VERIFICATION OF SHIP EMISSION ESTIMATES WITH MONITORING MEASUREMENTS TO IMPROVE INVENTORY AND MODELING

Final Report

Submitted by

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Contract Number
01-328

Prepared for
the California Air Resources Board
and the California Environmental Protection Agency

23 November 2004

Disclaimer

Acknowledgments

The science research team involved in the international atmospheric science study called Intercontinental Transport and Chemical Transformation (ITCT) 2002 is acknowledged for their efforts in conducting the ship plume study as a minor part of a larger experiment; particular acknowledgment goes to personnel of the NOAA Aircraft Operations Center and to Dr. Gao Chen, from NASA Langley Research Center, Hampton, VA, who made available results of the plume study. This experimental work included researchers and support from other institutions involved in ITCT 2k2, including the School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA; Aeronomy Laboratory, National Oceanic Atmospheric Administration, Boulder, CO; Ball Aerospace, Boulder, CO; Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO; Atmospheric Chemistry Division, National Center for Atmospheric Research, Boulder, CO; Department of Chemistry, Fort Hays State University, Hays, KS; and Division of Marine and Atmospheric Chemistry, Rosensteil School of Marine and Atmospheric Science, University of Miami, FL. This work was supported in part by NOAA OGP – 17 NA06GP0410. The post-mission analysis performed in NASA Langley Research Center was supported by the Tropospheric Chemistry Program of NASA's Earth Science Enterprise. Mr. Chris Patton of the Port of Los Angeles is acknowledged for obtaining fuel quality data from the operator.

A.P. Moller and its professional staff (both shoreside and onboard the Sine Maersk) are acknowledged for making their vessel available and coordinating the engine monitoring effort. MAN B&W is acknowledged for conducting and reporting the engine test for the Sine Maersk, funded by the Port of Los Angeles. In addition to contract funds from the State of California, partial support was provided by Toyota Motor Corporation, and by the Graduate College of Marine Studies, University of Delaware, Newark, DE.

This Report was submitted in fulfillment of ARB contract number 01-328, Verification of Ship Emission Estimates with Monitoring Measurements to Improve Inventory and Modeling, by the University of Delaware under the partial sponsorship of the California Air Resources Board. Work was completed as of August 2004.

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ABSTRACT

This research evaluates accuracy of current marine vessel emissions estimation methods. Pollutants that are addressed in this study include: NOx, SO_2, PM, CO_2, CO, and HC. This project contributes to research seeking to reconcile apparent differences between inventory estimation methodologies, atmospheric predictions, and field observations. Current emissions inventory methodologies are applied to two different marine vessels, the Sine Maersk, 6600 TEU container vessel built in 1998, and the New Spirit, a 26,562 gross ton (48,183 deadweight ton) bulk carrier built in 2002. Direct monitoring of engine stack emissions was conducted on the Sine Maersk in February 2004, and an aircraft plume study of the New Spirit was conducted as part of a 2002 international atmospheric science experiment. The agreement between emissions calculated using published emissions rates and monitored stack test results is relatively good. The results show that improved emission inventories are consistent with monitoring results; however, emissions rates derived from in-plume observations demonstrated greater disagreement with published emissions rates. Nonetheless, good agreement between monitoring and modeling emissions rates helps confirm that differences between inventory estimates and in-plume observations are likely a result of complex chemical processing within ship plumes.

EXECUTIVE SUMMARY

The California Air Resources Board (ARB) has been involved in the inventory, analysis, and regulation of air pollution from marine shipping for more than two decades. Port and coastal inventories of marine vessel emissions suggest that air quality goals might not be achieved in major regions of California without the reduction of emissions from this non-road source. Additional study undertaken by various agencies and organizations has attempted to improve commercial marine vessel inventories through various estimating methodologies. These studies calculate emissions by multiplying average emissions factors for marine engines by vessel activity or fuel consumption estimates. Generally, similar methodologies are applied consistently, although variability in assumptions produces different results. Most importantly, despite differing estimates among particular studies for the same ports, ship emissions inventories tend to support the conclusion that shipping is a significant source of pollution in heavily traveled port regions and shipping lanes off the California coast.

ARB is interested in best-practice inventory methodologies, in their ability to represent stack emissions, and in their validity as indicators of emissions impacting air quality. ARB is also interested in evaluating ongoing efforts by organizations to estimate the benefits of mitigating action, including technology controls and operational controls (e.g., reducing vessel speed in port). This research project identified three objectives supporting ARB's goals.

1. Summarize best-practice inventory methodologies. Current methodologies use engine-activity, fuel-consumption, and stack-emissions data from onboard ship sampling during normal vessel operations to calibrate, improve, and validate emissions-estimation methodologies. This is reported in a comparative context drawing from inventory methodologies used at international, state, and port levels, with specific comparison to the Vessel Speed Reduction agreement in Southern California.
2. Investigate potential discrepancies between large-scale vessel emissions studies, and direct monitoring of engines. This analysis relies on measurement results of stack emissions reported for the Sine Maersk.
3. Consider the extent that in-plume chemistry may modify primary emissions before diffusion and dispersion to the marine boundary layer. This involved evaluating differences when comparing observations obtained during a ship plume experiment conducted about 100 km off the California coast by the National Oceanic and Atmospheric Administration.

This report supports ongoing efforts by the State of California, regional and local air districts, port authorities, and the maritime industry to understand the magnitude of and impacts from ship air pollution. This report provides direct analysis showing good agreement between emissions estimated from published emissions factors and emissions test data; this tends to support the use of fleet-average emission factors, resolved according to engine and fuel types. The research also demonstrates that important processes may occur in the ship emission plume, modifying the pollutant concentrations and species that ultimately disperse into ambient air.

As presented in the report, current best-practice inventory methodologies employ similar approaches that can be summarized in five methodology steps:

- Step 1: Identify the vessel(s) to be modeled, and the number & types of engines in service
- Step 2: Estimate the engine service hours for the voyage or voyage segment
- Step 3: Determine the engine load profiles, including power and duty cycle

- Step 4: Apply emissions or fuel consumption rates for specific engine/fuel combinations
- Step 5: Estimate emissions or fuel consumption for the voyage or voyage segment

This report adopts these steps using data from published literature, direct measurement, and in-plume observation to verify the ability of inventory estimates to reflect actual conditions. The agreement between emissions calculated using emissions rates from literature and emissions calculated using stack test results is better than the comparison with estimates using emissions rates derived from in-plume observations. This is illustrated in Table ES-1 by averaging the results of vessel voyages for published, measured, and in-plume-derived emissions rates.

Table ES-1. Estimated main engine emissions in tons per day using published emissions rates and empirical emissions rates for a) container ship Sine Maersk[1] estimated full-cruise conditions of 80% rated power; and b) bulk carrier New Spirit[2] observed at-sea conditions (corresponding to ~62% of full-cruise speed).

	CO_2	NOx	SO_2	PM	HC	CO
Sine Maersk using published rates	619	19	11	2.0	0.6	1.5
Sine Maersk using stack monitoring rates	608	22	9	1.8	0.1	0.2
Percent difference	2%	-12%	19%	11%	508%	640%
New Spirit using published rates		0.7	0.4	0.07		
New Spirit using in-plume observed rates		0.5	0.3	0.03		
Percent difference		41%	23% (33%)	114%		

1. For the Sine Maersk, the MAN B&W report included data for engine speed but not vessel speed, so "full-cruise" conditions are assumed to represent 80% rated power (see Table 2, column I).
2. For the New Spirit, the at-sea conditions during the plume study corresponded to about 30% power; one possible reason for this may be that the vessel was in an economy cruising mode (typical of bulk carriers). Corresponding "full-cruise" conditions for the New Spirit would increase activity assumptions and, therefore, the emissions reported here, but would not modify the comparative differences reported for New Spirit. The difference between estimates using published and in-plume-derived rates adjusting for main engine fuel sulfur content is 23%; if this adjustment was not made, the difference would be about 33%.

The results provide confidence that improved emission inventories will be consistent with monitoring results. The results support efforts such as the Vessel Speed Reduction (VSR) Program, which attempts to estimate the reduction in emissions when vessels calling on San Pedro Bay conform to the reduced speed guidelines. The results may also be important when estimating the performance of other emission control measures.

The comparison of emissions rates derived from in-plume observations with published emissions rates demonstrated greater disagreement. The good agreement between monitoring and modeling emissions rates at least helps to confirm that disagreement between inventory estimates and in-plume observations is not likely an inventory problem but is likely a result of complex chemical processing within ship plumes.

To improve the accuracy of commercial marine emissions inventories for all pollutants, more detailed characterization of vessel and engine activity is recommended. Vessel speed, engine load, and other main engine operating conditions contribute more to the variation among individual vessel emissions and, therefore, to the overall uncertainty of aggregate vessel inventory estimates. However, emissions monitoring continues to be valuable for baseline emissions testing and for evaluating reductions through various measures. Additional testing is recommended to reduce emissions rate uncertainty for some pollutants, and particularly to improve understanding of PM emissions.

INTRODUCTION

This report is intended to assist the California Air Resources Board's role in defining and evaluating inventory methodologies for commercial marine vessels and assessing the validity of estimates when mitigating action is taken to reduce ship emissions. Current shipping activity descriptions incorporate better understanding of operating profiles and related power/fuel consumption. Ship emissions inventories are based on better emissions factors, adjusted for fuel type (done now), engine type (coarsely done now), vessel type (being attempted), age, and other important conditions. Geospatial assignment of this source of anthropogenic pollution is achieving better agreement between global, regional, and port-based estimates. This report considers the degree to which these improvements may produce reliable and accurate estimates of ship emissions.

Project Questions & Research Objectives

The following research questions motivate the research design and analysis presented in this report.

1. Why have atmospheric model predictions not matched general inventory estimation methodologies and field observations of ambient pollution in areas with large marine vessel presence?
2. Can researchers reconcile emissions inventory models, onboard measurements, and field observations?
3. What factors would most improve marine emission inventories and their application in atmospheric models?

These questions lead to three primary objectives for the project. First, the project summarizes best-practice inventory methodologies. Current methodologies use engine-activity, fuel-consumption, and stack-emissions data from onboard ship sampling during normal vessel operations to calibrate, improve, and validate emissions-estimation methodologies. This is reported in a comparative context drawing from inventory methodologies used at international, state, and port levels, with specific comparison to the Vessel Speed Reduction agreement in Southern California [*Los Angeles Board of Harbor Commissioners et al.*, 2001]. Second, the project investigates potential discrepancies between large-scale vessel emissions studies, and direct monitoring of engines. This analysis relies on measurement results of stack emissions reported for the Sine Maersk [*MAN B&W Diesel A/S*, 2004]. Third, the report considers the extent to which in-plume chemistry may modify primary emissions before diffusion and dispersion to the marine boundary layer. This involves evaluating differences among model and test results and discrete atmospheric observations obtained during a larger scientific study of air pollution transport by the National Oceanic and Atmospheric Administration, Intercontinental Transport and Chemical Transformation 2002 (ITCT 2k2). This third objective relies upon results from a ship plume experiment conducted about 100 km off the California coast during the NOAA ITCT 2K2 airborne field campaign.

