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Advocating the Development of Universal Onboard Marine Emission Measurement Protocols

ABSTRACT

The pressure on the marine industry to reduce emissions continues to grow. Since requirements to reduce emissions can have significant impacts on operations and costs, it is important that the industry respond in an efficient and effective manner to present and future challenges. An important factor in most efforts to reduce marine emissions is the need for an accurate method to measure baseline and controlled emissions onboard vessels in operation. Testing protocols need to be developed that are well engineered, clearly documented and widely shared. These protocols may need to vary depending upon the end use of the data, but by developing a set of protocols that meet these requirements within best practices for accuracy and quality assurance, the cost and difficulty in achieving the ultimate goal of reducing emissions will be minimized.

This paper discusses the need for a set of widely accepted protocols, delineates the challenges presented by on-site testing in a marine environment, discusses testing approaches, and instrumentation and defines areas requiring further research. The paper also sets forth recommendations for future actions that could be undertaken to move the process of normalizing requirements forward. As a cumulative voluntary effort of the individual authors, this paper does not represent the position of their respective organizations.

INTRODUCTION

Emission measurement protocols define how emissions must be measured. Test set-up, instrumentation, accuracy, test duration, and many other issues are defined so that the requirements are clear to all concerned with the test. Testing engines under laboratory conditions is well defined by existing protocols. Testing of engines on site while in operation presents additional challenges. Further challenges present themselves when testing engines in a marine environment.

However, testing marine engines under actual operating conditions provides important information that cannot be obtained from data generated in test cells. Onboard testing is a current and ongoing need. A number of emission measurement protocols have been applied to onboard testing of marine engines and others are in development or contemplated. The development of multiple protocols can result in a number of problems including incompatibility of data, higher testing costs, and inappropriate testing. Misapplied testing may either exceed or fail to meet actual testing requirements.

NEED FOR MARINE EMISSION MEASUREMENT PROTOCOL

Background

In recent years the maritime industry has seen its contributions to air pollution increasingly scrutinized. Environmentalists, regulators, and policy makers, having witnessed significant progress in the decline of criteria pollutants generated by stationary facilities and on-road transportation, are now directing attention to the marine sector.

Emission testing can be timely and useful for vessel operators, given recent policy development internationally and domestically. In 1997, the International Maritime Organization

(IMO) adopted a Protocol to amend MARPOL 73/78 (IMO 1998), adding a new Annex VI to the Convention entitled "Regulations for the Prevention of Air Pollution from Ships." When it comes into force, MARPOL Annex VI will set limits on the oxides of nitrogen (NOx) and sulfur (SOx) emissions from ship exhaust and prohibit deliberate emissions of ozone-depleting substances. In addition, IMO has begun discussions on climate-change gases, including carbon dioxide (CO_2), with the aim of developing technical measures to reduce their emissions. Eight of 15 required Flag States, accounting for about 26% of the required 50% gross tonnage of the world's merchant shipping, have ratified Annex VI as of 3 June 2003. These regulations may require operators of older vessels to conduct emissions testing as part of the Supplement to International Air Pollution Prevention Certificate, if the engines are modified to extend their useful life, adapt the vessel performance for new service, or for other purposes.

The U.S. Environmental Protection Agency (EPA) established engine emission controls for U.S.-flag commercial marine vessels operating domestically, and recently proposed regulations for large engines on oceangoing U.S. vessels (EPA 1998; EPA 2002). State and local governmental organizations charged with designing and implementing emission control programs have mounted significant efforts in recent years to improve air quality by reducing ozone concentrations and other pollution. EPA-mandated state implementation plans (SIPs), combined with federal mobile source emission control programs, have been very successful for other non-marine sources of air pollution. The main precursors of ozone, NOx and volatile organic compounds, have been reduced in many areas and average ozone levels are beginning to decrease.

EPA regulations specify that onboard emission testing may be used to "identify and hold manufacturers responsible for noncompliance with the emission standards" (including the Not-to-Exceed limits). The Clean Air Act authorizes EPA to pursue an emission-related recall if "a substantial number of engines, when properly maintained and used, do not conform to the regulations throughout their useful life" (EPA 1999). For Category 1 and 2 engines (categorization based on individual cylinder displacement), EPA is interested in, but does not require, in-use testing to confirm the operators maintain their Not-to-Exceed emission standards. EPA also expects operators who participate in the voluntary low-emitting engine program (known as the Blue Sky program) may use on-site emission testing to demonstrate compliance with the voluntary emissions standards. For Category 3 engines, EPA stipulates that "operators do not need to conduct onboard emission measurements after adjusting the engines (or before they enter U.S. territorial waters) to demonstrate that the engine continues to meet the standards after such adjustments. We intend to revisit these issues in our future rulemaking." (EPA 2002).

Current regional inventories place increasing importance on marine vessel emissions, especially NOx, SOx, and particulate matter (PM). EPA forecasts that increased transportation and trade associated with economic growth will cause emissions to increase and eventually outpace per-source reductions in air pollution. In San Francisco Bay and in Los Angeles County ship exhaust emissions account for more than 4% of current NOx inventories; projections for these regions suggest that emissions from marine vessels will double over the next decades, through trade growth and/or ferry expansion unless pollution controls are adopted. States like California and Texas are including emissions reduction goals for marine vessels in their SIPs to meet air quality goals under federal Clean Air Act requirements (California Air Resources Board 1994; TNRCC 1999).

