

ESTIMATION, VALIDATION, AND FORECASTS OF
REGIONAL COMMERCIAL MARINE VESSEL
INVENTORIES

Tasks 1 and 2: Baseline Inventory and Ports Comparison
Final Report

Submitted by
James J. Corbett, P.E., Ph.D.
University of Delaware

Coauthored by
Chengfeng Wang, Ph.D.
Jeremy Firestone, Ph.D.
University of Delaware

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ABSTRACT

This report presents results of Tasks 1 and 2 of a project to develop and deliver commercial marine emissions inventories for cargo traffic in shipping lanes serving U.S. continental coastlines. A primary objective of this project is to describe a regional scale methodology for estimating commercial marine vessel (CMV) emissions in coastal waters (i.e., the Exclusive Economic Zone or EEZ) that is consistent with port-based inventory methods. A set of geographically resolved inventories were produced that describe air emissions for a 2002 baseline year (Task 1). The work also evaluates several port-based inventories in terms of their potential agreement and validation of the regional inventory (Task 2). Methodologies and validation developed in this work will provide better regional inventories of commercial marine emissions for North America that supports the California Air Resources Board (ARB), Commission for Environmental Cooperation in North America (CEC), western regional states, United States federal, and multinational efforts to quantify and evaluate potential air pollution impacts from shipping in U.S, Canadian, and Mexican coastal waters.

EXECUTIVE SUMMARY

Current best practices for marine vessel emissions inventories have not been applied to spatially and temporally describe North American interport¹ shipping activity until now. This report presents inventory methodology, results, and validation for ships engaged in foreign commerce arriving at U.S. ports, and for ship activity in Canada and Mexico by commercial cargo and passenger vessels (excluding ferries). This report addresses Tasks 1 and 2 of the ARB scope of work, augmented by the CEC complementary scope tasks:

1. To provide a baseline inventory of CMV emissions at a regional scale appropriate for modeling impacts relevant to potential SECA designation.
2. To evaluate several port-based inventories in terms of their potential agreement and validation of the regional inventory.

For this project, we use a network model, the Waterway Network Ship Traffic, Energy and Environment Model (STEEM), to quantify and geographically represent inter-port vessel traffic and emissions as contrasted with in-port activities. This model can be used to characterize ship traffic, estimate energy use and assess environmental impacts of shipping, etc. We geographically characterize ship emissions for North America, including the United States, Canada, and Mexico.

We estimate that North American shipping to and from other global ports consumed about 47 million tons of heavy fuel oil and emitted about 2.4 million tons of SO₂ in 2002, with approximately 30 million tons fuel and 1.6 million tons SO₂ within the North American domain for this project. Comparison of our results with port and regional studies shows good agreement with and improved accuracy over existing methods. Shipping activity within the domain, defined for this project by consensus with the North American SECA team, is illustrated in Figure ES-1. Table ES-1 summarizes the interport inventory estimates for the baseline year of 2002. The table presents results for coastal regions (defined as the 200 nautical mile exclusive economic zone) by nation, and the total for all domain areas outside coastal regions.

The 2002 inventory of emissions from North American shipping represents the most accurate and complete inventory to date for interport activity from oceangoing commercial cargo and passenger vessels (excluding ferries). The inventory successfully applies bottom-up estimation methods, extending best-practices for commercial marine inventories to the largest spatially resolved scale so far, and the STEEM model is capable of conducting similar analyses for other regions and even globally. STEEM achieves many of the goals of nonroad marine modeling efforts, such as the U.S. EPA Mobile Vehicle Emissions Simulator (MOVES)². STEEM exceeds MOVES current design in two important ways: 1) our approach produces spatial and temporal assignment of emissions in GIS; and 2) our model considers individual vessel movements, rather than binning vessels of similar type. (Similar to binning by MOVES, our model applies emissions factor and engine activity assumptions by vessel type, but considers installed power, routing, and speed individually.)

With this baseline inventory, ARB can evaluate air quality and health impacts in California, and participate in other efforts to evaluate these impacts. In particular, the work provides part of the required information to request a North American SECA (or SECAs) on behalf of the United States, Canada, and Mexico at the International Maritime Organization (IMO).

¹ Interport shipping is ship activity while voyaging between ports; it does not include dockside hotelling operations.

² See <http://www.epa.gov/otaq/ngm.htm> for MOVES information.

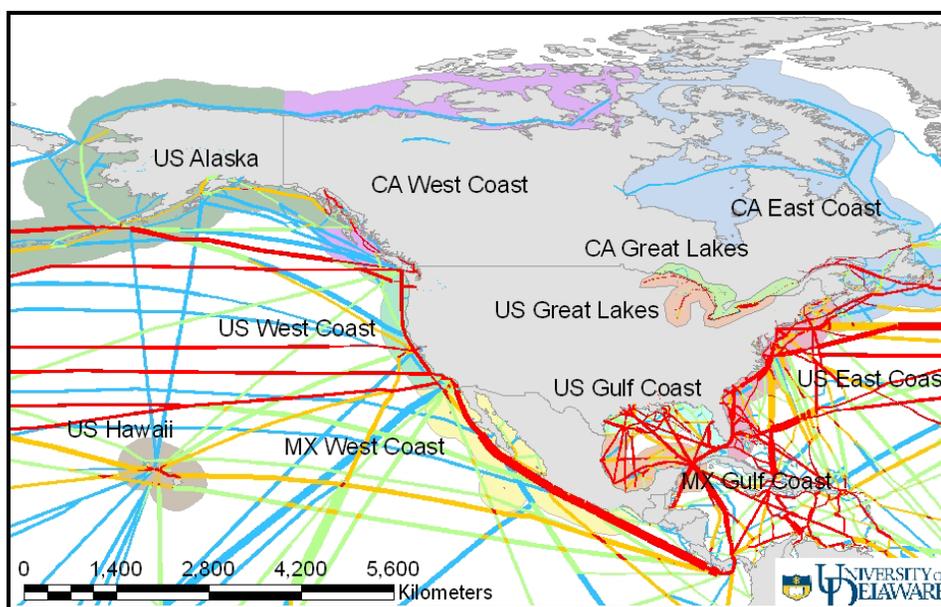


Figure ES-1. Illustration of spatial distribution of SO₂ from North American shipping; shaded areas represent approximate delineation of exclusive economic zones (EEZs).

Table ES-1. Baseline 2002 inventory of emissions and fuel use in North American Domain (metric tonnes)¹

	NOx as NO ₂	SO ₂	CO ₂	HC	PM	CO	Fuel Use
United States EEZ ²							
West Coast	135,000	80,200	4,817,000	4,470	11,300	10,500	1,480,000
East Coast	255,000	151,000	9,095,000	8,440	21,300	19,900	2,800,000
Gulf Coast	174,000	103,000	6,201,000	5,750	14,500	13,600	1,910,000
Great Lakes	16,200	9,620	578,000	540	1,350	1,260	178,000
Alaska	63,300	37,600	2,260,000	2,100	5,300	4,940	697,000
Hawaii	20,500	12,200	732,400	680	1,720	1,600	226,000
Canada EEZ ^{2,3}							
West Coast	21,900	13,000	781,000	720	1,830	1,700	241,000
East Coast	96,200	57,200	3,440,000	3,190	8,050	7,500	1,060,000
Great Lakes	10,100	5,980	359,000	330	840	800	111,000
Mexico EEZ ²							
West Coast	99,400	59,100	3,550,000	3,290	8,320	7,800	1,090,000
Gulf Coast	107,000	63,700	3,827,000	3,550	8,970	8,000	1,180,000
Total Coastal regions	998,000	593,000	35,640,000	33,100	83,500	77,900	10,980,000
Non-coastal regions ⁴	1,740,000	1,040,000	62,200,000	57,700	146,000	136,000	19,170,000
Total in Domain	2,740,000	1,630,000	97,800,000	90,800	229,000	214,000	30,160,000

1. Values are rounded to three significant figures for presentation; sums may vary as a result of rounding.
2. National estimates of EEZ boundaries are approximate, using an ArcGIS buffer of 200 nautical miles and informal divisions between nations.
3. Western Canada summaries include emissions in the Northwestern part of the domain; Eastern Canada summaries include emissions in the Northeastern part of the domain.
4. Non-coastal regions are areas in the Domain not within the EEZ of Canada, United States or Mexico.

INTRODUCTION

This report is intended to assist the role of the California Air Resources Board and the Commission for Environmental Cooperation in North America in defining and evaluating the potential impact to air quality and human health by oceangoing commercial marine vessels in transit.³ Current best practices for marine vessel emissions inventories have not been applied to spatially and temporally describe North American interport shipping activity until now. This report presents inventory methodology, results, and validation for ships engaged in foreign commerce arriving at U.S. ports, and for ship activity in Canada and Mexico by commercial cargo and passenger vessels (excluding ferries).

Tasks 1 and 2 Questions & Research Objectives

A primary objective of this project is to describe a regional scale methodology for estimating CMV emissions in coastal waters (i.e., the Exclusive Economic Zone or EEZ) that is consistent with port-based inventory methods. There are several deliverables that follow from this objective, including:

1. To provide a baseline inventory of CMV emissions at a regional scale appropriate for modeling impacts relevant to potential SECA designation. Using this methodology, this work produced a spatially resolved inventory of CMV emissions for North America for a baseline year of 2002. This represents a distance larger than the Exclusive Economic Zone for the continental United States and Canada and Mexico, a legal area beyond and adjacent to the territorial sea that provides certain federal authority to protect and preserve the marine environment [1].
2. To evaluate several port-based inventories in terms of their potential agreement and validation of the regional inventory. We conclude that different assumptions, inputs, or methods applied in port-based inventories produce expected differences reflecting more detailed local information at the port level that cannot be easily reflected at the regional scale. Based on our results, we offer recommendations to improve regional inventory methods or otherwise reconcile differences with port-based inventories.

This project will support ARB efforts to understand the significance of ship emissions. Later deliverables under tasks 3 and 4 will provide forecasts of CMV emissions under assumptions that include trade-driven fleet growth, technological changes, and potential designation of special areas under the International Maritime Organization's (IMO's) MARPOL Annex VI convention, called SOx Emission Control Areas (SECAs).

Background

Air pollutants from marine vessels account for a non-negligible portion of the emissions inventory and contribute to air quality, human health and climate change issues at local, regional and global levels [2-24]. Better estimation of the emissions inventory as well as its spatial representation is needed for atmospheric scientists, pollution modelers, and policy makers to evaluate and mitigate the impacts of ship emissions on the environment and human health. This represented a great challenge due to the mobility of ships, poorly integrated models, and limited data.

³ Does not include dockside hotelling operations, and may not represent detailed pier-side maneuvering activity.

Although emissions estimates and fuel use are related to the energy used by ships, recent studies call into question the validity of relying on the statistics of marine fuel sales [3, 25-28]. Best practices of estimating emissions from transportation overall, and marine vessel emissions inventories specifically, have focused on activity-based estimation of energy and power demands from fundamental principles [3, 25, 27, 29]. These approaches have shown that fuel allocated to international fuel statistics is insufficient to meet the estimated energy demand of international shipping. Even if marine fuel sales statistics were perfect, ships may consume fuel far from where they purchase it. At best, regional statistics provide limited insight into the spatial and temporal characteristics of ship energy consumption.

Principle existing approaches for producing spatially-resolved ship inventories generally can be categorized as either top-down or bottom-up. Top-down approaches assign global ship emissions inventories, which can be obtained statistically, to each location according to spatial proxies of emissions intensity. Corbett, et al. produced the first global spatial representation of ship emissions using a shipping traffic intensity proxy derived from the Comprehensive Ocean-Atmosphere Data Set (COADS), a data set of voluntarily reported ocean and atmosphere observations with ship locations [2, 10]. They assumed that the reporting ship fleet is representative of the world fleet, spatial distribution of ship reporting frequencies represents the distribution of ship traffic intensity, and emissions are proportional to traffic intensity. Endresen, et al. improved the global spatial representation of ship emissions by using ship size (gross tonnage) weighted reporting frequencies from the Automated Mutual-assistance Vessel Rescue system (AMVER) data set [4]. They implicitly assumed that ship energy consumption and emissions are proportional to ship size, which is not true for some types of ships, and they observed that COADS and AMVER lead to highly different regional perturbations [4]. Wang, et al. addressed the potential statistical and geographical sampling bias of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS, current version of COADS) and AMVER data sets, the two “best” global ship traffic intensity proxies, and made four advancements to improve the accuracy of the top-down approach using ICOADS as spatial proxy [30].