Background

Diesel engines power almost all commercial marine vessels because of the durability and efficiency of these engines, coupled with the lower price and higher energy density of diesel fuel, but emissions from these ships can degrade air quality. Emissions research and atmospheric modeling studies have shown that ship emissions contribute significantly to pollution in remote ocean areas, along coastlines, and in ports [*California Air Resources Board and South Coast Air Quality Management District*, 2000; *Capaldo et al.*, 1999; *Corbett and Fischbeck*, 1997; *Lawrence and Crutzen*, 1999; *Skjølsvik et al.*, 2000]. Annually, international shipping utilizes only between 2% and 4% of the world's fossil fuels, but it accounts for more than 14% of the global NOx emissions and more than 5% of the global sulfur emissions from human activity [*Corbett and Koehler*, 2003; *Corbett and Koehler*, 2004]. Ship emissions can increase the brightness and lifetime of clouds, as well as tropospheric ozone levels, affecting global climate change [*Ackerman et al.*, 2000; *Capaldo et al.*, 1999; *Kasibhatla et al.*, 2000; *Lawrence and Crutzen*, 1999].

The California Air Resources Board (ARB) has been involved in the inventory, analysis, and regulation of air pollution from marine shipping for more than two decades [*California Air Resources Board*, 1978a; 1978b; 1991]. Port and coastal inventories of marine vessel emissions suggest that air quality goals might not be achieved in major regions of California without the reduction of air emissions from this non-road source [*Booz Allen & Hamilton*, 1991; *Environmental Protection Agency*, 1991; *Hottenstein*, 1991; *Sierra Research*, 1991; *TRC Environmental Consultants*, 1989].

Additional study undertaken by various agencies and organizations has attempted to improve commercial marine vessel inventories through various estimating methodologies [*Acurex*, 1997; *Environmental Protection Agency and ARCADIS Gerharty & Miller Inc.*, 1999; *Port of Los Angeles et al.*, 1994; *Starcrest Consulting Group*, 2000; *Starcrest Consulting Group LLC et al.*, 2004; *Starcrest Consulting Group LLC et al.*, 2003]. These studies have all calculated emissions by multiplying average emissions factors for marine engines by vessel activity or fuel consumption estimates. Generally, similar methodologies are applied consistently across these studies, although variability in the assumptions regarding emissions factors and vessel operations produces different results. In this regard, recent studies conducted by ports have endeavored to better characterize actual operations and have corrected some methodological assumptions that were not justified by current vessel activity. In particular, the recent baseline inventory for the Port of Los Angeles applies the latest methodologies and most comprehensive data gathering effort for the port to date. Most importantly, despite differing estimates among particular studies for the same ports, ship emissions inventories tend to support the conclusion that shipping is a significant source of pollution in heavily traveled port regions and shipping lanes off the California coast [*Environmental Protection Agency*, 2003].

Geographically-resolved emissions inventories [*Corbett and Fischbeck*, 1997; *Corbett et al.*, 1999; *Endresen et al.*, 2003; *Olivier et al.*, 1996; *Skjølsvik et al.*, 2000] have shown that ships in global trade operate within 400 km of land 70% of the time (with 85% of ship traffic occurring along Northern Hemisphere trade routes). With long-range transport of air pollution, these emissions near the coastline contribute significantly to air quality problems in "downwind" regions. In fact, in many coastal and port regions along heavily-traveled international trade routes, annual emissions from ships equal or exceed those of adjacent land-based sources.

Moreover, modeling research demonstrates that the impact of emissions from shipping may be impacting air quality in California coastal regions [*Eddington and Rosenthal*, 2003]. Because of their proximity to land, ship emissions may contribute to pollution hundreds of kilometers inland. Emitted SO_2 and NO and their atmospheric oxidation products are thought to have residence times of ~1 to ~3 days, consistent with mean transport distances of ~400 to ~1200 km [*Schwartz*, 1989]. Streets et al. identify international shipping as a major source of sulfur emissions in Asia, contributing in excess of 10% of total sulfur deposition on land in Southeast Asia [*Streets et al.*, 1997; *Streets et al.*, 2000]. Research has produced similar results in other regions around the world [*Capaldo et al.*, 1999; *Det Norske Veritas (DNV)*, 1994; *International Maritime Organization*, 1998]. Also, the U.S. EPA estimates that marine diesel engines contribute approximately 17% of the NOx on a summer day for San Diego, 15% for Beaumont-Port Arthur, and 12% for San Francisco [*Booz Allen & Hamilton*, 1991; *Environmental Protection Agency*, 1999].

While this body of work is compelling, it is based largely on modeling analyses without confirmation through field observations in marine regions. Field measurements of ambient concentrations tend to support the greater concentrations predicted by atmospheric modeling studies [*Jaffe et al.*, 2001], particularly for sulfur emissions [*Capaldo et al.*, 1999; *Kasibhatla et al.*, 2000]. However, the agreement between model predictions and observations is not as good for other pollutants, particularly NOx concentrations [*Davis et al.*, 2001; *Kasibhatla et al.*, 2000]. Research looking directly at marine engine emissions rates for HC, CO is sparce, and ongoing PM research has not yet fully quantified emissions rates for high-sulfur marine fuels, considering both emissions monitoring, and atmospheric processes. This problem suggests that one or a combination of the following may be true: A) the emissions inventories are inaccurate and biased, at least for some pollutants; B) the chemical processes and/or atmospheric transport equations used for marine boundary layer regions in the models are incorrect; or C) the localized nature of ship-stack emissions produces in-plume chemistry conditions that differ from those used for larger-scale chemical transport models.

Recent inventory efforts have focused on improving non-road emissions inventories, including inventories for marine vessels, for air quality modeling and policy insights [*Kean et al.*, 2000]. Characterizing non-road inventories geographically, and explicitly treating the uncertainties that result from limited emissions testing, incomplete activity and usage data, and other important input parameters currently pose the largest methodological challenges. Since directly monitored data for non-road emissions, fuel-consumption, and activity level generally are not available, the development of non-road inventories must rely on a number of assumptions that introduce significant uncertainty. To date, most non-road inventories have applied national or regional average values that suffer from two weaknesses. First, these assumptions often are generated through engineering modeling or manufacturer test data, rather than in-service sampling. This means that certain assumptions may not apply to actual non-road vehicle operations. Second, emissions factors, fuel-consumption data, and activity-level information typically represent national averages (or regional averages at best), and therefore cannot capture the potential variability of non-road operations at the local level. The need for better methodologies and assumptions has been acknowledged internationally [*UNFCCC and Subsidiary Body for Scientific and Technological Advice*, 2004].

While accurate inventories provide important information, the ability to model the overall environmental impacts of anthropogenic activities depends on an accurate understanding of atmospheric science. For example, scientists conducted the Cooperative Program for Monitoring and Evaluation of the Long Range Transmission of Air Pollution in Europe (EMEP) to assist policy makers. This coordinated set of studies included a program of ship stack measurements to establish pollutant emission factors for marine engines and to establish regionally maps of ship activity [*Alcamo et al.*, 1990; *Amann et al.*, 1996; *Carlton et al.*, 1995; *Carlton et al.*, 1994;

Lloyd's Register, 1990; *Lloyd's Register*, 1993]. This work was later expanded to include ship emission maps for the Mediterranean Sea [*Lloyds Register Engineering Services et al.*, 2001]. These studies informed a set of atmospheric modeling analyses to determine the extent to which ships contributed pollution (mostly sulfur and nitrogen) to the Northern European and Scandinavian nations [*Benkovitz et al.*, 1994; *Benkovitz et al.*, 1996; *Bouwman*, 1993; *CONCAWE*, 1993]. This work was important, particularly for its strong focus on inventories, observations and integrated assessment.

Improved ship inventory methodologies and updated geographic allocation schemes suggest that ship emissions may be even greater than earlier estimates [*Corbett and Koehler*, 2003; *Endresen et al.*, 2003; *European Commission and ENTEC UK Limited*, 2002]. These updated inventories rely on better emission factor statistics; recent efforts to monitor engine exhaust emissions are providing better resolution of emissions during steady-state and transient engine loads [*Cooper and Peterson*, 1995; *Cooper*, 2001; *Cooper and Andreasson*, 1999; *Corbett and Robinson*, 2001]. Improved methodologies are being employed to estimate ship activity and resulting emissions, correcting model bias in earlier research.

However, while available field observations tend to support the nature of these findings, there are some problems reconciling the results of chemical transport models with available field observations [*Kasibhatla et al.*, 2000]. Rigorous uncertainty analyses identify and rank the most important inputs for improving the accuracy of ship inventories, but the uncertainty in the inventories alone cannot account for the over prediction of photochemical species in the models. Model predictions have not matched observations of ambient pollution in regions where shipping is a dominant local source [*Davis et al.*, 2001; *Durkee et al.*, 1998; *Durkee and niewicz*, 2000; *Ferek et al.*, 1998; *Kasibhatla et al.*, 2000]. No measurement campaigns have focused directly on this issue until now.

Similarly, while large-scale chemical transport models necessarily simplify certain reactions, the basic chemical processes for NOx and ozone are relatively well understood. This suggests that there may be "a gap in our understanding of the chemical evolution of ship plumes as they mix into the background atmosphere in the marine boundary layer" [*Kasibhatla et al.*, 2000]. Davis et al [2001] suggest "that for an actual plume setting the NOx lifetime could be greatly shortened by chemical processes promoted by ship plume emissions themselves. Similar chemical behavior was not found for SO_2."

This problem may be related to the transient and local nature of ship emissions, and in-plume chemistry differences from the atmospheric chemical reactions used in large-scale atmospheric models [*Davis et al.*, 2001]. As stated in NOAA's ITCT 2K2 White Paper [*NOAA*, 2001], "Field measurements must investigate this variability in sufficient detail so that the controlling chemical and meteorological processes are correctly identified and quantified. Monitoring must determine trends and identify sources. Models must correctly capture the variability and decipher the trends." This research will conduct modeling and monitoring activities that integrate with in-plume and ambient measurements concurrently during ITCT 2K2. This research will contribute to better inventories, improved model chemistry, and more comprehensive field observations.

Summary of Significance

This report supports ongoing efforts by the State of California, regional and local air districts, port authorities, and the maritime industry to understand the magnitude of and impacts from ship air pollution. This report provides direct analysis showing good agreement between emissions estimated from published emissions factors and emissions test data; this tends to support the use of fleet-average emission factors, resolved according to engine and fuel types. The research also demonstrates that stack emissions may change in the ship emission plume, modifying pollutant concentrations and species that ultimately disperse into ambient air.