Even local government agencies like the (San Francisco) Bay Area Air Quality Management District, the South (California) Coast Air Quality Management District, and the Ports of Los Angeles and Long Beach are attempting to quantify and reduce emissions from marine engines. A memorandum of agreement between multiple local and state agencies has established a voluntary speed reduction zone within 20 miles of the Ports of Los Angeles and Long Beach in San Pedro Bay (Los Angeles Board of Harbor Commissioners, Yamaki et al. 2001). This agreement attempts to reduce NOx emissions primarily by requesting all vessels to transit this region at 12 knots. This agreement, like other federal and international policies, is based on calculated benefits of speed reduction but would require emissions testing to verify the actual reductions.

Several states and local agencies are pursuing emissions testing as a means to increase the quality of data used in estimating total emissions from vessels operating in certain regions. For example, the Port of Los Angeles announced a Clean Air Plan in October 2002 that will support ship emissions research and efforts to retrofit vessels (i.e., demonstration projects) (Port of Los Angeles 2002). California regulators are also developing a cooperative effort to demonstrate and implement emission reduction technologies on large vessels. Similar activities have involved ferry testing, tugboat testing, and large vessel testing in ports including those of Houston, New York/New Jersey, Norfolk, San Francisco, and San Diego. Many state and local organizations are also considering incentive programs or providing funds for demonstration projects. Participation in these activities usually requires emissions testing by an operator.

Each of these regulations and actions highlight uncertainties with regard to emission measurement and give rise to the following questions:

- What are the best methods or protocols to physically measure emissions generated from vessels so that the effectiveness of regulations, incentive programs, and technologies can be evaluated?
- What testing techniques can be used to meet the significant challenges and variables of testing in the marine operating environment?
- Can current protocol requirements be modified to make in-service marine testing practical without significantly affecting accuracy and repeatability?

Purpose

The purpose of this paper is to explore the need for developing standard underway marine emission measurement protocols. Descriptions of measurement challenges created by the unique marine operating environment are examined. Suggestions for an initial protocol development are presented with instrumentation requirements discussed and contrasted against shore-side laboratory and in-use equipment measurement protocols. Finally, future actions necessary to develop standardized protocols are recommended.

Defining the Scope of an Initial Emission Test Protocol

Varied testing objectives will ultimately require the development of a number of specialized protocols. It is proposed that initially a generalized marine test protocol be identified or developed. From this base protocol, variations may be made to address specific situations. This paper will address a protocol that is limited to:

- Rigorous legal and scientific testing as opposed to less formal testing. Less stringent tests can be simplified by relaxing certain requirements of the more stringent standard.
- Steady state and transient operation.
- Direct connected and clutched/geared propulsion diesel engines driving propellers or waterjets and operating at either variable, stepped, or constant speeds.
- Auxiliary diesel engines driving alternators at constant speed.
- Diesel engines burning distillate or residual diesel fuel.
- The measurement of the criteria pollutants (NO_x, PM, SO_x, and hydrocarbons [HC]).

Prime movers other than diesel engines, fired boilers, and incinerators are not addressed. It is recommended that follow-on efforts would develop more specialized protocols. The following subsections address issues that need consideration for marine emission measurements.

PROTOCOL CONTENT

Unique Marine Issues

The installation of diesel engines on marine vessels typically combines characteristics of two well-regulated industries – over-the-highway trucking and power generation. Marine diesel engines see transient operation and variable intake air conditions like truck engines, and have space availability similar to power generation applications. However, measurement of emissions onboard vessels presents numerous challenges when compared to on-site testing of other on- and off-road diesel engines. Complicating factors for measuring marine diesel engine exhaust emissions include:

Sea Environment – Wind, current, and sea state effect the operation of the vessel and the resulting engine emissions. Heavy weather can cause severe vessel motions and vibration that may adversely affect both test equipment and personnel. Salt spray can cause corrosion and be detrimental to the operation of the test equipment.

Ambient Conditions – Air and sea temperatures, barometric pressure, and relative humidity will affect engine performance. The environmental conditions at the time of testing can vary widely and effect engine performance and emissions directly.

Condition of Underwater Hull – Fouling or roughness of a vessel's underwater hull and propeller affects the speed-power relationship of the engine and the speed-power relationship of the vessel. This can effect the maximum obtainable power of the engine, the emissions at specific engine speeds, and the emissions at specific vessel speeds.

Revenue Service – Most vessels under test will be in revenue service making access difficult except at certain times and locations. It may be cost prohibitive for a commercial operator to take his vessel out of revenue service for extensive emissions testing. If tests are conducted with passengers on board, safety and access become major issues.

Shipboard Engines – A wide variety of engine types can be found on commercial vessels. EPA has divided marine engines into Category 1, 2, and 3 based on both individual cylinder displacement and similarity to land-based engines (e.g. non-road farm equipment, locomotives, and stationary power generators, respectively). Emission measurement instrumentation and test protocols applicable to one category may not reflect the needs of another.