Bottom-up approaches were applied by Lloyd’s register and Entec UK Limited to produce regional ship emissions inventories for the European Monitoring and Evaluation Programme (EMEP) area, the Baltic Sea, and the Mediterranean Sea [16, 23, 24]. In this type of approach, ship and route specific emissions are estimated based on historical ship movements, ship attributes, and ship emissions factors. The locations of emissions are determined by the locations of the most probable navigation routes, which are great-circle (i.e., radius) routes between transoceanic origins and destinations, adjusted where prohibited by land, ice, or depth; the Lloyds and Entec work was more regional (not transoceanic) and generally followed straight-line routes. Streets, et al. estimated emissions from international shipping in Asian waters based on commodity flow associated with major sea routes [6, 7]. The accuracy of this method, which can be categorized as a bottom-up approach using trade as a proxy for emissions, is limited by the assumed relationships between the volume of trade flow and emissions, which are more closely related to ship installed power, load profile, etc., and by the aggregation of individual voyage routes into major shipping lanes.

Both bottom-up and top-down approaches have strengths and weaknesses. A top-down approach is quicker, demands relatively fewer resources and may cost less than a bottom-up approach [30]. Top-down inventories can be improved by updating the global inventories and/or the spatial/temporal proxy of the ship emissions intensity. While a top-down approach can

produce both global and regional ship emission inventories, producing emissions inventories at the global scale with existing bottom-up approaches is probably impossible because of the significant efforts associated with routing.

The accuracy of top-down approaches is limited by the accuracy of global inventories and the representativeness of spatial proxies. First, significant differences exist among the various global ship emission inventories [3, 4, 25, 26]. Activity-based energy consumption and emissions in the updated inventory by Corbett and Koehler roughly doubled the results of earlier studies [3]. Great uncertainty exists in the updated inventory such that upper bound of is about 60% higher than the lower bound [3]. Discrepancies among different studies and the range between lower and upper bound of the same study can be explained by the uncertainties of marine engine load factor, time in operation, and fuel consumption rates, which vary by ship type, size, age, fuel type, and market situation [25, 26]. Variation in these inputs represents first-order barriers to improving the accuracy of the global ship inventory. Second, since both ICOADS and AMVER data sets rely on voluntary reporting and neither of them is randomly sampled, both of them are statistically and spatially biased [30].

Although bottom-up approaches appear more accurate than top-down methods, large-scale bottom-up inventories also are uncertain because they must estimate engine workload, ship speed, and most importantly, the speculative locations of the routes which determine the spatial distribution of emissions. Given the large of number of ship movements and potentially dynamic shipping routes, the accuracy of regional annual inventories in bottom-up approaches is limited when selected periods within a calendar year studied are extrapolated to represent annual totals [16, 23].

Summary of Significance

For this project, we use a network model, the Waterway Network Ship Traffic, Energy and Environment Model (STEEM), to quantify and geographically represent inter-port vessel traffic and emissions as contrasted with in-port activities which have been well-characterized in other studies [31-35]. This model can be used to characterize ship traffic, estimate energy use and assess environmental impacts of shipping, etc. We geographically characterize ship emissions for North America, including the United States, Canada, and Mexico.

We estimate that North American shipping consumed about 47 million tons of heavy fuel oil and emitted about 2.4 million tons of SO₂ in 2002. Comparison of our results with port and regional studies shows good agreement with and improved accuracy over existing methods. Use of a network model (like STEEM) is superior to other approaches in five respects: (1) spatial pattern of ship traffic is derived from empirical locations of ships rather than speculative; (2) estimation of energy, fuel use and emissions does not rely on statistics of the world fleet and its operation profiles but instead uses regionally accurate historical shipping activities data; (3) Visual Basic for Application (VBA) and Python scripts automate some repetitive work within the GIS platform and make the model capable of producing multi-scale inventories; (4) inventories can be updated with current shipping activities and ship attributes data sets while reusing the waterway network; (5) the results derived from this model are more accurate than the top-down approach and even more accurate than regional/port studies by capturing transit traffic.

Results of this research will contribute to ARB and CEC efforts to establish accurate ship emissions inventories and improved modeling of their impacts. With this baseline inventory, ARB can evaluate air quality and health impacts in California, and participate in other efforts to

evaluate these impacts. This research will support ARB AND CEC efforts to develop effective measures to reduce ship emissions. In particular, the work provides part of the required information to request a North American SECA (or SECAs) on behalf of the United States, Canada, and Mexico at the International Maritime Organization (IMO).

MATERIALS AND METHODS

This section describes the methods and data used for this project. This project represents one of the first applications of a network model developed to evaluate ship activity characteristics on large regional and global scales using best-practice assumptions and methods comparable to the latest port-based inventories of ship activity. The Ship Traffic Energy and Environmental Model (STEEM) improves the accuracy, detail, and completeness of larger regional ship activity descriptions. This enables emissions inventory analyses that are not scaled from studies of a subset of ports or smaller regions or patched together from separate inventory efforts [31, 32]. Starting with a global empirical network of observed shipping lanes, commercial cargo and passenger ship arrivals and departures from all ports in North America are routed along coastal and transoceanic shipping lanes. Vessel engine, speed, and size data for these vessels are applied to estimate emissions from these vessels in both spatial and temporal domains.

In general, materials for this work include the global network developed at the University of Delaware primarily by Dr. Chengfeng Wang [36], vessel activity data for the United States from the U.S. Army Corps of Engineers [37], vessel data for Canada and Mexico from Lloyds Maritime Intelligence Unit (LMIU) provided by Environment Canada and the Council on Environmental Cooperation, respectively [38, 39]. Inventory assumptions and other model inputs were primarily derived from earlier ARB reports and published work by Dr. James Corbett [3, 25, 40], modified through discussion with EPA contractors and review of port-based best practices [29].

Ship Traffic Energy and Environmental Model (STEEM) Description

By applying advanced GIS tools and using improved data sets, STEEM adopts the strengths of both top-down and bottom-up approaches and attempts to overcome the weaknesses in each approach. First, the model builds an empirical waterway network based on shipping routes revealed from observed historical ship locations. The spatial allocation is more accurate than a bottom-up approach, which uses speculative routes, and than a top-down approach, which uses biased spatial proxies. Second, as in a bottom-up approach, this model estimates energy, fuel use and emissions using available historical ship movements, ship attributes, and the distances of routes. The calculations are expected to be more accurate than a top-down approach, which relies on the statistics of the world fleet and its operating profiles. Third, the automation of repetitive processes makes this method capable of producing global energy, fuel use, or emissions inventories, which is a daunting task with the existing bottom-up approach. Fourth, since the network can be updated, modified, re-used, and shared among users, STEEM could be more cost-effective than both the top-down and the bottom-up approaches. Figure 1 shows the framework of this model.

Figure 1 illustrates the ship traffic module of STEEM, which can geographically and temporally characterize ship traffic based on an empirical waterway network, historical ship movement data, and ship attributes data set. The lower boxes in Figure 1 illustrate how we applied ship attributes data to produce activity-based, spatially-resolved emissions inventories.

The empirical waterway network built in this model not only aligns the shipping lanes with actual shipping activity, but also defines the relationships among routes, segments and nodes with ArcGIS Network Analyst tools. In the empirical waterway network, intersections of shipping lanes and ports are defined as nodes, and shipping lanes between two immediate nodes

are defined as segments. Traffic can only flow in and out of segments through nodes. A route is defined as an actual non-stop path ships take between one origin and one destination port. We next describe the model when applied to ship energy, fuel use, or emissions. With minor modifications to account for different attributes, the model is generalizable to the other categories specified in the lower part of Figure 1.

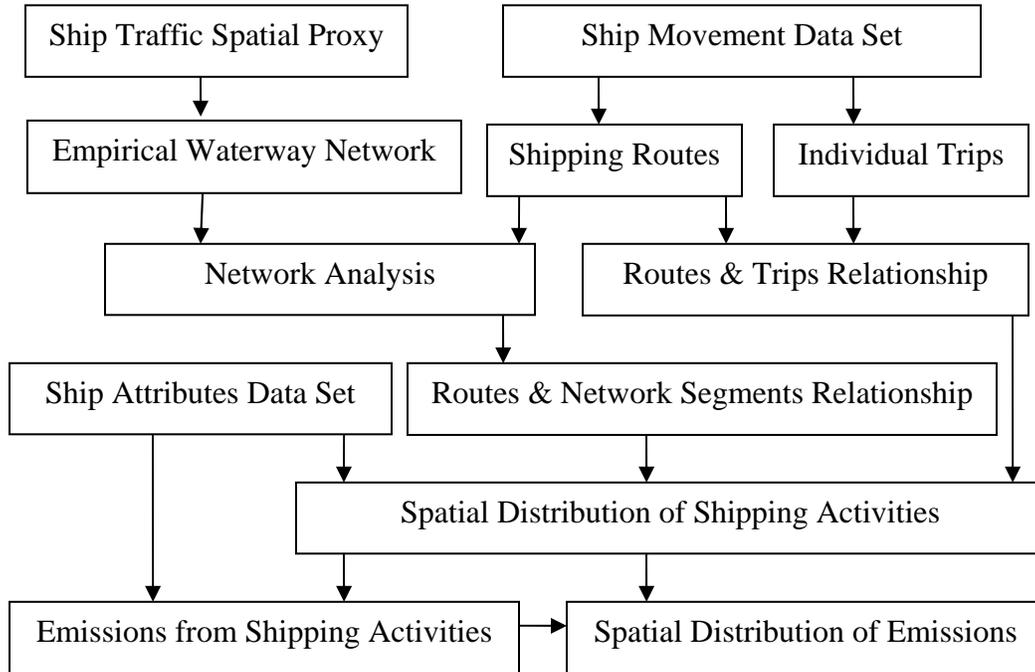


Figure 1. Illustration of Waterway Network Ship Traffic, Energy and Environment Model (STEEM) as applied to emission estimation.

Assume there are m segments and n routes in the empirical waterway network, the many-to-many relationships can be denoted as matrix A .

$$A = \begin{matrix}
 & b_{1,1} & b_{1,2} & b_{1,3} & \cdots & b_{1,n} \\
 & b_{2,1} & b_{2,2} & b_{2,3} & \cdots & b_{2,n} \\
 b_{3,1} & b_{3,2} & b_{3,3} & \cdots & b_{3,n} \\
 \vdots & \vdots & \vdots & \vdots & \vdots \\
 & b_{m,1} & b_{m,2} & b_{m,3} & \cdots & b_{m,n}
 \end{matrix} \tag{1}$$

Where, $b_{m,n}$ is a binary variable that shows whether segment m is part of route n (value of “0” if no, “1” if yes).

The actual number of trips on each route in any temporal period, where trips are defined as a one-way movement on one route, can be derived from ship movement data set. The relationships between routes and trips can be denoted as matrix B .

$$\begin{array}{c}
t_1 \\
t_2 \\
B = t_3 \\
\vdots \\
t_n
\end{array} \tag{2}$$

Where, t_n is the number of trips on route n within one period.

Depending on need and data availability, we can either assume ships are identical (as one group or in subsets by vessel type, fuel properties, etc.) or incorporate individual ship characteristics into the model. The number of trips or the indicator of traffic volume weighted by ship attributes on each segment can be denoted as matrix C .

$$\begin{array}{c}
v_1 \\
v_2 \\
C = A \times B = v_3 \\
\vdots \\
v_m
\end{array} \tag{3}$$

Where, v_m is the number of trips or the indicator of traffic volume of segment m in one period.

