IMPROVED GEOSPATIAL SCENARIOS FOR COMMERCIAL MARINE VESSELS

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Abstract

This project updates geographically resolved commercial marine emissions inventories and scenarios for cargo traffic in shipping lanes serving U.S. continental coastlines. Previous work delivered commercial marine emissions inventories for cargo traffic in shipping lanes serving U.S. continental coastlines. A primary objective of this project is to provide geographically resolved vessel specific estimates of commercial marine vessel (CMV) emissions in North American waters that are consistent with earlier studies for the California Air Resources Board (ARB). On a vessel-type specific bases, growth trends describing trade and energy requirements for North American cargo and passenger vessels are applied to 2002 data to produce unconstrained business as usual (BAU) estimates for 2010 (prior to international sulfur regulations), and a 2020 scenario assuming International Maritime Organization (IMO)-compliant reductions in global fuel sulfur. Two growth scenarios are illustrated: Scenario 1, approximating the same composite growth rates as previous work (pre-recession); and Scenario 2, employing lower growth rates. Vessel-type specific growth patterns provide better regional clarity 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. This work will provide greater detail and improved spatial scenarios of commercial marine emissions for North American coastal waters that supports the ARB, western regional states, federal and international efforts to quantify and evaluate potential air pollution and climate impacts from shipping.

Executive Summary

This report is intended to assist the role of the California Air Resources Board (ARB) and other agencies evaluating commercial marine vessel (CMV) activity now and in the future, including regulatory action by the International Maritime Organization (IMO) to reduce impact to air quality and human health by oceangoing CMVs in transit. A primary objective of this project is to update the results of the Ship Traffic Energy and Emissions Model (STEEM) estimating CMV emissions in coastal waters to be geospatially resolved by vessel type. A secondary objective is to evaluate these results in terms of future scenarios. Tasks in this work include:

Task 1 Produce Ship Emissions Inventories By Vessel Type.

Task 2 Evaluate Change in Ship Emissions for 2010 and 2020.

Task 3 Produce Summary Report.

Using vessel-type specific growth trends, we produce the following scenarios: 1) an unconstrained scenario applying vessel-type specific growth trends that correspond to the previous STEEM study for ARB, representing trends prior to the recession; and 2) lower-growth trends derived from vessel-type specific growth trends in the scenario model applied to the Second IMO Greenhouse Gas (GHG) Study 2009, representing long-term growth that qualitatively reflects a slow-growth recovery in shipping for North America. In both scenarios, we adjust emissions rates to reflect global IMO regulations per MARPOL Annex VI for NOx and SOx. This report summarizes the baseline model, presents an empirically representative growth rate based on the observed trend in installed power by ships calling on North America.

This work uses baseline conditions from the prior ARB STEEM project to produce vessel-type specific patterns. Replicating rates of change from prior work – and including rates of change reflecting recent global scenarios for growth in shipping – this work produces vessel-type specific future estimates. Associating these growth rates to the vessel-type specific patterns produces new combined patterns representing future freight activity by commercial marine vessels.

The STEEM model represents global shipping routes, although the study focused on the North American domain defined in the first STEEM project. North American domain totals reported here and delivered as shape files are three-quarters (~75%) of global estimation for emissions from shipping between North American ports and the origin or destination ports of the world; this is similar to the previous study totals. However, passenger, miscellaneous, and Roll-On/Roll-Off (RO-RO) ships spend more time within the North American study region and bulk carriers and fishing vessels spend less time in this North American domain. Vessel-type specific information is relevant to understanding which vessels are more likely to operate within national domains. This could indicate which vessel groups will evaluate cost-effective controls similarly, perhaps incentivizing some technologies and operational changes more than others among these groups of vessels.

The fastest growing shipping routes show the greatest growth in fuel use and the least reductions in SOx emissions from lower-sulfur fuels (or equivalent certified technologies meeting IMO Annex VI control requirements). Overall, container shipping moving goods to and from North American ports contributes the greatest amount of emissions and uses the most fuel among all ship types. This is partly because of the higher installed power associated with liner shipping of containerized goods, and partly due to the nature of consumption of imported goods in North American communities. The share of containerized shipping activity increases from roughly 35% to nearly 60% of total emissions attributed to containerized vessels by 2020, under high-growth scenarios. Under lower-growth scenarios these ship types still increase their activity faster relative to other ship types, contributing more than 40% to 2020 totals. Given that containerized shipping is intrinsically intermodal (connecting with rail and road), international goods movement will be linked with domestic goods movement decisions.

Introduction

This report is intended to assist the role of the California Air Resources Board (ARB) and other agencies evaluating commercial marine vessel activity, emissions, and trends while in transit around the waterways and coastlines of North America.

