0	119128.0	119128.0	119128.0	119128.0
Yes Data	FL lt 20	All	All	13376	2.149	No	475	10.097	Yes	1/(FL^e)	0.59	101.95	Yes	74	42476.7	15017.8	1877.2	663.7	474.9
Yes Data	FL ge 0	Not Ind.	All	36133	4.536	Yes	-44911	-2.622	No	FL	0.22	6.87	No	26	36133.0	36133.0	36133.0	36133.0	36133.0
Yes Data	FL ge 0	2 Stroke	All	25531	9.545	Yes	-21433	-4.421	No	FL	0.31	19.54	Yes	45	25531.0	25531.0	25531.0	25531.0	25531.0
Yes Data	FL ge 0	4 Stroke	All	41914	8.457	Yes	-45527	-5.378	No	FL	0.12	28.93	Yes	220	41914.0	41914.0	41914.0	41914.0	41914.0
Yes Data	FL ge 0	Not Ind.	All	8491	10.529	Yes	217	37.678	Yes	1/(FL^e)	0.98	1419.65	Yes	26	27898.3	15352.7	9349.0	8794.5	8708.3
Yes Data	FL ge 0	2 Stroke	All	12009	10.877	Yes	254	7.368	Yes	1/(FL^e)	0.56	54.29	Yes	45	34767.4	20055.3	13014.8	12364.6	12263.4
Yes Data	FL ge 0	4 Stroke	All	7358	5.506	Yes	703	30.568	Yes	1/(FL^e)	0.81	934.41	Yes	220	70198.2	29575.1	10134.7	8339.4	8060.1
Yes Data	FL ge 0	All	Diesel	25422	5.699	Yes	-21731	-2.952	No	FL	0.16	8.72	Yes	49	25422.0	25422.0	25422.0	25422.0	25422.0
Yes Data	FL ge 0	All	Gas Oil	49890	5.820	Yes	-63048	-3.826	No	FL	0.12	14.64	Yes	114	49890.0	49890.0	49890.0	49890.0	49890.0
Yes Data	FL ge 0	All	Hvy FO	24858	9.288	Yes	-19409	-4.306	No	FL	0.48	18.54	Yes	22	24858.0	24858.0	24858.0	24858.0	24858.0
Yes Data	FL ge 0	All	Int FO	21917	4.337	Yes	-14874	-1.605	No	FL	0.24	2.58	No	10	21917.0	21917.0	21917.0	21917.0	21917.0
Yes Data	FL ge 0	All	Light FO	39264	8.541	Yes	-41008	-5.398	No	FL	0.24	29.14	Yes	96	39264.0	39264.0	39264.0	39264.0	39264.0
Yes Data	FL ge 0	All	Diesel	7985	16.194	Yes	217	46.390	Yes	1/(FL^e)	0.98	2152.06	Yes	49	27428.6	14859.1	8844.0	8288.5	8202.0
Yes Data	FL ge 0	All	Gas Oil	6175	2.865	Yes	691	24.758	Yes	1/(FL^e)	0.85	612.94	Yes	114	68005.0	28035.5	8908.0	7141.5	6866.7
Yes Data	FL ge 0	All	Hvy FO	10050	9.107	Yes	909	5.745	Yes	1/(FL^e)	0.62	33.01	Yes	22	91334.5	38788.4	13642.3	11320.1	10958.8
Yes Data	FL ge 0	All	Int FO	13888	4.177	Yes	110	0.400	No	1/(FL^e)	0.02	0.16	No	10	13888.0	13888.0	13888.0	13888.0	13888.0
Yes Data	FL ge 0	All	Light FO	7760	4.340	Yes	814	12.752	Yes	1/(FL^e)	0.63	162.62	Yes	96	80592.1	33510.2	10979.0	8898.3	8574.5
Yes Data	FL ge 0	Not Ind.	Diesel	36133	4.536	Yes	-44911	-2.622	No	FL	0.22	6.87	No	26	36133.0	36133.0	36133.0	36133.0	36133.0
Yes Data	FL ge 0	2 Stroke	Diesel	21000	3.894	Yes	-17801	-1.653	No	FL	0.28	2.73	No	9	21000.0	21000.0	21000.0	21000.0	21000.0
Yes Data	FL ge 0	2 Stroke	Gas Oil	41885	2.332	No	-54126	-1.268	No	FL	0.45	1.61	No	4					
Yes Data	FL ge 0	2 Stroke	Hvy FO	24858	9.288	Yes	-19409	-4.306	No	FL	0.48	18.54	Yes	22	24858.0	24858.0	24858.0	24858.0	24858.0
Yes Data	FL ge 0	2 Stroke	Int FO	21917	4.337	Yes	-14874	-1.605	No	FL	0.24	2.58	No	10	21917.0	21917.0	21917.0	21917.0	21917.0
Yes Data	FL ge 0	4 Stroke	Diesel	10612	7.901	Yes	3980	-2.519	No	FL	0.35	6.34	No	14	10612.0	10612.0	10612.0	10612.0	10612.0
Yes Data	FL ge 0	4 Stroke	Gas Oil	50276	5.643	Yes	-63516	-3.731	No	FL	0.11	13.92	Yes	110	50276.0	50276.0	50276.0	50276.0	50276.0
Yes Data	FL ge 0	4 Stroke	Light FO	39264	8.541	Yes	-41008	-5.398	No	FL	0.24	29.14	Yes	96	39264.0	39264.0	39264.0	39264.0	39264.0
Yes Data	FL ge 0	Not Ind.	Diesel	8491	10.529	Yes	217	37.678	Yes	1/(FL^e)	0.98	1419.65	Yes	26	27898.3	15352.7	9349.0	8794.5	8708.3
Yes Data	FL ge 0	2 Stroke	Diesel	8448	69.083	Yes	197	96.674	Yes	1/(FL^e)	1.00	9345.81	Yes	9	26106.0	14691.2	9228.6	8724.1	8645.6
Yes Data	FL ge 0	2 Stroke	Gas Oil	8479	13.329	Yes	500	41.585	Yes	1/(FL^e)	1.00	1729.27	Yes	4	53202.0	24290.9	10455.4	9177.7	8978.9
Yes Data	FL ge 0	2 Stroke	Hvy FO	10050	9.107	Yes	909	5.745	Yes	1/(FL^e)	0.62	33.01	Yes	22	91334.5	38788.4	13642.3	11320.1	10958.8
Yes Data	FL ge 0	2 Stroke	Int FO	13888	4.177	Yes	110	0.400	No	1/(FL^e)	0.02	0.16	No	10	13888.0	13888.0	13888.0	13888.0	13888.0
Yes Data	FL ge 0	4 Stroke	Diesel	4511	4.293	Yes	993	4.049	Yes	1/(FL^e)	0.58	16.40	Yes	14	93343.6	35918.3	8437.2	5899.3	5504.5
Yes Data	FL ge 0	4 Stroke	Gas Oil	6250	2.812	Yes	694	24.324	Yes	1/(FL^e)	0.85	591.66	Yes	110	68301.0	28188.1	8991.9	7219.1	6943.4
Yes Data	FL ge 0	4 Stroke	Light FO	7760	4.340	Yes	814	12.752	Yes	1/(FL^e)	0.63	162.62	Yes	96	80592.1	33510.2	10979.0	8898.3	8574.5