To estimate fuel use and air emissions out of port areas, we assume ships travel at a typical cruising speed, which appears true in most cases. Fuel use and air emissions from individual trips can be estimated with current best-practice models based on route distance, ship characteristics, and ship operating profile. Total emissions e_n on route n in one period in which there were t_n trips can be estimated by equation (4), and fuel use f_n can be estimated by equation (5).

$$e_n = \sum_{i=1}^{t_n} f(d_n, s_i, m_i, a_i, l_m, l_a, e_p \dots) \tag{4}$$

$$f_n = \sum_{i=1}^{t_n} f(d_n, s_i, m_i, a_i, l_m, l_a, sfoc_f \dots) \tag{5}$$

Where, d_n is the length of route n , s is vessel speed, m is main engine power, a is auxiliary engine power, l_m and l_a are load factors for main and auxiliary engines, and e_p represents emission factor for pollutant p ; $sfoc$ in equation (5) represents specific fuel oil consumption (energy rate factor) for fuel type f . Equations (4) and (5) denote that total emissions e_n or fuel use f_n on route n in one period is a function of the length of route, the characteristics of the ships on that route, the operating profile of the ships, and other variables concerned like the quality of fuel, etc. Where vessel-specific estimates are not required, average vessel values can be assigned by vessel type (e.g., tankers, containerized vessels, bulk carriers) to estimate energy, fuel use, or emissions by route.

Energy, fuel use, or emissions from each route can be denoted as matrix D .

$$\begin{array}{c}
e_1 \\
e_2 \\
D = e_3 \\
\vdots \\
e_n
\end{array} \tag{6}$$

Fuel use and emissions per unit of length are determined by dividing the total emissions on one route by the length of that route, which is the sum of the lengths of all segments of the route. The length of each segment can be obtained by GIS tools and can be denoted as matrix E .

$$\begin{array}{c}
l_1 \\
l_2 \\
E = l_3 \\
\vdots \\
l_m
\end{array} \tag{7}$$

Where, l_m is the length of segment m .

The distance of each route can be determined by multiplying the transposition of matrix A with matrix E and is denoted as matrix F .

$$\begin{array}{c}
d_1 \\
d_2 \\
F = A' \times E = d_3 \\
\vdots \\
d_n
\end{array} \tag{8}$$

Where, A' is the transposition of matrix A , and d_n is the distance of route n .

Energy, fuel use, or emissions per unit of length for route n can be determined by equation (8) and can be denoted as u_n .

$$u_n = \frac{e_n}{d_n} \tag{9}$$

Energy and emissions per unit of length for all routes are denoted as matrix G .

$$\begin{array}{c}
u_1 \\
u_2 \\
G = u_3 \\
\vdots \\
u_n
\end{array} \tag{10}$$

Total energy, fuel use, or emissions from each segment within one period can be obtained by summing up the calculations from all trips on that segment during that period. Energy, fuel use, or emissions per unit of length for all segments are denoted as matrix H .

$$\begin{array}{c}
 h_1 \\
 h_2 \\
 H = A \times G = h_3 \\
 \vdots \\
 h_m
 \end{array}
 \tag{11}$$

Where, h_m is energy, fuel use, or emissions per unit of length for segment m . h_m indicates the distribution of emissions over the waterway network.

Total energy, fuel use, or emissions for segment m can be calculated by equation (12) and can be denoted as k_m .

$$k_m = l_m \times h_m \tag{12}$$

Total energy, fuel use, or emissions for each segment can be further allocated to each grid to produce spatially-resolved inventories per gridded area if the segment was established as a polygon.

Estimating Emissions from North American Shipping

This section describes the application of the STEEM to estimate energy use and SO₂ emissions from North American shipping. Inventory results for other pollutants are provided in the supplemental material and available at

<http://www.ocean.udel.edu/cms/jcorbett/sea/NorthAmericanSTEEM>.

Shipping Activities and Shipping Routes Data Sets

We derived ship movements from two data sets, the U.S. Army Corps Engineers (USACE) Foreign Traffic Entrances and Clearances data set and the ship movement data set from Lloyd’s Maritime Intelligence Unit (LMIU). The combination of these two data sets includes nearly all ship movements carrying North American waterborne commerce (excluding U.S. domestic commerce data, which were not part of these data sets⁴). After eliminating duplicates, the North American shipping activities data set for 2002 has about 172,000 unique trips. We assigned a unique trip ID to each trip. We also derived shipping routes from the shipping activities data set, which included prior and next port of call. We assigned a unique route ID to each route and established the one-to-many relationships between trips and routes (a trip can be assigned to one route while one route can have many trips). North American shipping activities for 2002 included voyages on about 21,000 unique routes.

Port Characteristic Data Set

We built a data set which includes all ports appearing in the shipping activities data set for 2002. We assigned each port a unique port ID, used to link the shipping activities data set to the waterway network. Most geographic locations (longitude and latitude) of ports come with the activities data set. Four databases are used to fill the missing data include Geographic Data for International Cities, Landmarks, etc,⁵ Geographic Data for U.S. Cities, Landmarks, etc,⁶ United

⁴ U.S. domestic shipping activity data sets are cargo-specific, rather than vessel specific, and therefore include many apparent duplicate voyages. The analysis to include these in the network waterway STEEM model is reserved for future work.

⁵ Available at http://earth-info.nga.mil/gns/html/cntry_files.html

Nations Code for Trade and Transport Locations (UN/LOCODE),⁷ and World Port Index – Digital Navigation Publication of the U.S. National Geospatial-Intelligence Agency.⁸ There are about 400 U.S. ports and about 1,300 non-U.S. ports in the 2002 U.S. Entrances and Clearances data set; about 950 ports are in the 2002 Lloyd’s movement data set. These ports are located based on longitude and latitude and connected to the network in ArcMap.

Ship Attributes Data Set

We built a ship characteristic data set, which includes all ships appearing in the shipping activities data set, i.e., ships engaged in North American waterborne commerce. Ship attributes in this data set include unique ship ID, ship type, gross register tonnage (GRT), installed power, and cruise speed. We grouped ships into nine major ship types including containers ships, bulk carriers, tankers, general cargo ships, RO-RO ships, passenger vessels, refrigerated cargo ships (reefers), fishing vessels, and miscellaneous vessels.

We combined ship data from ship attributes data sets that come with the shipping activities data sets, and ship registry data sets that are commercially available. Where ship power data are missing, the values were estimated for each vessel type by regressing the relationships between GRT and net register tonnage (NRT) and between Power and GRT. The results of the regressions are shown in Table 1. Where speed data are missing, the average service speed of a given type of ship in the data set was used. Table 2 summarizes the average speed we used, the average speed used by Lloyds Register in the Baltic Sea study and the average speed used by Entec UK Limited in the Study for the European Commission [16, 24].

Table 1. Relationships among ship NRT, GRT and main engine installed power

Ship Type	NRT and GRT ¹			GRT and Power ²		
	Number of Samples	y as GRT, x As NRT ³	R ²	Number of Samples	y as power, x As GRT ³	R ²
Container ship	1,372	$y = 2.9594x^{0.965}$	0.94	1,149	$y = 2.5008x^{0.8801}$	0.92
Tanker	2,814	$y = 4.3031x^{0.9172}$	0.95	1,817	$y = 18.189x^{0.6093}$	0.92
General Cargo	3,881	$y = 1.9999x^{0.9992}$	0.98	2,244	$y = 5.3799x^{0.7633}$	0.86
Bulk Carrier	4,820	$y = 2.4517x^{0.9619}$	0.98	1,700	$y = 66.728x^{0.4826}$	0.74
Reefer	512	$y = 4.6369x^{0.8976}$	0.87	227	$y = 1.2462x^{0.9783}$	0.91
RO-RO ⁴	848	$y = 3.056x^{0.987}$	0.93	965	$y = 692.09x^{0.2863}$	0.83
Passenger	459	$y = 1.6034x^{1.0258}$	0.99	299	$y = 0.6379x + 1411.5$	0.95
Fishing	227	$y = 3.1075x - 149.78$	0.96	3,440	$y = 19.266x^{0.6658}$	0.69
Miscellaneous	5,190	$y = 2.8151x^{0.9467}$	0.91	3,951	$y = 77.806x^{0.5283}$	0.51

Notes: 1. Samples are unique NRT and GRT pairs in USACE Entrances and Clearances data set 1997- 2003 [41]; 2. Samples are ships with GRT and main engine total installed power data in Lloyds Register CD-ROM 2004 [42]; 3. The regression type with higher R² between linear and power regression is chosen; 4. RO-RO is an industry acronym for Roll-on/Roll-off vessel.

The ship attributes data set also includes ship size and dimensions, including length, width, and draft for determining whether a specific ship can pass canals or restricted waters. In this work, ships are divided into three groups by size including: (1) ships small enough to use

⁶ Available at <http://geonames.usgs.gov/geonames/stategaz/index.html>

⁷ Available at http://164.214.12.145/pubs/pubs_j_wpi_sections.html

⁸ Available at <http://www.unece.org/cefact/locode/service/main.htm>

both the Panama Canal and the Suez Canal; (2) ships too big to pass Panama but small enough to pass the Suez Canal; and (3) ships too big to pass either of the two Canals. We did not consider the potential conditions where a loaded vessel cannot pass through a canal, but the same vessel may meet draft restrictions on empty or backhaul voyages.

Table 2. Average cruise speed by ship type

Ship Type	Number of Samples ¹	Average Speed (knots)	Lloyds Register Study (knots)	Entec Study (knots)
Container Ship	2,596	19.9	20.0	19.0
Tanker	7,082	13.2	15.0	14.4
General Cargo	9,308	12.3	14.0	12.0
Bulk Carrier	4,464	14.1	14.0	13.6
Reefer	850	16.4	20.0	17.0
RO-RO	2,996	16.9	18.0	15.0
Passenger	1,825	22.4	20.0	21.0
Fishing	8,199	11.7	13.0	13.6
Miscellaneous	10,116	12.7	11.0	12.0

Notes: 1. Samples are ships with service speed in Lloyds Register CD-ROM [42].

Assigning North American Shipping to the Empirical Waterway Network

The two global ship reporting data sets, ICOADS and AMVER, have been used as proxies of ship traffic to geographically resolve the global emissions inventories by researchers [4, 27, 43]. ICOADS is a data set of global marine surface observations collected by the Voluntary Observing Ships (VOS) fleet, which has about 4,000 ships worldwide [4, 44]. AMVER, sponsored by the United States Coast Guard, is a global ship reporting system for ship search and rescue. Participation of AMVER is free, voluntary, and open to merchant ships of all flags, but had been limited to ships over 1,000 gross tons, on a voyage of 24 hours or longer [45]. Some 8,587 different vessels reported to AMVER in 2004.

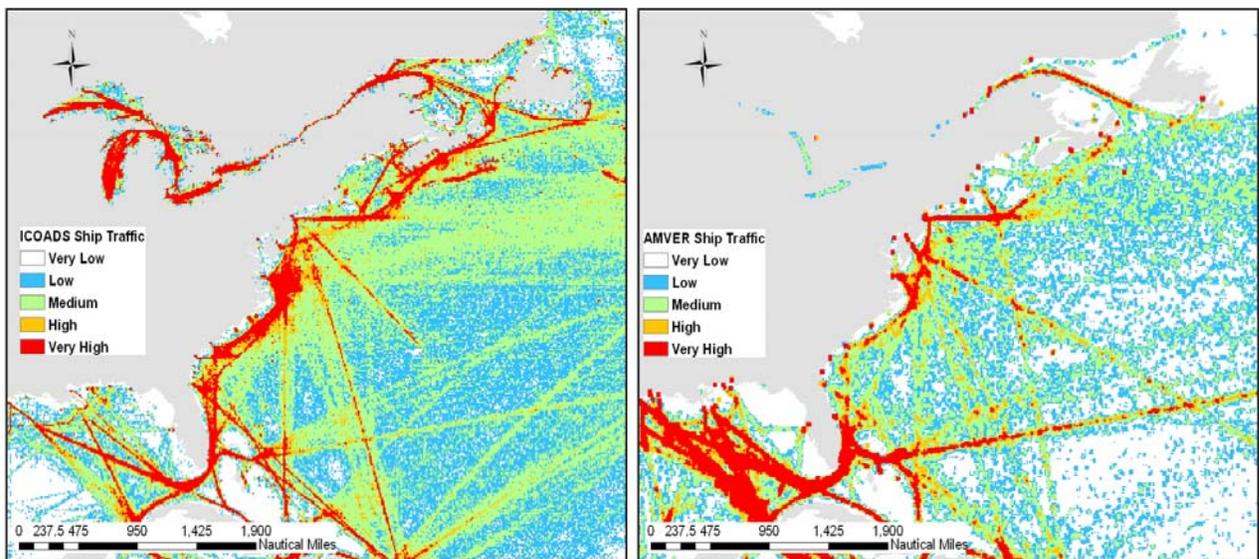


Figure 2. Comparison of shipping lanes derived from ICOADS and AMVER.