The research is especially important in considering efforts to reduce emissions, because appropriate confidence must be assigned to baseline estimates and estimates of reductions obtained through various mitigation efforts. This is especially important for the San Pedro Bay region in Southern California, where a voluntary speed reduction program involves modeling of emissions from actual vessel traffic and estimating the reduction in emissions attributable to reduced vessel speed. Confidence is needed in models estimating reductions in emissions due to operational controls such as speed reduction to assess and attribute regional air quality benefits to the maritime sector. This report lends confidence to the latest attempts to model emissions.

Moreover, while stack emissions represent one proxy measure for the contribution of shipping to ambient air quality, they may not represent accurately the emissions dispersed to the environment. The complex relationship between emissions and ambient air quality is well-known, but not well quantified for ships. This report provides analysis that directly considers the relationship between stack emissions, in-plume effects of chemical processing, and resulting impacts on ambient observations. While this report does not resolve debate about the impact of ship emissions on air quality, it demonstrates that stack emissions (whether estimated or measured) may be modified by plume chemistry; the research suggests that current atmospheric models may need to account for in-plume effects instead of directly applying accurate ship emissions inventories.

The methodologies and validation developed in this research will contribute to ARB efforts to establish accurate ship emissions inventories and improved modeling of their impacts. This research will support ARB efforts to develop effective measures to reduce ship emissions.

MATERIALS AND METHODS

Studying atmospheric impacts of ship emissions (and anthropogenic pollution in general) involves at least three connected efforts [*Benkovitz et al.*, 2003]: 1) creating inventories of pollution sources, both biogenic and human; 2) characterizing atmospheric fluid dynamics and meteorology; and 3) understanding physical and chemical changes as pollutants disperse and react in nature. Air pollution policy requires that this information identify likely causal linkages between sources, impacts and mitigation alternatives so that cost-effective action may be taken to protect human health and environment. This study is designed to contribute to the first and third of these elements.

The analysis includes the following tasks, tailored to the data made available from related projects to test engine emissions on one vessel and to conduct a plume study of another vessel.

1. Develop a spreadsheet model[1] to estimate vessel emissions under expected operating conditions (i.e., cruise speed, reduced speed). This work synthesized best practices and insights from recent inventory models applied in previous and other ongoing research at the international, national, and local levels. The analysis considers various operating conditions, both at-sea and in-port operations.
2. Apply this model to estimate emissions from vessels transits within the study area. At-sea estimates apply empirically valid assumptions, and in-port estimates use vessel-specific data provided by he Port of Los Angeles. Specifically, the Port of Los Angeles VSR model was modified to include vessel and routing detail for 23 oceangoing voyages by two cargo ships that call on California ports. Using actual vessel traffic system data provided by the Port of Los Angeles, this work characterizes operating conditions and estimated emissions during actual operations.
3. Compare emissions predictions with monitoring results and concurrent ship-stack plume observations for predetermined vessels. Vessel monitoring was performed on one container vessel, the Sine Maersk, with the cooperation of A.P. Moller. Ship-stack plume observations by aircraft were made on one bulk cargo ship, the New Spirit, as part of other ITCT 2K2 activities. These independent data gathering activities were not funded as part of this work, but the Principal Investigator coordinated with each of the teams conducting these efforts. From these comparisons, recommendations can be made regarding data collection, emissions estimation, and any in-plume adjustments that may help to better characterize the nature and impacts of emissions.
4. Report and other documentation. Spreadsheet models applied and calculations developed under this contract will be submitted as part of a draft final report submitted for comment. Comments received from ARB (in one consolidated package) within 45 days of draft final submittal will be incorporated into revisions for a final report, as appropriate.

[1] The project proposal suggested that these modeling methods would be provided under the name SEACalc®, which was intended to represent a body of unique research methods, analyses, and models related to ship emissions assessment calculations. Given the purpose of this study to consider best modeling practices (published in open literature or applied in public reports), it was unnecessary to associate this description and analysis of emissions estimating methods that are now more widely in use with SEACalc®.

Emissions Estimation Methodology

For many transportation modes, developing estimates of fleet-wide inventories requires application of indirect statistical relationships or fleet-average assumptions that ignore considerable variability among individual vehicles. This is necessary because the fleets are so large that obtaining individual vehicle engine and activity data is not feasible. Some inventory methodologies for commercial marine vessels have followed this practice, particularly older efforts. However, less than 100,000 commercial oceangoing vessels operate globally and fewer than 800 oceangoing ships make less than 3,000 ship calls annually on the Port of Los Angeles [*Corbett and Koehler*, 2003; *Starcrest Consulting Group LLC et al.*, 2004]. With these vehicle (vessel) counts, it becomes feasible to consider certain individual characteristics. Rather than estimating ship engine sizes or vessel activity based on statistical correlations with vessel tonnage, the current best practice obtains engine power directly for each vessel studied and applies vessel activity data to document or compute power, energy and fuel consumption. Current emissions rates (factors) are then applied to this "bottom-up" information to estimate emissions. This methodology can be summarized in the Equation 1.

$$\text{Fuel Consumption}_{\text{metric tonnes per year}} = \sum P_{\text{MW}} \cdot F_{\%\,\text{MCR}} \cdot t_{\text{hrs/yr}} \cdot SFOC_{\text{g/kWh}} \cdot \frac{1}{1000}$$

Equation 1

$$\text{Emissions}_{\text{metric tonnes per year}} = \sum P_{\text{MW}} \cdot F_{\%\,\text{MCR}} \cdot t_{\text{hrs/yr}} \cdot E_{\text{g/kWh}} \cdot \frac{1}{1000}$$

where

$\boldsymbol{P}_{\text{MW}}$ is accumulated installed engine power for each subgroup

$\boldsymbol{F}_{\%\,\text{MCR}}$ is engine load factor based on duty cycle profile

$\boldsymbol{t}_{\text{hrs/yr}}$ is average engine running hours for each subgroup

$\boldsymbol{SFOC}_{\text{g/kWh}}$ is the power-based specific fuel oil consumption

$\boldsymbol{E}_{\text{g/kWh}}$ is the power-based emissions factor for each pollutant

Essentially, any vessel emissions calculation requires, in some format, that engine power, load factor, emissions or fuel rate, and time in service be estimated; in a fuel-based inventory, power, load, and time inputs are essentially combined.[2] This data is needed for both main and auxiliary engines to be representative of total vessel activity.[3] In a fleet-wide inventory, individual vessel data can be directly summed or groups of vessels can be defined with similar engines, fuels, speeds, and other important characteristics. The sum of these bottom-up calculations, then, provides the fleet-wide estimate. Figure 1 presents an activity-based estimation methodology. The current best-practice for estimating emissions from commercial marine vessels estimates vessel activity, fuel consumption and emissions using the following general steps [*Corbett and Koehler*, 2003; *Starcrest Consulting Group LLC et al.*, 2004].

[2] Additional discussion the advantages of an activity-based inventory compared to alternative methodologies are discussed in Section 2.5 of the recent Port-Wide Baseline Air Emissions Inventory for the Port of Los Angeles (http://www.portoflosangeles.org/Environmental/documents.htm).

[3] This report focuses on methodology rather than total inventory estimates, and data available from the Port of Los Angeles for these vessels was more complete for main engine activity. Therefore, this report evaluates the ability of modeling to characterize main engine emissions. However, the insights are applicable to auxiliary engine activity-based modeling as well.

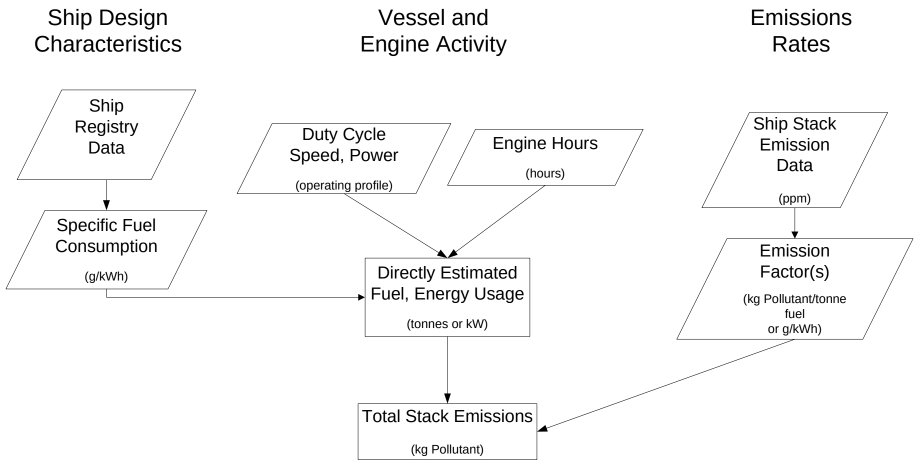

Figure 1. General methodology for estimating ship emissions

Step 1: Identify the vessel(s) to be modeled, and engines in service

At the local level, this is done routinely by vessel traffic services (VTS), such as those operated jointly by the U.S. Coast Guard and Marine Exchange of Southern California, in San Pedro Bay. For this work, VTS data was provided for the two vessels studied, either directly from the Marine Exchange of Southern California [*Aschemeyer*, 2003] or as part of the data in the Vessel Speed Reduction (VSR) Program model [*Patton*, 2003].

The Sine Maersk, a 6600 TEU container vessel built in 1998, makes regularly scheduled visits to San Pedro Bay, approximately four times per year. The vessel arrived in port in March, June, and September of 2002, and in January 2003, according to data in the VSR Program model [*Patton*, 2003]. A.P. Moller operates the Sine Maersk, and agreed to allow MAN B&W to conduct an onboard emissions measurement on the main engine (Hitachi model 12K90MC) during transit from Los Angeles to Tacoma, 9-11 February 2004. The tests were funded by the Port of Los Angeles in order to add new data and provide information on the impact of the voluntary VSR Program in San Pedro Bay [*MAN B&W Diesel A/S*, 2004].

Emissions tests performed on the main engine of the Sine Maersk followed a protocol following the "simplified measuring method" in the IMO NOx Technical Code [*International Maritime Organization*, 1998]. These tests were made under steady-state conditions at 12 knots, 25%, 50%, 75% and 85% load points; measurements were made in ascending order as the vessel transited out of San Pedro Bay and repeated in descending order as the vessel approached Tacoma. The 85% load point was substituted for the 100% load point specified in the NOx Technical Code because it represented the in-service maximum engine load (at 94 rpm). The auxiliary engine could not be operated at enough load points to produce composite emissions rates according to protocol.