REGRESSION SUMMARY FOR: SO2

A/F Criteria	Loads Covered	Cycles Covered	Fuels Covered	Intercept	Int-T	Sig?	Coeff	Coeff-T	Sig?	Param	r2	F	Sig?	Obs	Prediction at Fuel Sulfur Flow (g/kW-hr) …				
															0.05	1.00	5.00	25.00	75.00
All Data	FL ge 0	All	All	-0.7670	-1.669	No	2.4938	33.454	Yes	Fuel S	0.79	1119.20	Yes	298	0.125	2.494	12.469	62.345	187.035
All Data	FL ge 20	All	All	0.0724	0.239	No	2.0971	33.125	Yes	Fuel S	0.84	1097.25	Yes	207	0.105	2.097	10.486	52.429	157.286
All Data	FL lt 20	All	All	0.0202	0.016	No	2.6144	17.230	Yes	Fuel S	0.77	296.87	Yes	91	0.131	2.614	13.072	65.360	196.081
Yes Data	FL ge 0	All	All	-0.4792	-1.124	No	2.3735	28.924	Yes	Fuel S	0.78	836.57	Yes	239	0.119	2.374	11.868	59.338	178.013
Yes Data	FL ge 20	All	All	0.2349	0.730	No	2.0600	29.266	Yes	Fuel S	0.83	856.49	Yes	183	0.103	2.060	10.300	51.499	154.497
Yes Data	FL lt 20	All	All	-0.2861	-0.215	No	2.6365	13.595	Yes	Fuel S	0.77	184.83	Yes	56	0.132	2.636	13.182	65.912	197.737
Yes Data	FL ge 0	2 Stroke	All	-2.0526	-3.454	No	2.4836	28.628	Yes	Fuel S	0.96	819.59	Yes	36	0.124	2.484	12.418	62.089	186.266
Yes Data	FL ge 0	4 Stroke	All	-0.4113	-0.877	No	2.4005	24.802	Yes	Fuel S	0.75	615.13	Yes	203	0.120	2.401	12.003	60.013	180.038
Yes Data	FL ge 0	All	Diesel	-1.0787	-3.670	No	0.6258	9.525	Yes	Fuel S	0.66	90.72	Yes	49	0.031	0.626	3.129	15.646	46.938
Yes Data	FL ge 0	All	Gas Oil	0.2231	0.228	No	2.6522	3.218	Yes	Fuel S	0.09	10.35	Yes	111	0.133	2.652	13.261	66.306	198.917
Yes Data	FL ge 0	All	Hvy FO	-2.0296	-2.124	No	2.4103	16.769	Yes	Fuel S	0.93	281.20	Yes	22	0.121	2.410	12.052	60.258	180.774
Yes Data	FL ge 0	All	Int FO	-0.6356	-0.518	No	2.4319	16.579	Yes	Fuel S	0.97	274.85	Yes	10	0.122	2.432	12.160	60.798	182.394
Yes Data	FL ge 0	All	Light FO	-3.4758	-7.517	No	2.7430	41.171	Yes	Fuel S	0.95	1695.06	Yes	96	0.137	2.743	13.715	68.574	205.722
Yes Data	FL ge 0	Not Ind.	Diesel	-0.5717	-2.039	No	0.5481	9.863	Yes	Fuel S	0.80	97.28	Yes	26	0.027	0.548	2.740	13.702	41.106
Yes Data	FL ge 0	2 Stroke	Diesel	14.7217	1.918	No	-4.2272	-1.899	No	Fuel S	0.34	3.61	No	9					
Yes Data	FL ge 0	2 Stroke	Gas Oil	0.2575	4.072	No	0.9920	31.242	Yes	Fuel S	1.00	976.09	Yes	4	0.050	0.992	4.960	24.801	74.402
Yes Data	FL ge 0	2 Stroke	Hvy FO	-2.0296	-2.124	No	2.4103	16.769	Yes	Fuel S	0.93	281.20	Yes	22	0.121	2.410	12.052	60.258	180.774
Yes Data	FL ge 0	2 Stroke	Int FO	-0.6356	-0.518	No	2.4319	16.579	Yes	Fuel S	0.97	274.85	Yes	10	0.122	2.432	12.160	60.798	182.394
Yes Data	FL ge 0	4 Stroke	Diesel	-1.1326	-1.275	No	0.7276	3.179	Yes	Fuel S	0.46	10.11	Yes	14	0.036	0.728	3.638	18.189	54.568
Yes Data	FL ge 0	4 Stroke	Gas Oil	-0.0069	-0.007	No	3.0026	3.340	Yes	Fuel S	0.10	11.16	Yes	107	0.150	3.003	15.013	75.065	225.196
Yes Data	FL ge 0	4 Stroke	Light FO	-3.4758	-7.517	No	2.7430	41.171	Yes	Fuel S	0.95	1695.06	Yes	96	0.137	2.743	13.715	68.574	205.722
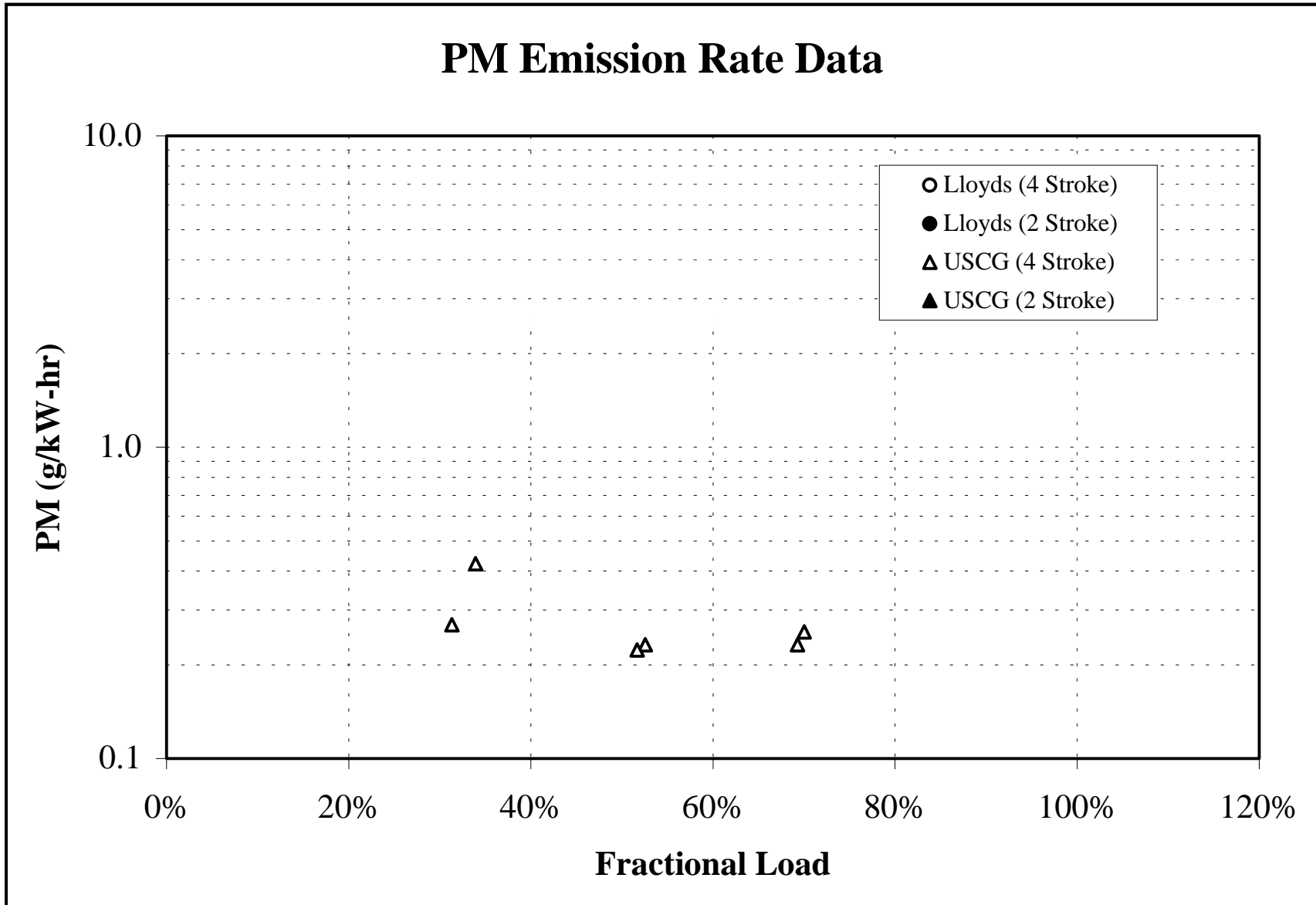
FIGURE A-1
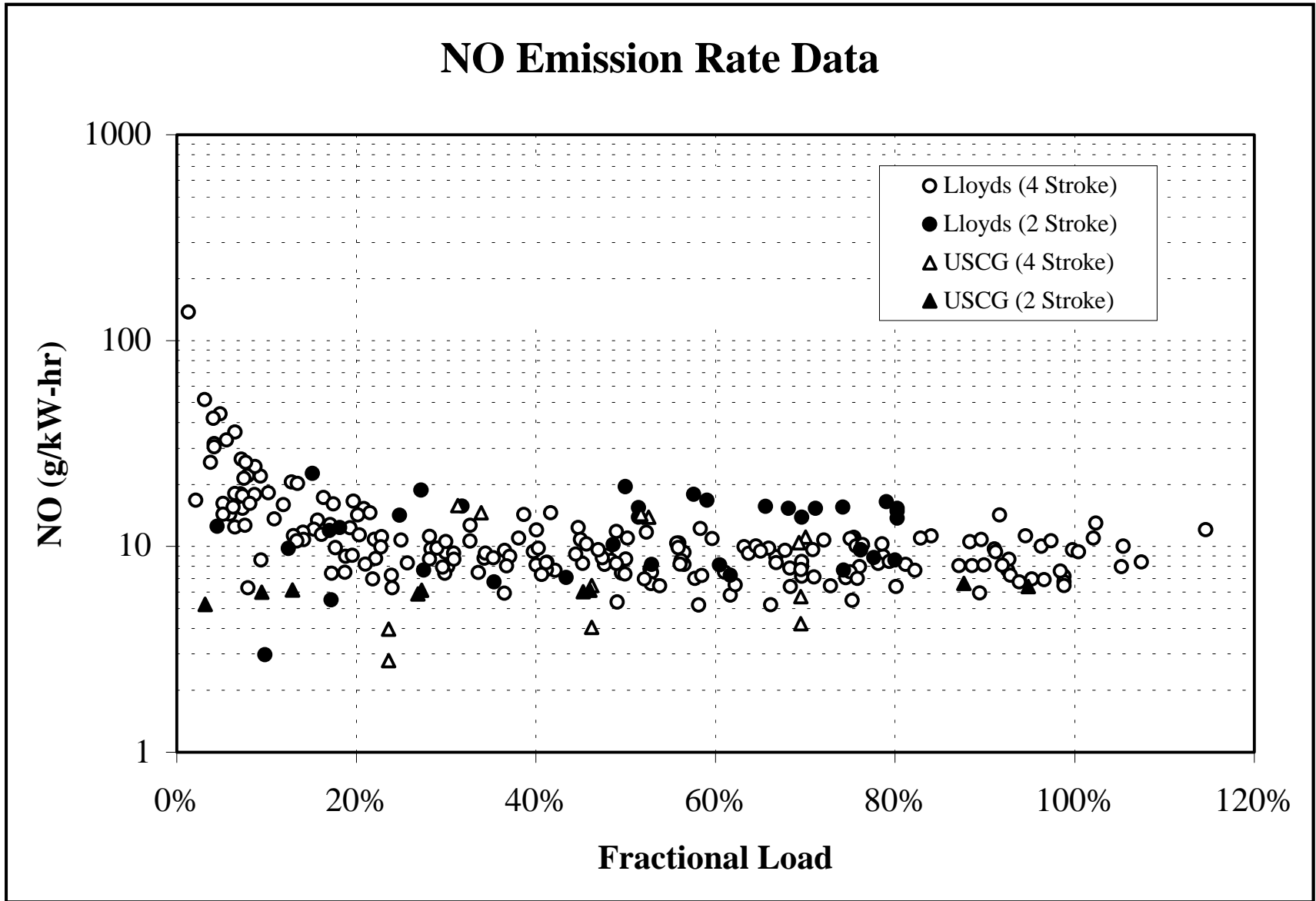
FIGURE A-2
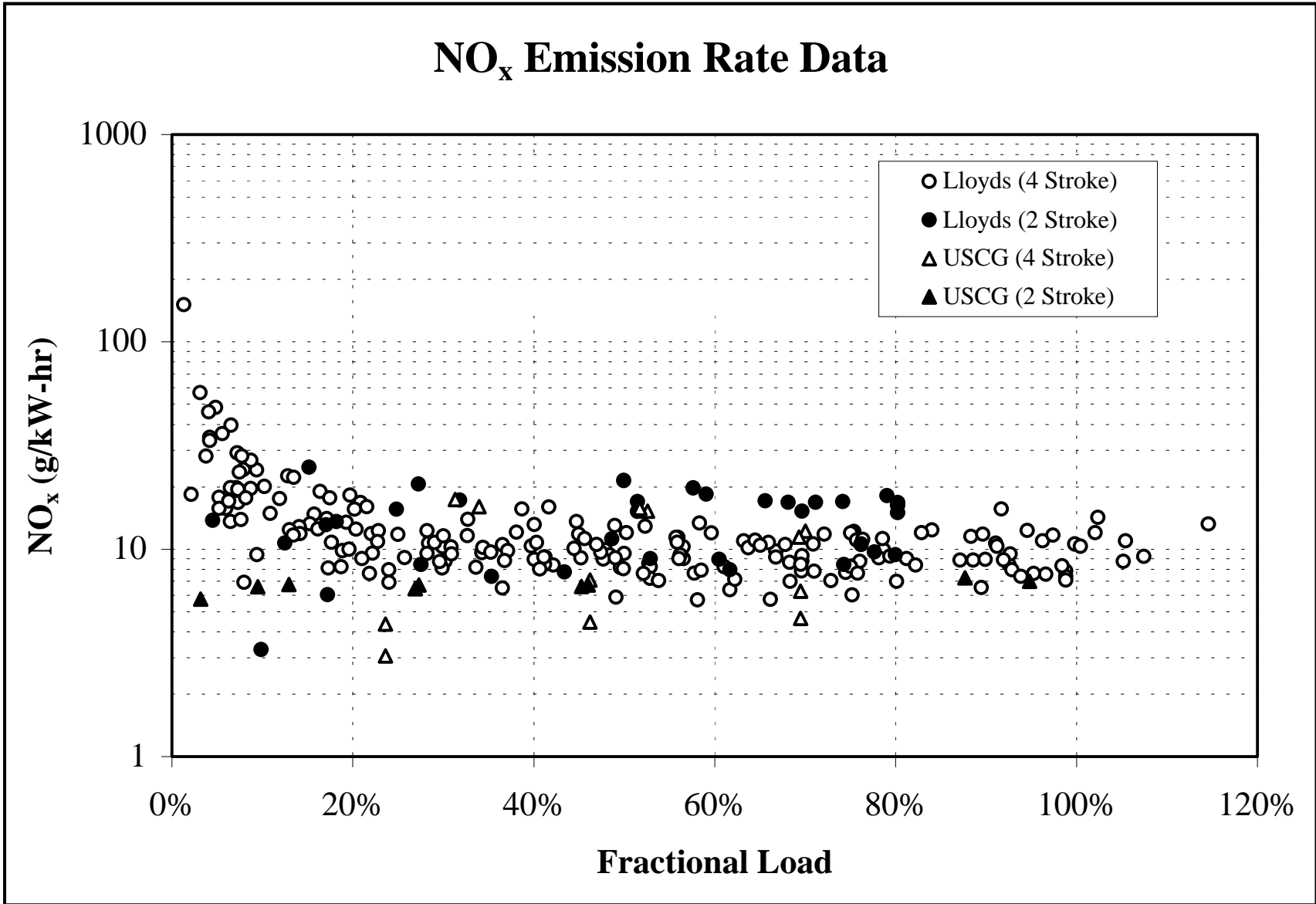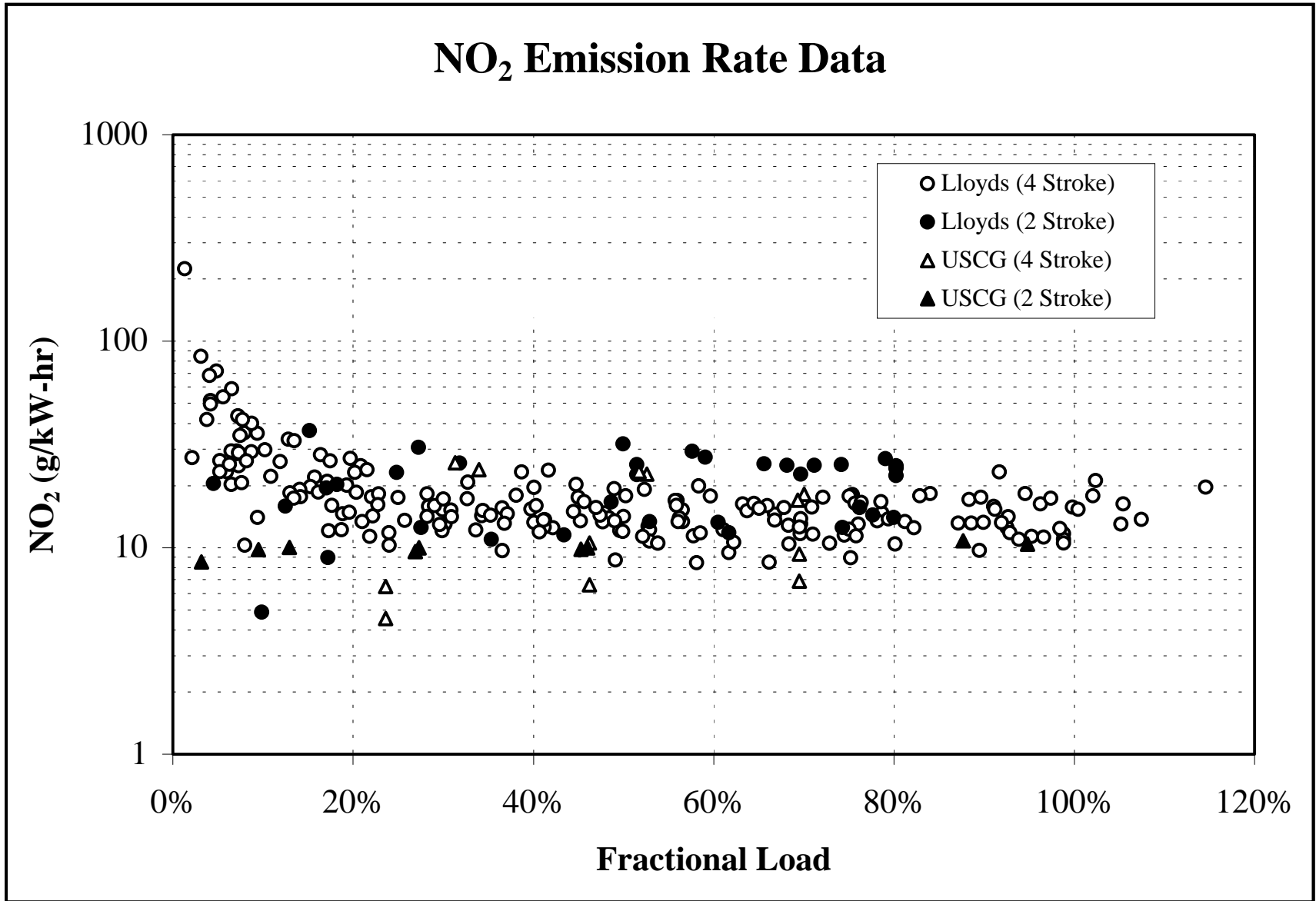
NO$_x$ Emission Rate Data

