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Naval Ship Engine Exhaust Emission Characterization

ABSTRACT Legislative and regulatory action is pending at the international, national and state level that will potentially require U.S. Navy compliance with ship engine exhaust emission standards. These standards are based on commercial ship applications and are not suitable models for the time history of naval ship main propulsion engine speed and power combinations. Naval ships are designed and operated much differently than commercial ships and must be considered independently in engine emission regulation. A strategy for testing naval diesel engines for exhaust emissions is presented in this paper. A simple procedure to develop naval ship engine duty (test) cycles by combining ship hull form characteristics, propulsion plant parameters, and ship operating profile is presented. Duty cycles model the time history of engine speed and power. Results for the U.S. Navy LSD 41 Class and MCM 1 Class are presented. Comparisons of the derived LSD 41 Class Duty Cycle with commercial standards show that commercial duty cycles are inappropriate for use in naval applications.

Introduction

Since the beginning of human civilization the benefit of increased industrialization has brought with it the price of pollution. In our modern world the internal combustion engine is the workhorse of commerce. As a source of power, its high energy conversion to weight density has made it the engine of choice for powering our automobiles, trucks, aircraft, and ships. With the shift from wind powered sailing ships, and horse drawn vehicles has come an exponential increase in human generated atmospheric chemicals. These pollutants have degraded the quality of life of our society by endangering public health, degrading the public welfare in decreased visibility and by damaging our infrastructure and natural world.

The U.S. Navy has a long history of using diesel main propulsion engines to power its ships. The first U.S. Navy surface ship to be powered by diesel engines was the 14,500 ton oiler USS *Maumee* commissioned on 23 October 1916. Today, diesel engines are used for main propulsion on amphibious ships, mine counter-measure ships, and many large and small auxiliary ships. Most U.S. Navy ships are equipped with medium speed diesel generators for ship service electric load; a smaller number (69) have diesel main propulsion (NAVSEA, 1991). In the past thirty years diesel engines have also replaced steam plants as the propulsion plants of choice for many commercial ships.

Medium speed diesel engines procured for the Navy must successfully pass a 1,000 hour durability test outlined in Military Specification MIL-E-21260D, "Engines, Diesel Marine, Propulsion and Auxiliary, Medium Speed," of March 1976. A sister document covers high speed diesel engine procurement. No procedure is currently specified by the Navy to test diesel engines for exhaust emissions during the procurement process, or when operational with the fleet.

The State of California has completed several air quality studies. These studies indicate marine vessels substantially contribute to pollutants in the ambient air inventory. Table 1 provides a comparison of marine vessel emissions versus other sources for the State of California in 1987. Included in these studies are emissions from all vessels, including diesel, gas turbine, and steam powered vessels. The vast majority of the approximately 22,500 vessels which operated in California waters during 1987 were diesel powered. Economic pressures forced the conversion of most steam and gas turbine commercial ships to more efficient diesel power during the 1970's and 80's. However, this trend has had a negative impact on ambient air quality as diesel engines produce approximately ten times more oxides of nitrogen (NO_X) than steam boilers (CARB, 1991). The percent contribution of NO_X and sulphur oxides (SO_X) by marine vessels is primarily due to lack of emission regulation compared to other more numerous sources, and the high sulphur content of fuels used for commercial diesel powered ships. Pollutants from ships being considered for future regulation are NO_X, SO_X, and particulate material (PM) which is comprised of carbon and embedded hydrocarbons.

Legislative and Regulatory Initiatives

The International Maritime Organization (IMO) has acknowledged that national and regional legislation to limit engine exhaust emissions from ships is inevitable.

TABLE 1

Marine Vessels Versus Other Sources (1,000 tons/day)

Source	HC	CO	NO_X	SO_X	PM
Stationary	5.30	6.0	0.97	0.21	11.00
On-Road	1.60	11.00	1.90	0.13	0.27
Off-Road	0.34	4.01	0.79	0.05	0.06
Marine	0.03	0.06	0.41	0.23	0.03
Total	7.27	21.07	4.07	0.62	11.36
% Marine	0.40	0.27	10.1	36.7	0.25

[CARB, "Public Meeting", 1991]

NOMENCLATURE

Explanation of Variables Used in This Paper

BHP	— Brake Horsepower
CAA	— Clean Air Act
CARB	— California Air Resources Board
CO	— Carbon Monoxide
CO_2	— Carbon Dioxide
EPA	— Environmental Protection Agency
g/bhp-hr	— Grams per Brake Horsepower Hour
g/kW-hr	— Grams per Kilowatt Hour
HC	— Hydrocarbon
ICOMIA	— International Council of Marine Industry Associations
IMO	— International Maritime Organization
ISO	— International Organization for Standardization
kW	— Kilowatt
MARPOL	— International Convention for the Prevention of Pollution from Ships
MPE	— Main Propulsion Engine
NAAQS	— National Ambient Air Quality Standards
NO_2	— Nitrogen Dioxide
NO_x	— Oxides of Nitrogen
PM	— Particulate Material
RPM	— Revolutions per Minute
SHP	— Shaft Horsepower
SIP	— State Implementation Plan
SO_x	— Oxides of Sulphur
SSDG	— Ship Service Diesel Generator