By studying the spatial and temporal dynamics of global ship traffic pattern derived from historical locations where ships reported to ICOADS and AMVER, we confirmed that ships travel along well-established shipping lanes [4, 10, 27, 43]. We compared traffic patterns revealed from ICOADS and AMVER data sets and confirmed the consistency of the traffic lanes from these two independent data sets. Figure 2 shows the similarity of the structure of the lanes from 20-year (1983-2002) ICOADS and about one year (part of 2004 and part of 2005) AMVER. The consistency of the two data sets further confirms the stability of the shipping network and justifies efforts to build an empirical network for repetitive use with updates and modifications when needed.

The empirical waterway network, which resembles the highway network on land, is composed of ports, which are origins and destinations of shipping routes; junctions, where shipping routes intersect; and segments (edges), which are shipping lanes between two connected junctions or ports. Each segment can have only two junctions or ports and ship traffic flow can enter and leave a segment only through a junction or a port. Since shipping lanes are not lines in reality but have a certain width which can be hundreds nautical miles wide in the ocean [46], polygons are more representative of the shipping lanes than polylines. In this work, we assigned each polyline segment a width, which was obtained by measuring the width of the shipping lanes in the spatial proxy of ship traffic.

We used twenty-year (1983-2002) ICOADS and about one year (2004-2005) AMVER to identify shipping lanes of the empirical waterway network. The network for North American waterborne commerce is comprised of about 9,000 segments, and each segment has a unique segment ID number. Attributes were added to the network to open and close certain segments, like the Panama Canal and the Suez Canal, for certain size of ships.

Figure 3 illustrates the empirical waterway network we built, and a sample of routes solved with ArcGIS Network Analyst. The network can be updated and modified by adding new lines, or by plugging more refined regional network data into this global network. The network also can be enhanced by differentiating lanes into seasonal lanes, weather lanes, and lanes for different ship type and size. For small scales (local or regional) of network, these issues can be taken into account to improve the spatial distribution of ship traffic.

Establishing relationships between routes and segments

Using ArcGIS Network Analyst tools, we established the many-to-many relationships between routes in the shipping activities data set and segments of the empirical waterway network. A route can be composed of many segments and a segment can be part of many routes. ArcGIS Network Analyst solves the most probable path on the network between each pair of ports for a certain size of ship. We assumed that ships take the least-energy path, which is the shortest distance in most cases unless prevented by weather or sea conditions, water depth, channel width, navigation regulations or other constraints. By conforming the shortest route to empirical shipping lanes (i.e., historically observed navigable routes for ships), the network approach intrinsically addresses these factors better than previous straight-line route assumptions. We wrote VBA and Python scripts to automate the process of solving the 21,000 routes. The outcome of this process is the relationship between unique route ID and segment ID.

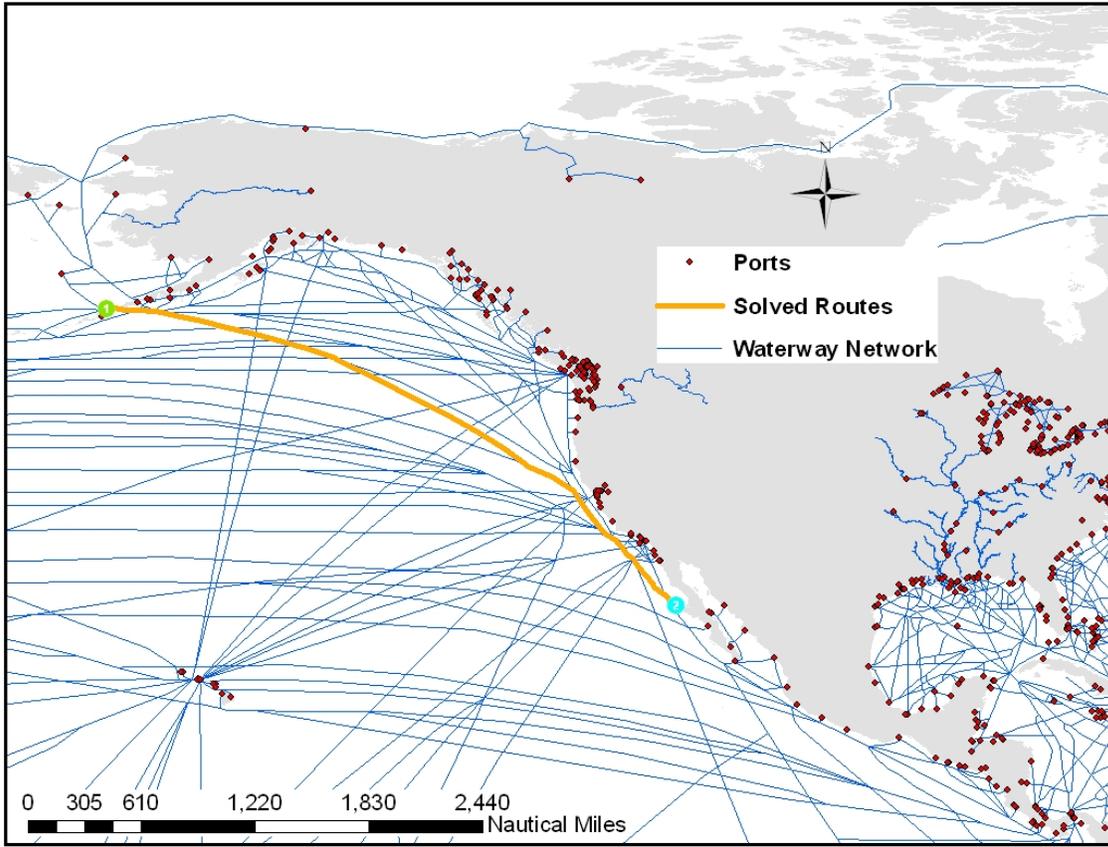


Figure 3. Illustration of the empirical waterway network and a sample of solved routes.

Summary of the relationships among the elements of the model

Through the processes described above, we established the relationships among the elements of the network including ship ID, trip ID, port ID, route ID, and segment ID. Figure 4 illustrates the relationships.

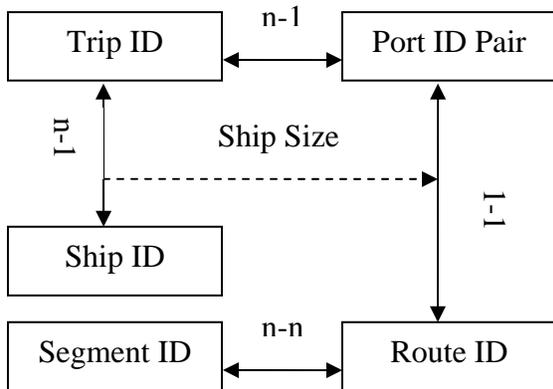


Figure 4. Illustration of relationships of the elements of STEEM.

The one-to-many relationships between ship ID and trip ID means that one ship can have many trips while one trip can be associated with only one ship. The many-to-one relationships between trip ID and port ID pair means one trip can be assigned to only one pair of port IDs while there can be many trips between one pair of port IDs. The one-to-one relationship between port ID pair (considering ship size) and route ID means that each route corresponds to one pair of ports for one group of ships with certain size. The many-to-many relationships between route ID and segment ID as denoted by matrix *A* means that a route can be composed of many segments and one segment can be part of many routes.

North American Inventory Domain

We produced a set of emissions estimates conforming to a consensus domain and resolution appropriate for most of the atmospheric modeling that will use our North American ship emissions inventory. This consensus resulted from several meetings with the SECA team, combined domain extents provided by ARB and the U.S. EPA. Originally, we proposed conforming to the most resolved geographic grid size used by ICOADS, which is 0.1 x 0.1 degrees (approximately 11 km x 11 km at the equator and approximately 11 km by 8 km at 45 degrees longitude). However, finer resolutions became possible with the application of STEEM routing analyses, and atmospheric modelers requested a resolution as fine as 4 km x 4 km (16 km²). The limitation on resolution for raster images was the computational time to resolve route segments into the final grid sizes.

Our inventory deliverables, therefore, required a projection that gridded cells in kilometers, and we delivered the North American inventory estimates for each pollutant with the following projection parameters from ESRI's ArcGIS software.

Projection: Equidistant_Cylindrical

Parameters:

False_Easting: 0.0 – *default ESRI parameter*

False_Northing: 0.0 – *default ESRI parameter*

Central_Meridian: 180.0 degrees – *UD defined*

Standard_Parallel_1: 0.0 – *default ESRI parameter*

Linear Unit: User_Defined_Unit (1000 m) – *UD defined*

In early March 2006, we delivered inventory files using the following domain:

left -1000 km, right 14000 km, top 8000 km, bottom 0 km.

Upon discussions with atmospheric modelers at Environment Canada and Levelton Engineering Ltd., we observed that the eastern extent of the inventory needed to be extended to include Nova Scotia and Newfoundland. We updated the inventory files for the following expanded domain:

left -1000 km, right 18000 km, top 8000 km, bottom 0 km.

Monthly Allocation of Emissions

In producing monthly profiles of emissions for the North American Inventory, we recognized three alternate approaches. The simplest approach is to evaluate the North American average variation in emissions by month and apply this uniformly to our annual inventories for

each pollutant. The average monthly variation in shipping in North America is shown in Figure 5; this is reasonably similar to global shipping activity variation reported by Corbett and Fischbeck [10].⁹ A second, more regionally descriptive approach is to consider the variation in emissions by major coastal region (e.g., West, Gulf, East, Great Lakes); this approach has the limitation of potential discontinuities that may occur when one region is adjusted differently than another. A third approach is to process the inventories on a monthly basis from the start; while this approach is the most accurate, we did not have budget or time in this project for the significant additional computing time that would be involved. We followed the first approach in producing monthly inventories using the variation in Figure 5, and reserve the third approach for future research.