Purpose and Scope

A primary objective of this project is to update the results of the Ship Traffic Energy and Emissions Model (STEEM) estimating commercial marine vessel (CMV) emissions in coastal waters to be geospatially resolved by vessel type. A secondary objective is to evaluate these results in terms of future scenarios. Tasks in this work include:

Task 1 Produce Ship Emissions Inventories By Vessel Type.

This task applies the activity-based methodology developed in STEEM to produce CMV emissions inventories for different vessel types. In at least three important ways, STEEM advances the quality of large-scale CMV inventories: (i) estimating emissions for large regions on the basis of nearly complete data describing historical ship movements, attributes, and operating profiles of individual ships, (ii) solving distances on an empirical waterway network for each pair of ports considering ship draft and width constraints, and (iii) allocating emissions on the basis of the most probable routes. Previously, STEEM estimated that the 172 000 ship voyages to and from North American ports in 2002 consumed about 47 million metric tonnes of heavy fuel oil and emitted about 2.4 million metric tonnes of SO_2, about 16.5% of SO_2 emissions from all sources in the U.S. in the same year [1]. North American shipping fuel use and SO_2 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. [2, 3]. This task delivers vessel-type specific inventories for the following six pollutants: Oxides of sulfur (SOx as SO_2), Oxides of nitrogen (NOx), Carbon dioxide (CO_2), Particulate matter (PM), Hydrocarbons (HC), and Carbon monoxide (CO).

Task 2 Evaluate Change in Ship Emissions for 2010 and 2020.

This task produces emissions scenarios for 2010 and 2020 using these vessel-type inventories and applying corresponding growth rates. Vessel-type specific future scenarios will produce spatial results revealing asymmetry among future trends for liner trades and bulk trades that will help understand which coastal regions and air basins may be most affected. At the request of ARB staff, we provide two future scenarios: Scenario 1 represents consistent growth rates with the previous ARB-sponsored STEEM work; Scenario 2 represents lower growth rates derived from the global average growth rates used in the Second IMO GHG Study 2009 [4]. Scenario 1 is presented geospatially by vessel type; second scenario goes beyond the original scope for this project, and is summarized in tabular form.

Task 3 Produce Summary Report.

The final report summarizes the work in one document with an executive summary and overall conclusions.

Background

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. The state of practice is now to construct activity-based emissions estimates for specific vessels or vessel group characteristics, and these approaches have been either mapped to geospatial locations (top-down) or constructed within a geospatial domain (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. In bottom-up methods, 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; ship and route specific emissions are estimated in-situ based these ship movements, ship attributes, and ship emissions factors. STEEM is a global model to quantify and geographically 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.

Previous Results for Baseline Inventory: North American shipping consumed about 47 million tons of heavy fuel oil and emitted ~2.4 million tons of SO_2 in 2002, with approximately 30 million tons fuel and 1.6 million tons SO_2 within the North American domain for this project. Comparison of our results with port and regional studies shows good agreement, and improved accuracy over existing top-down methods.

Previous Results for Forecasts: We estimated a growth trend for North America (including United States, Canada, and Mexico) of about 5.9%, compounded. We produced two classes of forecasts: 1) a *business as usual (BAU)* forecast applying a common growth trend without sulfur controls (but with existing IMO NOx requirements); and 2) a *with-ECA* scenario assuming IMO-compliant reductions in fuel sulfur to 1.5% by weight for all activity within the Exclusive Economic Zone (200 nautical miles) of North American nations. Our BAU scenario compares reasonably well with available energy and fuel usage trends and with trends describing growth in trade volume; our growth trends are lower than have been reported since 2002 by major US ports.

Baseline (2002) inventory results are being used by ARB, the U.S. Environmental Protection Agency (U.S. EPA), Environment Canada, and others to model atmospheric fate and transport of pollution, evaluate air quality impacts, and assess potential health effects attributed to ships. The base-year inventory and forecasts assist ARB in evaluating air quality and health impacts in California, and help evaluate national impacts on behalf of the United States, Canada, and Mexico at the IMO.

Summary of Significance

Three critical questions for understanding freight activity and environmental impacts defined two phases of the project:

1. **Baseline Conditions:** What are freight energy and activity patterns?
2. **Rates of Change:** What is the scenario trend in energy?
3. **Patterns of Change:** Where is future freight activity located?

This work answers these questions in ways not previously analyzed. This work uses baseline conditions from the prior ARB STEEM project to produce vessel-type specific patterns. Replicating rates of change from prior work – and including rates of change reflecting recent global scenarios for growth in shipping – this work produces vessel-type specific future estimates. Associating these growth rates to the vessel-type specific patterns produces new combined patterns representing future freight activity by commercial marine vessels.