In response, the IMO's Marine Environmental Protection Committee (MEPC) is currently working on standards for the prevention of air pollution from ships. Specifically targeted is the reduction of NO_X and SO_X without an increase in other air pollutants. The NO_X reduction is expected to be on the order of 30% from 1994 levels. IMO has agreed to formulate a new Annex, Annex 6— Prevention of Air Pollution From Ships, to the International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78. The draft of Annex 6 requires surveys, inspections and certification of machinery configuration of all ships of 400 tons gross tonnage or above for which the total installed power is greater than 1500 kilowatts (kW). NO_X emission limits for new marine diesel engines of more than 100 kW have been proposed. The limits are a function of the engine rated speed, which is defined as engine speed at rated power. The reliance upon a model equating NO_X to speed without regard for engine torque or cylinder pressures favors low speed engines and will likely lead to increased requirements for exhaust after treatment schemes on ships with medium and high speed diesel engines. Figure 1 provides the IMO maximum allowable NO_X emissions curve. The IMO proposal is based on engines operating on marine diesel oil using the applicable ISO 8178, Part 4 duty cycle to model ship operation. Proposed SO_X reduction of fifty percent of 1992 levels by 2000 is to be accomplished by a global cap of five percent fuel oil sulphur content and a limit of fuel sulphur of 1.5 percent on a regional basis in special areas. The special areas also have a total ship SO_X emission cap of 6.0 g/kW-hr. It is expected that Annex 6 will be published in 1997/98. (Draft New Annex, 1994).

Article 3, paragraph 3 of MARPOL 73/78 excludes public vessels which are operated in non-commercial service. However, it is probable that the U.S. Congress will mandate public vessel inclusion upon ratification, compelling U.S. Navy compliance. Congress did just that when it ratified Annex 5 to MARPOL 73/78 in 1987 requiring public vessels to comply with the solid waste disposal standards even though MARPOL 73/78 exempts public vessels.

The U.S. Congress first passed the Clean Air Act (CAA) in meaningful form in 1970, with significant amendment in 1990. The central theme of the CAA is a cooperative federal-state scheme to achieve nationwide acceptable air quality. Under the CAA, the Administrator of the Environmental Protection Agency (EPA) is required to establish national ambient air quality standards (NAAQS) for criteria pollutants. Ambient limits have been established for Particulate Material (PM), Nitrogen Dioxide

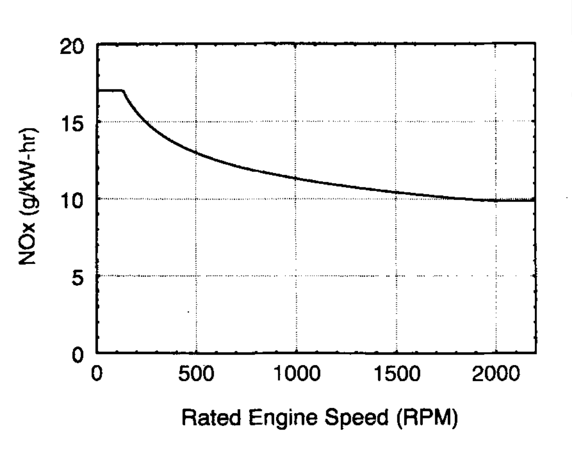

FIGURE 1. IMO NO_x Emissions Limits for Marine Diesel Engines *[Draft New Annex, 1994]*

(NO_2), Ozone, Carbon Monoxide (CO) and SO_X. Further, the CAA also requires each state to develop State Implementation Plans (SIPs) to achieve the federally mandated primary and secondary NAAQS. In SIP development a state must include enforceable emission limitations and other control measures.

To date the U.S. Congress and EPA have adopted a pareto regulation strategy. Standards have been established for stationary sources, and light-duty vehicles (automobiles and light-duty trucks). This practice regulates those air pollution sources where the greatest perceived benefit/cost ratio can be had. The emphasis for future regulation will likely be for the more numerous smaller stationary and mobile sources which include marine vessels. The EPA has broad authority to study, propose, enact, and enforce regulations of mobile nonroad emission sources. EPA has thus far declined to regulate marine vessels since it concluded that information was unavailable verifying existing test procedures as applicable to marine engines. EPA recognized that existing test procedures are not adequate for predicting marine diesel engine emissions (Federal Register, 1993). Draft regulations have been issued for recreational craft, but EPA appears to be awaiting the publication of the new MARPOL 73/78 Annex 6 before taking regulatory action toward ocean going vessels (Federal Register, 1994).

Regardless of EPA action, California Air Resources Board (CARB) has proposed new marine vessel engine emission standards, in-use marine vessel engine emission standards, new and existing source permit requirements, and a broad market based strategy aimed at reducing vessel exhaust emissions. Based upon meteorological studies, CARB has concluded that engine emissions from vessels operating up to 100 nautical miles offshore degrades California ambient air quality (CARB, "Regulatory Strategies", 1991). Therefore, their proposed rules will apply to all vessels operating within this region. In developing the ship operating profiles in this paper, only data for ship operations within 100 nautical miles of land were included.

Although the legislative and regulatory environment has been highly turbulent, action has thus far exempted public vessels for compliance to the evolving standards. The naval community must ensure that future regulations adequately consider the unique operation of naval vessels. Action must be taken now to estimate current emission levels so that when regulation does occur, the magnitude of the challenge will be known. For this reason, the development of naval test procedures is vital for providing repeatable emission data. Several duty cycles have been proposed to accomplish this. However, the unique operation of U.S. naval ships and their resulting engine emissions has not yet been properly modeled. Literature from the Netherlands (Stapersma, 1994) and United Kingdom (English and Swainson, 1994) indicates that similar work is underway there.