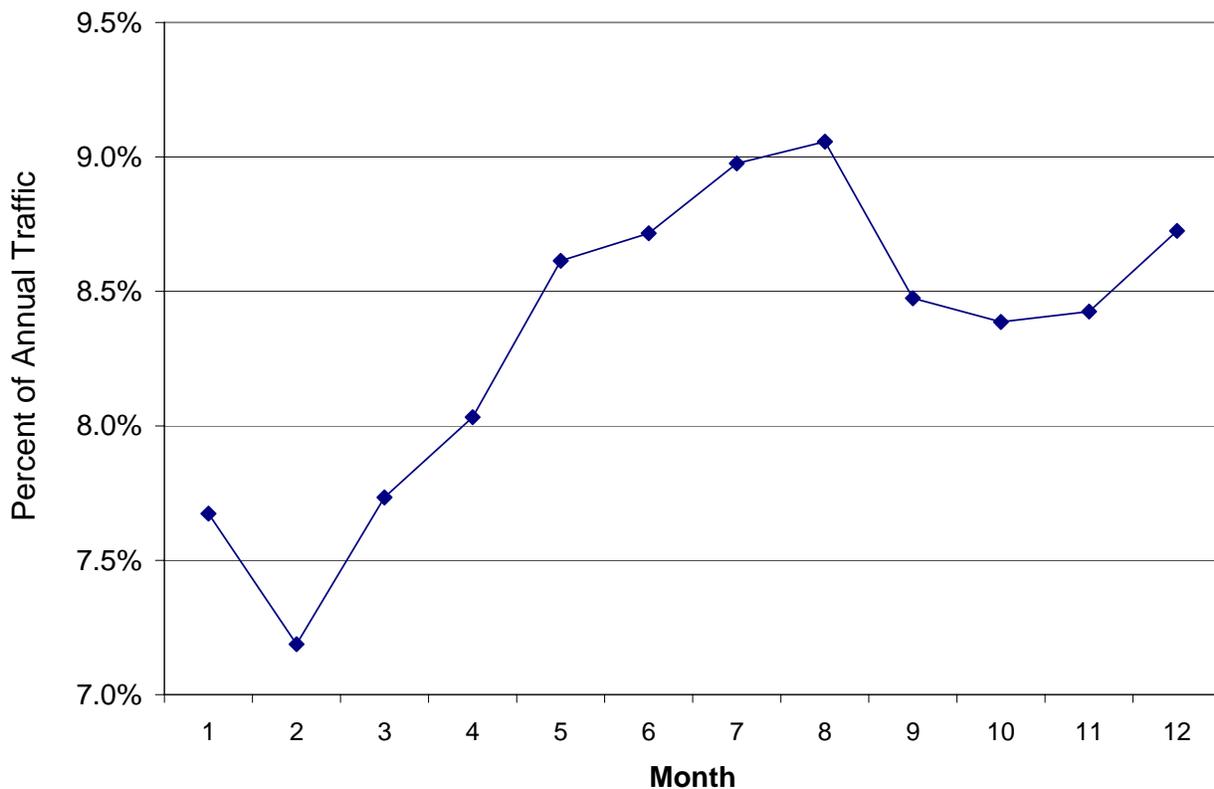


Figure 5. Monthly variation in emissions from North American Ship Traffic, derived from expected energy consumed as indicated from vessel installed power

⁹ One explanation for the peak shipping in the late summer is necessary logistics for peak shopping/consumption during the winter holiday season, starting at least around Halloween in the United States.

RESULTS AND DISCUSSION

This section describes specific input parameters chosen for STEEM, presents results specific to the 2002 baseline inventory required under Task 1, and the Task 2 results of comparison and validation using port-based and regional inventories.

Estimating Baseline Emissions

Main engine power of individual ships was used to estimate ship energy, fuel use, or emissions for each trip. We adopted the at-sea main engine load factors used by Corbett and Koehler for the updated emissions inventory for international shipping [3]. Based on engine manufacturer data used in other global analyses, we assumed that 55% of passenger vessel total main engine power is devoted to propulsion, and 25% of remaining power serves Auxiliary Engine (AE) power [3, 25]. We used maneuvering load profile (lower engine load factor and slower ship speed) for the first and last 20 kilometers of each trip when a ship is entering or leaving a port. If the trip was shorter than 20 kilometers, we assumed that ships were maneuvering for the whole trip; although this assumption may underestimate emissions from some short-sea routes. We assumed that main engines operate at 20% of the installed power during maneuvering, the same number used by Entec UK Limited [16].

Since most of auxiliary engine data for ships are missing in the ship attributes data set, average auxiliary power of each ship type was used to estimate the energy, fuel use, or emissions from auxiliary engines. California Air Resources Board (ARB) survey results indicate that "29 percent of the auxiliary engines used marine distillate and 71 percent used HFO, except for passenger vessels that use approximately 8 percent marine distillate and 92 percent HFO" [47]. This number was adopted to adjust the SO₂ emissions factor for auxiliary engines. Table 3 summarizes the engine power and at-sea load profile used in this work. The average total installed auxiliary engine power was adopted from ARB survey [47]; as documented by ARB and others, most vessels have multiple auxiliary engines.

Table 3. Summary of engine power and at-sea load profile

Vessel Type	Average ME Power (kW)	At-sea ME load (% MCR)	Average Total AE Power (kW)	At-Sea AE Load
Bulk Carrier	7,954	75%	1,169	17%
Container Ship	30,885	80%	5,746	13%
General Cargo	9,331	80%	1,777	17%
Passenger/Cruise	39,563	55%	39,563	25%
Reefer	9,567	80%	1,300	20%
RO-RO	10,696	80%	2,156	15%
Tanker	9,409	75%	1,985	13%
Miscellaneous	6,252	70%	1,680	17%

Emission Factors

We use the emissions factors shown in Table 4. Consistent with previous studies and with both the ICF report and ARB survey results, we will assume all main engines use residual fuel - this is standard practice especially in transit at sea. The emissions factors reported in the recent ARB report "Emissions Estimation Methodology for Ocean-Going Vessels" are nearly identical to those in the ICF best practices paper, and indeed nearly identical to emission factors

used in all recent analyses in the U.S., Canada, and Europe [3, 16, 29, 47, 48]. We use the composite EF for our work because our data do not explicitly identify by voyage whether the main engine is slow or medium speed or whether the auxiliary engine uses distillate or heavy fuel. This composite may be recalculated for the Great Lakes if data for that region enables more specific analysis of the vessel, engine, and fuel characteristics.

Table 4. Emission Factors

Main Engine Emission Factors - In-Transit Operations (g/kWh)							
Engine Type	Fuel Type	NOx	SOx	CO2	HC	PM*	CO**
Slow Speed	Heavy Fuel Oil	18.1	10.5	620	0.6	1.5	1.4
Medium Speed	Heavy Fuel Oil	14	11.5	677	0.5	1.5	1.1
Composite EF	Heavy Fuel Oil ****	17.9	10.6	622.9	0.6	1.5	1.4
Auxiliary Engine Emission Factors (g/kWh)							
Engine Type	Fuel Type	NOx	SOx	CO2	HC	PM	CO***
Medium Speed	Marine Distillate	13.9	4.3 MDO 1.1 MGO	690	0.4	0.3**	1.1
	Heavy Fuel Oil	14.7	12.3	722	0.4	1.5*	1.1
	Composite EF ****	14.5	9.1	713	0.4	1.2	1.1

* Emission Factors from ARB Staff

** Emission Factors from Environ Report

*** POLA, Page 101 [49]

**** Composite used population weighting from ARB OGV Survey, 2005

Considering the emissions factors used in previous studies, we used a composite SO₂ emissions factor of 10.6 g/kWh to estimate main engine SO₂ emissions [3, 16]. The SO₂ emissions factors for auxiliary engines using marine distillate oil (MDO) and heavy fuel oil are 4.3 g/kWh and 12.3 g/kWh respectively; for this study we do not assume oceangoing ships use marine gas oil (MGO). A composite SO₂ emission factor was adopted for each type of ship, weighted by the percent of marine distillate used by that type of vessel [47]. Table 5 summarizes the auxiliary engine SO₂ emissions factors used for each type of ship in this work. The percent in-use marine distillate of auxiliary engines was adopted from the ARB survey [47]. For estimating fuel consumption, 206 g/kWh was used as Specific Fuel Oil Consumption (SFOC) for transport ships and 221 g/kWh for miscellaneous (non-transport) ships, including fishing and factory vessels, research and supply ships, and tugboats, as adopted in other studies [3].

Table 5. Summary of auxiliary engine SO₂ emissions factor

Vessel Type	Percent In-Use Marine Distillate	Composite Aux. EF (g/kWh)
Bulk Carrier	29%	9.98
Container Ship	29%	9.98
General Cargo	29%	9.98
Passenger/Cruise	8%	11.66
Reefer	29%	9.98
RORO	29%	9.98
Tanker	29%	9.98
Miscellaneous	100%	4.3

We estimated that the inter-port transport of North American commerce (including global voyage transits on route segments outside the project domain) consumed more than 44.7 million tons of heavy fuel oil and emitted about 2.3 million tons of SO₂ in 2002, about 16.5% of SO₂ emissions from all sources in the U.S. in the same year [50]. Given that in-port emissions are about 2 to 6% of the total emissions, as reported by Streets et al. and Entec UK Limited [7, 16], total heavy fuel use and SO₂ emissions from North American shipping are approximately 47 million tons and 2.4 million tons, respectively. The North American shipping fuel use and SO₂ emissions are between 18-20% of the world commercial fleet estimated by Corbett and Koehler and between 28-34% of the world cargo and passenger fleet estimated by Endresen et al. [3, 4].

We estimated that ships carrying U.S. foreign commerce consumed about 38 million tons of fuel in 2002 (again including global voyage transits on route segments outside the project domain). This number agrees well with Energy Information Administration statistics that estimate that ships consumed about 44 million tons of fuel in 2002. U.S. domestic waterborne commerce, which we did not include in this work, may be partially responsible for the difference. Moreover, it is likely that the actual distance ships travel often is longer than the distance estimated by the STEEM because data for this work include North American voyages only between prior and next ports and do not model multi-port logistics activity common to commercial shipping (especially container ships).

Using this inventory, we estimated emissions and fuel use for North America coastal areas within the project domain as illustrated in Figure 6. The coastal zones resemble the 200 nautical miles Exclusive Economic Zone (EEZ) but the division among countries is for illustration purpose only. Table 6 presents total estimated emissions and fuel use within the domain defined for this project.

Container ships, bulk carriers, and tankers account for about 35%, 22%, and 17% of SO₂ emissions from North American shipping, respectively. Other types of ships jointly account for the remaining 24%. The top ten maritime countries collectively account for about 71% of the 2.3 million tons of SO₂ emissions. Panama, the largest flag of convenience country, accounts for 23% of the SO₂ emissions. Liberia, Bahamas, and the U.S. account for 13%, 8%, and 5% of the emissions, respectively. The Norwegian International Register, Singapore, Greece, Cyprus, Malta, and Hong Kong each account for between 3-4% of the emissions. The other 111 countries account for the remaining 29% of the emissions. The energy use profile is similar to the SO₂ emissions profile.

Producing Spatially Resolved Emissions Inventories for Various Pollutants (Task 1)

Based on the relationships among trips, routes and segments of the network, we allocated total emissions onto the waterway network. We buffered the waterway network with the width of each segment and calculated the area of the segments in ArcMap. We calculated the average of emissions per square kilometer by dividing total emissions for each pollutant in each segment with its area. We converted the buffered network to a raster file with a resolution of 4 kilometers by 4 kilometers and the value of each grid is the amount of emissions from this 16 square kilometer area. We adjusted the emissions within a 20-kilometer radius circle of ports with maneuvering load profiles. Table 6 summarizes the interport inventory estimates for the baseline year of 2002. The table presents results for coastal regions (defined as the 200 nautical mile exclusive economic zone) by nation, and the total for all domain areas outside coastal regions. Figure 6 illustrates the spatial distribution of annual SO₂ from North American shipping; monthly and annual pollutant inventories (SO_x as sulfur dioxide, NO_x as nitrogen dioxide, CO

as carbon monoxide, CO₂ as carbon dioxide, PM as PM_{2.5}, and HC as total hydrocarbons) are posted at <http://www.ocean.udel.edu/cms/jcorbett/sea/NorthAmericanSTEEM>.

Table 6. Baseline 2002 inventory of emissions and fuel use in North American Domain (metric tonnes)¹

	NO _x as NO ₂	SO ₂	CO ₂	HC	PM	CO	Fuel Use
United States EEZ ²							
West Coast	135,000	80,200	4,817,000	4,470	11,300	10,500	1,480,000
East Coast	255,000	151,000	9,095,000	8,440	21,300	19,900	2,800,000
Gulf Coast	174,000	103,000	6,201,000	5,750	14,500	13,600	1,910,000
Great Lakes	16,200	9,620	578,000	540	1,350	1,260	178,000
Alaska	63,300	37,600	2,260,000	2,100	5,300	4,940	697,000
Hawaii	20,500	12,200	732,400	680	1,720	1,600	226,000
Canada EEZ ^{2,3}							
West Coast	21,900	13,000	781,000	720	1,830	1,700	241,000
East Coast	96,200	57,200	3,440,000	3,190	8,050	7,500	1,060,000
Great Lakes	10,100	5,980	359,000	330	840	800	111,000
Mexico EEZ ²							
West Coast	99,400	59,100	3,550,000	3,290	8,320	7,800	1,090,000
Gulf Coast	107,000	63,700	3,827,000	3,550	8,970	8,000	1,180,000
Total Coastal regions	998,000	593,000	35,640,000	33,100	83,500	77,900	10,980,000
Non-coastal regions ⁴	1,740,000	1,040,000	62,200,000	57,700	146,000	136,000	19,170,000
Total in Domain	2,740,000	1,630,000	97,800,000	90,800	229,000	214,000	30,160,000

1. Values are rounded to three significant figures for presentation; sums may vary as a result of rounding.
2. National estimates of EEZ boundaries are approximate, using an ArcGIS buffer of 200 nautical miles and informal divisions between nations.
3. Western Canada summaries include emissions in the Northwestern part of the domain; Eastern Canada summaries include emissions in the Northeastern part of the domain.
4. Non-coastal regions are areas in the Domain not within the EEZ of Canada, United States or Mexico.