FIGURE A-3

FIGURE A-4
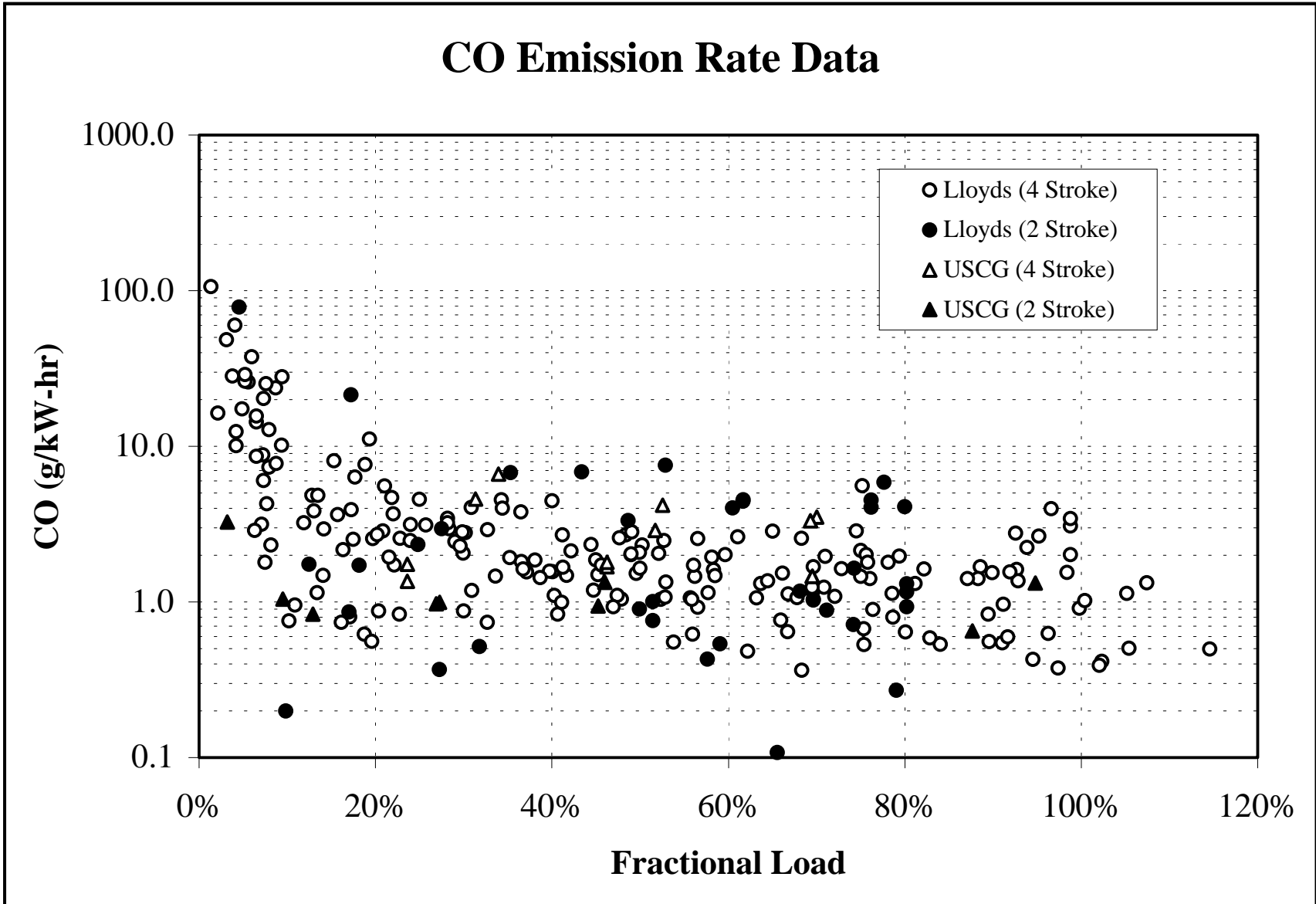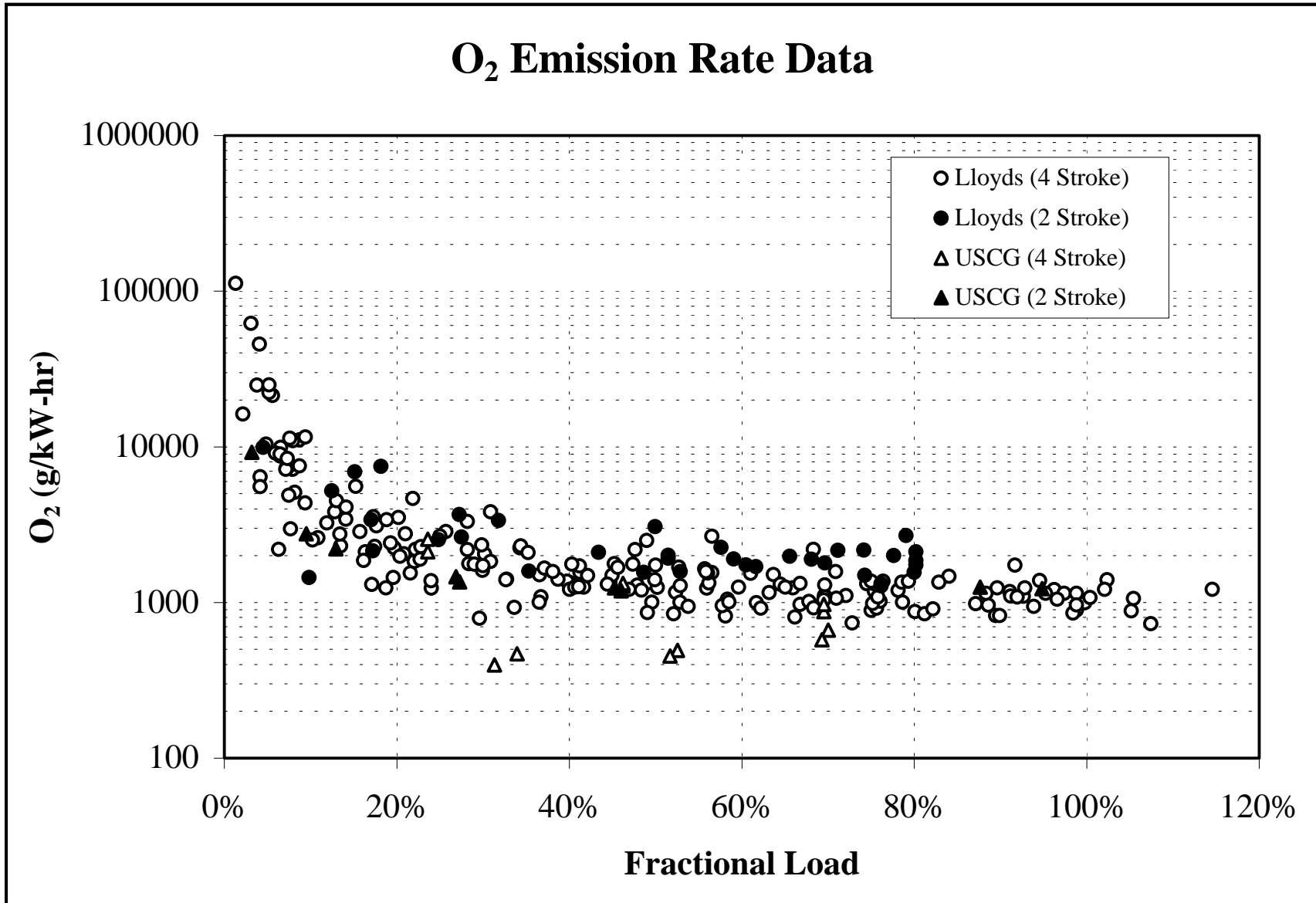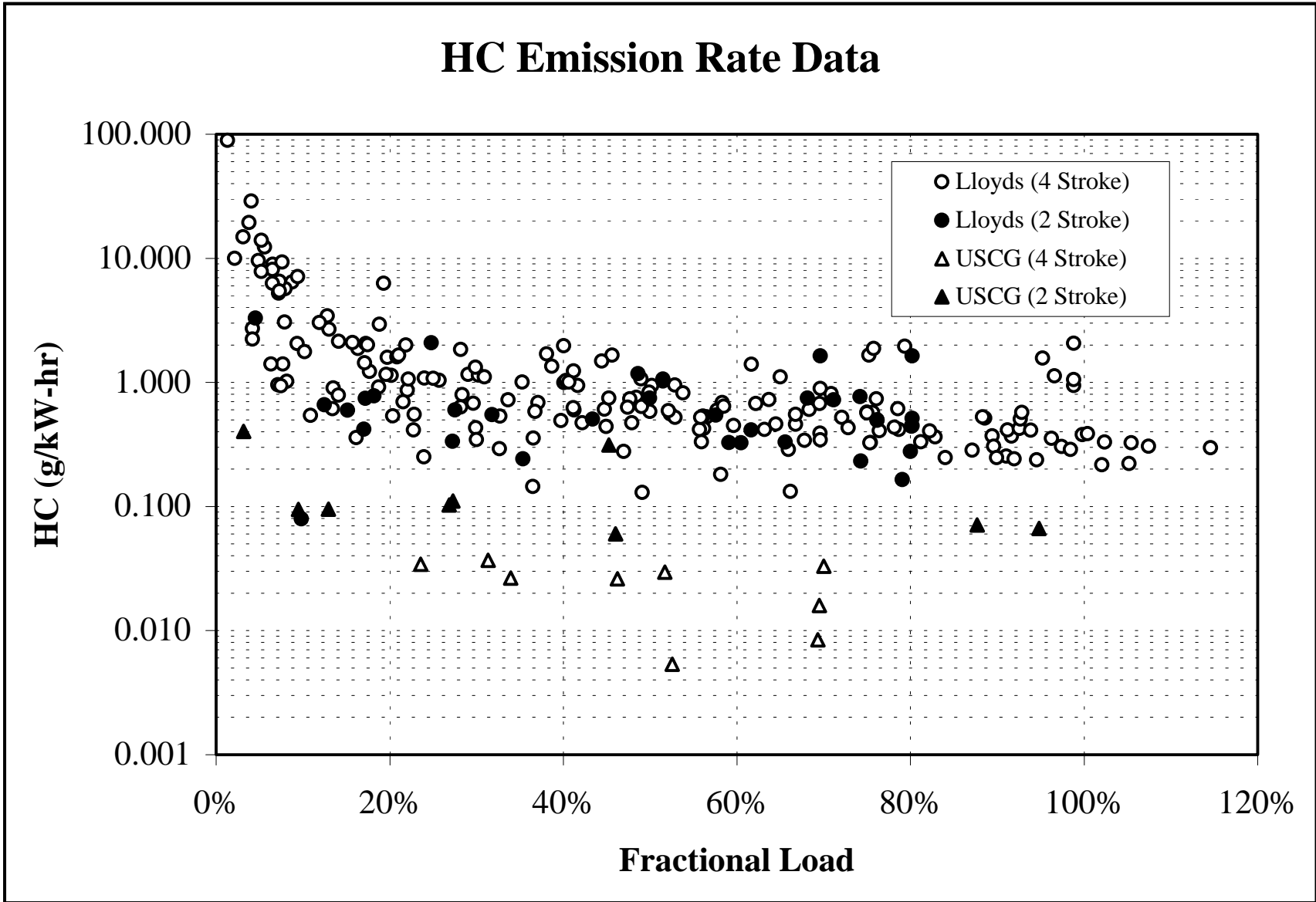
CO Emission Rate Data

FIGURE A-5

CO$_2$ Emission Rate Data

FIGURE A-6

O$_2$ Emission Rate Data

FIGURE A-7

FIGURE A-8

Dry Exhaust Emission Rate Data

FIGURE A-9

H₂O Emission Rate Data / FIGURE A-10

Wet Exhaust Emission Rate Data

FIGURE A-11

FIGURE A-12

NO$_x$ Emission Rate Data

FIGURE A-13

NO$_2$ Emission Rate Data

Legend:
- ○ Lloyds (gas oil)
- △ Lloyds (light fuel oil)
- ◆ Lloyds (intermediate fuel oil)
- ■ Lloyds (heavy fuel oil)

NO$_2$ (g/kW-hr)