Methodology of Duty Cycle Development

Duty cycle development establishes the normal time history of engine speed and power for a given application. The first step is to apply the fundamental principles of ship powering to relate ship speed to engine parameters. Secondly, analysis of ship operating logs must be performed to determine the time/speed operating profile. Log review provides the three independent variables of time, shaft RPM and power. Finally, the operating profile is converted into a duty cycle by applying the speed/power equations for representative operating points. The time history comprising the operating profile is an inference based on recorded ship speed and the speed versus power equations.

SHIP PROPULSION PLANT PARAMETERS

Derivation of the naval ship duty cycle required establishing the proper relationships between ship speed, propeller shaft horsepower (SHP) and rotation rate, and diesel engine speed and brake horsepower (BHP). Reduction gear ratio, mechanical efficiency, shaft turns-per-knot and ship speed versus power relationships must be determined.

For ships equipped with reduction gears, the reduction gear ratio (Λ) relates prime mover RPM to propeller shaft RPM. Equation (1) provides this relation which is required to determine prime mover RPM.

$$\Lambda = \frac{RPM_{Prime\ Mover}}{RPM_{Shaft}} \tag{1}$$

Power is lost due to component friction where power is transmitted from the prime mover to the propeller. Mechanical efficiency (η_{MECH}) compares SHP measured at the propeller and BHP measured at the prime mover output shaft. Equation (2) provides this relation which is required to determine prime mover output.

$$\eta_{MECH} = \frac{SHP}{BHP} \tag{2}$$

For ships equipped with Controllable Reversible Pitch (CRP) propellers, direct drive power transmission systems or electric propulsion, the relation between shaft and prime mover RPM is not as straight forward and must be handled on a case basis. The LSD 41 and MCM 1 Classes each have two CRP propellers and operate over two distinct speed ranges. At low ship speeds, speed is controlled by varying propeller pitch. At high ship speeds, speed is controlled by shaft RPM. In the pitch controlled regime the shaft is operated at a constant RPM; speed is varied by changing the pitch of the propeller. At higher speeds propeller pitch is set at 100 percent and speed is varied by shaft RPM. However, within the two regimes a mostly linear relation between pitch/rpm and speed exists. Therefore, ship speed may be modeled as linearly dependent on propeller pitch or shaft RPM. Equation (3) gives the ship speed equation for operation in the constant RPM region where speed is governed by propeller pitch. Equation (4) gives the ship speed equation for operation in the RPM controlled region. Where α and β are curve fit coefficients corresponding to the rate of change of speed and γ is the offset to account for the pitch controlled region.

$$Speed_{Ship} = \alpha \times Pitch_{Propeller} \tag{3}$$

$$Speed_{Ship} = \beta \times RPM_{Shaft} + \gamma \tag{4}$$

For ships equipped with constant pitch propellers, ship speed is directly proportional to shaft RPM, with the "Turns-per-Knot" (TPK) ratio the constant of proportionality.

The ship propulsion plant must provide sufficient power to overcome ships resistance to motion. During ship design, powering requirements are determined analytically and by scale model testing. Once the ship has been built, Standardization Trials establish the actual relation between ship speed and SHP. Figure 2 illustrates this relationship between ship speed and SHP. It is necessary to study this curve to determine SHP corresponding to ordered ship speed. The curve of Figure 2 is a combination of two curves covering the two ship resistance regimes. The frictional regime can be modeled as a quadratic equation as given by Equation (5) and the residuary dominated regime represented as a cubic equation by Equation (6). Equation (5) is valid up to twelve knots, and Equation (6) is valid from ten to twenty-five knots. The overlap of two knots illustrates the transition from frictional to residuary resistance control. Where γ, δ, μ, ϵ, ξ, and κ of Equation (5) and Equation (6) are constants describing the hydrodynamics of the hull form, which were determined by curve fitting the data. It is necessary to derive the specific speed/power equations for the ship class being modeled, Figure 2 and Equation (5) and Equation (6) are for illustrative purposes only.

$$Power = \gamma \times Speed^2 + \delta \times Speed \tag{5}$$

$$Power = \mu \times Speed^3 - \epsilon \times Speed^2 + \xi \times Speed - \kappa \tag{6}$$

OPERATING PROFILE DETERMINATION

An operating profile gives the time history of ship speed. It may be developed from shipboard installed special instrumentation to record speed changes over time or from the review of ships logs. For this paper, information gained from review of the ships Deck Logs was used to develop the class operating profiles. In keeping with the intention of CARB, the class operating profiles are derived from ship operation data limited to within 100 nautical miles of land. The primary log data used in this analysis were time and ordered ship speed (based on propeller pitch and shaft RPM).

The wide range of operator preferences coupled with the variety of ship evolutions and mission profiles complicates the development of a class operating profile. The operating profiles developed in this paper considered steady state operation only. The method of data collection used was not conducive to capturing transient information. However, this was deemed acceptable since several orders of magnitude separate the time spent in transient and time spent in steady state operations. The typical main propulsion diesel transient event is a relatively short order event.