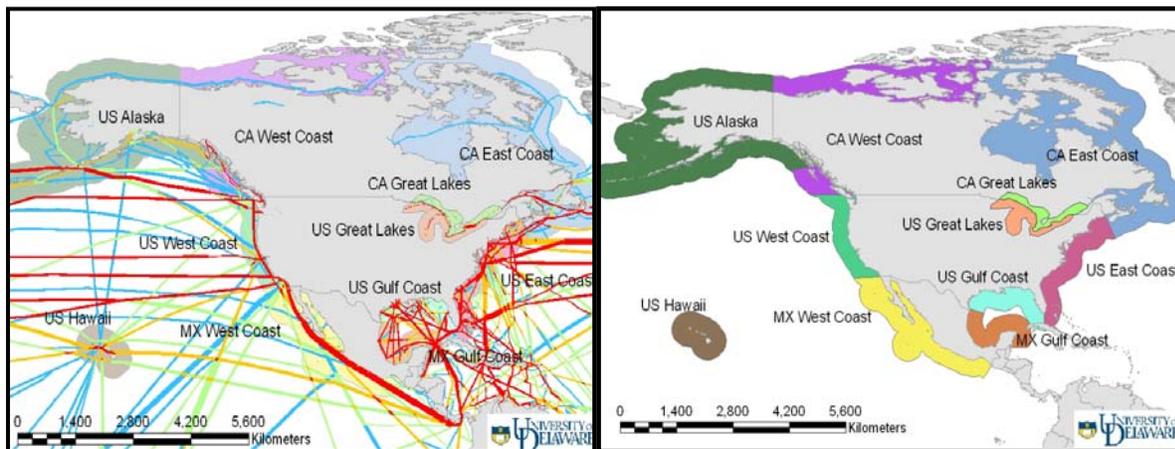


Figure 6. Illustration of spatial distribution of SO₂ from North American shipping; shaded areas represent approximate delineation of coastal exclusive economic zones (EEZs).

Comparison with Other Emissions Studies (Task 2)

We compared the emissions inventories that we produced using the top-down approach with ICOADS as the spatial proxy with the inventories produced in this work using STEEM [30]. In Figure 6, U.S. Coasts are the areas within the 200 nautical mile Exclusive Economic Zone (EEZ) as defined by NOAA in its Office of Coast Survey [51]; the Great Lakes include

Lake Superior, Lake Michigan, Lake Huron, Lake Erie, Lake Ontario, and connecting waters on both the U.S. and Canadian sides. Figure 7 shows that the emissions calculated with these two approaches agree very well for the US East Coast EEZ but differ to varying degrees on the other two coasts and the Great Lakes (both U.S. and Canadian side).

The amount of SO₂ emissions within the Gulf Coast EEZ estimated by the network approach is 109% higher than the amount estimated with ICOADS; the amounts by the network approach for the West Coast and the Great Lakes are 32% and 89% lower than the ICOADS approach. The discrepancies between the two inventories can be explained by geographic sampling bias of ICOADS which significantly oversamples the Great Lakes and undersamples the Gulf of Mexico [30].

We also compared our results with the inventories from other regional and port emissions inventories studies [33-35, 48, 52]. Figure 8 illustrates the domains of the ports and regions we compared. The Great Lakes include the lakes and connecting waters within the Canadian boundary [48]. “Western Canada” represents the coastal areas in British Columbia (B.C.) outside of the Greater Vancouver Regional District (GVRD) and Fraser Valley Regional District (FVRD), and a portion of Washington State, as defined in the Levelton report [52]. The Port of Los Angeles (POLA), Houston & Galveston area, and the Port of New York and New Jersey (NYNJ) are the areas defined by the Starcrest Consulting Group, LLC in its port-wide air emissions inventory reports [33-35].

Figure 9 shows that the regional/port air emissions inventories produced with different approaches look very different. The emissions inventory produced with the top-down approach using ICOADS as a spatial proxy is significantly higher for the Great Lakes on the Canadian side, but significantly lower for the “Western Canada”, the Port of Los Angeles (POLA), and the Port of New York and New Jersey. The conclusion can be drawn that ICOADS is spatially biased as observed in other studies and small-scale emissions inventories produced with ICOADS as spatial proxies may be greatly distorted [4, 30].

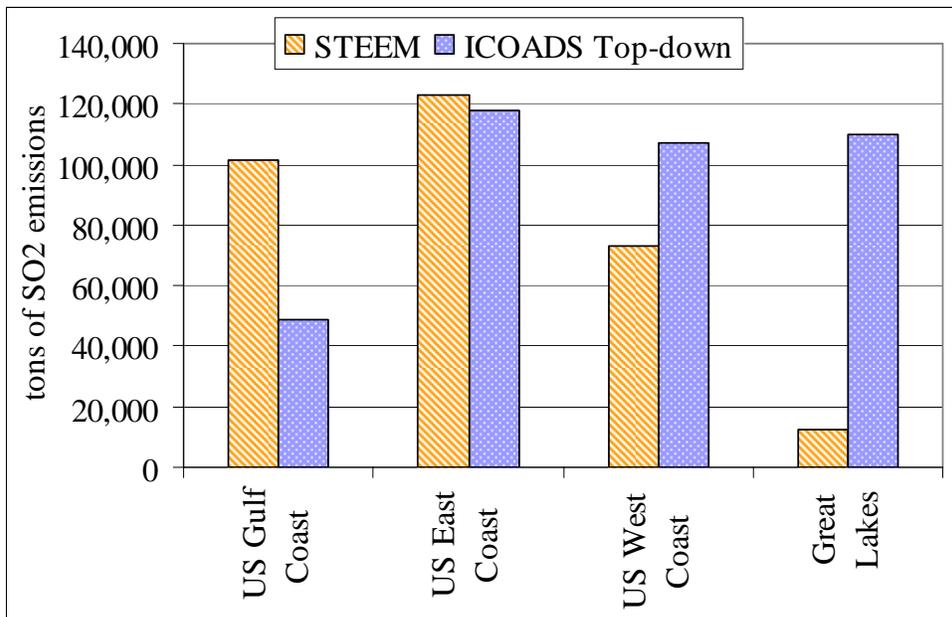


Figure 7. Comparison of the inventories produced with Waterway Network-STEEM and top-down approach using ICOADS.

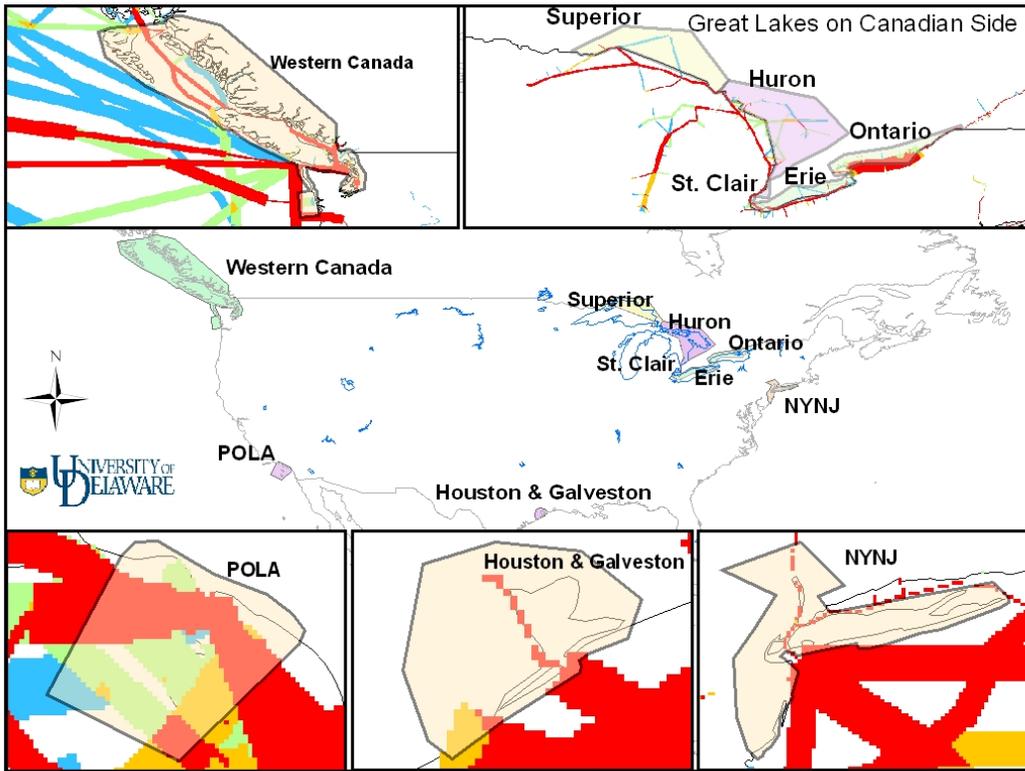


Figure 8. Illustration of domains of regional/port emission inventories studies

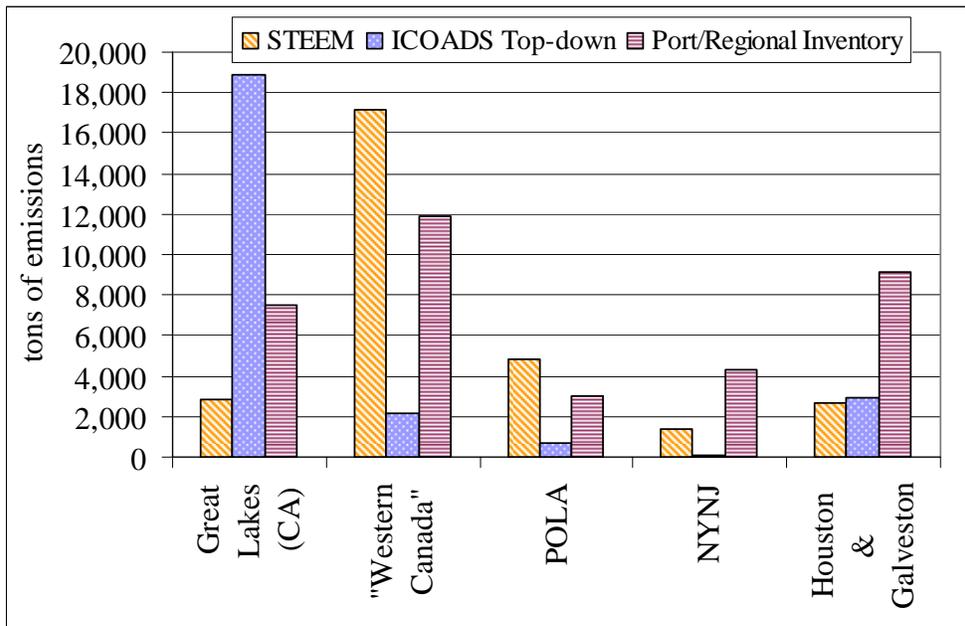


Figure 9. Comparison of emissions inventories of different approaches; emissions for Houston & Galveston are NO_x, emissions for the other areas are SO₂.

Figure 9 also shows that the amount of emissions estimated by STEEM are higher than that of the regional/port studies for the Port of Los Angeles and “Western Canada”, but lower for the Great Lakes on the Canadian side, the port of New York and New Jersey, and the Houston and Galveston area.