Fractional Load

FIGURE A-14

CO Emission Rate Data
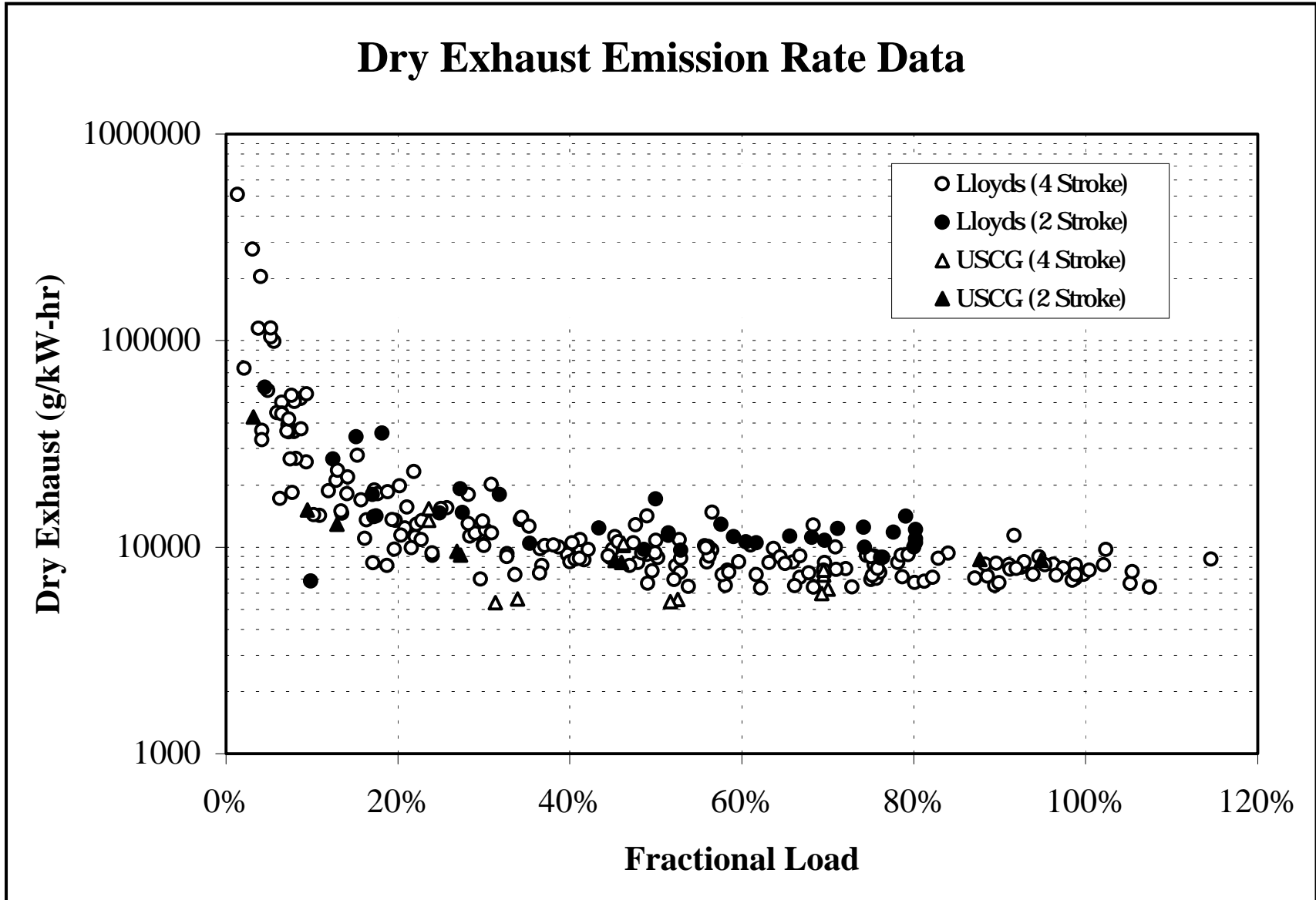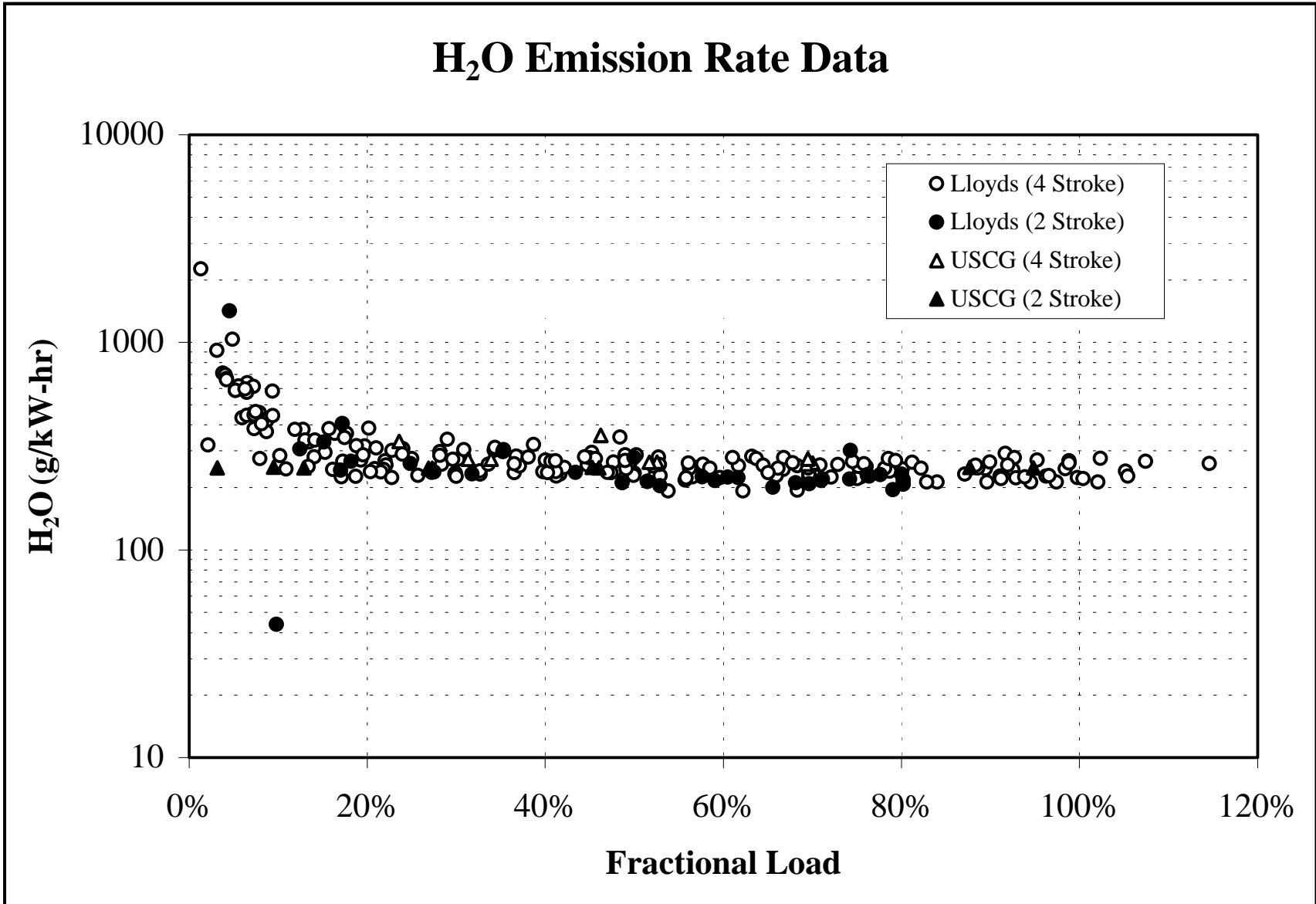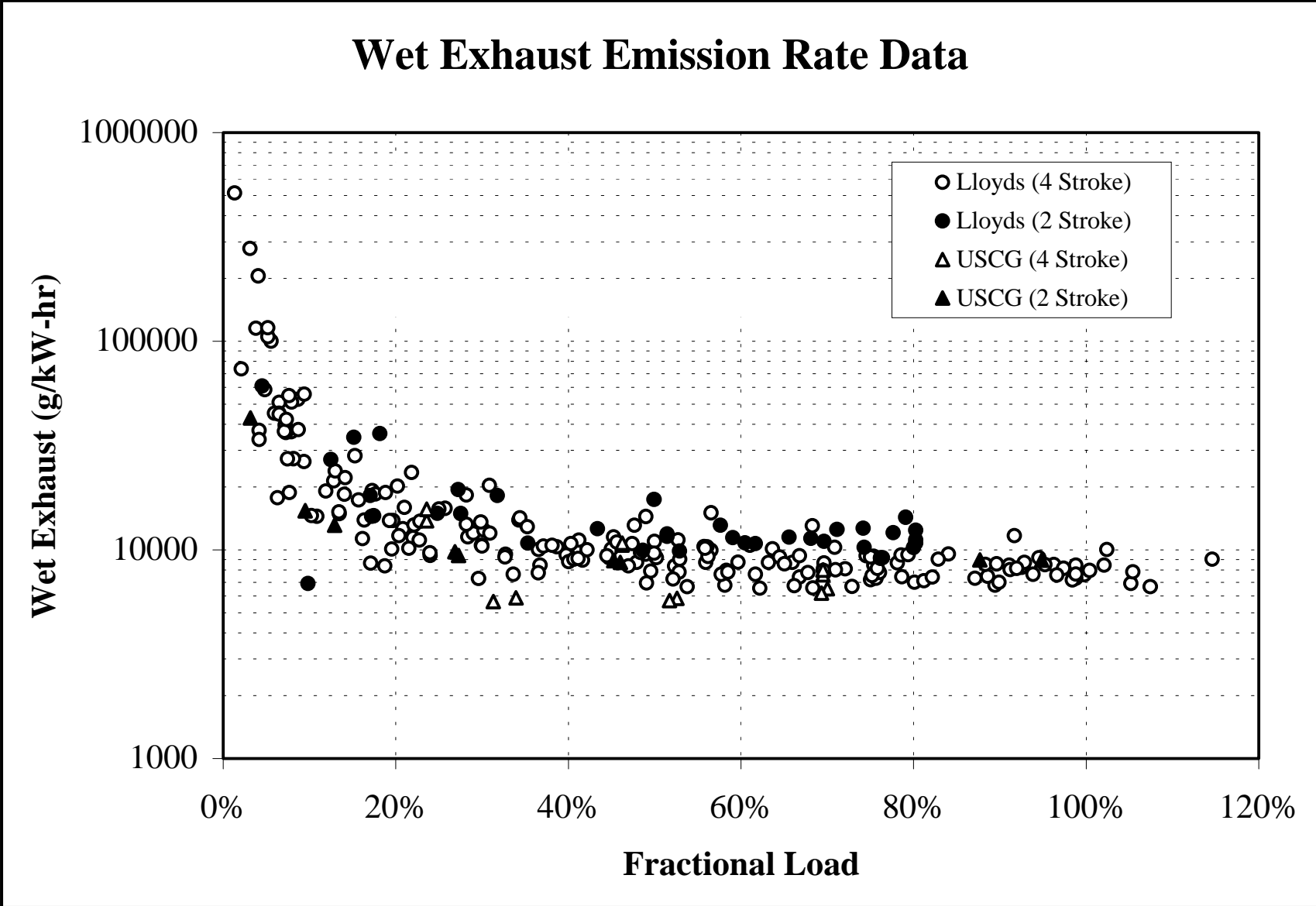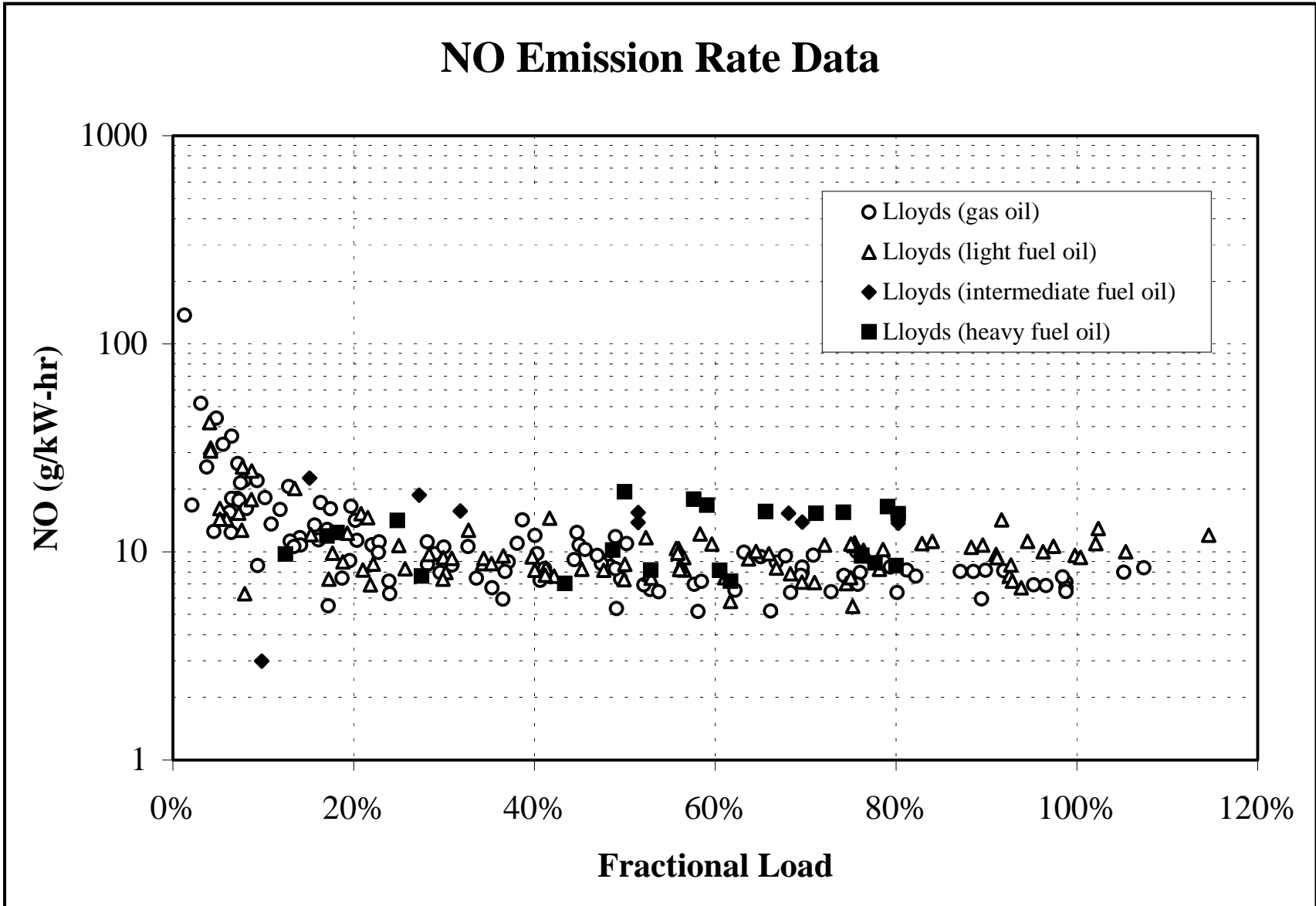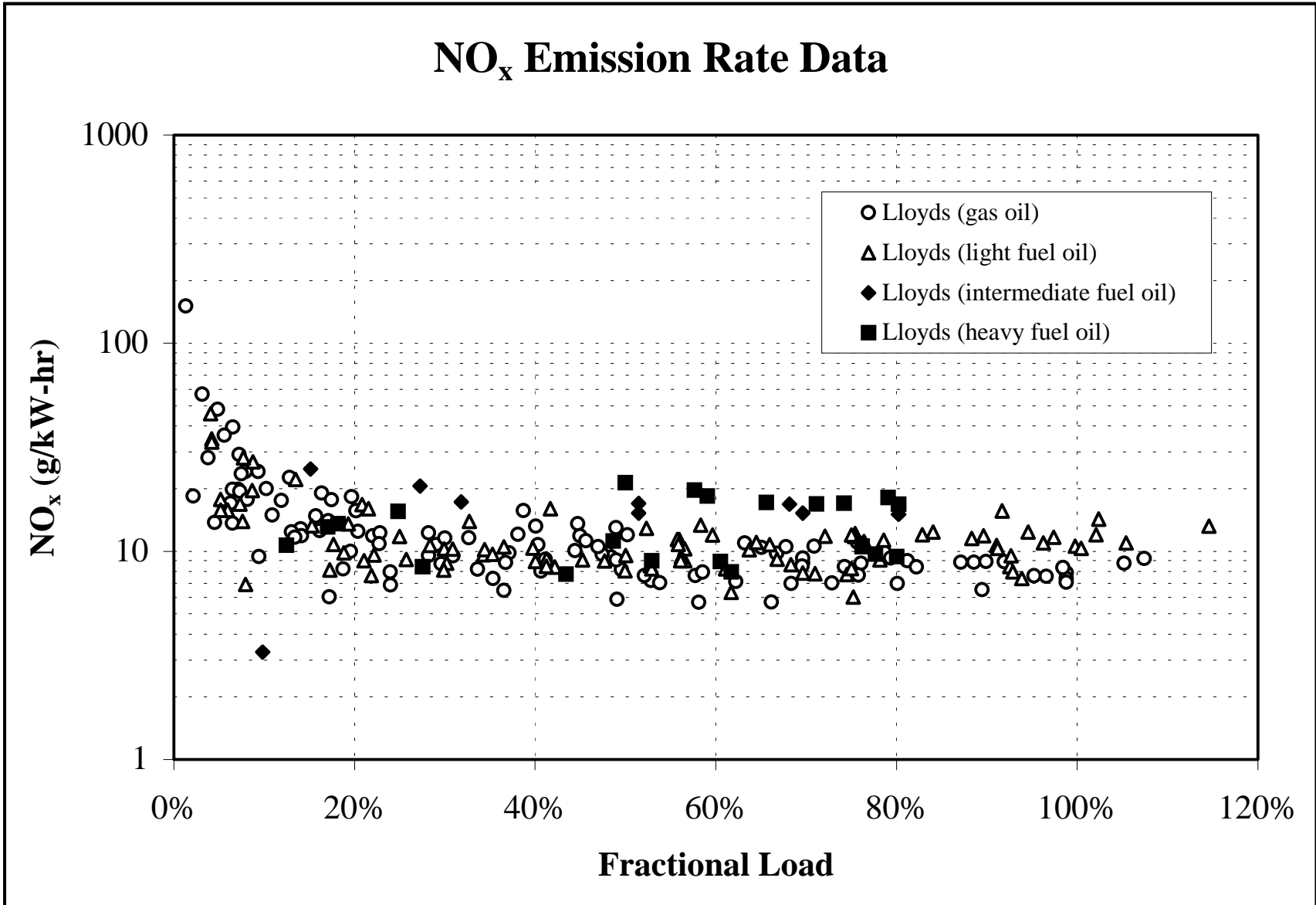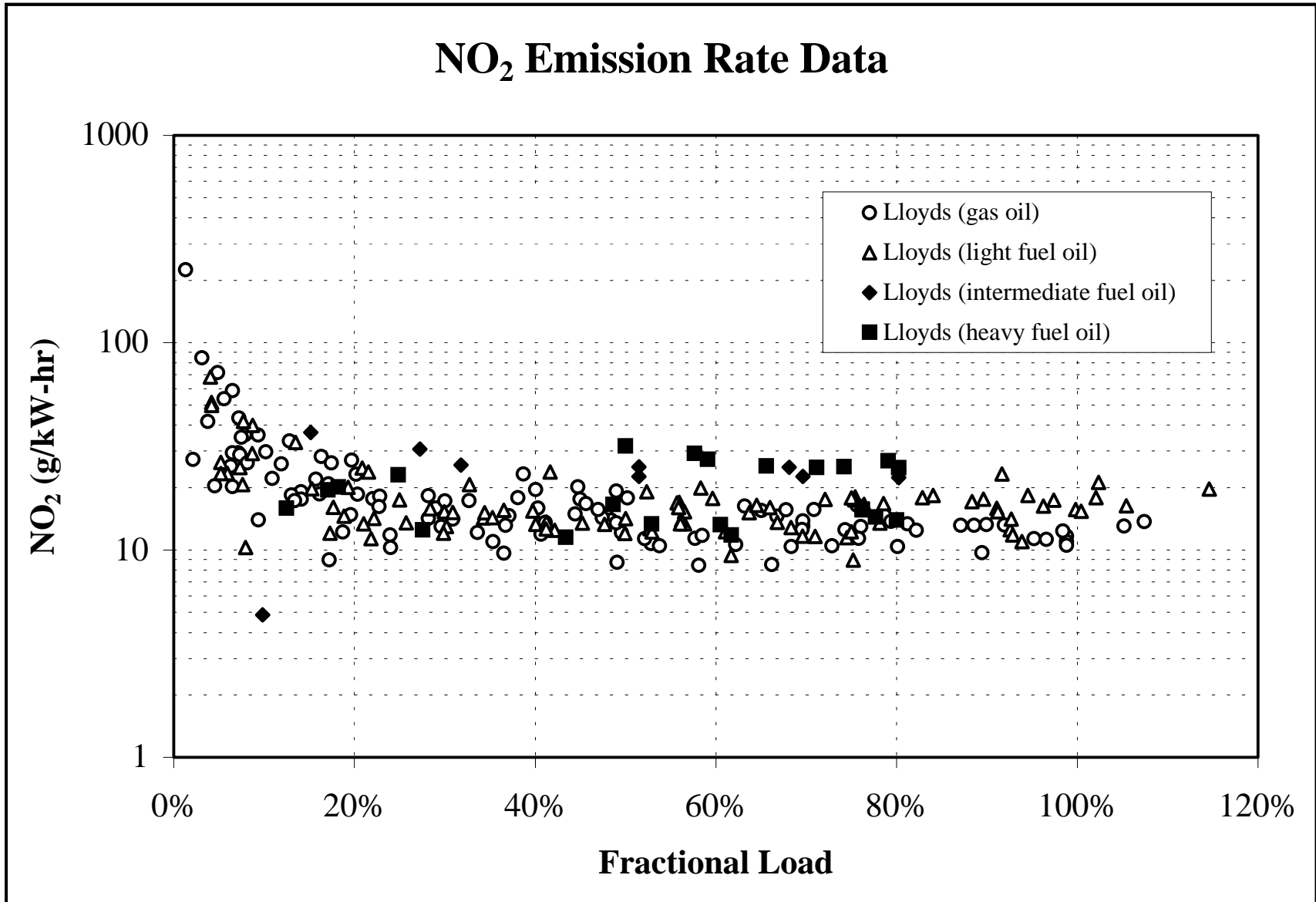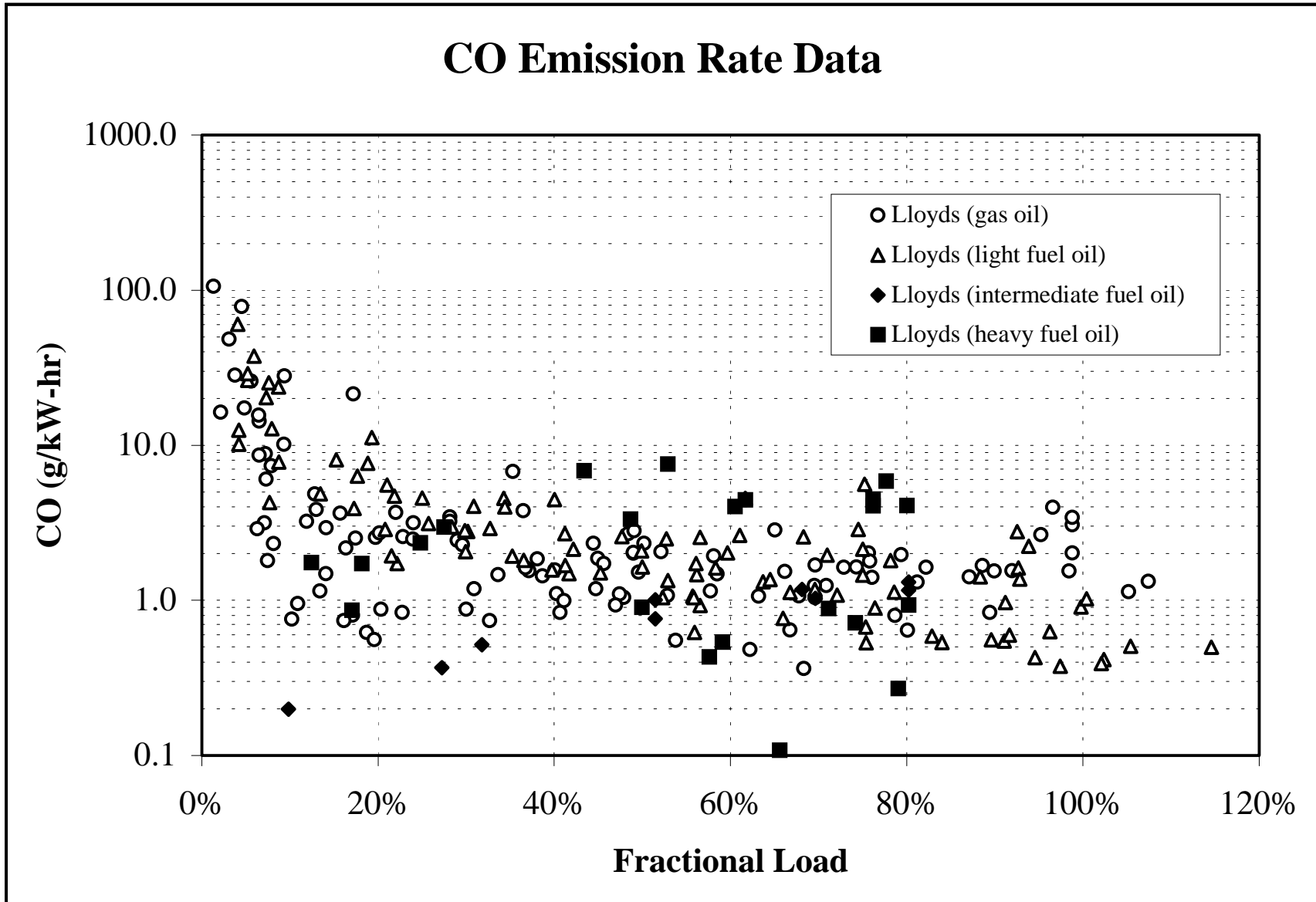
FIGURE A-15