Figure 3 gives the operating profile of the LSD 41 Class operating within 100 nautical miles of land, and Figure 4 the MCM 1 Class. Details of the profile development are given in Appendix A. The ship speeds and composite time factors given in Figure 3 should be representative of most naval diesel powered amphibious assault ships while they operate in areas close to shore. The LSD 41 Class speed profile shows that it operates primarily in the higher speed ranges centered around seventeen knots. This is not coincidence since seventeen knots is near the design endur-

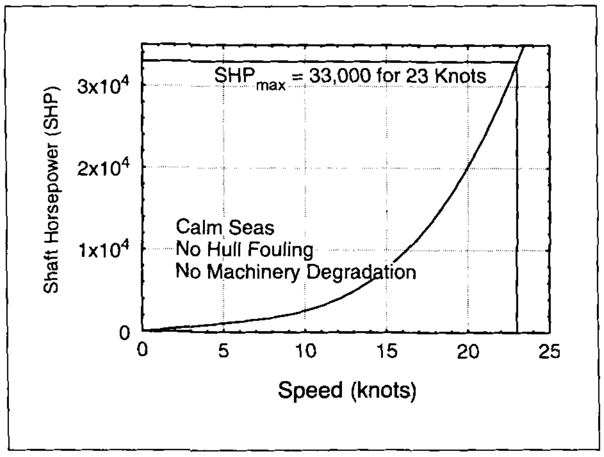

FIGURE 2. Typical Speed Power Curve

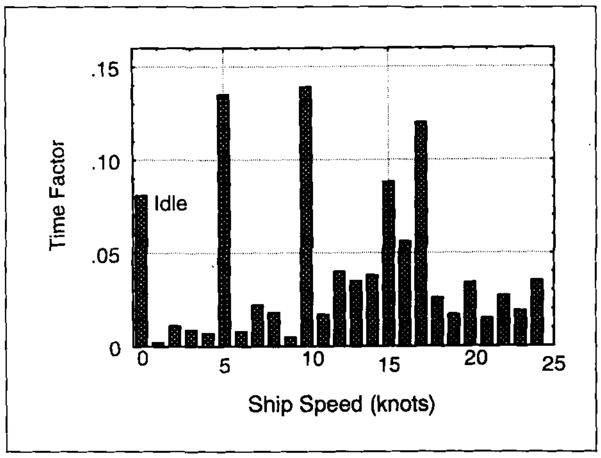

FIGURE 3. LSD 41 Class Operating Profile

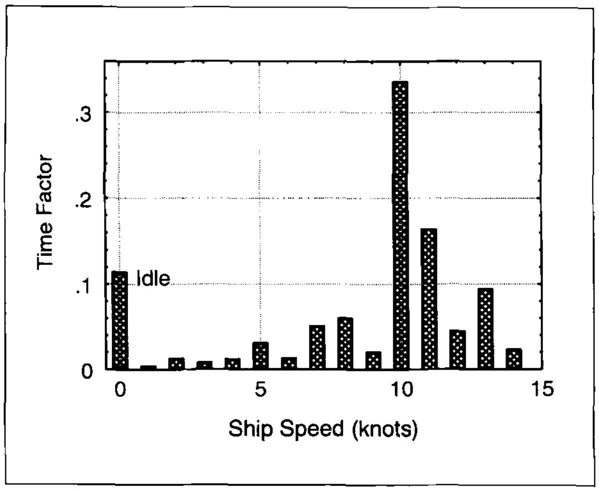

FIGURE 4. **MCM 1 Class Operating Profile**

ance speed for most U.S. Naval ships and is typical of speeds used for transit. Review of Figure 4 implies that the MCM 1 Class ships operate primarily in the higher speed ranges and at idle. The idle time factor for both ship classes was defined to include all intervals in which the engines were operated declutched for warm-up or cool-down, drills, and intervals during which the engines are online but not providing propulsion power. The difference in engine load for these conditions is insignificant. There is a significant spike at ten knots for the MCM 1 Class which corresponds to a favored speed for transit operations. The notable difference in the operating profile between the two ship classes illustrates the significance of ship's mission on propulsion plant operations, implying that the operating profile should be the primary factor on which the duty cycle time factors are based (Mayeaux, 1994).

MAIN PROPULSION DIESEL DUTY CYCLE

A duty cycle must provide an accurate model of the range of speed and power points at which an engine is operated, and also be concise and easy to use. A duty cycle consisting of five to ten modes is preferable to one using ten to fifteen, provided it accurately reflects engine operation. However, accuracy should not be sacrificed for brevity. The duty cycle must simulate the actual operating profile such that engine emissions are equivalent.

To date, most duty cycles have been developed for generic application to a wide variety of land based power systems. Several have been derived for commercial ship operations, but none for naval applications. Commercial ship engines are designed to provide optimum fuel economy at some cruising speed. Engines are sized according to ships full load weight. For an established cruising speed, the fraction of rated engine RPM and engine power are relatively constant. The theory behind ISO 8178, Part 4 Duty Cycles E1, E2 and E3 reflects operation at a few engine speed/power combinations. For most of their operational life commercial ships cruise at between fifteen and twenty knots, therefore the ISO 8178 duty cycles are sufficient to model this operational profile.