We understand that: (1) the STEEM captures transit traffic, which might be ignored in the port-wide studies (POLA and Western Canada) that used arrivals and departures of the specific ports (e.g., the POLA study does not include shipping activity to other than San Pedro Bay ports); (2) port-wide studies used more complete arrivals and departure data for the Great Lakes, the Port of New York and New Jersey, and Houston and Galveston; (3) emissions from dockside hotelling are included in the port-wide studies for the Port of New York and New Jersey, and the Houston and Galveston area but are not included in the STEEM results (the portion of hotelling emissions increases and might dominate the emissions inventory when the domain becomes smaller around the terminals and when ships spend less time in transiting); (4) the motivation behind the creation of the STEEM was to improve the emissions inventories from inter-port movements; emissions around ports have to be adjusted by either plugging in the inventories produced by port-wide studies or modifying the model itself to include the dockside emissions; (5) comparisons showing both higher and lower port and regional estimates suggest there is no systemic error in the STEEM; and (6) our assumption that ships generally maneuver within 20 km of ports may represent some port regions (e.g., Western Canada and Southern California) better than others, where ships may operate at sea-speeds until closer to port.

We also observe that the emissions from ships carrying foreign cargo within the 200 nautical miles coastal areas of the United States estimated by the STEEM are about five times of the results estimated by Corbett and Fischbeck using cargo as a proxy [9]. We understand that the STEEM is superior to the method used by Corbett and Fischbeck and is more accurate, consistent with the uncertainty discussion in the earlier paper and with the upward correction of more accurate work for the Northwest, United States also published previously in ES&T [8].

Uncertainty and Bounding

This analysis follows general best practices for calculating emissions inventories, which enables general analysis of uncertainty due to estimating input parameters. National level uncertainty includes four major elements: A) Uncertainty in input parameter assumptions (e.g., emissions factors, engine activity profile, etc.); B) Uncertainty in U.S. domestic shipping not included in foreign commerce vessel movement data; C) Uncertainty in U.S. Army Corp of Engineers data, and in Canadian and Mexican LMIU data; and D) Spatial uncertainty in routing choices, particularly within confined bay and port regions and seasonally for open ocean routes where weather routing may occur. Bounding of inventories can be done at the national level for the first two elements, because the quality of emissions estimating parameters is known and information on missing U.S. domestic shipping can be derived from fleet statistics. Additional bounding information may be implied by an evaluation of the completeness of LMIU data, with less precision. Effects of spatial uncertainty can only be described qualitatively without further analyses, as discussed in the next section on limitations and opportunities.

Model Uncertainty

An uncertainty analysis was performed on fundamental input parameters by defining aggregate ranges of confidence for input parameters on engine load profile, emissions factors (including fuel-quality variation), vessel engine data (i.e., power rating), and operating hours (derived from vessel speed data). While variability among individual vessels may be large, the

fleet-level uncertainty in average parameters is much smaller and can be bounded. Uncertainty in engine load profile is a function of at-sea and maneuvering operational practices that may differ among vessel types; for this analysis, a range of $\pm 15\%$ on the composite engine load was chosen for each vessel type. Pollutant uncertainty estimates from the Swedish Methodology for Environmental Data report on marine engine emissions factors were used [49]. These uncertainties ranges from $\pm 5\text{-}10\%$ for NO_x and CO_2 , to $\pm 10\text{-}20\%$ for CO and HC , to $\pm 20\text{-}50\%$ for SO_2 and total PM , with uncertainties greater than 50% for PM size fractions. For bounding, this study uses the higher uncertainty applicable to each emissions factor (e.g., $\pm 10\%$ for NO_x , $\pm 20\%$ for CO , and $\pm 50\%$ for SO_2); for total PM an uncertainty of $\pm 50\%$ was assumed although it may be greater. It may be noted that the uncertainty in SO_2 , in particular, is directly related to uncertainty in the fuel-sulfur level, while uncertainty in other factors (e.g., PM) may be influenced by fuel quality as well. Uncertainty in vessel engine data is considered to be small, since the data comes directly from ship registry data or from very strong parametric correlations by vessel type. Given the quantity of ship data, this bounding analysis assumed that uncertainty in installed power and other engine parameters (including vessel speed) is certain to $\pm 10\%$ fleetwide. Engine operating hours correspond to at-sea and maneuvering time, and depend on route and speed; for this bounding analysis, we estimate that this can vary by about $\pm 3\%$ on average.

Table 7 presents the national total estimates bounded by model effects from these uncertain inputs. Figure 10 illustrates the influence of primary uncertain inputs on different pollutant estimates. This shows that the uncertainty of output is nearly symmetric, but that the emission factor (i.e., fuel-sulfur content for SO_2 and possibly for PM) is the most uncertain input for SO_2 , PM , HC and CO . For NO_x and CO_2 , similar internal engine combustion conditions (e.g., similar cylinder peak temperatures, pressures, etc.) result in similar emissions factors; this results in greater certainty for emissions factors and relatively greater contribution to variance from uncertainties in engine load, power, and hours of operation. Localized and in-port inventory uncertainties are expected to be larger than national-level bounds estimated here.

Table 7. Model uncertainty in baseline 2002 emissions for North American Domain (metric tonnes)

	NO_x as NO_2	SO_2	CO_2	HC	PM	CO
Domain Best Estimate	2,740,000	1,630,000	97,800,000	90,800	229,000	214,000
(90th percentile bounds)¹	($\pm 6\%$)	(-18%, $+17\%$)	($\pm 6\%$)	($\pm 9\%$)	(-18%, $+19\%$)	(-8%, $+9\%$)
Lower Bound ¹	2,580,000	1,340,000	92,150,000	80,000	190,000	200,000
Upper Bound ¹	2,920,000	1,910,000	103,890,000	100,000	270,000	230,000

1. Model uncertainty bounds result only from uncertain input parameters in estimating methodology; they do not include uncertainties in the quality of voyage data, discussed elsewhere in this section.

Uncertainty Due to Missing U.S. Domestic Voyage Data

Estimates are also uncertain because voyage data was not available in usable form for U.S. domestic shipping; this represents ship activity not included in foreign commerce vessel movement data from the U.S. Army Corps of Engineers. The U.S. domestic fleet (sometimes referred to as the Short Sea Shipping fleet) is illustrated in Figure 11. Without consideration of spatial activity, it was possible to use the ship registry data and the U.S. foreign commerce entrance and clearance data to identify those U.S.-flag vessels engaged solely in domestic commerce. Using typical model input parameters for this fleet, it was possible to estimate emissions from U.S. domestic ships engaged in similar oceangoing/coastwise commercial service within the North American domain.

Table 8 and Figure 12 show that the influence of these vessels on national baseline inventory results for 2002 may be small – within about 2-3% of the results presented in this study – but adding domestic shipping would increase these inventories. Even if all of U.S.-flag domestic shipping activity were to occur on the West Coast, the emissions increase between 10% and 13%.

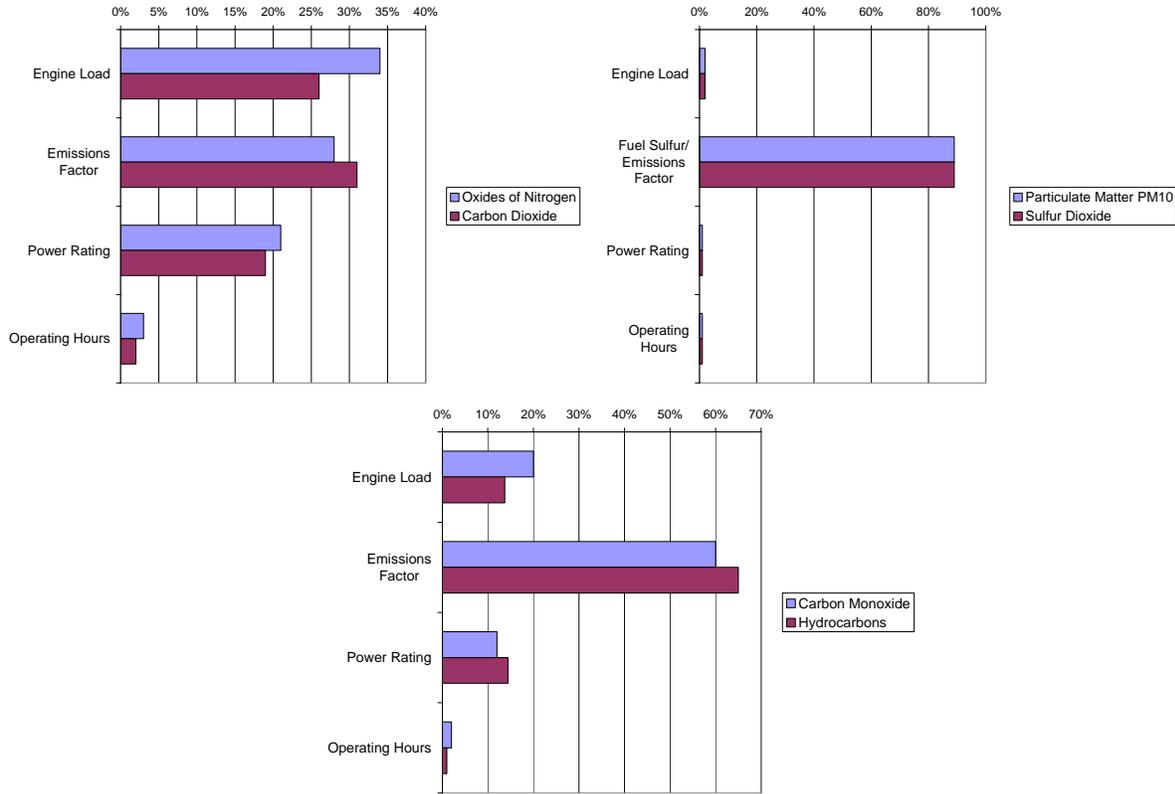


Figure 10. Uncertainty in model output from input parameters scaled by contribution to output variance.

Possibly Incomplete Vessel Voyage Data

A comparison of U.S. Army Corps of Engineers foreign commerce data and LMIU data provided by Environment Canada indicates that significant uncertainty may exist if the vessel arrival and departure data are not complete. LMIU data for all Canada includes some 31,698 movements between Canada and the U.S. in 2002, whereas USACE data only included 22,872 U.S.-Canadian voyages. These differences do not necessarily imply errors in the inventory, since these voyages were evaluated and duplicate voyages were removed. It does, however, raise the question of uncertainty due to completeness of voyage data.

Based on this discrepancy, we reviewed the recent analysis by Levelton Engineering for Transport Canada [56], which used Canadian *Information System on Marine Navigation* (INNAV) data for determining voyages involving Canadian ports. According to the Canadian Coast Guard, “*INNAV is a state-of-the-art system of computers, databases, sensors and communications links that provides information on vessels such as their location, their identity, their port of origin and their destination, to users including port authorities, customs, RCMP and other federal departments involved in national security. It was developed by the Canadian Coast Guard to be used in its Marine Communications and Traffic Service centres. It is now operational in all 11 major centres across eastern Canada.*”

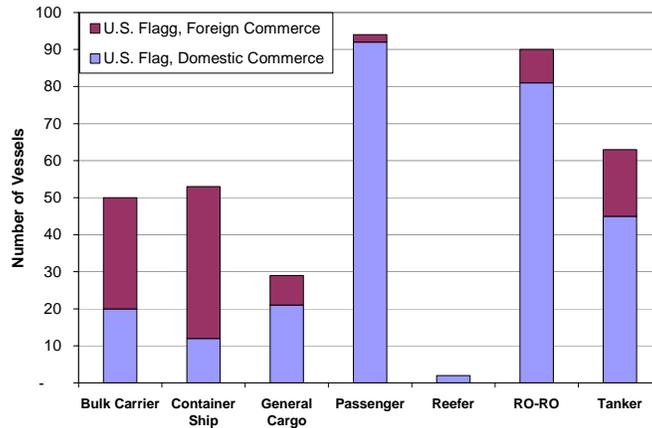


Figure 11. U.S. flag fleet by ship type, and by the number of vessels engaged in foreign commerce versus domestic only (e.g., Short Sea) commerce.

Table 8. Emissions summary for U.S.-flag vessels in domestic only service.