Payload – Commercial vessels will often operate under different levels of passenger or freight loading on subsequent trips. Changes in loading will affect vessel draft, transient response time, and engine horsepower.

Maneuvering – Vessels change speeds rapidly when maneuvering (i.e., coming into port, docking, avoiding traffic, picking up a harbor pilot, engaged in a utility service, contending with river curves and currents, etc). The inertial forces, associated dynamics, and work produced by an engine in response can be widely inconsistent between subsequent maneuvers and trips.

Calibration Gases – Some of the compressed gases needed for instrument calibration are flammable or explosive. Large volumes of compressed gas are closely regulated on vessels especially on passenger vessels where they may be prohibited.

Cost of Test Personnel Onboard – The cost associated with situating test personnel on a vessel, often for several days, can be significant.

Wet Exhaust Installations – In order to simplify design, some small vessels utilize wet exhaust systems. Water is injected into the exhaust to reduce its temperature and the stream is directed overboard. This limits the optional locations for the exhaust measuring probe/s. Some marine engine exhaust is ducted to exit the hull near or into the water so that a probe in the exhaust exit would not be practical.

Operating Modes – Operating modes that reflect those occurring under normal operation in the region of interest are of primary importance for emissions measurement. Port authorities are interested in reducing emissions within the port that may include operation in a restricted speed zone, low power transit in and out of the port, significant transient operation while maneuvering during docking, and operation of auxiliary engines at the dock. Coastal counties need to determine emissions from vessels at or near full operational power while transiting close to land. In general, engines should be operated as close as possible to the normal operating conditions as determined from logbooks and discussion with operators.

Fuel – Marine fuel characteristics vary widely and can have a significant effect on the engine exhaust emissions. The fuel normally used by the ship may not have much resemblance to the test fuel used during emission certification testing of the engine. For residual fuels, which are bunkered around the world, the variability of fuel composition is tremendous. Shipping companies also have varied fuel quality policies.

Residual fuel can have entrained nitrogen that will convert to NOx when combusted. It is helpful to know the amount of nitrogen in the fuel to determine its effect on the stack NOx emissions. Fuel sulfur also has a significant effect on stack emissions. Increased fuel sulfur level results in increased PM.

Test Set-up – On the positive side, there is usually adequate room for test equipment on vessels where the engine/s are situated in an engine room. Some of the instrumentation required for emissions testing may already be available. For example, fuel flow rate and shaft power instrumentation is common on large vessels.

Test Approaches

In the absence of the controlled test conditions achievable in the laboratory, data accuracy and repeatability possible in that environment may be unattainable in real-world operation. The unique marine issues that remain largely unaddressed compound the challenge of obtaining relevant, meaningful, and scientifically sound engine emissions data. In developing one or more standardized onboard marine diesel engine emissions protocols, these issues must be adequately considered and addressed.

Clearly defining the motivations for emissions testing will enable the definition of objectives and the selection of test procedures to achieve necessary accuracy without undue cost and effort. The appropriate test approach must be determined based on these criteria.

Specific motivations driving onboard marine engine emissions testing are listed in Table 1, along with the required use of the data.
The listed motivations are not intended to be comprehensive, but are presented to highlight the differences in test stringency and data accuracy required for different purposes. For example, testing to improve engine performance may not be fully documented. On the other hand, if modeling characterization may ultimately be used to legally contest existing inventory claims, then it may need to be documented with greater detail and at greater expense than if it were used to inform our understanding of the science. Clearly, tests having diminished accuracy will be less defendable legally and a less credible basis for justifying economic rewards. Motivations 1 through 4 warrant a more exacting protocol in order to achieve an increased level of accuracy, repeatability, and standardization. Of course, obtaining data for public relations does not negate the need for a reasonable level of accuracy and repeatability. However, a company may be able to demonstrate its "good-neighbor" corporate citizenship without the most formal of test protocols.

Methodology

Type of Characterization Impact – Shipboard exhaust emissions may be characterized by three different sampling techniques: raw, dilute, or remote. Currently, the most widely recognized protocol for testing of off-road engines is the International Organization for Standardization (ISO) 8178 Parts 1 – 9 ("Reciprocating Internal Combustion Engines – Exhaust Emission Measurement") permits either raw or dilute sampling. Other protocols exist and include Title 40 CFR Parts 89 (off-road), 92 (locomotive), and 94 (marine), and the Society of Automotive Engineers (SAE) J144, J244, and J1004. It should be recognized that remote sensing systems, where the constituents in the exhaust plume are examined as they exit the stack in the natural environment, have been employed for on-road and stationary sources. These could play an important role in the emissions inventory from marine vessels (Glover, E. L. et al. 1989, Wenzel, T. et al. 1996,

TABLE 1 - Motivations for Emissions Testing

No	MOTIVATION	DATA USE
1	Post installation regulation compliance demonstration	Legal/certification
2	Incentive program emission reduction demonstration	Legal/demonstration
3	Emission inventory characterization	Legal/data collection
4	Modeling characterization	Scientific/data collection
5	Improvement of engine performance and efficiency	Technology management
6	Demonstration of environmental stewardship	Public relations
7	Increase in private and/or public knowledge	Public relations

Figueiredo, S. A. 2000). The selection of appropriate measurement methods will depend first and foremost on the intended use of the data; then, on whether constituents of the exhaust stream or plume are to be analyzed and data points at specific operating conditions or cumulative measurements (via "continuous" analysis of gaseous sampled flow and accumulated "particulate" filtered samples) encompassing transient operation are required; and finally, on the level of accuracy required and constraints on instrumentation location. Test cost, time available for testing, and disruption to normal revenue-generating operation are important factors governing test composition and the associated methodology.