Naval ship engines are sized for performance rather than efficiency. The ship hull is established and propulsion plant sized to provide some design sustained speed in excess of the endurance (cruise) speed. For example, the operating profile of Figure 3 shows that the LSD 41 Class has a top speed of twenty-four knots. However, it operates most frequently at seventeen knots. This apparent overcapacity in propulsion plant power results in an extremely wide range of engine operating combinations. The majority of naval ship hulls are displacement type but of many different shapes, each having a distinct speed power relation. The diversity of diesel engine sizes and types, coupled with the wide variety of hull form designs, complicates the use of generic speed power simplifications. Each hull design has a unique resistance relationship resulting in myriad diesel engine options. For these reasons, a simple four or five mode duty cycle may not be appropriate to describe naval ship engine operation. Rather, the operating (speed) profile must be determined, then engine speed and power calculated based on appropriate relationships.

Figure 5 illustrates the flow of information required to synthesize the points of a duty cycle. The procedure will yield engine speed, engine power and time spent at each point for each speed given in the operating profile. The task of the engineer is to collect similar points to derive a duty cycle with a reasonable number of points to give an accurate model. Ranges covered by each speed point were grouped by engine speed and power around each major speed spike indicated in Figures 3 and 4.

Derived Ship MPE Duty Cycles

LSD 41 CLASS MPE DUTY CYCLE

The LSD 41 Class may be operated with either one or two engines per shaft. Both conditions must be included in the resulting duty cycle because of the different engine speed and power points. The LSD 41 MPE Duty Cycle, as developed from the method given in Figure 5, is given in Table 2.

MCM 1 CLASS MPE DUTY CYCLE

As the LSD 41 Class, the MCM 1 Class may be operated with either one or two engines per shaft. Therefore, both conditions must be included in the resulting duty cycle. The MCM 1 MPE Duty Cycle is provided in Table 3.

The number of modes for both the LSD 41 Class and MCM 1 Class Duty Cycles provide a good representation of these ships observed operation. It should be understood that actual engine emission testing will likely reveal similar emission data for modes adjacent to one another. In this

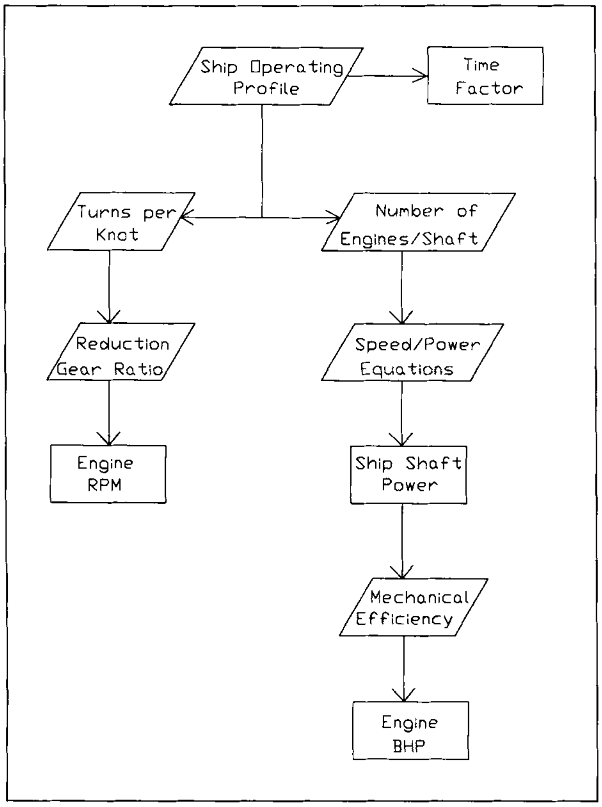

FIGURE 5. Duty Cycle Development Flow Chart

case, good engineering judgement would dictate a reduction in the number of modes to be tested.

Duty Cycle Comparison

Diesel engine duty cycle comparisons were performed to validate methodology used in preparing the naval ship duty cycle, and compare it to industry accepted standards. Detailed engine emission information for the LSD 41 Class Colt-Pielstick 16 PC2.5 V400 medium speed diesel MPE is not available in the open literature. To perform the duty cycle comparisons, emission contour maps provided in *The Motor Ship* (1992) for the Colt-Pielstick PC4-2B were used. Three dimensional information is displayed as a contour map in two dimensions. These graphs for NO_X, CO, gaseous HC and carbon dioxide (CO_2) were normalized to rated power and RPM to give maximum speed and power values of unity. Figure 6 provides a typical NO_X emission contour plot used in this analysis. The propeller curves for the LSD 41 Class are shown on Figure 6 to illustrate the technique used to describe engine emissions as a function of ship speed.

Propeller curve plots of single and twin engines per shaft, the derived LSD 41 Class 11-Mode Duty Cycle and seven industry duty cycle points were superimposed on the emission contour maps. Brake specific emission levels were then read from the curves by linear interpolation. The specific emission data was then reduced using the procedure of ISO 8178, Part 2. Table 4 provides the results of this comparison for the LSD 41 Class. The actual test points for each duty cycle are given in Appendix B.

Data presented in Table 4 shows strong correlation between the propeller curve and duty cycle predictions. Differences between emission values are on the order of two percent and deemed negligible. Since the propeller curve is assumed to reflect actual operation, this provides a high degree of assurance that the 11-Mode duty cycle is accurate.