General Type	IC Engines ¹	NOx	SO ₂ ²	CO ₂	HC	PM	CO
Bulk	78%	75	57	3,349	3	6	6
Container	67%	1,257	1,096	64,413	42	105	98
General	100%	422	250	14,701	14	35	33
Passenger	95%	1,022	632	37,143	34	86	80
RoRo	92%	7,023	4,510	265,016	235	589	549
Tanker	58%	2,779	2,802	164,659	93	233	217
Reefer	100%	1,851	1,096	64,413	62	155	145
U.S. Domestic Service	82%	14,430	10,443	613,694	484	1,209	1,129
U.S. Coastwise Foreign		663,102	394,176	20,112,219	18,661	47,149	43,956
Impact on Coastwise Emissions		+2.2%	+2.6%	+3.1%	+2.6%	+2.6%	+2.6%

1. Internal combustion engines represent the percent of engines subject to current and proposed regulations by IMO, EPA, and various states. Other engine types include steam turbine (primarily) and gas turbine, etc.
2. For SO₂, all engine types were included to allow for an inventory of all sulfur emissions from residual fuels.
- 3.

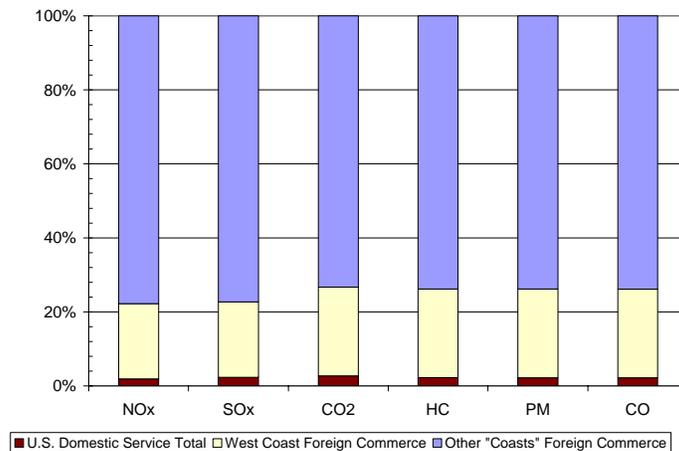


Figure 12. Comparison of interport emissions estimated for U.S. domestic fleet, and foreign commerce fleet on the West Coast and other North American coastlines.

Levelton identified 1789 unique vessels and 29,603 movements for Eastern Canada alone in the INNAV data (including the Great Lakes). This suggests that INNAV is a more complete data set than those used for this project, and/or that INNAV includes or defines movements not considered voyages by LMIU. We think the first may be more likely, and the INNAV may include smaller vessels in domestic voyage, particularly ferry vessel movements and short voyages in the Great Lakes regions.

For Southern California, the data from the USACE and data provided by LMIU showed nearly identical voyage counts. This suggests that LMIU may use Army Corps statistics for California and other U.S. regions. However, given the State of California inventory using California State Lands Commission data also was within 2% of the inventory for California based on this work, we expect that there is very little missing data for foreign commerce voyages in this region, and that domestic voyages may be included only sparsely, if at all, in LMIU data.

Based on this information, we conclude that emissions inventories in regions where USACE data and LMIU data may underestimate voyages could underestimate total emissions for Canada-U.S. by as much as 38% to 64%, respectively. Assuming similar comparisons of LMIU data for Mexico, this uncertainty could apply across North America, although differences among data sources are likely variable by region. In summary, there is some evidence that the inventory presented here may be conservative, since it may exclude some vessel movements. Further work is merited to ensure that the data used in this study includes (is duplicative of) the INNAV data, and to expand INNAV quality data to all of Canadian maritime traffic. Then the model could be applied to consider whether all or some of the additional INNAV voyages involve ships using residual fuel, and to represent them spatially.

CONCLUSIONS AND RECOMMENDATIONS

The 2002 inventory of emissions from North American shipping represents the most accurate and complete inventory to date for interport activity from oceangoing commercial cargo and passenger vessels (excluding ferries). The inventory successfully applies bottom-up estimation methods, extending best-practices for commercial marine inventories to the largest spatially resolved scale so far, and the STEEM model is capable of conducting similar analyses for other regions and even globally. STEEM achieves many of the goals of nonroad marine modeling efforts, such as the U.S. EPA Mobile Vehicle Emissions Simulator (MOVES)¹⁰. STEEM exceeds MOVES current design in two important ways: 1) our approach produces spatial and temporal assignment of emissions in GIS; and 2) our model considers individual vessel movements, rather than binning vessels of similar type. (Similar to binning by MOVES, our model applies emissions factor and engine activity assumptions by vessel type, but considers installed power, routing, and speed individually.)

Our results for U.S. EEZ regions in the North American interport shipping inventory can be compared to US domestic freight overall, and compared to US domestic marine statistics [53, 54]. For carbon dioxide, our results in U.S. EEZ regions are 32% of CO₂ estimate by EPA for all shipping (ships and boats plus bunkers) and 85% of bunkers only; our estimates represent 6% of CO₂ for U.S. surface freight transportation. The comparison of our work with international bunkers is very good agreement, given the independent analysis and considering that we do not account for bunkers used in port or for fuel used on voyages in addition to transits from prior port or to next port. For NO_x, our estimates are 70% of 2002 EPA NO_x estimates from shipping, and represent approximately 12% of NO_x from all U.S. surface freight modes (heavy-duty diesel truck, locomotive, and marine including bunkers). For SO₂, our estimates in U.S. EEZ regions are 2.5 times greater than estimated by EPA for shipping, and 1.2 times greater than SO₂ from U.S. surface freight transportation. For PM_{2.5}, our inventory estimates in U.S. EEZ regions are 1.4 times greater than current estimates for US shipping, and 34% of U.S. surface freight transportation.

It is important to recognize that at least parts of our inventory may represent shipping not included in these national inventories, and that our inventory does not include some marine activity included in these comparison statistics. For example, we do not include inland river navigation¹¹, and our data does include Canadian and Mexican vessel activity that may transit within U.S. coastal regions. In this regard, the emissions estimated in this work both augment and complement current national inventories. Therefore, further work would be required to evaluate the degree that our inventory may increase existing estimates; therefore, the percentages resulting from this comparison represent a first-order comparison.

Our comparison with RTI's model for the baseline year shows similar good agreement in terms of fuel usage [55]. We estimate that some 38 to 44 million tons of fuel were consumed in 2002 to support ship activity described in our model, for U.S. foreign commerce and three-nation North American vessel activity, respectively. The RTI model for estimating bunker fuel demand estimates approximately 51 million tons of fuel for 2002, following a methodology that derives

¹⁰ See <http://www.epa.gov/otaq/ngm.htm> for MOVES information.

¹¹ Inland river navigation refers to voyages entirely within inland river regions, typically not navigable by deep-draft or oceangoing vessels. River transits by deepwater vessels in bays and deepwater river channels are included in this study (e.g., in San Francisco Bay to Benicia or Redwood City, or in the Columbia River to the Port of Portland).

fuel energy requirements from a combined analysis of cargo trade flows and vessel size, speed, and energy characteristics of the fleet expected to transport North American (primarily U.S. cargoes). This represents a 75% to 88% agreement between baseline year estimates from STEEM and the RTI energy estimates. We consider the agreement with RTI's estimate to be similar to the good agreement with national CO₂ estimates, discussed above, identifying likely explanatory differences as bunkers used in port, and/or fuel used on voyages in addition to transits from prior port or to next port, and potential biasing assumptions in the top-down RTI methodology.

We compared coastal and domain results to inventories derived directly from the subset of fleet activity reporting to ICOADS, a top-down proxy used previously for WRAP and other regional and global analyses. Our comparison shows that STEEM corrects for ICOADS under sampling in coastal areas. Specifically, the percent of total domain emissions within 200 nautical miles of land is 25% in ICOADS and 36% in STEEM. This comparison with ICOADS suggests the use of ICOADS or other spatial samples as a top-down proxy remains a valid means of allocating ship emissions. As shown in Figure 7, excluding the Great Lakes the total North American emissions estimates for STEEM and ICOADS are within 10-15% of each other, with the greatest limitations where the sample data is sparse (near shore), where over-reporting may occur (in the Great Lakes), or where there may be biased reporting by ship type (ICOADS reporting high in the West Coast and low in the Gulf Coast, probably due to containership overrepresentation in ICOADS).

Study Limitations and Opportunities for Improvement

Overall the inventories produced for this project using STEEM are shown to be valid geospatial depictions of emissions from commercial ship activity in North America. Some limitations reveal potential for future analyses to become more accurate and descriptive.

First and most obvious, representing emissions from all ships depends upon complete ship activity data. We became aware, for example, that Canadian ship activity included in INNAV appears to be more complete than ship activity described in LMIU data provided by Environment Canada for this project [48]. Ship activity not described in STEEM could be using shipping lanes and route segments different than those assigned to ship activity currently in STEEM. We believe that the empirical waterway network built on 20-year observed ship locations likely reveals most of the major shipping routes; however, missing ship activity may occur on these routes with different intensity than estimated by STEEM; this could produce within-region biases that could be overcome by directly modeling additional ship activity (eg., INNAV movements) in the empirical network.

Second, vessel activity by ships that are not currently addressed in STEEM may include many small movements across short distances and/or near ports. These activities were not typically in the Canadian data provided for STEEM, and may represent additional unique waterway paths that ships in the INNAV data are using. This would mean that the prorated network could assign these movements inaccurately to shipping routes and segments revealed in the current network. As discussed in Wang et al [57], the empirical shipping network can be refined in confined regions and nearer to port to describe these more local movements. However, some coding may be required to allow the major ship activity to conform to the primary routes, and enable these minor routing assignments only for appropriate movements.

Third, shipping activity near ports does not uniformly shift to common maneuvering conditions, and our uniform assumptions of activity input parameters within 20 km of port

introduce errors for local port estimates of underway emissions. This will be adjusted for the SECA team project post-hoc by ICF and Environ. However, network coding in STEEM can be modified so that ship activity parameters on segments near ports are independently assigned local engine load factors and speeds.

Fourth, some shipping lanes within a region may be used (or usable) primarily during certain months or seasons. This could result from winter conditions, for example, especially in the Great Lakes perhaps. Such conditions would suggest that monthly analyses in STEEM could better reveal the seasonality of shipping activity using the current and/or regionally modified empirical routes.

Last, port-based inventories should explicitly define their domain extent and boundaries for clearer comparison. This was possible for recent inventories by Starcrest Consulting Group and by Levelton, but domains were not clearly defined for many other port inventories, including the national summary of port emissions by EPA.

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LIST OF ACRONYMS

AMVER	Automated Mutual-assistance Vessel Rescue system
ARB	California Air Resources Board
AE	Auxiliary Engine
CEC	Commission for Environmental Cooperation in North America
CMV	Commercial Marine Vessel
COADS	Comprehensive Ocean-Atmosphere Data Set
EEZ	Exclusive Economic Zones
EMEP	European Monitoring and Evaluation Programme
FVRD	Fraser Valley Regional District
g/kWh	Grams per Kilowatt-Hour
GVRD	Greater Vancouver Regional District
GRT	Gross Register Tonnage
IMO	International Maritime Organization
INNAV	Information System on Marine Navigation
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IVL	Swedish Environmental Research Institute
Knots	Nautical Miles Per Hour
kW	Kilowatts
LMIU	Lloyds Maritime Intelligence Unit
MDO	Marine Distillate Oil
MGO	Marine Gas Oil
MARPOL	Maritime Pollution Convention
MCR	Maximum Continuous Rating
MOVES	U.S. EPA Mobile Vehicle Emissions Simulator
NRT	Net Register Tonnage
POLA	Port of Los Angeles
NYNJ	Port of New York and New Jersey
NO _x	Oxides of nitrogen
PM	Particulate matter
Reefer	Refrigerated Cargo Ships
SFOC	Specific fuel oil consumption

LIST OF ACRONYMS

SECA	SO _x Emission Control Area
SO _x	Oxides of sulfur
STEEM	Waterway Network Ship Traffic, Energy and Environment Model
USACE	U.S. Army Corps Engineers
U.S. EPA	United States Environmental Protection Agency
UN/LOCODE	Nations Code for Trade and Transport Locations
VOS	Voluntary Observing Ships
VBA	Visual Basic for Application