FIGURE A-16

O$_2$ Emission Rate Data

FIGURE A-17

FIGURE A-18

Dry Exhaust Emission Rate Data

FIGURE A-19

FIGURE A-20

Wet Exhaust Emission Rate Data
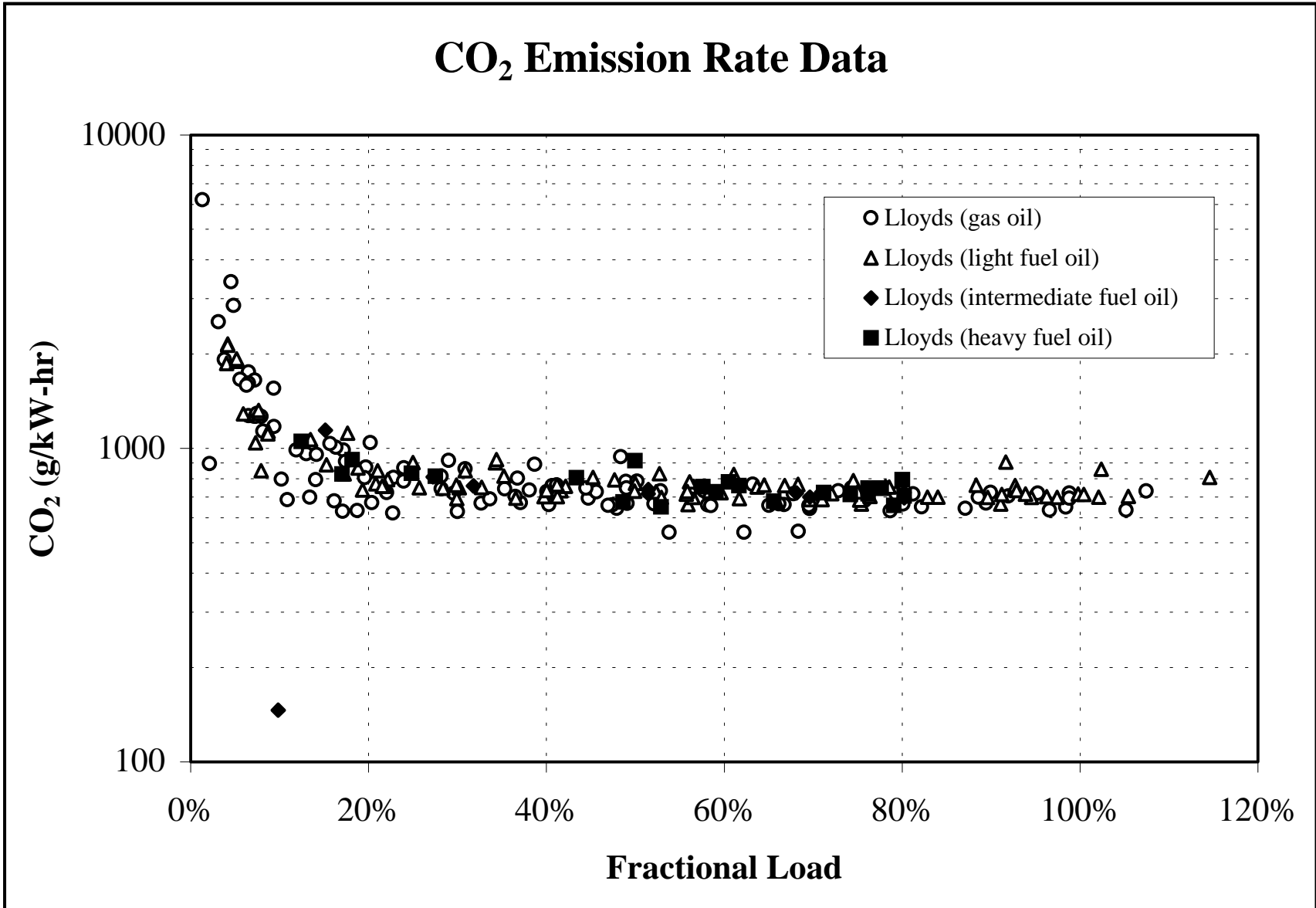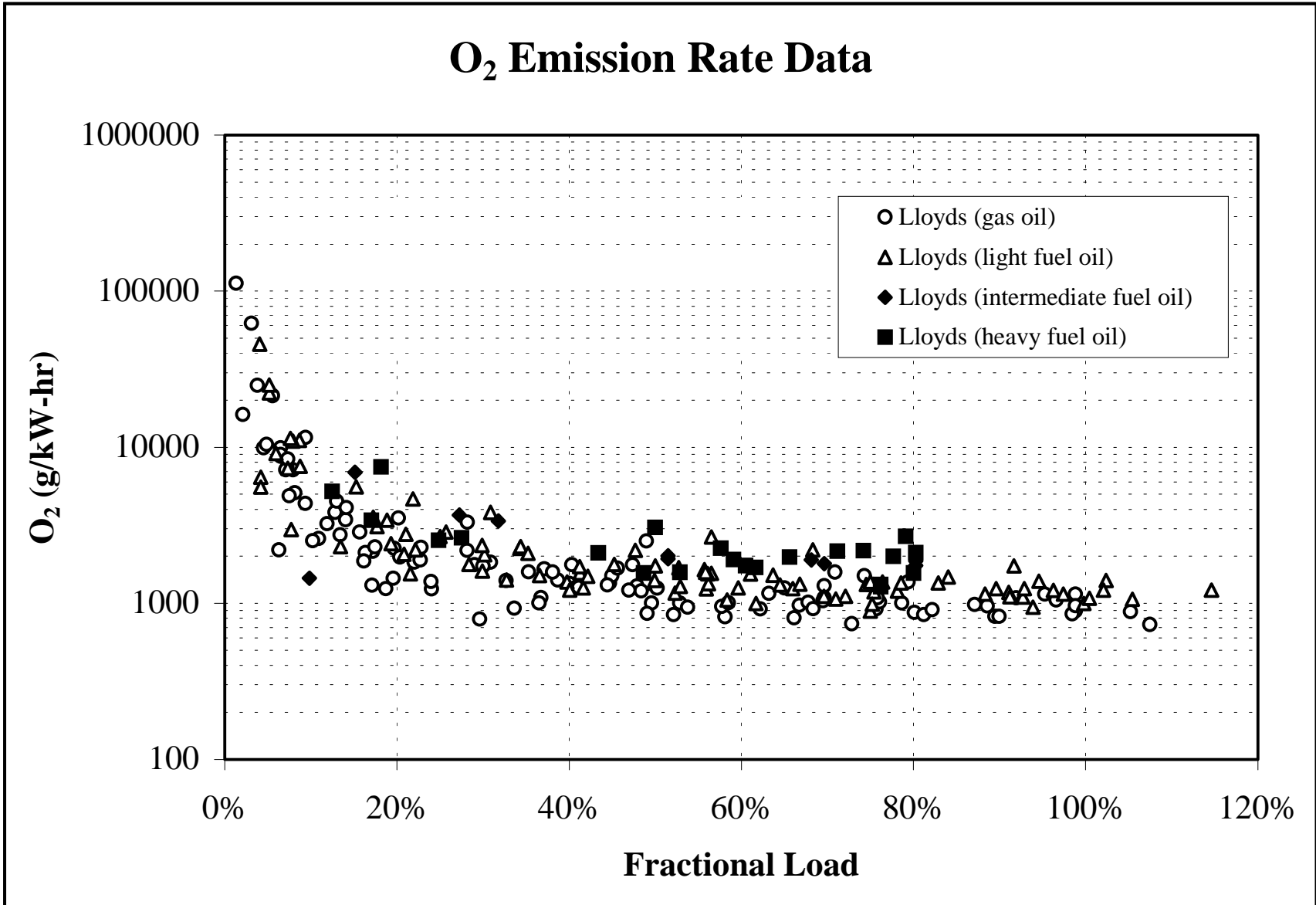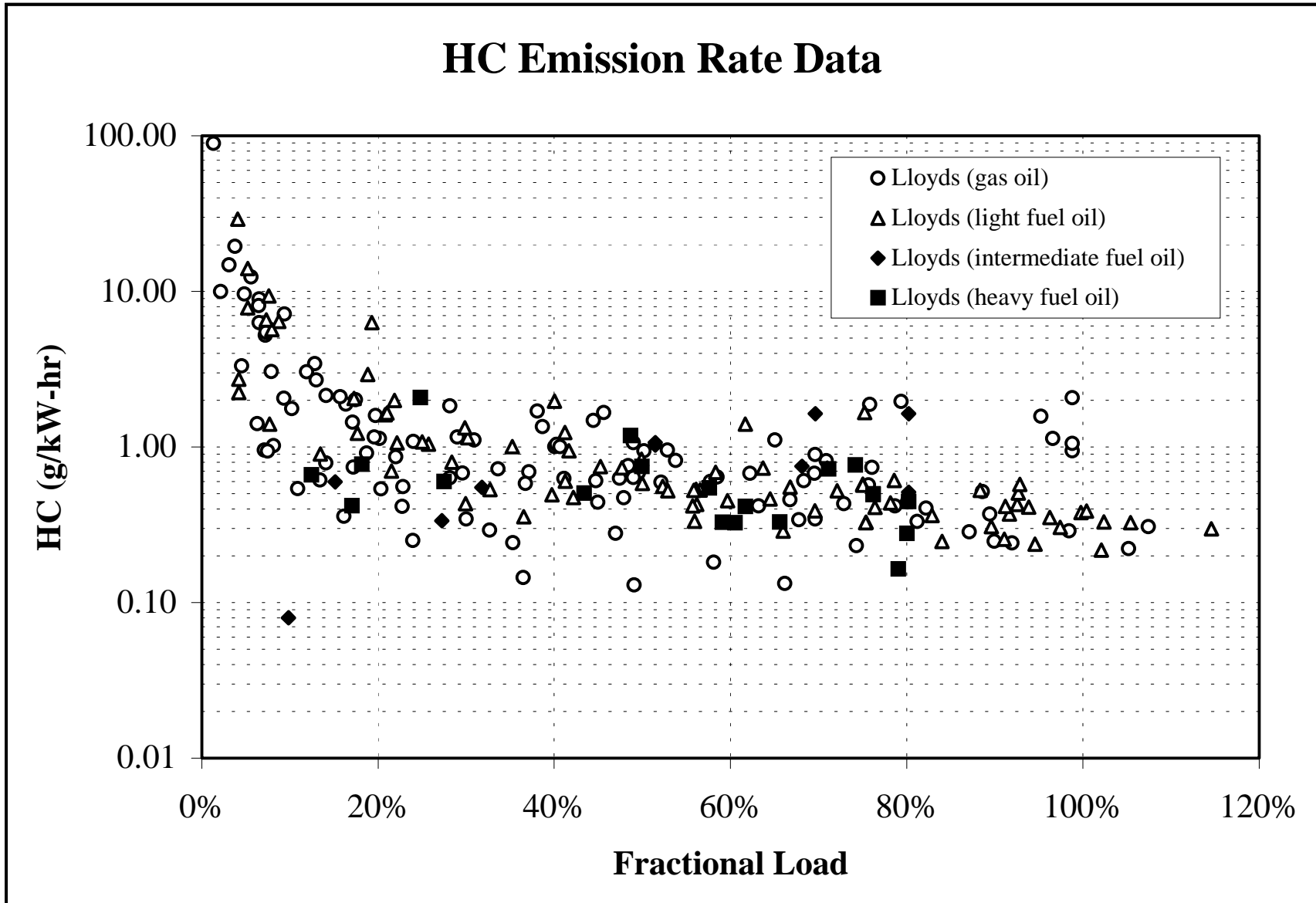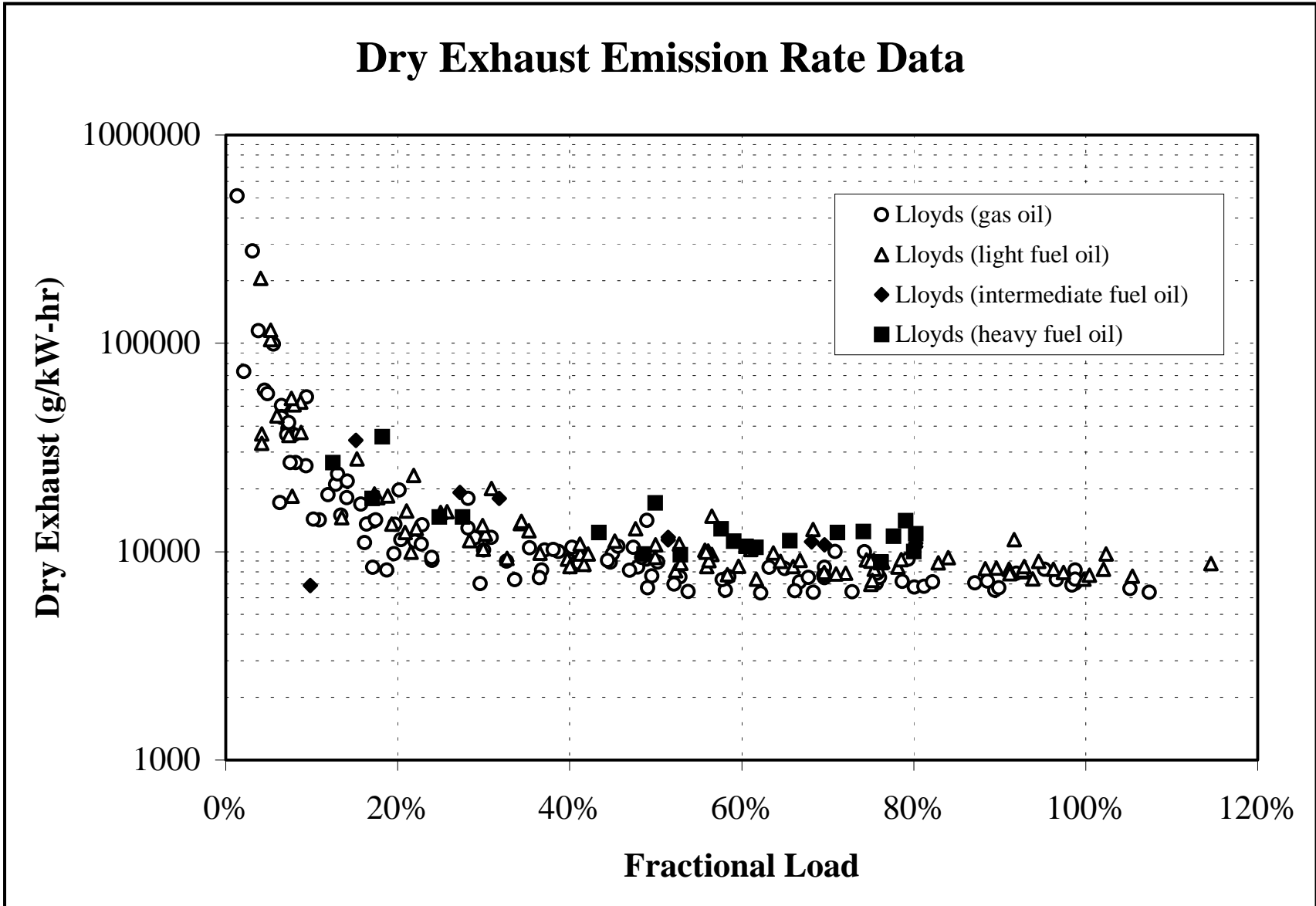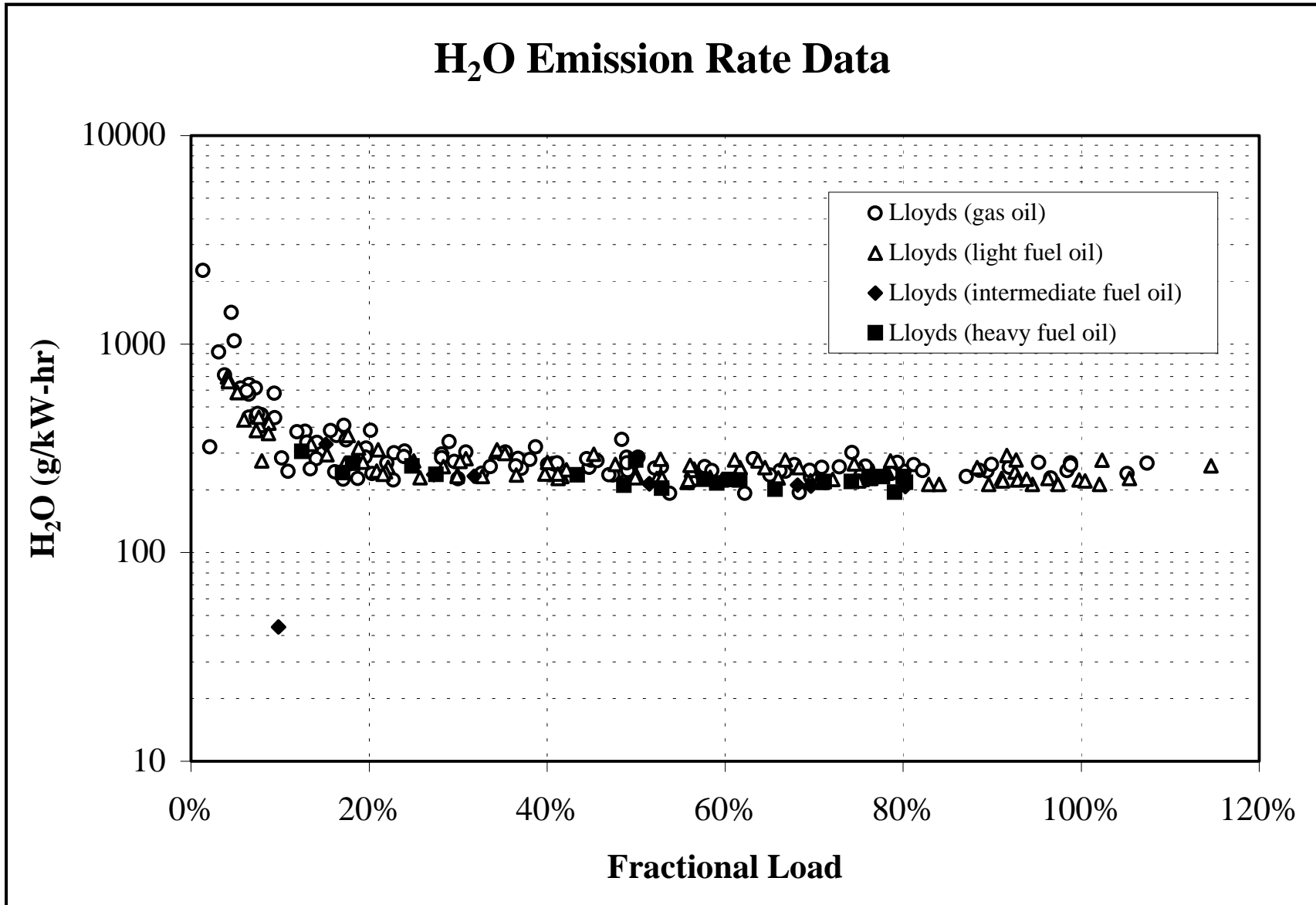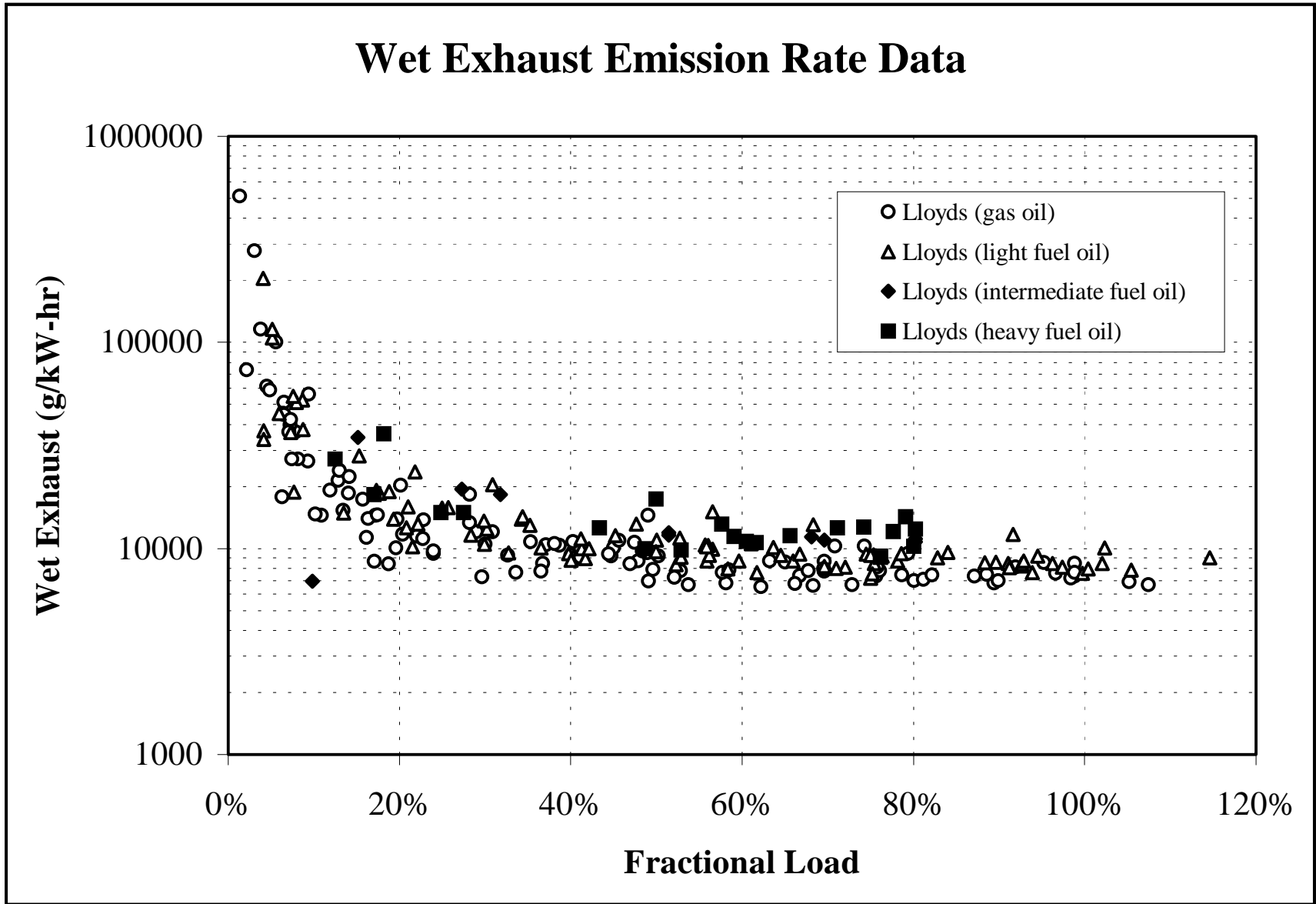
FIGURE A-21