Methods

This work builds upon activity-based geospatially located emissions for commercial marine vessels developed in the STEEM model, to differentiate the previous results by vessel type, and to produce vessel-type specific growth scenarios to describe future years. In general, materials for this work include the global network developed at the University of Delaware primarily by Dr. Chengfeng Wang, vessel activity data for the United States from the U.S. Army Corps of Engineers, vessel movement data for Canada and Mexico from Lloyds Maritime Intelligence Unit (LMIU) provided by Environment Canada and the Commission for Environmental Cooperation, respectively. Ship characteristics were also obtained from Lloyd's ship registry data. Inventory assumptions and other model inputs were primarily derived from earlier ARB reports and published work by Dr. Corbett, modified through discussion with U.S. EPA contractors and review of port-based best practices.

Emissions trends are derived from a pluralistic evaluation of historic time series of the above data and forecast studies that together describe: a) growth expected in international goods movement in economic terms (e.g., seaborne trade); and b) correlated trends in energy required to move more goods in service of global trade in terms of ship fleet characteristics (e.g., vessel type and installed power). For cargo activity, we reviewed studies at port, regional, national, and global scales, all of which document strong growth trends and/or forecast similar rates of continued growth. For vessel activity specific to North American ports, we were able to construct detailed trend characteristics information including vessel type, power, size, and speed characteristics for the period between 1997 and 2003; at the global scale, we developed longer time-series trends in ship characteristics by year of build and from related global studies.

Brief Summary of STEEM 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. Figure 2 depicts the North American domain for results reported here.

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.

STEEM 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 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 sets[1]). After eliminating duplicates, the North American shipping activities data set for 2002 has about 172,000 unique trips. North American shipping activities for 2002 included voyages on about 21,000 unique routes.

The STEEM Model has been described in earlier publications and reports [5-9]; recently the STEEM network architecture was merged into the Geospatial Intermodal Freight Transportation (GIFT) Model [10-13].

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1 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.

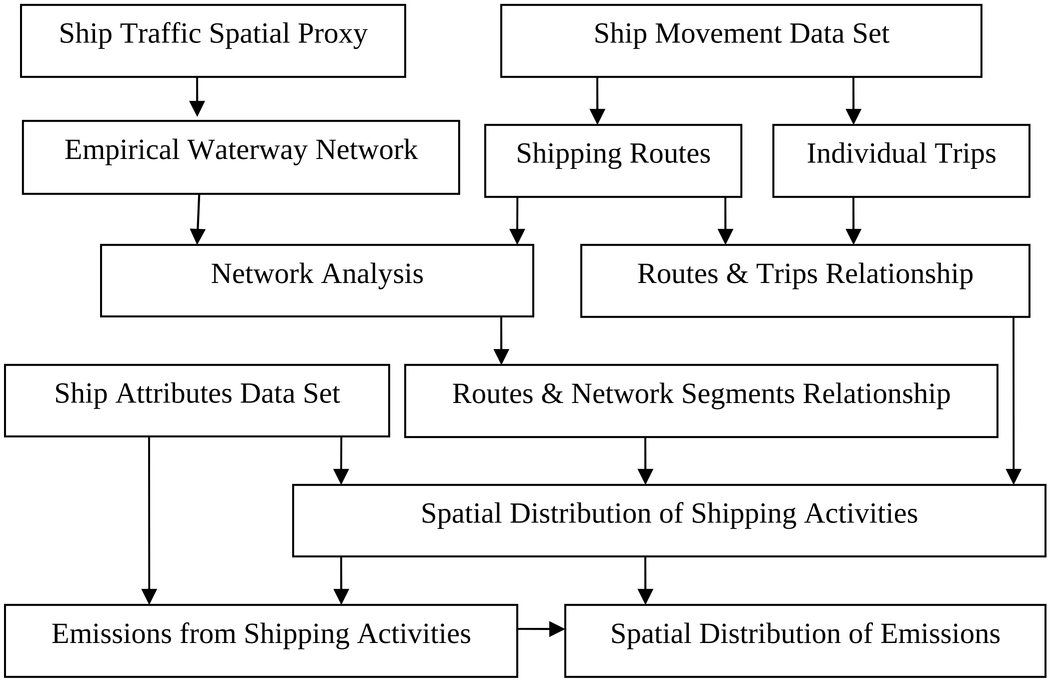
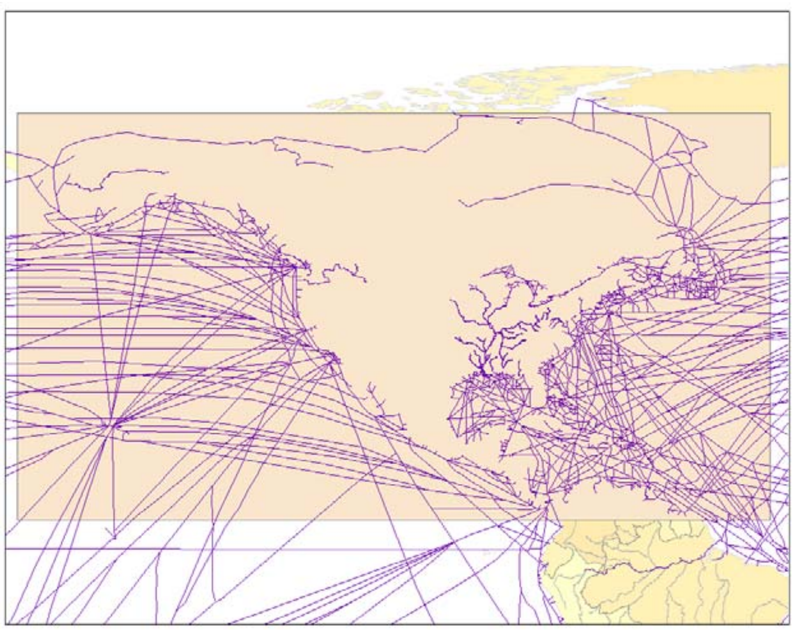