The New Spirit, a 26,562 gross ton (48,183 deadweight ton) bulk carrier built in 2002, made one visit to San Pedro Bay in 2002 and one in 2003. The vessel arrived in port on 28 April 2002, and departed on 7 May 2002 for Vancouver, British Columbia, Canada [*Aschemeyer*, 2003]; the Port of Los Angeles Vessel Speed Reduction (VSR) Program also characterized the port movements for this vessel [*Patton*, 2003]. This coincided with the ITCT 2K2 ship plume experiment, conducted around noon on 8 May 2002, about 100 km off the coast of California

[*Chen et al.*, 2004]. Satellite images taken during a previous study in 1994 demonstrated that this area has heavy ship traffic [*Durkee et al.*, 2000b]. The experiment design required no prior coordination with vessels transiting the region, treating the vessel traffic as a route of opportunity for the experiment. Only after the experiment, using vessel photographs taken by the science team and assistance from the Principle Investigator of this project, was the vessel identified and characterized (main engine Sulzer 6RTA48T). Auxiliary engine data was incomplete and activity could not be characterized fully. Later, the Port of Los Angeles provided additional data for this vessel regarding fuel specifications from the most recent bunkering prior to this voyage [*Patton*, 2004].

These vessels are not expected to produce similar quantities of emissions, due primarily to their engine power, vessel speed, and operating profiles. In short, they perform different work and serve different sectors of the maritime transportation system. Container ships typically operate on a liner schedule, where on-time service and reliability requirements have resulted in large capacity, faster vessels, with powerful main engines. Bulk carriers carry a variety of specialized dry cargoes ranging from ore to grain products, and often operate with greater flexibility in destinations and scheduling. Given this type of service, sometimes termed “tramp” service in the industry, vessels may visit a given port less frequently and may transit between ports at “economy speeds” to reduce cost.

The Sine Maersk was chosen for this study because it represents a large, modern container ship and because related research provided the onboard monitoring results for analysis. The New Spirit was chosen as a vessel of opportunity by the ITCT 2k2 field scientists conducting the airborne plume study. This project (as determined by available data) compares modeling with stack test results for one vessel and modeling with plume observations for another vessel. Originally, the hope was to have plume observations and stack monitoring for the same vessel. Since that was not possible for this work, no direct and explicit comparisons can be made between plume observations for the New Spirit with the stack monitoring of the Sine Maersk. Rather, insights into the ability of estimation techniques are revealed by applying these to each vessel’s main-engine empirical data.

Step 2: Estimate the engine service hours for the voyage or voyage segment

Vessels may spend significant time in port with main engines and/or auxiliary engine(s) not in service; however, there may also be long periods of main engine idling, or auxiliary engine operation (referred to as hotelling) to support ship board activities during port visits. Either onboard operating logs can be reviewed or the vessel transit can be closely monitored to provide data regarding the engine operating time (and load). One good source of explicit vessel activity data for San Pedro Bay is the VSR model; this model was used to obtain a weighted-average calculation of channel distances and vessel speeds.[4] The VSR model does this by computing total distance of each channel segment and dividing this by the average of speeds observed at channel segment markers. The model accounts for expected changes in speed between markers by averaging the speeds at the endpoints of each segment. The data provided by the VSR model is shown in Table 1.

[4] The VSR model is not the only way to achieve this estimate, but it is one of the most detailed trip-specific sources available for any port. It also represents activity specific to the ports where the two vessels operated and therefore provided appropriate data needed to estimate engine load and operating hours for this study. The VSR model is maintained by the Port of Los Angeles.

For open ocean operations, referred here as "full-cruise" speed, main engines are expected to be operating continuously. This was observed directly during the Sine Maersk test and was assumed for the New Spirit analysis.

Table 1. Summary of VSR model data regarding the speed and distances during vessel transits through the Air Quality Control Zone (AQCZ). The Air Quality Control Zone is the region in San Pedro Bay where the vessel speed reduction program applies.

Activity Date (Arrival or Departure)	Vessel Name	Weighted Avg. Actual Speed in AQCZ (knots)	Lloyd's Service Speed (knots)	Actual-to-Service Speed Ratio	Actual Distance in AQCZ (nmi)	Time in AQCZ (hours)
		A	B	C = A/B	D	E = D/A
25-Mar-02	Sine Maersk[1]	12.00	25	0.48	21.5	1.79
28-Apr-02	New Spirit	12.34	14.5	0.85	21.75	1.76
7-May-02	New Spirit	14.19	14.5	0.98	21.5	1.51
21-Jun-02	Sine Maersk	12.22	25	0.49	21.75	1.78
24-Jun-02	Sine Maersk	11.95	25	0.48	21.5	1.80
21-Sep-02	Sine Maersk	13.34	25	0.53	21.75	1.63
24-Sep-02	Sine Maersk	12.49	25	0.50	21.5	1.72
4-Jan-03	Sine Maersk	16.36	25	0.65	21.75	1.33
10-Jan-03	Sine Maersk	11.69	25	0.47	21.5	1.84
12-Apr-03	Sine Maersk	8.65	25	0.35	21.5	2.49
14-Apr-03	Sine Maersk	11.30	25	0.45	21.5	1.90
31-May-03	New Spirit	13.55	14.5	0.93	21.5	1.59
01-Jun-03	New Spirit	13.78	14.5	0.95	21.75	1.58
09-Aug-03	Sine Maersk	19.06	25	0.76	21.5	1.13
11-Aug-03	Sine Maersk	18.99	25	0.76	21.5	1.13
08-Nov-03	Sine Maersk	18.00	25	0.72	21.5	1.19
10-Nov-03	Sine Maersk	19.46	25	0.78	21.5	1.11
14-Dec-03	New Spirit	11.83	14.5	0.82	21.5	1.82
23-Dec-03	New Spirit	13.34	14.5	0.92	21.75	1.63
07-Feb-04	Sine Maersk	11.59	25	0.46	21.5	1.86
09-Feb-04	Sine Maersk	12.10	25	0.48	21.5	1.78
08-May-04	Sine Maersk	16.67	25	0.67	21.5	1.29
10-May-04	Sine Maersk	14.63	25	0.59	21.5	1.47

1. Data for the arrival of this vessel was incomplete and is not included in this analysis.

Step 3: Determine the engine load profiles, including power and duty cycle

Engine load profiles are a set of load factors corresponding to different engine speeds (and corresponding vessel speeds, for main engines). At full-cruise speed, the load factor is estimated to be about 80% of maximum continuous rating (MCR), to improve fuel economy and reduce maintenance costs. According to the test report for the Sine Maersk, that vessel may have a full-cruise speed close to 80% of MCR, given that the maximum engine load was approximately 85% [*MAN B&W Diesel A/S*, 2004]; therefore, the model follows the convention supported by recently gathered data representing typical operations in San Pedro Bay [*Starcrest Consulting Group LLC et al.*, 2004]. Earlier vessel emission research also applied an empirical adjustment factor to the rated power; however, as inventory methodologies have advanced and are based on more detailed vessel characterizations, the power adjustment inserted unjustified bias into the inventory and is no longer used [*Starcrest Consulting Group LLC et al.*, 2004].

Based on observed vessel speed, the New Spirit was not operating at 80% of MCR when selected for the ITCT 2k2 plume study by the field team. Its speed was observed to be about 9.7 knots, approximately 67% of rated speed. This implies an engine load of 30% if the vessel is assumed to follow the propeller law cubic relationship.

Most studies have applied the ISO standard duty cycles for marine engines [*ISO*, 1996]; however, fleet data suggests that, on average, main engines may not operate according to these default profiles [*Corbett and Koehler*, 2003; *Corbett and Koehler*, 2004]. Certainly, the load profile for vessels considering only the portion of the voyage within the VSR Program would not fit the ISO duty cycle; for this analysis, the load profile developed from the VSR model was used.

Load factors at slower speeds are estimated using the propeller law, which defines an approximate cubic relationship between a change in vessel speed and propulsion power. This relationship is approximate and varies from vessel to vessel. As shown in Figure 2 for the Sine Maersk, this relationship appears adequate for modeling purposes, although in this case the relationship predicts less power than actually observed for most of the loads. Roughly estimating the composite error if the vessel operated according to an approximate E3 duty cycle (using observed power and speed instead of those identified in ISO 8178, part 4), the composite error in the model for the Sine Maersk may be as much as 12% if all vessels demonstrated similar actual relationships between speed and power. Table 2 summarizes the composite load factor using this approach.

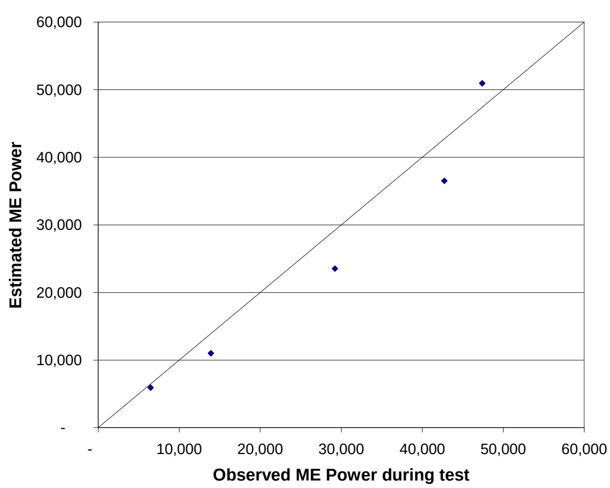

Figure 2. Comparison of observed main engine power and estimated power using general propeller law.

<u>Step 4: Apply emissions or fuel consumption rates for specific engine/fuel combinations</u>

Emissions and specific fuel oil consumption (SFOC) rates (also referred to as factors) vary according to engine type and size, speed, load, fuel type, and age. In-service engines are shown to typically have higher emissions than new engines mounted on manufacturers' test-beds; this is partly because test fuels are different from fuels purchased commercially by industry, and also because of operating and maintenance variations and normal engine wear.

Table 2. Summary of energy and power estimates following the VSR model format.