The CARB 8-Mode Duty Cycle gives the next best NO_X comparison at 0.6 g/bhp-hr (7%) greater than propeller curve prediction. CO predictions provided by the LSD 41 Class Propeller Curve, LSD 41 Class 11-Mode Duty Cycle, ICOMIA 36-88 Duty Cycle, and U.S. EPA 13-Mode Duty Cycle are equivalent. The CARB 8-Mode is second best in predicting HC emissions at 0.1 g/bhp-hr (17%) below the propeller curve. For CO_2, the U.S. EPA 13-

TABLE 2

LSD 41 Class MPE Duty Cycle

Mode	Ship Speed	Engines/Shaft	Engine Speed (Fraction of Rated)	Engine Power (Fraction of Rated)	Time Factor
1	0	0	Idle	0.000	0.083
2	5	1	0.387	0.065	0.064
3	5	2	0.387	0.032	0.128
4	10	1	0.398	0.158	0.077
5	10	2	0.398	0.078	0.141
6	15	1	0.615	0.468	0.051
7	15	2	0.615	0.234	0.109
8	17	1	0.700	0.704	0.040
9	17	2	0.700	0.352	0.160
10	20	2	0.833	0.612	0.093
11	24	2	1.000	1.000	0.054

[Markle, 1993]

TABLE 3

MCM 1 Class MPE Duty Cycle

Mode	Ship Speed	Engines/Shaft	Engine Speed (Fraction of Rated)	Engine Power (Fraction of Rated)	Time Factor
1	0	0	Idle	0	0.123
2	3.8	1	0.442	0.205	0.031
3	3.7	2	0.442	0.100	0.013
4	7	1	0.536	0.328	0.047
5	7	2	0.442	0.164	0.018
6	8.4	1	0.657	0.434	0.034
7	9.8	1	0.778	0.732	0.073
8	10.3	2	0.685	0.401	0.305
9	11.6	1	0.881	1.000	0.130
10	11.3	2	0.772	0.518	0.081
11	12.6	2	0.863	0.693	0.101
12	13.9	2	0.935	0.877	0.025

[Mayeaux, 1994]

Mode Duty Cycle follows the LSD 41 Class 11-Mode Duty Cycle at 22 g/bhp-hr (5%) over the value of the propeller curve. In short, no single duty cycle offers the consistency of the LSD 41 Class 11-Mode Duty Cycle in predicting LSD 41 Class engine exhaust emissions.

The conclusion drawn from Table 4 data is that no commercial standard evaluated provided a consistent model for predicting levels of the four pollutants. The analysis presented using normalized emission data for engine classes was done to provide a means of comparison between the derivative and existing commercial duty cycles. The predictions are not representative of emissions from the LSD 41 Class over the course of normal operations. Mayeaux (1994) found similar results for the MCM 1 Class.

TABLE 4

LSD 41 Class MPE Duty Cycle Emission Prediction Summary (g/bhp-hr)

Method	NO_x	CO	HC	CO_2
LSD 41 Class Propeller Curve	8.5	1.5	0.6	475
LSD 41 Class 11-Mode Duty Cycle	8.3	1.5	0.7	483
ISO 8178-4 E3 Duty Cycle	9.9	1.0	0.3	433
ISO 8178-4 E1 Duty Cycle	6.9	1.6	1.0	499
ICOMIA 36-88 Duty Cycle	6.8	1.5	1.0	499
Japanese Heavy-Duty Diesel Cycle	9.8	1.2	0.4	444
U.S. EPA 13-Mode Duty Cycle	7.3	1.5	1.0	497
CARB 8-Mode Duty Cycle	9.1	1.1	0.5	452
U.S. Navy Endurance Test	7.7	1.0	0.4	444

[Markle and Brown, 1995]

Summary and Conclusion

Future EPA and international regulations will require engines to be prequalified for emission levels by demonstrating performance on a test bed using a predetermined duty cycle. The U.S. Navy, Naval Sea Systems Command Code 03X3, published *Internal Combustion (Gas Turbine and Diesel) Engine Exhaust Emission Study* in 1991. On page 6-1 of this study, the following observation is made: "Before the Navy can begin an emission test program it must decide the test points for which to collect emission data . . . " This paper recommends a methodology for determining the test points for diesel powered ships. Similar procedures could easily be developed for other naval ship propulsion systems.

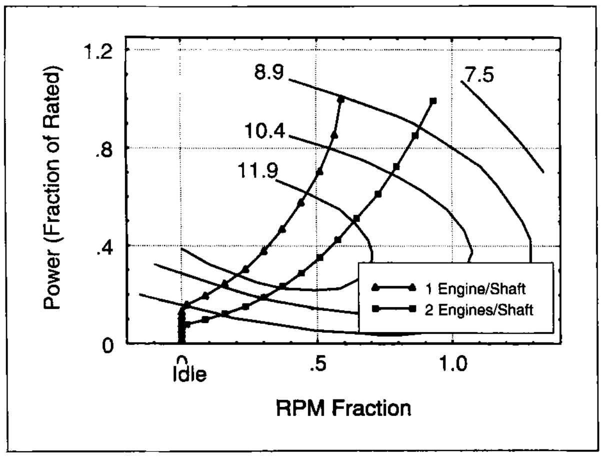

FIGURE 6. Colt-Pielstick PC4-2B NO_x Emission Contour Plot (g/bhp-hr)

Comparison of the data in Tables 2 and 3 shows the same trend existing between Figures 3 and 4. Although both are naval ships, differences in operating profile and ship speed power relationships have resulted in very different duty cycles. The engine speed and power points cannot be combined into a single naval ship duty cycle. Ideally, operating profiles should be compiled for each naval ship mission type (i.e. mine hunting, amphibious assault, small auxiliary ship, auxiliary ship, etc . . .) and ship class specific duty cycles developed to capture actual engine operation.