Measurement of the contained exhaust stream requires access for a sample probe or sensors. For the majority of commercial vessels, the most desirable location for the probe/s and/or sensor/s is in the vertical stack duct/s downstream from the waste heat boiler and spark arrestor or spark-arrestor/silencer. Practical considerations may dictate location in the engine room exhaust ducting, further upstream from the stack exit. For smaller vessels designed with hull-ported exhaust discharges, the probe/s and or sensor/s will be located in the exhaust ducting. Wet exhaust installations will limit probe/sensor location to ducting sections between the turbocharger and water injection. Exhaust stream sampling offers greater consistency of measurement at any given set of engine operating conditions. However, there may be less than optimal flow characteristics depending on operating condition and the selected location for convenient sampling access.

Alternately, emissions may be measured by examination of the exhaust plume in an attempt to obtain a representative measure of the more stabilized state and composition of constituents retained in the atmosphere. The number of uncontrolled variables and physical difficulty of plume sampling make this an unrealistic and cost-prohibitive option in most circumstances. Remote optical techniques under development may prove to be more viable for gaseous emissions.

A hybrid approach has been adopted for most land-based mobile source measurement. Gaseous emissions are measured from the raw exhaust, while "particulate" emissions are quantified based on a partial flow of raw exhaust diluted within an auxiliary chamber or tunnel and drawn through a fiberglass filter. The partial flow dilution tunnel is incorporated in order to simulate, in some measure, the exhaust mixing with atmospheric air.

<u>Data End Use Impact</u> – As discussed above, the most important consideration for determining a shipboard emissions measurement protocol is the intended use of the data. For a careful characterization of emissions released during a certain period of representative operation, total released pollutant constituents should be assessed. For generating emissions data for modeling purposes (e.g. motivation no. 4 in Table 1), emissions at specific operating conditions and some sample representative transients could suffice. For certain inventory purposes and a comparison of emission reduction achieved after a change is made to an engine (e.g. motivation nos. 1-3 in Table 1), emissions at specific operating conditions may be adequate. To ensure that emissions characteristics of an engine do not change during the course of its service life and the associated maintenance, repairs, and upgrades, a parameter check such as that prescribed in the IMO Annex VI NO_x Technical Code can be performed. Wider latitude is reasonable for shipboard testing than that permitted under ISO 8178 for test-cell analyzer measurement error, repeatability, signal noise, and zero and span value drift.

Once accuracy benchmarks have been established, specific test approach and associated instrumentation and methodology can be defined. That process is expected to be addressed from within a wider framework of regulators and stakeholders. Many situations will require that emissions generated during transient operation be measured. Transient measurement or modeling will always be critical for vessels such as tug and towboats, where transient operation is much more predominant.

<u>Measurement Parameters</u> – A protocol envisioned to accommodate the three primary motivations identified would likely include measurement provisions for combinations of the following parameters: intake air conditions (temperature, absolute pressure, and humidity); intake air volumetric flow rate; scavenge or boost air pressure; fuel mass flow rate; engine torque; engine speed; fuel rack setting; and controllable pitch setting (for controllable pitch propeller [CPP] vessels). The stringency of the

ISO 8178 ambient correction may be relaxed but variations should be documented corresponding to the accuracy benchmarks for the different types of testing. In addition, a fuel correction more comprehensive than that specified in ISO 8178 for fuel-bound nitrogen and fuel sulfur, may be needed since fuel composition and properties have a significant impact on emissions. Prior to an emissions test, the fuel should be analyzed, and during the test, fuel type, composition, and properties kept constant. The best approach may be to take fuel samples at the engine during the test runs to assure representative samples.

Because of the wide range of residual (including both heavy and intermediate) fuel oil composition and properties, relative to those of distillate fuel, there is a distinct need for an emissions fuel correction. Other ISO 8178 requirements such as specifications for minimum lengths of straight pipe (in terms of number of pipe diameters) before and after the sampling location should be incorporated. The accuracy and repeatability and resultant quality and credibility of emissions data is a direct function of applying good science to the following: sample extraction and conditioning; PM dilution ratio and filtering standardization; PM dilution ratio response to transient conditions; analyzer/mini-dilution tunnel calibration; and torque, intake air, fuel mass flow rate, and ambient condition measurements.