Activity Date (Arrival or Departure)	Vessel Name	Actual-to-Service Speed Ratio	Load Factor	Lloyd's ME Power (KW)	Full-cruise ME Power (kW)	Composite ME Power (kWh)
		F (see Table 1)	$G = F^3$	H	I = 0.80*H	J = E*G*I
25-Mar-02	Sine Maersk	0.48	0.11	54,840	43,872	8,691
28-Apr-02	New Spirit	0.85	0.62	6,708	5,366	5,826
7-May-02	New Spirit	0.98	0.94	6,708	5,366	7,625
21-Jun-02	Sine Maersk	0.49	0.12	54,840	43,872	9,115
24-Jun-02	Sine Maersk	0.48	0.11	54,840	43,872	8,622
21-Sep-02	Sine Maersk	0.53	0.15	54,840	43,872	10,862
24-Sep-02	Sine Maersk	0.50	0.12	54,840	43,872	9,417
4-Jan-03	Sine Maersk	0.65	0.28	54,840	43,872	16,349
10-Jan-03	Sine Maersk	0.47	0.10	54,840	43,872	8,247
12-Apr-03	Sine Maersk	0.35	0.04	54,840	43,872	4,518
14-Apr-03	Sine Maersk	0.45	0.09	54,840	43,872	7,708
31-May-03	New Spirit	0.93	0.82	6,708	5,366	6,950
01-Jun-03	New Spirit	0.95	0.86	6,708	5,366	7,266
09-Aug-03	Sine Maersk	0.76	0.44	54,840	43,872	21,924
11-Aug-03	Sine Maersk	0.76	0.44	54,840	43,872	21,779
08-Nov-03	Sine Maersk	0.72	0.37	54,840	43,872	19,567
10-Nov-03	Sine Maersk	0.78	0.47	54,840	43,872	22,854
14-Dec-03	New Spirit	0.82	0.54	6,708	5,366	5,294
23-Dec-03	New Spirit	0.92	0.78	6,708	5,366	6,813
07-Feb-04	Sine Maersk	0.46	0.10	54,840	43,872	8,104
09-Feb-04	Sine Maersk	0.48	0.11	54,840	43,872	8,838
08-May-04	Sine Maersk	0.67	0.30	54,840	43,872	16,777
10-May-04	Sine Maersk	0.59	0.20	54,840	43,872	12,919

Average emissions and fuel consumption rates are a composite of rates at various engine loads (dependent on duty cycle). While emissions rates vary with load, for the most common load points between 50% and 90%, a review of industry engine data indicate that there is not much variation in the load profile for a given engine [*Corbett and Koehler*, 2003]; this was also observed during the Sine Maersk test [*MAN B&W Diesel A/S*, 2004]. In general, cargo ships have more fuel-efficient, larger engines than non-cargo ships.

Some literature suggests that fuel-based factors are inferior to power-based factors because fuel-based factors do not show the same increase in emissions factors at low loads [*Energy and Environmental Analysis and Research*, 2000]. The ENTEC report clearly reconciles these differences by stating, "emission factors in kg/tonne fuel can be obtained by taking the g/kWh factor and dividing by the specific fuel consumption" [*European Commission and ENTEC UK Limited*, 2002]. When this fuel-based conversion is done, the relatively higher fuel consumption at low loads and the relatively higher emission rates (in g/kWh) at low loads tend to cancel out; the result is that fuel-based emission factors are flatter over the load range. Overall, the inventory results are nearly identical using either approach, if the fuel consumption is directly based on engine activity.

IVL, the Swedish Environmental Research Institute, has produced the most recent and most detailed published report of average emissions and SFOC rates [*Cooper*, 2004]. This data was used in recent emissions inventories in both Europe and the Port of Los Angeles in the United States [*European Commission and ENTEC UK Limited*, 2002; *Starcrest Consulting Group LLC et al.*, 2004]. The IVL study focused on 28 air pollutants, identifying emissions rates as a function of engine and fuel type. Three operational modes ("at sea", "maneuvering" and "in port") take into account both main engine and auxiliary engine emissions. Emissions rates were derived from exhaust measurements from ca. 62 ships involving ca.180 marine engines, including the widely cited Lloyd's Marine Engine Exhaust Programme. For fleet-wide inventories, weighted average emissions factors can be calculated, based on the engine-fuel combinations for each vessel type, age factors affecting fuel consumption deterioration, and whether portions of the fleet adopt control technologies.

The Swedish Environmental Research Institute study includes estimates of the uncertainty by pollutant in the average emissions rates reported, by pollutant; this makes the study very valuable for comparing modeled emissions using average versus measured emissions. Emission factors used to model the emissions from vessels studied in this report are taken from the IVL work, consistent with the recent inventory for the Port of Los Angeles (Table 3). For comparison, Table 3 presents emission rates reported by Sine Maersk, along with average rates for NOx and SOx reported by the Lloyd's Register Marine Exhaust Emissions Research Programme [*Carlton et al.*, 1995] and NOx emissions rates originally used in the VSR model [*Patton*, 2003].

Table 3. Emission factors for main engines used in model estimates, g/kW-hr.

Engine-fuel type	NOx	CO	CO_2	HC	PM_{10}	$PM_{2.5}$	SO_2
IVL emissions rates[1]	18.1	1.4	588	0.6	1.92	1.54	10.5
Sine Maersk emissions rates	20.6	0.19	578	0.1	1.70		8.79
Lloyd's emissions rates	17	1.6	660	0.5	1.5		4.2*%S
Original VSR model rates	Note 2						

1. The IVL emissions rates include a reanalysis of Lloyd's Marine Emissions Research Programme test data.
2. Rate varies with load according to statistical relationship; NOx (in g/kWh) = -1.8162 x % MCR at Actual Operating Conditions + 18.77; the average for these factors among the voyages modeled is 18.26 g NOx/kWh, with a minimum and a maximum of 17.07 g NOx/kWh and 18.58 g NOx/kWh, respectively.

For the New Spirit, emissions rates for certain pollutants were derived from plume observations. Much of this discussion is taken from a manuscript primarily authored by ITCT 2k2 research scientists, and coauthored with the Principle Investigator [*Chen et al.*, 2004]. Several studies have stated the need for experimental data to better elucidate the dynamical and chemical processes of ship plumes [*Corbett*, 2003; *Davis et al.*, 2001; *Lawrence and Crutzen*, 1999; *von Glasow et al.*, 2003]. Observations of ship plumes can better help us determine the rate of the plume dispersion and also provide the observed pollutant concentration as potential modifiers of stack emissions due to plume chemistry.

This effort is inherently more uncertain and, because the vessel was identified ad hoc only on 8 May 2002 during the ITCT 2k2 experiment campaign, the ability to validate observations with model calculations is limited to general information about the vessel activity. The vessel was transiting at about 67% of its rated speed, and was heading almost directly into the wind; these factors combine with observed atmospheric conditions (high wind speed and neutral to unstable stability for buoyancy) to enable rapid dilution of the plume. This implies that this study may have been carried out at emission concentrations below typical values for ship plumes under other conditions. Also, the closest sampling of the plumes occurred within 5 km downwind from the ships, raising the expectation that chemical processing in the plume may result in observations that differ from stack measurements. Nonetheless, analysis of plume data enables us to assess our understanding of ship plume chemistry, factors controlling NOx loss, and the chemical interaction between particulate matter (both background and ship emitted) and plume gases [*Chen et al.*, 2004].[5]

The ITCT analysis estimated whether CO_2 emissions would fit observed plume enhancements, based on rated main engine fuel consumption of the identified bulk carrier at 27 ton/day (see Appendix). At the observed ship speed of ca. 5 m/s (9.72 knots) and the rated vessel speed of 14.5 knots, engine load was 67% of full speed (~30% of full power) which translates to a fuel consumption rate of ~0.3 kg C (carbon)/s. Using the mass ratio of CO_2 emitted to fuel consumed, the CO_2 emission rate would be 1.09 kg/s. A Gaussian plume dispersion model was then used to estimate the CO_2 mixing ratio at 5 km downwind where the ship plume was first spotted [*Chen et al.*, 2004]. The model predicted centerline CO_2 plume enhancements for these two conditions were 0.22 and 2.0 ppmv, respectively. This brackets the observed CO_2 enhancement of ca. 1 ppmv. Considering the large uncertainties in the dispersion model, it is clear that better models need to be incorporated in ship plume studies to represent the plume dispersion processes under actual ambient conditions [*Chen et al.*, 2004].

Direct observations of ship plumes can be used to estimate the emission rates (i.e., emission of certain species in g/kg fuel consumed or in g/kWh). Emissions rates were derived for NOx, and SO_2, based on plume observations closest to the ship. Ratios of $\Delta NOx/\Delta CO_2$, $\Delta SO_2/\Delta CO_2$, and $\Delta Ntotal/\Delta CO_2$ in the plume and in ambient air were evaluated using time series data collected by the aircraft. Particle emissions calculations focused on small size ranges (0.005–0.15 µm and 0.15–1.0 µm in diameter), but since the majority of diesel PM is in the small size ranges this study considers these results representative of total PM.

Emission factors estimated from plume measurements are summarized in Table 4 for the New Spirit [*Chen et al.*, 2004]. The uncertainties quoted in the table reflect both instrument precision and atmospheric variability in background levels. The estimated NOx emission factors are consistent with other in situ estimates [*Hobbs et al.*, 2000; *Sinha et al.*, 2003] and the values commonly used in emission inventory studies [*Corbett et al.*, 1999; *Corbett and Koehler*, 2003]. However, SO_2 emissions rates are significantly lower than those estimated for main engines burning marine fuel oil [*Corbett et al.*, 1999; *Corbett and Koehler*, 2003; *Hobbs et al.*, 2000;

[5] Interested readers are directed to the growing scientific literature investigating the influence of plumes on pollution fate and transport, particularly the research articles cited in this report.

Sinha et al., 2003]. This may indicate that the sulfur content in the fuel used in the ships observed during ITCT was much lower.

Table 4. Emission factors for New Spirit derived from nearest plume observation.

Species	Fuel-based g/kg fuel	Power-based[1] g/kWh	Typical Range[2] g/kWh
NOx (as NO_2)	66 ± 26	13 ± 5	19 ± 8
SO_2[3]	30 ± 4	6 ± 0.8	8 ± 1
PM	4.6 ± 1.4	0.9 ± 0.3	7 ± 5 1.6 – 6.2[4]

1. Power-based emissions rates assume a SFOC rate of 195, per [*Cooper*, 2004].
2. Typical ranges from recent literature [*Cooper,* 2004; *European Commission and ENTEC UK Limited,* 2002].
3. These ranges represent the vessel plume observations containing both main engine emissions at 2.19% residual fuel-sulfur levels and auxiliary engine emissions at 0.86% distillate fuel-sulfur levels [*Patton*, 2004].
4. Ranges reported by other atmospheric science studies [*Hobbs et al.*, 2000; *Sinha et al.*, 2003].

Average fuel sulfur contents are about 2.7% for international marine fuels [*Corbett and Koehler*, 2003; *Endresen et al.*, 2003; *European Commission and ENTEC UK Limited*, 2002; *International Maritime Organization and Marine Environment Protection Committee*, 2001]. Of course, fuel-sulfur levels vary according to when and where fuel is purchased. A recent inventory of commercial marine vessels in Los Angeles confirmed that average sulfur levels used aboard ships on the West Coast of North America is near the world average (averaging 2.64%); interestingly, this inventory also observed some vessels with main engine fuel-sulfur levels at or below 2% [*Starcrest Consulting Group LLC et al.*, 2004]. The fuel delivery report obtained for this study indicates that the fuel-sulfur content for the main engine on the New Spirit was most likely in the range of 1.9 to 2.2%. Based on the fuel sulfur content values, the SO_2 emission factors are estimated to be 7 to 9 g/kWh, compared to an upper bound of 6.8 g/kWh estimated from plume observations (see Table 4). This discrepancy, although not very large, suggests that the SO_2 emission factors derived from observations may be inconsistent with the estimated fuel sulfur content [*Chen et al.*, 2004].