Figure 1. Illustration of Waterway Network Ship Traffic, Energy and Environment Model (STEEM) as applied to emission estimation.

Figure 2. Model domain for North American Shipping.



Activity-based Emissions Estimates

STEEM employs 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. For this work, we used data from the previous STEEM results reporting the sum of installed power attributes by vessel-type and waterway segment.

Pollutant emissions and fuel use are obtained by multiplying the power in kilowatt-hours (kWh) by the emissions rates or fuel consumption rates in grams per kilowatt-hour (g/kWh). For 2002 and 2010, emissions rates reflect the currently uncontrolled engine emissions for each vessel type, shown in Table 1; for 2020, Table 2 presents emissions rates adjusted to reflect IMO Annex VI compliance [14].

Table 1. Summary of emissions factor in 2002, 2010 (g/kWh).

Vessel Type	Percent Distillate	Composite SOx Aux. EF	Fuel Use	NOx	SOx	CO_2	HC	PM	CO
Bulk	29%	9.98	206	17.9	10.6	622.9	0.6	1.5	1.4
Container	29%	9.98	206	17.9	10.6	622.9	0.6	1.5	1.4
Fishing	100%	4.3	221	14	11.5	677	0.5	1.5	1.1
General	29%	9.98	206	17.9	10.6	622.9	0.6	1.5	1.4
Miscellaneous	100%	4.3	221	14	11.5	677	0.5	1.5	1.1
Passenger	8%	11.66	206	17.9	10.6	622.9	0.6	1.5	1.4
Reefer	29%	9.98	206	17.9	10.6	622.9	0.6	1.5	1.4
RO-RO	29%	9.98	206	17.9	10.6	622.9	0.6	1.5	1.4
Tanker	29%	9.98	206	17.9	10.6	622.9	0.6	1.5	1.4

1. Data from composite EF data reported in prior STEEM study [7].

Table 2. Summary of emissions factor in 2020, derived from composite EF from earlier STEEM study.

Vessel Type	Percent Distillate	Composite SOx Aux. EF	Fuel Use	NOx	SOx	CO_2	HC	PM	CO
Bulk	29%	4.21	206	15.38	1.96	622.9	0.6	0.40	1.4
Container	29%	4.21	206	15.38	1.96	622.9	0.6	0.40	1.4
Fishing	100%	4.21	221	14.00	1.96	677	0.5	0.40	1.1
General	29%	4.21	206	15.38	1.96	622.9	0.6	0.40	1.4
Miscellaneous	100%	4.21	221	14.00	1.96	677	0.5	0.40	1.1
Passenger	8%	4.21	206	15.38	1.96	622.9	0.6	0.40	1.4
Reefer	29%	4.21	206	15.38	1.96	622.9	0.6	0.40	1.4
RO-RO	29%	4.21	206	15.38	1.96	622.9	0.6	0.40	1.4
Tanker	29%	4.21	206	15.38	1.96	622.9	0.6	0.40	1.4

Scenario Development

The previous ARB project produced power-based growth rates for selected ports and North American regions. We derive emissions forecast trends directly from aggregate installed power of ships calling on North American ports; this is because emissions are directly proportional to engine power and load, which for at-sea conditions is highly correlated with total installed power on commercial ships.[2] Table 3 reproduces from the prior report an overview of power-based growth rates for selected ports and

2 This direct proportionality of stack emissions to engine power is implicit in the use of power-based emissions factors in activity-based inventory best practices.

North American regions. To be consistent with these results, we use a ~5.9% Compound Annual Growth Rate (CAGR) for the 2002-2020 periods. This corresponds to a 2002-2010 CAGR of 5.1%. Upon request from ARB staff, we also produce scenario estimates using the same growth rates as the IMO-hi global average to capture a "low-growth North America." This produced a composite growth rate of 2.9% in 2020 and 2.8% in 2010, much lower growth rate than the 5.9% CAGR, especially given that North America grows faster than world average.