APPENDIX B

SUMMARY OF REPORTS REVIEWED

"Marine Exhaust Emissions Research Programme"
By Lloyd's Register
Summary

The Marine Exhaust Emissions Research Programme tested the emissions of nitric oxide (NO), carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO_2), and sulfur dioxide (SO_2) from marine vessels. Emissions were tested on a total of 48 engines installed on 39 vessels, representing a cross section of marine vessels and included bulk carriers, container ships, dredgers, ferries, tankers, and tugs. Phase I quantified the exhaust emissions from marine diesel engines operating under steady state conditions, which is summarized here. The summary is broken into two parts: medium speed engines, slow speed engines.

Of the total vessels tested, 37 engines in 31 vessels were reportedly medium speed engines. Examination of the data revealed that of these 37 engines, 36 were medium speed and one was a high speed engine. The vessels were monitored under steady state operation over a range of load conditions from idle through full power. Each ship was tested for emissions between 4 to 6 different engine loads. Exhaust gases were sampled at the point of discharge into the atmosphere. Non-dispersive infrared (NDIR) analyzers monitored NO, SO_2, CO, and CO_2. Samples of the fuel and lubricating oil in use at the time of trial were also evaluated. Exhaust emission factors were then calculated in terms of kg pollutant per ton of fuel.

Detailed data on each engine revealed very large differences in measured power at 100% load relative to the engine rated power, with measured power being anywhere from 50 to 130% of rated power. No explanation of these differences were provided in the text. In addition, only raw emission concentration data was provided for each engine so that engine brake specific emissions at each test point could not be easily determined. Engine specifications other than rated power were not disclosed.

The following emission factors were derived from the medium speed engines tested:
- NOx 59 kg/ton fuel
- CO 8 kg/ton fuel
- HC 2.7 kg/ton fuel
- CO_2 3250 kg/ton fuel
- SO_2 (21.0xS) –2.1 kg/ton fuel
    Where S = sulfur content of fuel (% by weight)

There is no detailed explanation in the text as to how the emission factors were derived, but the factors appear to be for a 85% engine load.

Emissions were tested on 11 slow speed engines installed on 9 vessels. One of these vessels had also been included in the medium speed sample. The following emission factors in kg pollutant per ton of fuel were calculated from the slow speed engine measurement program:

- NOx 84 kg/ton fuel
- CO   9 kg/ton fuel
- HC   2.5 kg/ton fuel
- CO2 3165 kg/ton fuel
- SO2 (21.0xS) where

  Where S = sulfur content of fuel (% by weight)

In a related series of tests, Lloyds examined the implications of transient operation during port arrival and departure stages. Emissions on a fuel specific basis for HC and CO were significantly different from emissions measured at steady state, with HC emissions higher by 50% and CO higher by 280%. NOx emissions were about 10% lower.

"Port of Vancouver Marine Vessel Emissions Test Project – Final Report"
By Environment Canada
Summary

The objective of this study was to perform a detailed study of the emission contribution from marine shipping activities within selected Canadian regions/ports to the local ambient air quality. In order to accomplish this the ERMD measured exhaust emissions from a selected sample of large marine vessels operating in the waters in and around the Port of Vancouver. The selected sample of marine vessels included low speed diesel cargo and container vessels, medium speed diesel ferry and cruise ships, and a high speed diesel work boat (tug) with emphasis placed on the cargo and container vessels The engine test sample included nine loe speed diesels, one medium speed and one high speed diesel, as well as five auxiliary engines.. These vessels were examined in four operating modes: maneuvering, low-speed cruise, normal cruise, and hotel power while at berth.

The report describes the four operating modes in very general terms and there is no information on what the engine load factor was during these conditions, or the degree of transient operation, although it can be inferred that maneuvering could consist of a higher degree of transient operation. The auxiliary engines were tested only at the hoteling mode. Not all engines were tested at all modes. Detailed engine specifications were not provided although the engine make and model were identified.

To measure the exhaust emissions on the vessels while in operation, the sampling and analysis system had to be portable rugged, and easily assembled, as well as provide meaningful data comparable to a more permanent installation of analyzers. Both main engines and auxiliary engines were tested. Main engines were tested in three different operational modes: maneuvering, low cruise, and normal cruise. Eleven main engines were tested, however one engine was tested only in the normal cruise operational mode. A table summarizing the results is presented below:

		NO$_x$	THC	CO	CO$_2$	PM
Maneuvering	High	184.74	1.33	61.1	3357	13.39
	Low	35.48	0.37	3.29	2787	1.47
Low Cruise	High	172.65	22.9	21.11	3362	12.4
	Low	39.36	0.22	0	3212	1.78
Normal Cruise	High	178.86	1.19	9.7	3393	16.32
	Low	48.58	0.15	0	2818	1.04
Auxiliary	High	86.22	3.78	7.64	3457	9.97
	Low	24.44	0.93	2.75	2855	0.65

Fuel samples were taken to analyze the sulfur content. The calculated SO$_2$ emissions varied from 4.7 kg/tonne to 63.8 kg/tonne.

The study results were compared to the IMO emission limits and to the Lloyds Marine Exhaust Emissions Research Programme. The spread in emission rates from the vessels is evenly distributed around the IMO limit. The emissions factors were claimed to show reasonable agreement between this study and the Lloyds study, even though there are significant differences between the test procedures and analytical instrumentation.

"BC Ferries Emissions Test Program Report for BC Ferry Corporation"
by Environment Canada
Summary

The objective of this study was to quantify the emissions from a cross section of ferries from the British Columbia fleet. Eight vessels in the British Columbia Ferry Corporation (BCFC) fleet, were tested for the emission rates of oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO2), hydrocarbons, and particulate matter (PM). One engine from each of the vessels was tested except for the vessel named Quinsam where two engines were tested at cruise.

This study utilized a portable commercial continuous emission monitor (ECOM-AC) for the measurement of CO, CO2, NO, NO2, and O2 and a stainless steel mini dilution system for the collection of particulate sample filters. A fuel sample was collected and analyzed at a commercial laboratory to determine the sulfur content. The sampling system was connected to the exhaust ducting of the ship's propulsion or auxiliary engine. Emissions were tested from a main propulsion engine while the vessel was underway at normal cruising speed, as well as when the vessel was at dock. The emission calculations are based upon those outlined in ISO 8178-1, which are based on a carbon balance between the fuel and exhaust.

The details of the test cycle used are described only in very general terms. Tests were conducted conditions described only as 'cruise' and 'docking' and there is reference to the fact the main engines were operating at about 85% of maximum rated power at cruise and at 15% during 'docking'. However, the data presented in the tables together with the data on rated power (which must be inferred from a chart) do not support these statements. No data on the engine specifications are provided, and in one instance, the cruise RPM stated in the table appears very unlikely to be correct.

The emission rates of the eight vessels analyzed are comparable at cruise were claimed to Lloyds factors generated from research conducted by Lloyds Registry and reported in Marine Exhaust Emissions Research Programme. Below are the average emission rates from main engines during cruise (kg/tonne fuel) in comparison to the Lloyds results.

Pollutant	BCFC Factors	Lloyds Emission Factors
NO_x	68.7	75
CO	4.9	3
CO_2	3150	3190
PM	2.0	1-1.5

The table below shows the average emission rates from main engines while docked in comparison to the emission factors developed by Lloyds Register.