A duty cycle must provide an accurate correlation and prediction of actual emissions performance over some range of operation. The range of operation will include different applications that must be modeled individually. To facilitate the U.S. Navy ship design process, a two step procedure for engine emission certification is proposed. First, prequalify the engine at the same time the U.S. Navy Endurance Test is performed by measuring emissions at Endurance Test speed/power points. The Endurance Test continues for 1,000 hours offering ample time to measure engine emissions under steady state conditions. The emissions test procedure should follow the guidelines of ISO 8178, Part 2. Concurrent emission measurement done in this manner should not present a burden to the engine manufacturer. Second, certify the engine after matching engine to hull form.

Emission data derived from the Endurance Test would form the basis for engine certification by the Navy. After marrying a specific hull design with a certified engine, emission prediction refinement, using the procedure of Figure 5, would be required. The environmental impact statement prepared by the ship program manager should reflect the refined emission prediction. Existing naval ship MPE's should be tested at speed/power points and time factors derived from Figure 5, using ISO 8178, Part 2 for procedural guidance. Ship service diesel engines should be exhaust emission pre-qualified and final emission certified following a similar procedure. In the case of constant speed diesel generators, it is probable that a modified ISO 8178, Part 4 duty cycle D2 could be adopted by the Navy for final emission certification. The time factors (weight factors) of D2 can be readily modified to match actual ship operation by cursory review of the ship's electrical logs.

Industry standard duty cycles of ISO 8178, Part 4, EPA and others were shown to be inappropriate for estimation of naval ship engine exhaust emissions. The certification method presented in this paper is applicable to both main propulsion and ship service diesel engines.

Appendix A: Operating Profile Statistics

The operating profiles and subsequent duty cycles for the LSD 41 and MCM 1 Classes presented in this paper were developed by review of ship operating logs. Data was recorded for operations out to 100 nautical miles from land. This appendix provides the statistics and comparisons of the data between the ships reviewed.

LSD 41 CLASS

Four LSD 41 Class ships logs, covering several months of operation within 100 nautical miles of land, were analyzed. Two ships were homeported in Little Creek, Virginia, and two were homeported in San Diego, California. Table 5 presents a summary of the operational time evaluated.

MCM 1 CLASS

The operating logs for three ships of the MCM 1 Class were reviewed to form the MCM 1 Class Operating Profile of Figure 4. The three ships selected had recently completed similar operations that are representative of the twelve ship class. Results are presented in Table 6. Included in the six months reviewed are unequal portions in which all engines were out of commission due to repair work.

OPERATING PROFILE VARIATION

The LSD 41 Class Operating Profile provided in Figure 3 is a composite of the four ships profiles. Figure 7 illustrates the variation between the four ships and shows that each ship is operated in generally the same manner. Trends given by the four curves are of the same shape; they track within a band of eighteen percent variation. The greatest variation occurs at speeds above ten knots. The indicated variation is largely dependent upon the evolutions each ship was engaged in as well as the preference of the individual operator.

TABLE 5

LSD 41 Class Main Propulsion Engine Ship Data Summary

	LSD 43	**LSD 44**	**LSD 46**	**LSD 47**
Name (USS)	*Fort McHenry*	*Gunston Hall*	*Tortuga*	*Rushmore*
Coast	West	East	East	West
Dates (1993)	12 Jul–16 Dec	14 Sep–30 Nov	3 Mar–20 Sept	1 Jun–16 Dec
Data Points	5,011	2,816	4,267	3,013
Engine Time in Minutes				
Total	252,324	133,052	159,845	145,517
Secured	74,589	54,499	76,872	51,025
Running	177,735	78,553	82,973	94,492
Declutched	1,458	1,306	1,892	1,571
@ Idle	2,886	1,725	2,357	1,155
@ Power	173,391	75,522	78,724	91,766

[Markle, 1993]

TABLE 6

MCM 1 Class Main Propulsion Engine Ship Data Summary

	MCM 12	MCM 11	MCM 13
Name (USS)	*Ardent*	*Galdiator*	*Warrior*
Dates (1994)	1 May–31 Oct	1 May–31 Oct	1 May–31 Oct
Data Points	4,926	6,330	3,757
Engine Time in Minutes			
Total	211,318	221,760	161,640
Secured	191,321	187,603	139,130
Running	19,997	34,157	22,510
Declutched	623	1,830	965
@ Idle	2,974	2,155	1,022
@ Power	16,400	30,172	20,523

[Mayeaux, 1994]