<u>Emission Constituents</u> – Constituents of interest will continue to be primarily the regulated criteria pollutants listed above in the Defining the Scope of an Initial Emission Test Protocol section. Once these pollutants are reduced to levels satisfactory to health effects scientists and regulators, it is likely that other constituents will be more carefully examined and regulated. This has been demonstrated by legislation development for PM speciation, size (e.g. 2.5 category and nanoparticles) and number, and climate-change or “greenhouse” gases. Introduction of certain emission control technologies may also generate a greater interest in ammonia slip from selective catalytic reduction (SCR) and heavy metals from fuel-borne catalysts and lubricating oil additives.

<u>Units of Objective Variables</u> – Measured species are to be presented as mass emissions. Reporting measured mass emissions in fuel specific units (e.g. grams/gallon of fuel) is easiest because the relative fuel quantity can be estimated accurately from measurements of carbon dioxide, carbon monoxide, and hydrocarbons in the exhaust. However, emission data should be collected to present constituent mass on an energy or brake power (or “brake”) specific basis in order to minimize sources of error and ensure the valid comparison of multiple sets of data collected at different times under different ambient air, sea, and hull conditions. The power output of the engine being measured must be determined in order to establish the data brake specific basis. Extrapolation to other models can then justifiably be made on a fuel mass specific basis, recognizing the corresponding impact on accuracy.

Instrumentation

To measure and report emissions from an engine on a brake power-hour specific mass basis, there are three different parameters that must be known. It is assumed that raw sampling techniques will normally be used for the gaseous emissions and a mini- or micro-dilution system will be used for particulate matter since full-flow dilution systems would be impractical for any moderately sized engine. In cases where PM is being measured using a mini-dilution tunnel, gaseous emissions could be drawn from the tunnel and measured at dilute levels. First, the concentration level of the constituent emission must be measured. Second, the mass flow through the engine must be known, and finally, the power or work output from the engine must be measured. Regardless of the system employed for data collection, the system should be verified in a test cell as described in the Quality Assurance and Quality Control section below.

Traditionally, the available technologies for measuring gaseous emissions from heavy-duty vehicles could be classified into two broad categories: garage grade inspection and maintenance (I/M) analyzers, and laboratory-grade analyzers. However, with recent advances in on-board, in-use emissions measurement science (Gautam et al., 2000a, 2000b, 2001, 2002a, 2002b; Carder et al., 2001; Thompson et al. 2002), it may be more prudent to classify the available technologies into four categories, based upon the level of accuracy and precision that can be achieved. It should be noted that there have been many efforts in the past to measure in-use emissions from heavy-duty diesel engines and that there continues to be efforts to develop in-use emissions systems for on- and off-road equipment. Presently, efforts range from research to developmental to commercial systems and include commercial entities such as Sensors, Horiba, Clean Air Technologies, and EF&EE (Engine, Fuel, and Emissions Engineering, Inc.). EPA has developed the ROVER and SPOT/PEMS systems and has also developed a pull-along trailer for on-road plume work. The University of California at Riverside (CE-CERT) has developed its own pull-along full-scale dilution tunnel and West Virginia University has developed a mobile emissions measurement system to perform in-use measurements.

Laboratory grade analyzers deliver the highest levels of accuracy and precision. The second level comprises portable emissions measurement systems that were developed for in-use testing but may not meet all of the protocol requirements. The third level is low-cost I/M grade analyzers typically found in repair garages. It should be noted that I/M type analyzers are typically designed for gasoline or sparked ignited emission levels and do not accurately measure diesel constituent levels of NOx, carbon monoxide (CO), or total hydrocarbons (THC). The fourth level includes all new technologies that would need to be verified.

The following sections describe a standard measurement system that is currently accepted and meets all existing marine engine certification requirements. As portable emissions measurement systems (the second level of instruments described above) are perfected and certified, it is expected that it will be possible to achieve higher levels of measurement accuracy using simpler, less expensive test methods. Any standard that is implemented should allow deviations from the specified procedures if equivalent measurements can be demonstrated or if the parties involved agree to the modifications.

Considering current and pending technology, it is anticipated that the most cost effective method of measuring the emissions on vessels, will be to continuously measure the fuel flow and the raw concentration of the exhaust constituents of THC, CO, CO_2, NOx, and oxygen (O_2). CO_2 provides a redundant check of the fuel consumption and O_2 can be used for determining the air-to-fuel ratio. It is not advisable to measure the regulated gaseous emissions of THC and NOx from an integrated bag sample since secondary reaction can still occur in the bag during the collection phase and during the analysis phase. Concentrations of CO and CO_2 emissions should be measured with a solid state nondispersive infrared (NDIR) analyzer, a heated flame ionization detector (FID) for THC (if local safety codes permit the use of FID fuel on-board a vessel), a chemiluminescence analyzer with a nitrogen dioxide (NO_2) to nitrogen oxide (NO) converter for NOx, and a paramagnetic or electrochemical cell for O_2. All of these constituents should be recorded continuously (at least 1 Hz data rate) over the given mode test duration. A specified duration of operation should be used to determine the mass emissions from the test mode. THC and CO emissions are of secondary concern and optionally may be omitted from the measurement requirements. If non-regulated constituents (ammonia [NH_3], NO_2, N_2O, volatile organic compounds [VOCs], etc.) are to be measured, then the best engineering approach should be taken. It is preferable to measure each constituent on a continuous basis since many have a relatively short half-life (a few hours). Batch or even integrated analyses may have to be performed because of limitations in technology. Potential methods for measuring these constituents include, but are not limited to, Fourier transform infrared (FTIR) spectroscopy, tunable diode laser absorption spectrometer (TDLAS), and photo-acoustical methods.