Pollutant	BCFC Factors	Lloyds Emission Factors
NO_x	72.1	58
CO	8.2	45
CO_2	3043	3190
PM	3.7	6-8

The emission factors observed varied greatly between engines at the same test condition (by as much as a factor of three), but the averages appear invariant by mode.

Three auxiliary engines were also tested, at full load and rated speed. Observed emissions on a fuel specific basis varied by a factor of 4 for NOx and PM emissions

"Shipboard Marine Engine Emission Testing for the United States Coast Guard"
By Volpe National Transportation Systems Center and U.S. Coast Guard Headquarters
Naval Engineering Division
Summary

The objective of this study was to quantify the emissions for nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), unburned hydrocarbons (UHC), and particulate matter (PM) of a selected number of vessels of the United States Coast Guard (USCG) fleet. CO_2 and O_2 levels in exhaust gas were monitored and smoke opacity determined. This study also sought to update the emission inventory for USCG vessels in area under California Air Resources Board (CARB) jurisdiction using emission data obtained from this study, as well as update emission reduction strategies based on the results. The USCG selected six vessels for source testing which would give emission data for a cross section of engine types operating at different load conditions. Only ship board engines used for propulsion were tested. Each vessel had two engines for a total of 12 engines tested, of which 8 were medium speed and 4 were high speed diesels. One vessel also had 2 gas turbine engines which were tested.

To determine the NO_x, CO, and SO_2 emissions, continuous emission monitoring (CEM) was used following EPA methods. An analysis of batch samples provided the UHC estimates and PM estimates were acquired using a novel, micro dilution method. Opacities were estimated for three vessels which were equipped with vertical stacks and exhaust plumes could be observed.

The test procedure employed was a steady-state cycle at idle, 25%,50%, 75% and 100% of the maximum rated power. The description is not completely clear about how power was determined, and the reported power data do not agree very well with the rated power of the engines. In one case, the measured power at the 100% load point differed from the rated power by 85 percent. In one case, no full power data was measured.
Below are tables summarizing the estimates for diesel engine emissions.

Power		NO_x (g/kWh)		CO (g/kWh)		SO_2 (g/kWh)	
		High	Low	High	Low	High	Low
100%	Starboard	18.7	6.85	1.38	0.83	1.66	0.12
	Port	14.7	6.3	1.24	0.55	1.56	0.1
75%	Starboard	16.9	8.7	3.27	1.21	1.9	0.11
	Port	15.2	6.41	2.98	0.87	2.04	0.09
50%	Starboard	20.9	8.94	4.01	0.89	2.65	0.1
	Port	21.1	8.14	2.61	0.83	2.98	0.09
25%	Starboard	23.8	6	6.1	0.74	2.51	0.1
	Port	23.2	4.22	4.91	0.98	2.69	0.09
Idle	Starboard	47.9	8.76	89	3.67	5.77	0.48
	Port	49.5	9.67	118	3.95	5.1	0.42

Power		UHC (g/kWh)		PM (g/kWh)	
		High	Low	High	Low
100%	Starboard	0.59	0.02	0.81	0.14
	Port	0.42	0.01	0.23	0.13
75%	Starboard	0.53	< 0.001	0.44	0.18
	Port	0.37	0.02	0.69	0.15
50%	Starboard	0.84	0.01	0.46	0.19
	Port	0.6	0.04	0.52	0.19
25%	Starboard	3	0.03	0.8	0.17
	Port	2.05	< 0.001	0.81	0.27
Idle	Starboard	6.86	0.42	3.22	3.08
	Port	5.69	0.71	3.26	2.22

Power		O_2 (%)		CO_2 (%)		Opacity (%)	
		High	Low	High	Low	High	Low
100%	Starboard	13.1	10.7	8.28	5.46	10	5
	Port	13.3	10.4	8.27	5.52	9	5
75%	Starboard	13.2	9.88	8.29	5.66	15	5
	Port	13.3	9.02	8.31	5.66	16	5
50%	Starboard	15.8	8.08	9.43	3.91	15	9
	Port	14.9	7.77	9.45	4.25	15	9
25%	Starboard	18.9	7.79	9.46	1.99	19	8
	Port	18.3	7.06	9.57	1.84	19	8
Idle	Starboard	19.4	18.7	1.61	1.03	10	5
	Port	19.7	18.8	1.51	1.18	10	5

For one vessel, 378-ft WHEC Sherman, both the diesel engines and gas turbines were source tested. Below is a table summarizing the gas turbine emissions data.

Pollutant		100% Power		75% Power		50% Power	
		Starboard	Port	Starboard	Port	Starboard	Port
NO_x	g/kWh	5.98	6.94	3.7	4.01	3.42	3.63
CO	g/kWh	0.1	1.07	1.26	1.24	2.67	2.94
SO_2	g/kWh	0.35	0.29	0.18	0.13	0.28	0.25
UHC	g/kWh	0.1	0.02	0.74	0.33	0.23	0.1
O_2	%	17	17.4	17.8	18	18.1	18.4
CO_2	%	2.73	2.79	2.38	2.56	2.05	2.28

From the source testing results, an emission inventory for NOx, CO, UHC, PM, and SO2 was estimated for each of the selected classes of USCG vessels. The table below shows the range of emission rates for each pollutant.

Pollutant	High	Low
NO_x	727.8	54.6
CO	73.3	8.1
UHC	13.2	0.1
PM	98.7	1.0
SO_2	9.2	2.3

This study concludes by discussing emission control options that may be available for marine diesel engines. These include engine modifications, exhaust after treatment, and fuel selection.

"Analysis of Marine Emissions in the South Coast Air Basin" by Acurex
Summary

This study analyzes the NOx reductions expected from International Maritime Organization (IMO) emission standards, national emission standards and reduction of ship cruising speeds in the South Coast. Oceangoing vessels would be affected by the IMO standards and harbor vessels would be regulated under national emissions standards, while all vessels would be affected by speed reductions in the South Coast Air Basin.

The report utilizes a detailed classification of vessels by 8 ship types, with detailed records on ship activity by type obtained from the 1996 Acurex report on the Marine vessel inventory for the South Coast. To assess the expected reductions from and IMO emissions standard, NOx emissions from main and auxiliary engines need to be examined. Reductions in main engine emissions are estimated by first developing NOx emission rates (in g/kWh) using test data from Lloyd's Marine Exhaust Emissions Research Programme. The report, however, did not appear to address the issue of the poor match between engine rated power versus observed power at the full power emissions measurement setting. Emissions calculations were performed in accordance with the NOx Technical Code using a carbon balance methodology, which yielded NOx emission rates for several engine loads for each engine tested. However, some curve-fitting was necessary to fill in the gaps where Lloyd's data was lacking. Two curve-fitting methods were used: engine specific, combined.

In the engine specific method, first two sets of emission factors in grams of NOx per kWh were developed, one for uncontrolled engines and one for IMO-controlled engines. Next, calendar year specific factors were developed, which reflected the mix of ships in operation in the South Coast built before and after January 1, 2000 and was based on the age profile developed in the inventory study. Then, slow speed and medium speed engine emission factors, both uncontrolled and calendar year IMO factors were averaged to calculate load specific factors for the fleet under the two scenarios: uncontrolled and calendar year controlled operation. These load-specific factors were then weighted by the total energy spent by each ship speed type at each engine load to calculate energy-weighted average NOx emission factors in g/kWh. The energy-weighted average NOx uncontrolled emission factors were then compared with IMO-controlled results for each calendar year to calculate a percentage NOx reduction associated with the introduction of the IMO NOx emission limit. This percentage reduction was then applied to the relevant portion of the NOx inventory from the inventory study, to give an estimated reduction in tons of NOx per year.

However, because the data are limited, a reasonable use of the data is to combine all of the results for all of the engines tested (still treating medium speed and slow speed separately) into a single scatter plot and apply a linear fit to the data. This study chose to use the curves fit to the data for 10 percent MCR and higher to estimate emissions

reductions. To determine the effect of IMO standards, the linear fit curve was moved down until the E2/E3 cycle results would equal the IMO standard. Two equations (slow and medium speed) were developed to calculate uncontrolled emissions and two equations (slow and medium speed) to calculate full IMO-controlled emissions. The uncontrolled and full-IMO controlled factors were then weighted to produce calendar year-specific factors as in the engine specific methodology. As also in the engine specific method, the calendar year-specific factors were weighted for medium speed versus slow speed operation and energy-weighted based on annual energy consumption by approximate engine load. An ultimate reduction in 2010 of 0.8 NOx tpd is projected from main engines which call at the San Pedro Bay Ports. The IMO standards will also reduce emissions from oceangoing vessels that pass through South Coast waters without calling on the Ports. Comparison of uncontrolled NOx rates at 80 percent MCR and the 2010-controlled NOx rates at 80 percent MCR (energy-weighted average of medium and slow speed factors) of these transiting vessels shows that for the engine-specific method a 4 percent NOx reduction is expected from the main engines of transiting vessels or 0.3 tpd.

A methodology similar to above was used to estimate NOx reductions from auxiliary engines. Emissions factors for uncontrolled engines came from data prepared by TRC Environmental Consultants. The arithmetic average of the emission rates (in g/kWh) for the engines tested is used to represent the uncontrolled emissions rates of all auxiliary engines operating in the South Coast waters in a year. The IMO-controlled emissions were developed assuming that all of these engines would emit at their IMO standard. Calendar year-specific NOx emission rates for auxiliary engines are calculated from an age profile. The age profile of the auxiliary engines is assumed as the same as the age profile of the ships themselves since auxiliary engines are not typically replaced. A percentage reduction was then calculated by dividing the calendar year-specific NOx factors by the uncontrolled NOx factor. By 2010, it is expected that NOx emissions from these auxiliary engines would decline by 1.2 tpd.

This study also estimates the NOx reductions that would be created from harbor and fishing vessels assuming that EPA adopts the Tier 2 standards from 1600+ rpm engines and that IMO standards will apply to engines of less than 1600 rpm. To estimate the NOx reductions, the propulsion engines within each category type were categorized based on engine rated power and speed (rpm) and the applicable NOx standard identified, as well as the applicable uncontrolled NOx emission rate. Then calculating an energy-weighted average controlled and uncontrolled NOx rate in 2010. The two energy-weighted averages were then compared to calculate the NOx reductions expected in 2010 from IMO and national standards. From these calculations, it is expected that NOx emissions from harbor and fishing vessels would be reduced by 0.8 tpd if the above standards were adopted.

Speed reduction is one of the most promising operational modifications for reducing ship emissions. Eight speed reduction scenarios were analyzed. Each scenario specifies the distance from the start of the reduced speed zone to the precautionary area, the maximum

speed allowed, and whether or not the speed limit is applied to all vessels. For each scenario, distances by operational mode (full cruise and reduced speed zone cruise – all other modes unaffected) were recalculated. These distances were then used to calculate revised hours by operating mode and shiptype. Using scenario speeds and speed power curves provided by the Navy and their consultant, John J. McMullen (JJMA), engine load by operating mode and shiptype were estimated. The revised hours and engine loads were then used to calculate energy consumption (total annual energy consumption and energy consumption by energy profile loads). Next, the IMO-controlled NOx emission rates determined above and the revised energy consumption were used to calculate normalized emissions in 2010, with IMO and speed reduction compared with baseline operation. Total increased time spent cruising due to speed reduction was calculated and compared to baseline operation to calculate the associated increased emissions from auxiliary engines. The net NOx reductions attributable to speed reduction in 2010 were then calculated. For the scenarios analyzed the 2010 NOx reductions from speed reduction alone range from 1.6 tpd to 5.2 tpd.

"Inventory of Air Pollutant Emissions From Marine Vessels"
By Booz-Allen & Hamilton, Inc.
Summary

This study estimates the amount of air pollution generated by commercial marine vessels along the coastline of California. A three-step process, assessing in sequence vessel population, activity, and emissions, was used to calculate the tons of emissions of the following pollutants: oxides of nitrogen (NO_x), hydrocarbons (HC), carbon monoxide (CO), oxides of sulfur (SO_x), and particulate matter (PM).

Population assessments of ocean-going commercial vessels were determined based on information obtained from the marine exchanges of the San Francisco Bay area and ports of Los Angeles and Long Beach and the local port authorities and bar pilot associations for the smaller ports. Vessel populations were assessed in the following classifications: ocean-going, harbor, and fishing vessels. The main classifications were then further broken down by vessel type, size, mode of propulsion, and horsepower. For ocean-going population, the population is expressed in units of individual vessel port calls per year by port. An average duration of call for each vessel category was calculated for a sample population of vessel calls at the ports in San Francisco Bay Area and of Los Angeles and Long Beach. The population of harbor vessels was extracted from the U.S. Army Corps. Of Engineers report Waterborne Transportation Lines of the United States, 1988, while the population of fishing vessels was taken from the 1990 roster of vessels registered as commercial fishermen with the California Department of Fish and Game.

The levels and types of activity associated with the vessels in each of these classifications were defined in terms of calculated annual fuel consumption. Equations for fuel consumption rates published by the U.S. Department of Transportation, Maritime Administration Port Vessel Emissions Model were used to calculate fuel consumption rates for each type and size of ocean going vessels. These equations use vessel deadweight tonnage, horsepower, and throttle setting as a proportion of full power to calculate fuel consumption in gallons per hour. To determine an average vessel size in deadweight tons and rated shaft horsepower, a sample population of vessel movements in February, May, August, and November of 1989 was used. The sample vessels were categorized according the population classifications and for each category of vessel, an average vessel size in deadweight tons and rated shaft horsepower were calculated. These averages were then applied to all vessels falling into that category. Then for an entire year, each vessel call in at each port was recorded as a tally in the appropriate category of vessel type, propulsion mode, and deadweight tonnage range.

A distinction was then made between energy consumption in-port (either underway or moored) versus at-sea. In-port activity in the underway mode at each port is characterized by a unique series of speed and distance vectors for each port destination. The total fuel consumed by each vessel type, for each propulsion type, and in each weight class is calculated by adding the fuel consumed over the series of vectors for the port, doubling that figure to account for arrival and departure, and multiplying by the total number of annual vessel calls. Fuel consumption of vessels while moored is directly determined by the amount of time spent moored. The time spent moored is calculated by subtracting out the time spent underway from the total time of each

vessel call. For each classification of vessels, the average number of hours spent moored was then derived. The total amount of fuel consumed by each vessel classification moored in each port during one year was calculated by multiplying the average number of hours spent moored by the number of port calls by that classification of vessel, the full-power fuel consumption rate and the percentage of full-power fuel consumption associated with the mooring activity for each vessel classification.

At-sea vessel movements are defined by vectors which represent transit distances between ports in the basins and the California coastal water boundaries. At-sea fuel consumption is calculated by first determining the total miles traveled at sea in the basin. The total miles are calculated by multiplying the number of vessels in each classification by the above vectors lengths. The total miles are divided by the average at-sea operating speed for each of the vessel classifications and then multiplied by the full power fuel consumption rate and a factor of 0.8 (which represents the typical at-sea throttle setting). The final result is the total amount of fuel consumed in the basin during at-sea operation.

Rates of fuel consumption for harbor and fishing vessels were calculated in much the same manner as above. The operating profile of each type of vessel was characterized by the proportion of total operating time that is spent at 20%, 50%, and 80% of full rated power output. The amount of operating time for each type of vessel per year is characterized as the number of hours of operation on an operating day and the number of days of operation per year. From this the average rates of fuel consumption were calculated for each classification of vessel.

Emissions generated by each classification of vessels were calculated based on the amount and type of fuel consumed and the applicable emission factors. This study uses emission factors drawn from the 1985 U.S. Environmental Protection Agency report (AP-42) Compilation of Air Pollutant Emission Factors and the U.S. Maritime Administration's 1986 Port Vessel Emissions Model. AP-42 contains emission factors for diesel propulsion and auxiliary engines of less than 2,500 horsepower while the Port Vessel Emissions Model provides emission factors for diesel propulsion plants in excess of 2,500 horsepower. For ocean-going commercial vessels, emission factors have been applied to the annual fuel consumption figures derived for each port and at-sea basin.