Emissions observed in the ship plume are a mix of main engine and auxiliary engine(s) emissions. The auxiliary engines aboard many vessels, including the New Spirit, typically use a different fuel with lower fuel sulfur contents (typically lower than 1% and often near 0.5% sulfur by weight) than the main engines. Data for the New Spirit suggest that it was using marine diesel oil as auxiliary fuel, with even lower sulfur content than the main engine residual fuel oil. If so, the values observed in Table 1 might be consistent with estimates using combined fuel sulfur values (a blend of main and auxiliary engine exhaust), although this cannot be confirmed from the available data. For example, the power-based emission factor appropriate to fuel-sulfur levels in residual fuel used by the main engine is closer to 8.5 g/kWh; this higher value is used in calculations of main engine emissions for this study.

Step 5: Estimate emissions or fuel consumption for the voyage or voyage segment

The final step in estimating emissions is to multiply the composite power (in kWh) that represents the voyage or voyage segment by the emissions rate (in g/kWh). For each of the port calls in the San Pedro Bay region, estimates were made using published rates, measured emissions rates for the Sine Maersk, and emissions rates derived from plume observations.

RESULTS

Tables 5 through 10 report emissions using different emissions rates following the activity-based model methodology for NOx, SO_2, PM_{total}, CO_2, CO, and HC, respectively.

Table 5. NOx emissions estimates in kilograms per transit, under different emission factor assumptions.

Activity Date (Arrival or Departure)	Vessel Name	Emissions (kg) per published literature	Emissions (kg) per Sine Maersk Engine Test 2004	Emissions (kg) per ITCT 2002 Plume Measurements	Emissions (kg) per VSR 2003
25-Mar-02	Sine Maersk	157	179		161
28-Apr-02	New Spirit	105		75	103
7-May-02	New Spirit	138		98	130
21-Jun-02	Sine Maersk	165	188		169
24-Jun-02	Sine Maersk	156	178		160
21-Sep-02	Sine Maersk	197	224		201
24-Sep-02	Sine Maersk	170	194		175
4-Jan-03	Sine Maersk	296	337		299
10-Jan-03	Sine Maersk	149	170		153
12-Apr-03	Sine Maersk	82	93		84
14-Apr-03	Sine Maersk	140	159		143
31-May-03	New Spirit	126		89	120
01-Jun-03	New Spirit	132		93	125
09-Aug-03	Sine Maersk	397	452		394
11-Aug-03	Sine Maersk	394	449		391
08-Nov-03	Sine Maersk	354	403		354
10-Nov-03	Sine Maersk	414	471		409
14-Dec-03	New Spirit	96		68	94
23-Dec-03	New Spirit	123		87	118
07-Feb-04	Sine Maersk	147	167		151
09-Feb-04	Sine Maersk	160	182		164
08-May-04	Sine Maersk	304	346		306
10-May-04	Sine Maersk	234	266		238

As seen in Table 5, NOx emissions based on rates from the February 2004 monitoring are a bit higher than the emissions using published emissions rates (or using rates in the 2003 version of the VSR model). Emissions based on rates from the ITCT 2002 plume study are lower than emissions using published rates.

Table 6. SO_2 emissions estimates in kilograms per transit, under different emission factor assumptions.

Activity Date (Arrival or Departure)	Vessel Name	Emissions (kg) per published literature	Emissions (kg) per Sine Maersk Engine Test 2004	Emissions (kg) per ITCT 2002 Plume Measurements
25-Mar-02	Sine Maersk	91	76	
28-Apr-02	New Spirit	61		50
7-May-02	New Spirit	80		65
21-Jun-02	Sine Maersk	96	80	
24-Jun-02	Sine Maersk	91	76	
21-Sep-02	Sine Maersk	114	95	
24-Sep-02	Sine Maersk	99	83	
4-Jan-03	Sine Maersk	172	144	
10-Jan-03	Sine Maersk	87	72	
12-Apr-03	Sine Maersk	47	40	
14-Apr-03	Sine Maersk	81	68	
31-May-03	New Spirit	73		59
01-Jun-03	New Spirit	76		62
09-Aug-03	Sine Maersk	230	193	
11-Aug-03	Sine Maersk	229	191	
08-Nov-03	Sine Maersk	205	172	
10-Nov-03	Sine Maersk	240	201	
14-Dec-03	New Spirit	56		45
23-Dec-03	New Spirit	72		58
07-Feb-04	Sine Maersk	85	71	
09-Feb-04	Sine Maersk	93	78	
08-May-04	Sine Maersk	176	147	
10-May-04	Sine Maersk	136	114	

Table 6 shows that SO_2 emissions based on rates from the February 2004 monitoring are lower than emissions using published emissions rates. Emissions based on rates from the ITCT 2002 plume study are also lower than emissions using published rates.

Table 7. PM emissions estimates in kilograms per transit, under different emission factor assumptions.

Activity Date (Arrival or Departure)	Vessel Name	Emissions (kg) per published literature	Emissions (kg) per Sine Maersk Engine Test 2004	Emissions (kg) per ITCT 2002 Plume Measurements
25-Mar-02	Sine Maersk	17	15	
28-Apr-02	New Spirit	11		5
7-May-02	New Spirit	15		7
21-Jun-02	Sine Maersk	18	16	
24-Jun-02	Sine Maersk	17	15	
21-Sep-02	Sine Maersk	21	19	
24-Sep-02	Sine Maersk	18	16	
4-Jan-03	Sine Maersk	31	28	
10-Jan-03	Sine Maersk	16	14	
12-Apr-03	Sine Maersk	9	8	
14-Apr-03	Sine Maersk	15	13	
31-May-03	New Spirit	13		6
01-Jun-03	New Spirit	14		7
09-Aug-03	Sine Maersk	42	38	
11-Aug-03	Sine Maersk	42	38	
08-Nov-03	Sine Maersk	38	34	
10-Nov-03	Sine Maersk	44	40	
14-Dec-03	New Spirit	10		5
23-Dec-03	New Spirit	13		6
07-Feb-04	Sine Maersk	16	14	
09-Feb-04	Sine Maersk	17	15	
08-May-04	Sine Maersk	32	29	
10-May-04	Sine Maersk	25	22	

Table 7 shows that PM emissions based on rates from the February 2004 monitoring are somewhat lower than emissions using published emissions rates, while emissions based on rates from the ITCT 2002 plume study are substantially lower than emissions using published rates.

Table 8. CO_2 emissions estimates in metric tons per transit, under different emission factor assumptions.

Activity Date (Arrival or Departure)	Vessel Name	Emissions (tonnes) per published literature	Emissions (tonnes) per Sine Maersk Engine Test 2004
25-Mar-02	Sine Maersk	5.1	5.0
28-Apr-02	New Spirit	3.4	
7-May-02	New Spirit	4.5	
21-Jun-02	Sine Maersk	5.4	5.3
24-Jun-02	Sine Maersk	5.1	5.0
21-Sep-02	Sine Maersk	6.4	6.3
24-Sep-02	Sine Maersk	5.5	5.4
4-Jan-03	Sine Maersk	9.6	9.4
10-Jan-03	Sine Maersk	4.8	4.8
12-Apr-03	Sine Maersk	2.7	2.6
14-Apr-03	Sine Maersk	4.5	4.5
31-May-03	New Spirit	4.1	
01-Jun-03	New Spirit	4.3	
09-Aug-03	Sine Maersk	12.9	12.7
11-Aug-03	Sine Maersk	12.8	12.6
08-Nov-03	Sine Maersk	11.5	11.3
10-Nov-03	Sine Maersk	13.4	13.2
14-Dec-03	New Spirit	3.1	
23-Dec-03	New Spirit	4.0	
07-Feb-04	Sine Maersk	4.8	4.7
09-Feb-04	Sine Maersk	5.2	5.1
08-May-04	Sine Maersk	9.9	9.7
10-May-04	Sine Maersk	7.6	7.5

Table 8 shows that CO_2 emissions based on rates from the February 2004 monitoring agree very well with emissions using published emissions rates for CO_2. Carbon dioxide emissions rates were not explicitly calculated as part of the plume study report.

Table 9. CO emissions estimates in metric tons per transit, under different emission factor assumptions.

Activity Date (Arrival or Departure)	Vessel Name	Emissions (kg) per published literature	Emissions (kg) per Sine Maersk Engine Test 2004
25-Mar-02	Sine Maersk	12	2
28-Apr-02	New Spirit	8	
7-May-02	New Spirit	11	
21-Jun-02	Sine Maersk	13	2
24-Jun-02	Sine Maersk	12	2
21-Sep-02	Sine Maersk	15	2
24-Sep-02	Sine Maersk	13	2
4-Jan-03	Sine Maersk	23	3
10-Jan-03	Sine Maersk	12	2
12-Apr-03	Sine Maersk	6	2
14-Apr-03	Sine Maersk	11	2
31-May-03	New Spirit	10	
01-Jun-03	New Spirit	10	
09-Aug-03	Sine Maersk	31	4
11-Aug-03	Sine Maersk	30	4
08-Nov-03	Sine Maersk	27	4
10-Nov-03	Sine Maersk	32	4
14-Dec-03	New Spirit	7	
23-Dec-03	New Spirit	10	
07-Feb-04	Sine Maersk	11	2
09-Feb-04	Sine Maersk	12	2
08-May-04	Sine Maersk	23	3
10-May-04	Sine Maersk	18	2

Table 9 shows significant differences between CO emissions based on rates from the February 2004 monitoring and estimated emissions using published emissions rates. This may indicate differences in the combustion efficiency of the Sine Maersk and engines whose test inform the published average rates, or that testing for CO is too limited and would benefit from further study. Carbon monoxide emissions rates were not explicitly calculated as part of the plume study report. It should be noted that diesel engines are typically very minor CO sources.

Table 10. HC emissions estimates in metric tons per transit, under different emission factor assumptions.

Activity Date (Arrival or Departure)	Vessel Name	Emissions (kg) per published literature	Emissions (kg) per Sine Maersk Engine Test 2004
25-Mar-02	Sine Maersk	5	0.9
28-Apr-02	New Spirit	3	
7-May-02	New Spirit	5	
21-Jun-02	Sine Maersk	5	0.9
24-Jun-02	Sine Maersk	5	0.9
21-Sep-02	Sine Maersk	7	1.1
24-Sep-02	Sine Maersk	6	0.9
4-Jan-03	Sine Maersk	10	1.6
10-Jan-03	Sine Maersk	5	0.8
12-Apr-03	Sine Maersk	3	0.4
14-Apr-03	Sine Maersk	5	0.8
31-May-03	New Spirit	4	
01-Jun-03	New Spirit	4	
09-Aug-03	Sine Maersk	13	2.2
11-Aug-03	Sine Maersk	13	2.1
08-Nov-03	Sine Maersk	12	1.9
10-Nov-03	Sine Maersk	14	2.3
14-Dec-03	New Spirit	3	
23-Dec-03	New Spirit	4	
07-Feb-04	Sine Maersk	5	0.8
09-Feb-04	Sine Maersk	5	0.9
08-May-04	Sine Maersk	10	1.7
10-May-04	Sine Maersk	8	1.3

Similar to CO, Table 10 shows significant differences between HC emissions based on rates from the February 2004 monitoring and estimated emissions using published emissions rates. This may indicate differences in the combustion efficiency of the Sine Maersk and engines whose test inform the published average rates, or that measurement efforts focused on HC are too limited and would benefit from further study. Hydrocarbon emissions rates were not explicitly calculated as part of the plume study report. It should be noted that diesel engines are typically very minor HC sources.