The Second IMO GHG Study 2009 developed scenarios for future emissions from international shipping that were consistent with the Intergovernmental Panel on Climate Change (IPCC) set of scenarios. IPCC scenarios project a potential future estimate from driving forces such as population, economy, technology, energy, land use, and agriculture. The IMO study adopted a similar approach, identifying key driving variables of economic demand, change in transport (CMV) efficiency, and energy sources [4]. As articulated in the IPCC storyline description, the A1 scenarios reflect "a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality. Details of the IMO growth inputs are described in Section 7 of the Second IMO GHG Study 2009 [4]. Table 4 presents the vessel-type specific growth rates for installed power used in this project.

Table 3. *Prior Study's* Power-based growth rate summary for commercial ships 2002 -2020 (CAGR)

Ports, or Region	Emissions Growth Rate
Los Angeles/Long Beach	5.24%
Oakland/San Francisco	5.68%
New York/New Jersey	6.03%
California (all ports)	5.53%
U.S. West Coast	5.93%
U.S. National	5.86%
Canada	6.57%
Mexico	5.06%
North America (U.S., Canada and Mexico)	5.86%

1. Growth rates represent an average of exponential and linear fit extrapolations, presented in terms of compound annual growth rate (CAGR).
2. US data are from USACE and Lloyds Registry data, per this and other work by Wang and Corbett.
3. Canada and Mexico data are from Lloyds Movement data (LMIU)

Table 4. Vessel-type specific power-growth rates used in this work.

	Scenario 1	Scenario 2
Vessel Specific Growth Rates	Composite 5.9% to 2020	2020 using IMO-hi Scenario
Bulk	1.5%	2.3%
Container	11.0%	4.6%
Fishing	0.1%	0.1%
General	1.0%	1.3%
Miscellaneous	0.5%	1.0%
Passenger	6.0%	1.7%
Reefer	9.0%	4.6%
RO-RO	6.0%	4.6%
Tanker	2.0%	2.0%

Results

While the geospatial domain for this project replicates the North American region reported previously, the analysis provided global and regional results for comparison with previous STEEM analyses and with other global studies. These are described in this section.

Global Results with North America Data

Table 5 presents the sum of installed power calculated across all STEEM routes by vessel type, in megawatts (MW); this represents more than the installed power summed across individual vessels – in represents the total for all vessel trips. Table 6 illustrates results of emissions and fuel use for 2002 shipping data for North American nations totaled along the full extent of the global routes. These results replicate the previous study totals within ~4%. The previous study reported estimates 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 SO_2 in 2002. Data processed for this project produced 2002 estimates of ~45 million tons of heavy fuel oil consumed and ~2.3 million tons of SO_2 emitted. Other recent work reports North American shipping activity to consume some ~38 million tons fuel [15, 16].

Table 5. Installed power data (kW) for 2002 and future years under Scenarios 1 and 2.

		Scenario 1		Scenario 2	
Vessel Type	**Sum of 2002 power**	**Sum of 2010 power**	**Sum of 2020 power**	**Sum of 2020 power**	**Sum of 2010 power**
Bulk Carrier	48,369	50,578	58,698	65,337	51,845
Container	76,720	104,924	297,923	138,177	87,877
Fishing	117	117	118	118	117
General Cargo	18,182	18,732	20,692	21,533	18,905
Miscellaneous	3,740	3,797	3,991	4,252	3,853
Passenger	12,325	14,679	26,288	15,325	12,960
Reefer	4,811	6,230	14,748	8,664	5,510
RO-RO	16,987	20,231	36,231	30,594	19,457
Tanker	36,701	38,947	47,476	47,356	38,924

Table 7 and Table 8 present global estimates of emissions under Scenario 1 growth rates. These estimates suggest substantial growth in shipping activity if recent (pre-recession) trends continue for North American goods movement by ships. This is reflected in the ~18% increase in fuel use by 2010 (from 2002), and in the ~230% increase in fuel use in 2020. However, this Scenario also reveals the important mitigation measures of IMO Annex VI, in which some NOx controls will be implemented and global emissions of sulfur will reduce substantially. NOx increases are only double that of 2002 under Scenario 1. Compared to 2002 baseline, the change in SOx in 2020 is a *net reduction by ~55% despite growth in shipping*.

Table 9 and Table 10 present global estimates of emissions under Scenario 2 growth rates. These estimates suggest more modest growth in shipping activity if recession and recovery trends are substantially altered for North American goods movement by ships. This is reflected in the ~10% increase in fuel use by 2010 (from 2002), and in the ~150% increase in fuel use in 2020. As before, this Scenario also reveals the important mitigation measures of IMO Annex VI, in which some NOx controls will be implemented and global emissions of sulfur will reduce substantially. NOx increases are only ~130% greater than 2002 under Scenario 2. Compared to 2002 baseline, the change in SOx in 2020 is a *net reduction by ~70% reflecting more modest growth in future shipping*.