In-port emissions for underway and mooring operations were calculated separately. The rate at which a vessel emits pollutants for underway operations varies according to the proportion of full power at given throttle settings defined as 80%, 50%, and 20% of rated horsepower. For motorships, a single emission factor is used for all underway modes while emission from steamships is calculated using two sets of emission factors, one for full power and one for maneuvering. The following equation for underway emissions from motorships was used:

$$TE = \frac{FC * EF}{1000}$$

where: TE = Total annual emissions of specific pollutant (pounds per year)
       FC = Total annual amount of fuel consumed underway in 'port' water

(gallons per year)

EF = Emission factor for specific pollutant (pounds per 1,000 gallons of fuel)

For steamship operations the emission calculation is expanded to:

$$TE = \frac{(FC_{FULL})(EF_{FULL}) + (FC_{HALF} + FC_{SLOW})(EF_{MANEUVERING})}{1000}$$

where: FC_{MODE} = Total annual amount of fuel consumed in underway operating mode (gallons per year)

EF_{MODE} = Emission factor for specific pollutant at operating mode (pounds per 1,000 gallons of fuel)

The calculations for emissions associated with mooring activity are similar to those for underway operations. For all classes of large ocean-going motorships, emission factors for 500KW auxiliary generators were assumed and for steam vessels, hotelling emissions were calculated using the factors prescribed for plants using residual bunker fuel for ship's service power. Annual emissions for all vessel classifications were summarized as an annual total for each port.

To calculate at-sea emissions, a single set of emission factors were applied for steamships and another for motorships since the study assumes that all of the coastal traffic operates at full throttle setting while in transit. The full-power operation emission factor for steamships was applied to the total amount of fuel consumed by each classification to obtain annual emissions while the emission factors for all operating modes was used for motorships. The resultant annual emissions for all vessel classifications were finally totaled for each basin.

The calculation of total emissions for harbor and fishing vessels involves using emission factors from AP-42, however where factors were omitted in this EPA report emission factors from Port Vessel Emissions Model were used. As in the case of ocean-going commercial vessels, the emissions from harbor and fishing vessels were calculated on the basis of operating mode, expressed as a percentage of rated shaft horsepower so the following equation is used to calculate emissions:

$$TE = (FC) * [(OP_{80\%})(EF_{FULL}) + (OP_{50\%})(EF_{HALF}) + (OP_{20\%})(EF_{SLOW})]$$

where: FC = Total annual amount of fuel consumed (gallons per year)

OP_{POWER} = Percentage of operating time spent at each operating mode

EF_{MODE} = Emission factor for specific pollutant at each operating mode (pounds per 1,000 gallons of fuel)

The following table shows the total statewide emissions for each pollutant:

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Pollutant	Emissions
	(tons of pollutant per day)
NO_x	412.29
HC	28.67
CO	57.53
SO_x	226.25
PM	27.60

"Marine Emissions Quantification – BCFC Ferries Operating in Greater Vancouver Regional District Air Shed"
By Lloyd's Register
Summary

At the request of British Columbia Ferry Corporation (BCFC), Lloyd's Register (LR) conducted a desk based air emissions quantification exercise on all BCFC vessels operating in the Greater Vancouver Regional District (GVRD) Airshed. The basis for this emission quantification study were modified fuel consumption data models provided by BCFC. These models were for all classes of vessels operating on each of the five routes which pass, either entirely or partly, through the GVRD Airshed. The models include details of route description, vessel class details, voyage profiles, lay-up fuel consumption, and fuel details.

To estimate the emissions from oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), sulfur dioxide (SO_2), and particulate matter (PM), first data relating to the whole route was input into the model. The data entered into the model included:

- brake specific fuel consumption (bsfc) figures for the main propulsion engines
- bsfc figures for the generators of all the vessels and for the main engines of the Route 8 vessels
- the duration of each crossing
- the average loads and bsfc for each generator

The following items were calculated:

- volume of fuel consumed by each vessel's main engines whilst on a crossing
- fuel consumed by each vessel's generator whilst in service

Based on the above information the total route fuel consumption figure was derived from the model. The model derived fuel consumption total was then compared with the actual known quantity of fuel consumed. Next, the percentage loading of the main engine whilst vessels were operating along that route were adjusted in order to match these two fuel consumption numbers. Fuel specific emission factors were then developed for each of the main engine and generator types from data generated by Lloyds and used to estimate the emissions per vessel per route.

The results show that the BCFC vessels contribute less than 4 percent of total SO_2 emissions by marine vessels. However, these vessels do emit 15 to 16 percent of NO_x emissions from all marine vessels into the airshed. Below is a table summarizing the results by showing an annual total emission estimate for each of the pollutants tested:

Pollutant	BCFC Totals
	Kg/year
NO_x	1,565,658
CO	129,162
CO_2	74,300,883
SO_2	67,935
PM	36,898
hydrocarbons	60,874

Note: Sulfur dioxide estimates in this study were presented for three different sulfur contents of fuels (0.03%, 0.05%, 0.27%). The total emission of each sulfur dioxide estimates were combined to calculate the final SO_2 estimate.

"Marine Vessel Emissions Inventory and Control Strategies" by Acurex
Summary

This study develops an inventory for marine vessel emissions that contribute to the air quality problem in the South Coast Air Basin and sets out to resolve any discrepancies from earlier inventory reports and marine vessel inventories. The inventory assessment includes a baseline inventory for 1993, a "backcast" to 1990, and a forecast of the 2000 and 2010 inventories for five pollutants which include: nitrogen oxides (NOx), sulfur oxides (SOx), hydrocarbons (HC), carbon monoxide (CO), and particulate (PM). Inventories for several categories of ships that travel through the waters of the South Coast Air Basin are presented in this report and appendices. The ship categories include: ocean going vessels, tugboats and other harbor vessels, fishing vessels, U.S. Navy vessels, U.S. Coast Guard vessels.

Ocean going vessels include those vessels calling on the San Pedro Bay Ports and the Chevron offshore facility at El Segundo, as well as those transiting through the area without calling into the ports. Ocean going vessels were first grouped in by shiptype. They were further broken down by propulsion type (motorships or steamships) and then categorized by size and speed using a "design category" parameter. For each category, fuel consumption at cruise speeds are calculated by combining route-weighted average distance with average service speed for each shiptype. Fuel consumption in reduced speed modes (within the precautionary area and maneuvering in the harbor) are also calculated. Fuel consumption within the precautionary area is calculated using the assumption that power varies as ship speed cubed. Fuel consumption while maneuvering in the harbor is estimated based on test data from Lloyds Marine Exhaust Research Programme and on engineering judgement. Emissions were then calculated using emission factors in pounds of pollutants per thousand gallons of fuel consumed.

The emissions of the ocean going vessels are calculated using emission factors (pounds of pollutant per thousand gallons of fuel consumed). For the vessels calling at El Segundo, adjustments were made to the cruising emissions to avoid double counting. The emissions in the forecasted years are based on cargo and fleet forecasts for the San Pedro Bay Ports.

Emissions calculations were made for mooring tugboats, non-mooring tugboats and ocean going tugs. This study chose to simplify by using annual fuel consumption data to estimate annual consumption. Emission factors in pounds per thousand gallons of fuel consumed for medium speed diesel engines were used to calculate total emissions. The number of tugs and horsepower ratings are assumed to remain the same through 2010 so the emissions results are the same since they are ultimately calculated based on the amount of fuel used.

For fishing vessels, fuel consumption based on four modes of operation and emission factors in pounds per 1000 gallons of fuel consumed for medium speed diesel engines, taken from the Lloyd's Marine Exhaust Emissions Research Programme, were used to calculate total emissions for each of the five pollutants. Since there was no data to support a projection of South Coast fishing activity, a "no growth" scenario was the most reasonable assumption. Based on information from the Navy, U.S. Navy vessel emissions were calculated using emission factors in grams of pollutant per horsepower-hour of shaft power output. A Coast Guard report in

which emissions test results are presented for several Coast Guard vessels is the basis for emissions from these vessels.

Based on the above calculations, marine vessels generate significant quantities of NO_x, SO_x, HC, CO, and PM. Overall, the ocean-going vessels calling in at the San Pedro Bay Ports emit the most tons per day of all five pollutants in 1990 and 1993, as well as in 2000 and 2010. Fishing vessels emit the next largest amounts in all pollutants except particulate. Emissions of all pollutants decline from 1990 to 1993 but are expected to increase from 1993 to 2010. Reducing emissions from marine vessels is important for improving air quality in the South Coast Air Basin and three types of measures are contained in the South Coast Air Quality Management District's Air Quality Management Plan and in the California State Implementation Plan for Ozone. They include: applying emissions standards uniformly worldwide and, for non-ocean-going vessels nationwide; reducing emissions occurring in the South Coast Air Basin with in-basin operational modifications such as speed reductions or shipping lane relocation; developing special (voluntary) projects that reduce emissions locally.

APPENDIX C

ACUREX CLASSIFICATION OF SHIPTYPES

MARINE EMISSIONS INVENTORY
Ocean-going VesselsCalling on SPB Ports: Average Rated Power and Fuel consumption in Cruise Mode

Shiptype		design categories	corresponding dwt categories			Avg. LMIS bhp for category	BSFC gram/bhp-hr	cruise fuel consumption for category (gal/hour)
Auto Carrier	Motorships	0-200	0	-	5,800	-		
		200-400	5,800	-	16,500	13,552	100	328
		400-600	16,500	-	30,300	16,003	100	387
		>600*	30,300	+		18,000	100	435

Shiptype		design categories	corresponding dwt categories			Avg. LMIS bhp for category	BSFC gram/bhp-hr	cruise fuel consumption for category (gal/hour)
Bulk Carrier	Motorships	0-200	0	-	14,100	8,143	100	197
		200-400	14,100	-	40,000	10,103	100	244
		400-600	40,000	-	73,600	12,508	100	302
		600-800	73,600	-	113,300	15,626	100	378
		800-1000	113,300	-	158,400	23,763	100	575
		>1000	158,400	+		31,200	100	755
	Steamships	600-800	73,600	-	113,300	16,500	250	918
		800-1000	113,300	-	158,400	24,000	250	1,335
		1000-1200	158,400	-	208,200	27,500	250	1,530

Shiptype		design categories	corresponding dwt categories			Avg. LMIS bhp for category	BSFC gram/bhp-hr	cruise fuel consumption for category (gal/hour)
Container Ship	Motorships	0-200	0	-	1,900	8,000	100	193
		200-400	1,900	-	5,500	15,044	100	364
		400-600	5,500	-	10,200	15,364	100	372
		600-800	10,200	-	15,700	19,234	100	465
		800-1000	15,700	-	21,900	25,499	100	617
		1000-1200	21,900	-	28,800	26,117	100	632
		1200-1400	28,800	-	36,300	30,116	100	728
		1400-1600	36,300	-	44,400	38,739	100	937
		1600-1800	44,400	-	53,000	42,533	100	1,029
		1800-2000	53,000	-	62,100	47,651	100	1,152
		2000-2200	62,100	-	71,600	53,207	100	1,287
		>2200	71,600	+		67,080	100	1,622
	Steamships	600-800	10,200	-	15,700	32,000	250	1,780
		800-1000	15,700	-	21,900	31,238	250	1,737
		1000-1200	21,900	-	28,800	38,000	250	2,114
		1200-1400	28,800	-	36,300	0	250	0
		1400-1600	36,300	-	44,400	0	250	0
		1600-1800	44,400	-	53,000	69,833	250	3,884
		1800-2000	53,000	-	62,100	0	250	0
		2000-2200	62,100	-	71,600	36,000	250	2,002

Shiptype		design categories	corresponding dwt categories			Avg. LMIS bhp for category	BSFC gram/bhp-hr	cruise fuel consumption for category (gal/hour)
General Cargo	Motorships	0-200	0	-	11,600	2,598	100	63
		200-400	11,600	-	32,900	10,179	100	246
		400-600	32,900	-	60,500	12,988	100	314
		600-800	60,500	-	93,100	16,870	100	408
		800-1000	93,100	-	130,200	35,008	100	847
		>1000*	130,200	+		26,000	100	629

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Shiptype		design categories	corresponding dwt categories			Avg. LMIS bhp for category	BSFC gram/bhp-hr	cruise fuel consumption for category (gal/hour)
Passenger Sh p	Motorships	0-100	0	-	1,400	13,943	100	337
		100-200	1,400	-	4,000	20,544	100	497
		200-300	4,000	-	7,400	26,103	100	631
		300-400	7,400	-	11,500	28,859	100	698
		400-500*	11,500	-	16,000	33,831	100	818
		500-600	16,000	-	21,100	-	100	-
		600-700	21,100	-	26,600	-	100	-
		700-800*	26,600	-	32,500	48,747	100	1,179
	Steamships	0-100	0	-	1,400	-	250	-
		100-200	1,400	-	4,000	-	250	-
		200-300	4,000	-	7,400	24,500	250	1,363
		300-400	7,400	-	11,500	30,220	250	1,681
		400-500	11,500	-	16,000	-	250	-
		500-600	16,000	-	21,100	44,000	250	2,447
			21,100	+				

Shiptype		design categories	corresponding dwt categories			Avg. LMIS bhp for category	BSFC gram/bhp-hr	cruise fuel consumption for category (gal/hour)
Reefer	Motorships	0-100	0	-	1,500	5,134	100	124
		100-200	1,500	-	4,200	6,530	100	158
		200-300	4,200	-	7,800	8,989	100	217
		300-400	7,800	-	12,100	12,846	100	311
		400-500	12,100	-	16,900	12,385	100	300
		500-600	16,900	-	22,200	16,609	100	402
		600-700	22,200	-	28,000	20,797	100	503
		700-800	28,000	-	34,200	23,200	100	561
		>800*	34,200	+		25,500	100	617

Shiptype RORO		design categories	corresponding dwt categories			Avg. LMIS bhp for category	BSFC gram/bhp-hr	cruise fuel consumption for category (gal/hour)
	Motorships	0-200	0	-	2,500	-		
		200-400	2,500	-	7,200	16,683	100	403
		400-600	7,200	-	13,300	19,085	100	462
		600-800	13,300	-	20,500	27,900	100	675
		800-1000	20,500	-	28,700	30,150	100	729
		1000-1200	28,700	-	37,700	34,987	100	846
	Steamships	600-800*	13,300	-	20,500	32,000	250	1,780
		800-1000*	20,500	-	28,700	31,000	250	1,724
		1000-1200	28,700	-	37,700	30,000	250	1,669
		>1200*	37,700	+		32,000	250	1,780

Shiptype Tanker		design categories	corresponding dwt categories			Avg. LMIS bhp for category	BSFC gram/bhp-hr	cruise fuel consumption for category (gal/hour)
	Motorships	0-200	0	-	12,800	5,894	100	143
		200-400	12,800	-	36,300	11,840	100	286
		400-600	36,300	-	66,700	15,252	100	369
		600-800	66,700	-	102,800	16,251	100	393
		800-1000	102,800	-	143,600	19,130	100	463
		1000-1200	143,600	-	188,800	24,726	100	598
		1200-1400	188,800	-	238,000	22,690	100	549
		>1400*	238,000	+		35,000	100	846
	Steamships	0-200	0	-	12,800	7,000	250	389
		200-400	12,800	-	36,300	12,333	250	686
		400-600	36,300	-	66,700	15,587	250	867
		600-800	66,700	-	102,800	20,000	250	1,112
		800-1000	102,800	-	143,600	24,457	250	1,360
		1000-1200	143,600	-	188,800	26,667	250	1,483
		1200-1400	188,800	-	238,000	28,350	250	1,577
		1400-1600	238,000	-	290,800	33,600	250	1,869
		1600-1800	290,800	+		32,000	250	1,780

Notes

1. Calculation of cruise fuel consumption assumes cruise at 80% MCR and assumes a fuel density of 0.95 kg/l

2. BSFC is estimated based fuel consumption estimates for 1983 and newer ships from Reference 18