Discussion

While this analysis does not provide a closed-loop analysis of emissions monitoring, modeling, and plume observation for a given vessel, it does begin to coherently address the potential differences among these. This section discusses some of the primary observations that may be made with regard to the results.

Overall comparisons

As expected, the agreement between emissions calculated using emissions rates from literature and emissions calculated using stack test results is better than the comparison of emissions calculated from literature emission rates with estimates using emissions rates derived from in-plume observations. In other words, reconciling emissions monitoring data with model estimates will entail less adjustment than reconciling ship-stack plume observations with model estimates. This is illustrated in Table 11 by averaging the results of each set of vessel voyages for published, measured, and in-plume-derived emissions rates.

Table 11. Estimated main engine emissions in tons per day using published emissions rates and empirical emissions rates for a) Sine Maersk[1] estimated full-cruise conditions of 80% rated power; and b) New Spirit[2] observed at-sea conditions (corresponding to ~62% of full-cruise speed).

	CO_2	NOx	SO_2	PM	HC	CO
Sine Maersk using published rates	619	19	11	2.0	0.6	1.5
Sine Maersk using stack monitoring rates	608	22	9	1.8	0.1	0.2
Percent difference	2%	-12%	19%	11%	508%	640%
New Spirit using published rates		0.7	0.4	0.07		
New Spirit using in-plume observed rates		0.5	0.3	0.03		
Percent difference		41%	23% (33%)	114%		

1. For the Sine Maersk, the MAN B&W report included data for engine speed but not vessel speed, so "full-cruise" conditions are assumed to represent 80% rated power (see Table 2, column I).
2. For the New Spirit, the at-sea conditions during the plume study corresponded to about 30% power; one possible reason for this may be that the vessel was in an economy cruising mode (typical of bulk carriers). Corresponding "full-cruise" conditions for the New Spirit would increase activity assumptions and, therefore, the emissions reported here, but would not modify the comparative differences reported for New Spirit. The difference between estimates using published and in-plume-derived rates adjusting for main engine fuel sulfur content is 23%; if this adjustment was not made, the difference would be about 33%.

Comparing estimates using average published emissions rates and measured emissions rates, the percent differences in emissions of CO_2, PM, NOx, and SO_2 are small. In fact, the measurement uncertainty reported for the Sine Maersk measurement results nearly equal to the differences shown here. Greater differences exist between estimates using average published emissions rates and in-plume-derived rates. In particular, the SO_2 emissions in the plume are lower and the PM emissions are higher than would be estimated based on published emissions rates. It may be speculated that the reduction in SO_2 is associated with the increase in PM. Without attempting to explain or define a relationship given this limited data, it is known that higher fuel-sulfur contents are associated with higher particulate emissions [*Lyyranen et al.*, 1998] and that gaseous SO_2 processes to form aerosols and may affect particle size.

The differences between results using measured rates of CO and HC and published emissions rates is much larger, with errors using the published rates on the order of five to six times measured rates. This is not necessarily surprising, given the relatively low emissions of CO and HC from large, slow-speed diesel engines [*Heywood*, 1988], and given that aggregated average emissions rates are drawn from studies most concerned with NOx, SOx, PM, and CO_2. In other words, high uncertainties are primarily due to limited in-service test data for CO and HC [*Cooper*, 2004]. Therefore, one might expect greater differences between an emission test on a large marine diesel engine and results of limited testing done on marine engines for trace pollutants (like CO and HC) that are emitted at rates much lower than other criteria pollutants.

Uncertainty versus variability

Figure 3, parts a, b, and c illustrates that uncertainty in emissions factors derived from measurements, even where many measurements are aggregated to obtain average emission factors, does not present significant problems for model estimation. It appears that using published emissions factors instead of measured rates would under predict NOx emissions from the Sine Maersk during port calls in San Pedro Bay, but within the uncertainty in the measurement itself (see Figure 3a). The converse is also true: the uncertainty in published emissions rates would include the measured rates reported for the Sine Maersk (see Figure 3b). For other pollutants, applying published emissions rates under the same methodology would over-predict emissions. However, understanding the specific operating profile does matter. As shown in Figure 3b, variability in vessel operations can be significant, even for a frequently arriving vessel in a familiar port. In general, model estimates agree very well with individual measurements.

The primary sources of uncertainty considered in these figures are related to the emissions rates themselves – either from aggregation of many tests to published emissions rates, or from uncertainty reported for the monitoring and/or plume observations. As shown in Figure 3, emissions rates are uncertain but affect the overall estimates less than variability in vessel operation. Models that explicitly consider activity data for each port call, usually incorporating vessel traffic services data as done by the Port of Los Angeles VSR model, can reduce uncertainty that arises when variability in vessel activity is averaged or ignored.

Again, this reinforces a primary methodological insight discussed in the background section of this report: Understanding vessel and engine activity, including load, speed, and fuel type, is critical to accurate estimates of emissions, except where our understanding or data for specific pollutant emissions rates is incomplete.

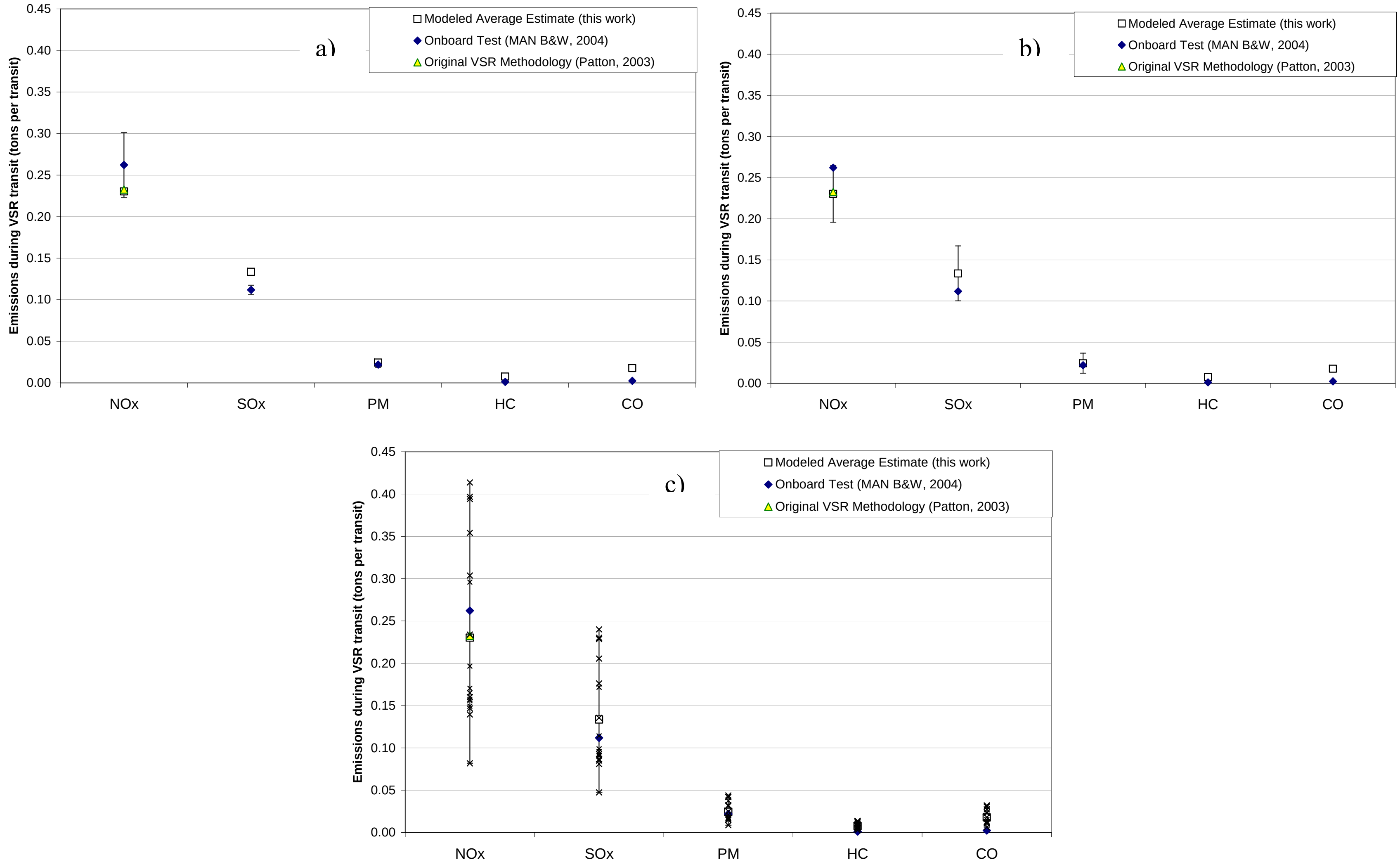

Figure 3. Comparison of transit emissions estimates with modeled and measured average emissions factors a) Applying measurement uncertainty reported for emission factors [*MAN B&W Diesel A/S*, 2004]; b) Applying uncertainty estimates from emission factor summaries [*Cooper*, 2004]; and c) Demonstrating variability among transit estimates at different speeds. All transit estimates represent the Sine Maersk.

SUMMARY AND CONCLUSIONS

This research outlines the general best-practice methodology currently being applied to produce inventories of emissions for commercial marine vessels. While certain details can vary at different scales of estimation (e.g, the individual vessel, fleet, port or local region, nation, or global scales), the activity-based methodology can provide accurate and transparent estimates of emissions and energy use.

Stack gas measurement conclusions

The results of this study lend confidence that improved emission inventories will be consistent with monitoring results. The implications of this are important for efforts such as the VSR Program, which attempts to estimate the reduction in emissions associated with reduced speed guidelines for vessels in the San Pedro Bay. The results may also be important when estimating the performance of other emission control measures.

However, the agreement between monitoring and modeling varies among pollutants. Well-studied pollutants (e.g., NOx and SO_2) are represented more accurately in published average emissions rates than other ship pollutants (e.g., CO and HC). For pollutants where agreements with measurements are not very good, the average emissions rate tends to overestimate emissions.