Table 6. Global summary of 2002 STEEM results by nation and by vessel type (metric tons).

Nation of port Vessel type	NOx	SOx	CO_2	HC	PM	CO	Fuel Use
Canada	**433,000**	**257,000**	**15,111,000**	**15,000**	**36,000**	**34,000**	**5,009,000**
Bulk Carrier	185,000	109,000	6,420,000	6,200	15,000	14,000	2,128,000
Container	127,000	75,000	4,423,000	4,300	11,000	10,000	1,466,000
Fishing	900	700	42,000	30	100	100	14,000
General Cargo	31,000	18,000	1,074,000	1,000	2,600	2,400	356,000
Miscellaneous	2,500	2,000	120,000	100	300	200	39,000
Passenger	3,200	2,000	112,000	100	300	300	38,000
Reefer	1,400	900	50,000	50	100	100	17,000
RO-RO	33,000	20,000	1,164,000	1,100	2,800	2,600	386,000
Tanker	49,000	29,000	1,706,000	1,600	4,100	3,800	566,000
Mexico	**133,000**	**79,000**	**4,633,000**	**4,400**	**11,000**	**10,000**	**1,537,000**
Bulk Carrier	24,000	14,000	823,000	800	2,000	1,800	273,000
Container	60,000	35,000	2,084,000	2,000	5,000	4,700	691,000
Fishing	100	100	5,000	4	10	10	1,700
General Cargo	6,800	4,000	237,000	200	600	500	79,000
Miscellaneous	1,400	1,100	68,000	100	200	100	22,000
Passenger	5,100	3,100	178,000	200	400	400	60,000
Reefer	700	400	24,000	20	100	100	8,000
RO-RO	8,800	5,200	307,000	300	700	700	102,000
Tanker	26,000	15,000	907,000	900	2,200	2,000	301,000
USA	**3,321,000**	**1,977,000**	**116,226,000**	**111,000**	**279,000**	**260,000**	**38,571,000**
Bulk Carrier	658,000	389,000	22,886,000	22,000	55,000	51,000	7,586,000
Container	1,186,000	701,000	41,281,000	40,000	99,000	93,000	13,681,000
Fishing	700	500	32,000	20	100	100	11,000
General Cargo	288,000	170,000	10,015,000	10,000	24,000	23,000	3,321,000
Miscellaneous	48,000	38,000	2,345,000	2,000	5,000	4,000	765,000
Passenger	212,000	130,000	7,387,000	7,000	18,000	17,000	2,499,000
Reefer	84,000	49,000	2,922,000	3,000	7,000	7,000	973,000
RO-RO	262,000	155,000	9,110,000	9,000	22,000	20,000	3,021,000
Tanker	582,000	344,000	20,248,000	20,000	49,000	46,000	6,713,000
Grand Total[1]	**3,886,000**	**2,312,000**	**135,970,000**	**130,000**	**327,000**	**304,000**	**45,117,000**

1. Global summary represents the global extent of all routes for the North American voyage data.

Table 7. Global estimates of 2010 Scenario 1 STEEM results by nation and by vessel type (metric tons).

Nation of port Vessel type	NOx	SOx	CO_2	HC	PM	CO	Fuel Use
Canada	**499,000**	**296,000**	**17,428,000**	**17,000**	**42,000**	**39,000**	**5,777,000**
Bulk Carrier	193,000	114,000	6,714,000	6,500	16,200	15,000	2,226,000
Container	174,000	103,000	6,049,000	5,800	14,600	14,000	2,005,000
Fishing	900	700	42,000	30	100	100	14,000
General Cargo	32,000	19,000	1,106,000	1,100	2,700	2,500	367,000
Miscellaneous	2,500	2,000	122,000	100	300	200	40,000
Passenger	3,800	2,300	134,000	100	300	300	45,000
Reefer	1,900	1,100	65,000	100	200	100	22,000
RO-RO	40,000	24,000	1,387,000	1,300	3,300	3,100	460,000
Tanker	52,000	31,000	1,810,000	1,700	4,400	4,100	600,000
Mexico	**160,000**	**95,000**	**5,600,000**	**5,400**	**13,500**	**13,000**	**1,857,000**
Bulk Carrier	25,000	15,000	861,000	800	2,100	1,900	285,000
Container	82,000	48,000	2,851,000	2,700	6,900	6,400	945,000
Fishing	100	100	5,100	4	10	10	1,700
General Cargo	7,000	4,100	244,000	200	600	500	81,000
Miscellaneous	1,400	1,100	69,000	100	200	100	23,000
Passenger	6,100	3,700	212,000	200	500	500	72,000
Reefer	900	500	31,000	30	100	100	10,000
RO-RO	10,000	6,200	365,000	400	900	800	121,000
Tanker	28,000	16,000	963,000	900	2,300	2,200	319,000
USA	**3,947,000**	**2,348,000**	**138,039,000**	**132,000**	**332,000**	**309,000**	**45,811,000**
Bulk Carrier	688,000	406,000	23,931,000	23,000	58,000	54,000	7,933,000
Container	1,622,000	959,000	56,457,000	54,000	136,000	127,000	18,711,000
Fishing	700	500	32,000	20	100	100	10,600
General Cargo	297,000	175,000	10,318,000	10,000	25,000	23,000	3,422,000
Miscellaneous	49,000	39,000	2,380,000	2,000	5,000	3,900	777,000
Passenger	253,000	154,000	8,798,000	8,000	21,000	20,000	2,976,000
Reefer	109,000	64,000	3,784,000	4,000	9,000	8,500	1,260,000
RO-RO	312,000	184,000	10,850,000	10,000	26,000	24,000	3,598,000
Tanker	617,000	365,000	21,487,000	21,000	52,000	48,000	7,124,000
Grand Total[1]	**4,607,000**	**2,739,000**	**161,067,000**	**155,000**	**387,000**	**360,000**	**53,446,000**