In the absence of any established PM measurement system for in-use, on-board emissions measurements, it is recommended that a mini-dilution tunnel be used to measure the TPM.

For the measurement of mass flow through the engine, there are three choices in order of preference. Each method has inherent advantages and disadvantages. First, fuel flow and exhaust constituents can be measured to infer the exhaust flow rate. This method requires that the fuel system be tapped into and the supply and return fuel be measured if the fuel flow is not available from existing onboard sensors. The advantage of this method is that since the exhaust constituents are already being measured, the only additional measurement is the fuel. Second, intake air flow and fuel flow may be measured to infer exhaust mass flow. The advantage of this system is that it provides for a redundant intake flow measurement. However, it may be difficult on the large displacement engines to install an intake flow meter. Third, exhaust flow can be measured directly. This would prove the easiest and quickest method in many instances. Disadvantages of measuring direct exhaust flow include complications imposed by water injected into the exhaust in wet exhaust installations, lack of access to the exhaust duct, high temperatures, and particle environment.

For the determination of the power or work output, three methods may be employed, and these are discussed below in order of declining accuracy.

1) The engine torque and speed may be measured during testing. Speed is measured with relative ease, by using an optical or electromagnetic sensor at either end of the engine, or by intercepting an existing engine speed sensor. Torque may be measured by inserting a pre-calibrated torque-measuring device (torque cell) in the lineshaft, or by attaching strain gauges, with an appropriate bridge and transmitter, to the output shaft. If strain gauges are applied, they must be calibrated by attaching a calibration arm and a reacting arm (or lock) to the shaft, and calibrating the torque output with either dead weights or a pre-calibrated load cell.
2) In cases where strain gauges are used but where it is not possible to calibrate the gauges over a range of torques from first principles, it may be necessary to use a two-point calibration, based on a zero-torque point, and a high-power operating point of the engine. At high-power output the engine brake specific fuel consumption is generally known reliably, and the consumption may be used to infer a torque from the engine. The strain gauge can be assumed to be linear between these two points. This would allow an acceptably accurate determination of the engine torque at low torque levels (typical for modest propeller speeds).
3) In cases where no engine torque instrumentation can be applied, the researcher must resort to calculating brake specific emissions from an engine fuel consumption map. This will prove to be acceptably accurate at high loads, but at lower propeller speeds, where operating torque falls below about 30% of maximum torque, the engine fuel consumption in brake specific terms may not be well known, and there will be associated inaccuracies in emission calculations.

One must be aware that measured shaft torque does not reflect auxiliary loads due to pumps or generators driven from the engine. When two engines drive one output, the power balance between the engines also must be considered.

Speed, and especially torque could be inferred from electronically controlled engines. It should be noted that currently, there are three standards that are used in engine control unit (ECU) serial communication, namely, SAE Standards J1587, J1922, and J1939. Generally, a protocol adapter (hardware) is required to communicate between the ECU and a computer via a serial (RS-232) interface. However, torque estimation from ECU broadcast may be limited to a narrow range of fuel properties.

Operating Conditions/Cycles

For maximum utility of shipboard emissions data it is imperative that this data be both reproducible and representative of actual operation. The repeatability of exhaust emission measurements is dependent on the degree to which engine operational and measurement conditions can be reproduced. For primarily steady-state operation this is a relatively straightforward process. The steady-state emissions that are measured under controlled onboard operating conditions are weighted based on activity data collected from "normal" steady state operation. The activity data is time based, i.e. the percentage of time spent at each mode during a "typical" day.

This can be achieved with much greater ease if measurements are made at steady-state engine operating conditions and do not include the transient conditions that occur during normal operation. However, steady-state measurements fall short in providing engine emissions characterization when significant transients are involved. Unfortunately many of the areas of primary concern are associated with a high percentage of vessel transient operations. Of particular concern are emissions generated near shore or in ports where they combine with other emission sources and contribute to air quality degradation. Emissions released over open water are generally of less interest than those from operation close to shore.

Emissions from maneuvering, accelerating to cruise, and decelerating from cruise cannot be accurately derived from steady-state operating conditions or “modes” alone. Total emissions equivalent to a transient in-use operation cycle can be estimated by weighting distinct select steady-state modes. However, such estimation presupposes the availability of previous empirical comparisons of those modes with a particular transient cycle. Modeling permits further extrapolation from measured transient cycle comparisons, although the accuracy is dependent upon the level of prior mapping and verification. Differences in engine design technology may not permit a single modeled response to transients that is applicable to all engines, not even necessarily among engines within a relatively narrowly-defined engine type or category. Furthermore, emissions reduction technologies (catalyzed diesel particulate filters [DPFs], SCR systems, etc.) are generally engine specific and designed based on the function of the vehicle and available space in the exhaust stream. For example, two identical engines in two different vessels, one employed primarily in steady-state operation and the other primarily in transient operation may have two totally different after-treatment systems based upon exhaust temperature profiles.