Plume analysis conclusions

The comparison of emissions rates derived from in-plume observations with published emissions rates showed significant disagreement. Questions posed among atmospheric scientists include whether the inventories may be wrong, whether our understanding of nonlinear atmospheric chemistry may be incomplete, or whether chemical transport models are representative. The good agreement between monitoring and modeling emissions rates at least helps to confirm that disagreement between inventory estimates and in-plume observations is not likely an inventory problem but is likely a result of complex chemical processing within ship plumes.

As seen in Table 11, the reduction in gaseous SO_2 emissions may be associated with the increase in PM emissions. This report cannot explain or define the plume-specific factors in this relationship, but it is well understood that sulfur emissions can contribute to aerosol (fine particle) formation, both directly and through adsorption on existing particles.

This conclusion is consistent with ongoing research showing that better inventories are only part of the solution to better evaluation of ship emissions impacts on air quality or climate change. Without special calibration, chemical transport models that have included geographically resolved ship emissions inventories appear to over-predict observed effects of certain pollutants from shipping, such as oxides of nitrogen (NOx), but show better agreement with field observations for others, such as oxides of sulfur (SOx) [*Capaldo et al.*, 1999; *Davis et al.*, 2001; *Kasibhatla et al.*, 2000; *Lawrence and Crutzen*, 1999]. These results support the importance of continued research into these issues.

Recommendations

The most important recommendations from this research address improved modeling; however, recommendations are also offered for better plume studies and testing. First, improving inventories of commercial marine vessels requires more detailed characterization of vessel and engine activity. This appears more important than additional monitoring of uncontrolled baseline emissions. This recommendation is valid for criteria pollutants and for CO_2; however, additional testing appears needed to better understand the nature and amount of PM emissions, and emissions of minor marine diesel pollutants. Characterizing vessel speed, engine load, and other main engine operating conditions contribute more to the variation among individual vessel emissions and, therefore, to the overall uncertainty of aggregate vessel inventory estimates.

Second, modeling methodologies will need to consider whether emissions reductions can be computed by simply adjusting emissions factors according to average reductions or whether new information about the vessel, engine, and emission control technology operation will be needed. This will also be important to address concerns about deterioration of engine or control technology performance over time; further longitudinal analyses of emissions can be pursued to predict emissions and validate or certify reduction techniques [*Cooper and Andreasson*, 1999]. In this regard, emissions monitoring continues to be valuable as regulators and operators move from baseline emissions testing to evaluation of reductions achieved through various technologies and operational measures.

There remains potential for improved understanding of transients and variability from one voyage to another. Transient emissions tests are important to identify engine conditions during voyages where the average emissions factors may fail to represent the overall composite loads. This has been observed in some studies [*Behr et al.*, 2003; *Corbett and Robinson*, 2001], and is a concern for regulators, e.g., not-to-exceed requirements for transients [*Environmental Protection Agency*, 1999]. Variability in emission test data from one voyage to another may also be important, although the Sine Maersk test did show consistent emissions under similar loads over a multi-port voyage. That study did not, however, evaluate the effects on emissions rates of potential modifications to the combustion system from routine maintenance or unplanned repairs. This would require either multiple episodes of testing on a given vessel or development of continuous or predictive monitoring systems for maritime applications [*Cooper and Andreasson*, 1999].

Additional research focused on ship exhaust plumes may help reconcile these questions. Studies have shown that ship emissions produce aerosols that form ship tracks and that these dynamics are important to understanding radiative effects of clouds [*Durkee et al.*, 2000a; *Durkee et al.*, 2000b; *Russell et al.*, 2000; *Russell et al.*, 1999]. Additionally, studies have shown that in-plume chemistry may shorten the lifetime of emitted gaseous pollutants [*Chen et al.*, 2004; *Davis et al.*, 2001; *Hobbs et al.*, 2000; *Sinha et al.*, 2003]. This work may improve the performance of models which include ship emissions in local, regional, and global chemical transport models. Until then, poorly understood influences of ship-engine pollution may confound field efforts to study long-range intercontinental pollution transport unless considered in better closed-loop studies reconciling monitored, modeled, and observed emissions [*NOAA*, 2001]. Better understanding of "what the environment sees" is useful for regulators to evaluate geospatial benefits of emissions reductions from marine vessels.

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LIST OF ACRONYMS

AQCZ	Air Quality Control Zone; the region in San Pedro Bay where the vessel speed reduction program applies
ARB	California Air Resources Board
CO	Carbon monoxide
CO_2	Carbon dioxide
DNV	Det Norske Veritas
EMEP	Cooperative Program for Monitoring and Evaluation of the Long Range Transmission of Air Pollution in Europe
HC	Total Hydrocarbons (unspecified or considered as methane)
IMO	International Maritime Organization
ISO	International Organization for Standardization
ITCT 2k2	Intercontinental Transport and Chemical Transformation 2002
IVL	IVL, the Swedish Environmental Research Institute
knots	Nautical miles per hour
MCR	maximum continuous rating
NASA	National Aeronautic and Space Administration
nmi	Nautical miles
NOAA	National Oceanic and Atmospheric Administration
NOx	Oxides of nitrogen
PM	Particulate matter
SFOC	Specific fuel oil consumption
SO_2 (or SOx)	Sulfur dioxide (or oxides of sulfur)
TEU	Twenty-foot equivalent unit; generally considered to be one container unit
U.S. EPA	United States Environmental Protection Agency
UNFCCC	United Nations Framework Convention on Climate Change
VSR	Vessel Speed Reduction Program; voluntary program to reduce air emissions from ships in San Pedro Bay through speed control
VTS	Vessel traffic services

APPENDIX: New Spirit Information and Sine Maersk Information

New Spirit Vessel Particulars

Ship Name	NEW SPIRIT	Call Letters	HOAI
Owner	NEW LIGHT MARITIME S.A.	Port of Registry	PANAMA
Class	NK	Bulkheads	6
When Built	MARCH,2002	Holds	5
Builder	OSHIMA SHIPBUILDING CO., LTD.	Hatches	5
Material	STEEL	Winches	---
Special Survey	MARCH, 2007	JIB Crane	---
Length O. A.	189.33 m	Main Engine	DIESEL UNITED SULZER 6RTA48T
Length B. P.	180.60 m	When Made	NOV., 2001
Breadth MLD.	30.95 m	Maker	DIESEL UNITED LTD.
Depth MLD.	16.40 m	Where Placed	AFT
Draft (Designed)	10.75 m	Horse Power	MCO 10,730 CSO 9,120
Gross Tonnage	26,562	R.P.M.	MCO 120 CSO 113.7
Net Tonnage	16,450	Main Boiler	---
Dead Weight	48,183 M.T.	When Made	---
Displacement	55,476 M.T.	Maker	---
Light Displacement	7,293 M.T.	Working Pressure	----
Service Speed	14.5 Kts	Donkey Boiler	---
Capacity : Grain : Bale :	60,956 m^3 59,778 m^3	Generator	YANMAR 6N18L-SU
Fuel Oil :	1,731 m^3	Special Equipment	---
Fresh Water	301 m^3	Hatch Size	
Ballast Water	26,115.2 m^3	No.1 CH	17.10X15.60M
		No.2 & No. 4 CH	21.60X15.60M
		No.3 & No. 5 CH	19.80X15.60M
Consumption			
At Port IDLE	F.O. 2.7 mt/day		
At Sea	F.O. 27.0 T/D D.O. 0 T/D		

WPI

WESTPORT PETROLEUM, INC.

BUNKER RECEIPT

VESSEL NAME: NEW SPIRIT	DATE: 5-3-02
TERMINAL LOCATION: LA 186½	DELIVERY LOCATION: LB/32

PRODUCT	GROSS BARRELS	NET BARRELS	WEIGHT METRICTONS
380	6471.41	6370.45	1001.49
MDO	253.76	253.43	36.00

PROPERTIES

Product	Viscosity CST@ 50 Deg C	API Gravity	Sulfur % WT.	Flash Deg F	Pour Deg F	BS&W % Vol
380	339.9	11.3	2.19	190	35	0.05
MDO	1.87	26.5	0.86	158	<0	0.05

No disclaimer of any type or form will be accepted on this Bunker Receipt and if any words of disclaimer are applied, they will not alter, impair or waiver WESTPORT PETROLEUM, INC.'s maritime lien against the vessel or affect the vessel's ultimate responsibility for the debt incurred through this transaction. This sale is subject to the standard terms and conditions of sale for marine fuel by WESTPORT PETROLEUM, INC.

REMARKS:

DELIVERY COMPANY: WEST OIL	Received for use as bunkers, together with representative sample, the quantities shown above. Exact quantities are subject to correction in case of error.
BY: [signature]	MASTER/CHEIF ENGINEER: [signature]
DATE: 5-3-02	DATE: 5-3-02

300 North Lake Avenue, Suite 1020
Pasadena, California 91101
Telex: 188354 WPT UT
Fax: 626-577-7850 Tel: 626-796-0033

BUNKER RECEIPT

IDEMITSU KOSAN CO., LTD.
INDUSTRIAL ENERGY DEPARTMENT
NO. 1-1, MARUNOUCHI 3-CHOME, CHIYODA-KU
TOKYO 100-8321, JAPAN
PHONE : 81-3-3213-3138
FAXNO : 81-3-3213-1145

Account of	HIKAWA SHOJI KAISHA,LTD. N.Y.K.		Delivery Depot	Tokuyama,Japan
M/S S/S	" NEW SPIRIT "		Delivery Date from Depot	28th,Mar.,2002
Port	Sasebo,Japan		D/O No.	92175
Description	Marine Diesel Oil Bunker Fuel 180			
Quality	Density g/cm³ @ 15℃ 0.8645 0.9828	Flash Point ℃ 75 75	Viscosity CST @ 50℃ 2.53 174	Water % 0.00 0.05
Quantity	Kiloliter 23.100 661.000	Metric Ton 19.970 649.499	Long Ton 19.655 639.243	

The foregoing quality and quantity are correct in every respect.

Date Mar. 29, 2002

Chief Engineer C/E [signature] 3/29. 2002

Captain

出羽880-76

Sine Maersk Vessel Particulars

Ship Name	SINE MAERSK	Call Letters	HOAI
Owner	A.P. MOLLER	Port of Registry	DENMARK (DIS)
Class	S-Class	Container Capacity	6,600 TEU
When Built	1998	Main Engine	12K90Mk mk6
Builder	ODENSE STEEL SHIPYARD LTD.	When Made	1998
Length O. A.	347 m	Maker	HITACHI MAN B&W
Breadth MLD.	42.8 m	Main Engine Power	548,40 kW
Draft (Designed)	14.5 m	R.P.M.	94
Gross Tonnage	91,600	Generator	7L32/40
Net Tonnage	50,100	Generating power	15,000 kW
Dead Weight	104,696	Service Speed	25 Kts