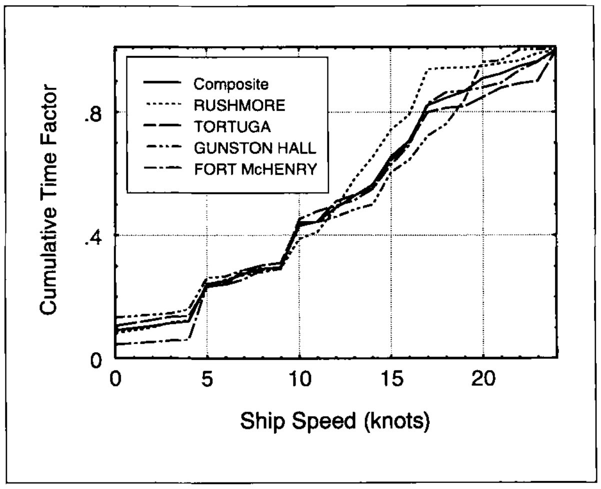

FIGURE 7. LSD 41 Class Operating Profile Cumulative Time Factor Comparison

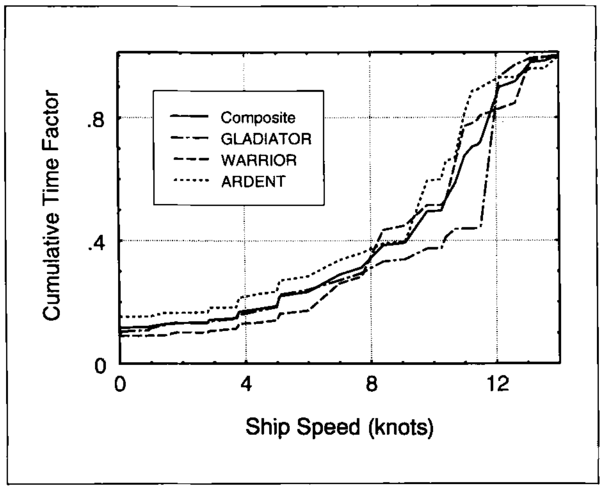

FIGURE 8. MCM 1 Class Operating Profile Cumulative Time Factor Comparison

Figure 8 demonstrates the variation of how each of the MCM 1 Class ships considered in the analysis were actually operated. The variations at low speeds is minimal, with significant deviations beginning at a speed of approximately eight knots. This variation reflects the influence of operator preference in developing a class wide operating profile. The large deviation for the USS *Gladiator* beginning at approximately eight knots was created when the ship was tasked with an additional transit beyond that assigned to the other two ships analyzed. This was an isolated event which had little impact on the class wide operating profile (Mayeaux, 1994.)

Appendix B: Industry Duty Cycles Evaluated

This appendix contains the test points for the seven duty cycles that were used for comparison purposes. They appear in the order given in Table 4. Parent documents may be found in the Reference section. Engine speed and power have been normalized to the rated condition.

TABLE 7

ISO 8178-4 E3 Duty Cycle

Mode	Engine Speed	Engine Power	Time Factor
1	0.63	0.250	0.15
2	0.80	0.500	0.15
3	0.91	0.750	0.50
4	1.00	1.000	0.20

[ISO 8178, 1992]

TABLE 8

ISO 8178-4 E1 Duty Cycle

Mode	Engine Speed	Engine Power	Time Factor
1	Idle	0.000	0.40
2	0.60	0.250	0.25
3	0.60	0.500	0.15
4	0.60	0.750	0.14
5	1.00	1.000	0.06

[ISO 8178, 1992]

TABLE 9

ICOMIA Marine Engine Duty Cycle (Standard No. 36–88)

Mode	Engine Speed	Engine Power	Time Factor
1	Idle	0.000	0.40
2	0.40	0.253	0.25
3	0.60	0.465	0.15
4	0.80	0.716	0.14
5	1.00	1.000	0.06

[Morgan and Lincoln, 1990]

TABLE 10

Japanese Heavy-Duty Diesel Duty Cycle

Mode	Engine Speed	Engine Power	Time Factor
1	Idle	0.00	0.035
2	0.40	1.00	0.071
3	0.40	0.25	0.059
4	0.60	1.00	0.107
5	0.60	0.25	0.122
6	0.80	0.75	0.286

[NAVSEA, 1991]

TABLE 11

EPA 13-Mode Duty Cycle

Mode	Engine Speed	Engine Torque	Time Factor
1	Idle	0.00	0.067
2	Intermediate	0.02	0.08
3	Intermediate	0.25	0.08
4	Intermediate	0.50	0.08
5	Intermediate	0.75	0.08
6	Intermediate	1.00	0.08
7	Idle	0.00	0.067
8	Rated	1.00	0.08
9	Rated	0.75	0.08
10	Rated	0.50	0.08
11	Rated	0.25	0.08
12	Rated	0.02	0.08
13	Idle	0.00	0.067

[NAVSEA, 1991]

TABLE 12

CARB 8-Mode Duty Cycle

Mode	Engine Speed	Engine Power	Time Factor
1	Idle	0.00	0.05
2	Rated	0.75	0.15
3	Rated	0.50	0.15
4	Idle	0.00	0.05
5	Max. Torque	1.00	0.15
6	Max. Torque	0.75	0.15
7	Max. Torque	0.50	0.15
8	Max. Torque	0.30	0.15

[Stiglic, 1990]

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TABLE 13

U.S. Navy Medium Speed Diesel Engine Endurance Test

Mode	Engine Speed	Engine Power	Engine Speed
1	0.250	1.00	1.00
2	0.125	0.85	1.00
3	0.021	0.00	Idle
4	0.229	1.00	1.00
5	0.021	0.00	Idle
6*	0.063	0.50	0.75 (Reverse)
7	0.021	0.00	Idle
8	0.021	0.85	1.00
9	0.229	1.10	1.00
10	0.021	0.00	Shutdown

[MIL-E-23457B, 1976]

*For main propulsion engines, for constant speed engines (i.e. SSDG) fifty percent load at rated speed in the forward direction.

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