Collecting consistent real data from repeat runs of “typical” in-use operation incorporating both transient and steady-state operation is difficult when that operation includes a high proportion of transients. Repeatability is particularly a problem when transients vary significantly because of changes in operator performance and sea, wind, and current conditions. Prescribing and attaining standard combinations of steady-state and transient conditions for certain maneuvering operations may be not be possible.

The best approach to measuring and quantifying transient in-use emissions may be to measure the emissions from vessels during actual transient operation. Although the results from repeated tests may vary, it may be possible to draw some broad conclusions after a number of such tests are completed. These conclusions may lead to methods to estimate emissions generated during "typical" evolutions such as docking or emissions generated during a specific amount of time engaged in a "typical" evolution. With enough data, it might also be possible to conclude that the transient operation produces such a small quantity of specific emissions that it may be ignored or simply taken as a small percentage of a larger evolution's quantity of emissions. The associated cost and repeatability are perhaps the two most significant questions still open for this approach.

Alternatively, attempting to adhere to one of a limited number of ISO 8178 sequences of steady-state operating modes may significantly overestimate or underestimate emissions for the wide variety of vessel applications or routes (Corbett and Robinson 2001). No protocol has addressed the procedure(s) for collecting transient emissions data. However, procedures have been developed for on-road gaseous emissions (Gautam et al. 2000b) but not for particulate matter. The only procedure (40CFR86) that provides for transient emissions incorporates a full-flow dilution tunnel and this will be impractical for most marine engines.

Ultimately, the selection or prescription of steady-state and/or transient test operating conditions depends on the intended use and accuracy of the collected data.

Modifications to Standards

The best default approach to conducting emission measurements from in-use marine engines may be to follow ISO 8178. Although this standard is generally applied to engine dynamometer testing, it does allow for on-site testing. Specifically, “Part 2: Measurement of Gaseous and Particulate Exhaust Emissions at Site” details the procedures for marine applications. ISO allows for flexibility in this standard and that deviations from the specified procedure are permitted if equivalent measurements can be demonstrated or if the parties involved agree to the modifications. However, any alternate measurement or modification to the standard should be based on scientific or technical needs and not economic concerns. For example, the type of analyzers and measurement systems that may be selected for onboard, in-use emissions measurements may not conform to the strict requirements of the ISO-8178 standards. Analyzers for in-use emissions measurements were discussed above.

Another example of a modification to the protocol could be the valid range of atmospheric conditions that is specified in ISO 8178-2.5.2.

The standard requires that the test conditions must be within a specified ambient pressure and temperature range. However, if the intent of the testing were to obtain the atmospheric loading (i.e., to establish SIP data) throughout the year then it may be appropriate to disregard this requirement and report the emissions data along with the test conditions to identify that this requirement was relaxed.

Another example of a modification to the existing standard is the requirement to have the total PM filters pre-weighed and post-weighed within a specified time limit as stated in ISO 8178-2.11.1. In most instances, it will be impractical to have the particulate filter conditioning equipment on board for marine testing. The analytical scales are too sensitive to vibration and the environmental control units are too large to justify having on board during the testing. It will also be unlikely that the scale and control units could be placed on shore and the filters transported to the vessel during testing. Therefore, the only practical method of handling the filter media is through shipping the pre-weighed media from a laboratory setting to the test site, using the media, and then shipping the media back to the laboratory for post weight.

Quality Assurance and Quality Control

One of the most important elements of a good emission measurement is the level of quality assurance and quality control. Most existing protocols include requirements for calibration, repeated measurement, and other documentation to ensure that testing is consistent and comparable with other engine tests. This section describes some of the elements to consider with regard to quality control goals. It is preferable that a similar size and make engine be used in the system verification. It is recommended that an engine dynamometer with full flow CVS be used to evaluate the system. However, it is recognized that only engines up to ~1000 bhp are capable of being tested in most full-flow CVS test cells and that large displacement engines can only be tested at manufacturers test facilities and a select number of sites worldwide via raw sampling techniques. A full-flow CVS system eliminates many uncertainties in emissions testing.

Because of the revenue service of the vessels to be tested, it will be likely that access to the vessel will be limited. Therefore, redundant measurements should be employed to provide the information to insure confidence of the data. For example, this could be as simple as examining fuel usage records to verify the fuel flow measurement during testing to having redundant equipment on board to measure, or infer, the necessary parameters. As another example, carbon dioxide could be measured with an NDIR analyzer as required by ISO 8178 and also measured with an FTIR, which could be used for ammonia and nitrous oxide measurements.

Because of the nature of in-use testing, it will be desirable to have repeated runs at a given operating (mode) point. The time should be allocated to collect these data. The exact number of repeats will be determined by cost and time available to perform the tests. It is suggested that at least three repeats be performed for selected modes to obtain an indication of the variance of the data. There are numerous reasons why test runs will be eliminated from the data set. For instance, while experience will give an indication about the gaseous emissions constituents and these constituents can generally be post-processed immediately after the mode, the particulate matter filters will take hours or days before it can be post weighed and the particulate matter emissions data analyzed.