1. Global summary represents the global extent of all routes for the North American voyage data.

Table 8. Global estimates of 2020 Scenario 1 STEEM results by nation and by vessel type (metric tons).

Nation of port Vessel type	NOx	SOx	CO_2	HC	PM	CO	Fuel Use
Canada	**775,000**	**103,000**	**31,443,000**	**30,000**	**20,000**	**71,000**	**10,423,000**
Bulk Carrier	192,000	25,000	7,792,000	8,000	5,000	18,000	2,583,000
Container	424,000	56,000	17,176,000	17,000	11,000	39,000	5,692,000
Fishing	900	100	42,000	30	20	100	14,000
General Cargo	30,000	4,000	1,222,000	1,200	800	2,700	405,000
Miscellaneous	2,600	400	128,000	100	100	200	42,000
Passenger	5,900	1,000	239,000	200	200	500	81,000
Reefer	3,800	500	154,000	100	100	300	51,000
RO-RO	61,000	8,200	2,483,000	2,400	1,600	5,600	823,000
Tanker	54,000	7,200	2,206,000	2,100	1,400	5,000	732,000
Mexico	**289,000**	**39,000**	**11,721,000**	**11,000**	**7,000**	**26,000**	**3,887,000**
Bulk Carrier	25,000	3,300	999,000	1,000	1,000	2,000	331,000
Container	200,000	26,000	8,094,000	8,000	5,000	18,000	2,682,000
Fishing	100	20	5,000	4	3	10	1,700
General Cargo	6,600	900	269,000	300	200	600	89,000
Miscellaneous	1,500	200	73,000	100	-	100	24,000
Passenger	9,400	1,600	379,000	400	200	900	128,000
Reefer	1,800	300	74,000	100	-	200	25,000
RO-RO	16,000	2,100	654,000	600	400	1,500	217,000
Tanker	29,000	3,800	1,174,000	1,100	700	2,600	389,000
USA	**6,713,000**	**907,000**	**272,351,000**	**262,000**	**173,000**	**611,000**	**90,382,000**
Bulk Carrier	686,000	91,000	27,773,000	27,000	18,000	62,000	9,206,000
Container	3,957,000	522,000	160,306,000	154,000	102,000	360,000	53,128,000
Fishing	700	100	33,000	20	20	100	11,000
General Cargo	281,000	38,000	11,398,000	11,000	7,300	26,000	3,780,000
Miscellaneous	52,000	7,800	2,502,000	1,800	1,500	4,100	817,000
Passenger	389,000	67,000	15,756,000	15,000	10,000	35,000	5,329,000
Reefer	221,000	31,000	8,959,000	8,600	5,700	20,100	2,983,000
RO-RO	480,000	64,000	19,431,000	19,000	12,000	44,000	6,443,000
Tanker	647,000	86,000	26,193,000	25,000	17,000	59,000	8,685,000
Grand Total[1]	**7,777,000**	**1,048,000**	**315,514,000**	**303,000**	**201,000**	**707,000**	**104,692,000**

1. Global summary represents the global extent of all routes for the North American voyage data.

Table 9. Global estimates of 2010 Scenario 2 STEEM results by nation and by vessel type (metric tons).