The filters used in the particulate matter collection will most likely be pre-weighed in an established laboratory, shipped to the test site, used, and then shipped back to the laboratory for post weighing. This method of filter handling can provide equivalent on-site accuracy if procedures are in place. It will be necessary to use field blanks consisting of unused filter media and used media. The unused media provides filter contamination information and the used media provides mass loss information. The media should be the same type and size as used in the testing. The used media should be loaded to the equivalent loading as would be found during testing and could be the filters used in the system verification.

Any in-use system must demonstrate that it is not prone to vibration that is common on board marine vessels. For example, an NDIR system that incorporates a luft-type detection scheme will give erroneous readings if the analyzer experiences vibrations or change in position. Although it is possible to design vibration isolation systems to reduce the vibration, it is difficult to account for the magnitude and frequency of the vibration unless the vibration is measured on the vessels prior to designing or installing the system. Through the judicious selection of analyzers that do not respond to "normal" vibration, the effects of vibration will be eliminated. All systems should be evaluated for vibration response before they are placed in the field for the testing. There are two evaluations that should be performed: static and dynamic. For the static evaluation, the given analyzer or transducer is operated (sampling a known source) and slowly inclined from the horizontal plane. Any response from the known value indicates that there is an orientation bias in the sensor. If there is response greater than a 2% full scale up to a 30 degree angle then that sensor should not be used. For the dynamic evaluation, the transducer is placed in a vehicle. The transducer is again operated, sampling a known source, while the vehicle is driven over the road. If there is response greater than a 2% of full scale during the test then that sensor is not used.

Reporting

The reporting of the emissions from in-use testing should include vessel information, engine(s) information, selected operating modes, information regarding the fuel properties and preparation, the emissions system verification, and any deviations from the protocol. Because of the service of most large marine vessels, each of these vessels may be a unique data set that will most likely not be repeated in another vessel. Vessel information should include hull and propulsion design and conditions. Engine information should include model and factory rating along with the drive train connection to the propulsion system. Selected operating modes should be identified and justified. The fuel properties and any fuel conditioning system(s) prior to the engine should be identified. The properties for the fuel analyses should be determined prior to testing for each fuel used. A minimal fuel analysis should consist of heating value, cetane number, density, distillation, viscosity, and sulfur level along with the relevant test methods (ASTM, ISO, etc.). The lubrication oil should also be identified. Additional analyses should be agreed upon prior to testing.

All emissions data should be reported as an average. There should be two different "error" bars associated with the average data. The first error bar is the uncertainty derived from the system verification in the established laboratory and the second error bar is the standard deviation due to the test-to-test variability. The method of reporting the emissions and the determination of the benefits of technologies should be determined prior to testing.

In cases where testing is conducted to compare technologies or fuels, it may prove necessary to conduct a complete set of tests on the first fuel or technology before conducting the tests on the second fuel or technology. In some cases, the wind or sea may change over the duration of these tests, and it may not be possible to evaluate each technology at exactly the same operating points because the speed vs. load characteristic of the vessel (and propeller) may change. In this case it will be necessary to fit curves to the data for emissions (preferably in brake-specific mass units) against engine power for each technology or fuel, and then compare the two curves.

RECOMMENDATIONS FOR FUTURE ACTION

This paper has provided the background and factors that have created a need for universal marine emissions measurement protocols. The paper has also addressed the challenges to creating acceptable protocols that will produce accurate, repeatable emission measurements on vessels in underway conditions. The next challenge is to establish how such protocols can be developed.

It is understood that ultimately such protocols will be national and international. However, in view of the fact that many localities have an immediate need, we believe that an effort to layout guiding principles and attempt to normalize regional efforts could be fruitful.

It is proposed that the Society of Naval Architects and Marine Engineers (SNAME) may be the vehicle to initiate such an effort, perhaps in collaboration with the International Council on Combustion Engines (CIMAC). Although SNAME is non-regulatory, it publishes numerous bulletins and guideline used extensively by the industry. The Environmental

Panel of the Ships' Machinery Committee is already investigating the subject of emission measurement protocols. A collaborative effort with the CIMAC Exhaust Emission Controls Working Group (EEC WG) is being preliminarily considered.

It is proposed that the SNAME Environmental Panel convene an informal invitational workshop to investigate the normalization of onboard marine emissions measurement. This workshop would invite the participation of interested parties including regional, state, local and port entities involved in or contemplating the development of protocols, EPA, and emissions measurement and ship operations experts.

CONCLUSIONS

The authors believe that it is time to normalize onboard marine emission testing requirements. Failure to do so will impede the goal of reducing emissions. A growing body of data generated by different testing protocols will make the achievement of that goal more difficult and expensive for all concerned. The paper has addressed many of the issues that must be considered. Undoubtedly, more issues will be identified as the process progresses. Pooling the resources of stakeholders will result in an improved resolution for all concerned including the marine industry, regulators, the world population, and the environment.

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