Nation of port Vessel type	NOx	SOx	CO_2	HC	PM	CO	Fuel Use
Canada	**474,000**	**281,000**	**16,548,000**	**16,000**	**40,000**	**37,000**	**5,486,000**
Bulk Carrier	198,000	117,000	6,882,000	6,600	17,000	15,000	2,281,000
Container	146,000	86,000	5,066,000	4,900	12,000	11,000	1,679,000
Fishing	900	700	42,000	30	100	100	14,000
General Cargo	32,100	19,000	1,116,000	1,100	2,700	2,500	370,000
Miscellaneous	2,600	2,000	123,000	100	300	200	40,000
Passenger	3,400	2,100	118,000	100	300	300	40,000
Reefer	1,700	1,000	58,000	100	100	100	19,000
RO-RO	38,000	23,000	1,334,000	1,300	3,200	3,000	442,000
Tanker	52,000	31,000	1,809,000	1,700	4,400	4,100	600,000
Mexico	**146,000**	**87,000**	**5,119,000**	**4,900**	**12,000**	**11,000**	**1,698,000**
Bulk Carrier	25,000	15,000	882,000	800	2,100	2,000	292,000
Container	69,000	41,000	2,387,000	2,300	5,700	5,400	791,000
Fishing	100	100	5,100	4	10	10	1,700
General Cargo	7,100	4,200	246,000	200	600	600	82,000
Miscellaneous	1,400	1,100	70,000	100	200	100	23,000
Passenger	5,400	3,300	187,000	200	500	400	63,000
Reefer	800	500	28,000	-	100	100	9,200
RO-RO	10,000	6,000	351,000	300	800	800	116,000
Tanker	28,000	16,000	962,000	900	2,300	2,200	319,000
USA	**3,650,000**	**2,172,000**	**127,701,000**	**122,000**	**307,000**	**285,000**	**42,377,000**
Bulk Carrier	705,000	417,000	24,530,000	24,000	59,000	55,000	8,131,000
Container	1,359,000	803,000	47,285,000	46,000	114,000	106,000	15,671,000
Fishing	700	500	32,000	20	100	100	11,000
General Cargo	299,000	177,000	10,414,000	10,000	25,000	23,000	3,454,000
Miscellaneous	50,000	39,000	2,415,000	1,800	5,400	3,900	788,000
Passenger	223,000	136,000	7,768,000	7,500	19,000	17,000	2,627,000
Reefer	96,000	57,000	3,347,000	3,200	8,100	7,500	1,114,000
RO-RO	300,000	177,000	10,435,000	10,000	25,000	23,000	3,460,000
Tanker	617,000	365,000	21,475,000	21,000	52,000	48,000	7,120,000
Grand Total[1]	**4,271,000**	**2,540,000**	**149,367,000**	**143,000**	**359,000**	**334,000**	**49,560,000**

1. Global summary represents the global extent of all routes for the North American voyage data.

Table 10. Global estimates of 2020 Scenario 2 STEEM results by nation and by vessel type (metric tons).

Nation of port Vessel type	NOx	SOx	CO_2	HC	PM	CO	Fuel Use
Canada	**558,000**	**74,000**	**22,617,000**	**22,000**	**14,000**	**51,000**	**7,497,000**
Bulk Carrier	214,000	28,000	8,673,000	8,400	5,500	19,000	2,875,000
Container	197,000	26,000	7,966,000	7,700	5,100	18,000	2,640,000
Fishing	900	100	42,000	30	20	100	14,000
General Cargo	31,000	4,200	1,272,000	1,200	800	2,900	422,000
Miscellaneous	2,800	400	136,000	100	100	200	44,000
Passenger	3,400	600	139,000	100	100	300	47,000
Reefer	2,200	300	91,000	100	100	200	30,000
RO-RO	51,800	6,900	2,097,000	2,000	1,300	4,700	695,000
Tanker	54,300	7,200	2,201,000	2,100	1,400	4,900	730,000
Mexico	**178,000**	**24,000**	**7,216,000**	**6,900**	**4,600**	**16,000**	**2,393,000**
Bulk Carrier	27,000	4,000	1,112,000	1,100	700	2,500	369,000
Container	93,000	12,000	3,754,000	3,600	2,400	8,400	1,244,000
Fishing	100	20	5,200	4	3	10	1,700
General Cargo	6,900	900	280,000	300	200	600	93,000
Miscellaneous	1,600	200	77,000	100	-	100	25,000
Passenger	5,500	900	221,000	200	100	500	75,000
Reefer	1,100	200	43,000	40	30	100	14,000
RO-RO	14,000	1,800	552,000	500	400	1,200	183,000
Tanker	29,000	3,800	1,171,000	1,100	700	2,600	388,000
USA	**4,353,000**	**588,000**	**176,805,000**	**170,000**	**112,000**	**396,000**	**58,665,000**
Bulk Carrier	763,000	101,000	30,914,000	30,000	20,000	69,000	10,248,000
Container	1,835,000	242,000	74,350,000	72,000	47,000	167,000	24,641,000
Fishing	1,000	100	33,000	20	20	100	11,000
General Cargo	293,000	39,000	11,861,000	11,000	8,000	27,000	3,934,000
Miscellaneous	55,000	8,300	2,665,000	2,000	1,600	4,300	870,000
Passenger	227,000	39,000	9,185,000	8,800	5,800	21,000	3,107,000
Reefer	130,000	18,000	5,263,000	5,100	3,300	12,000	1,752,000
RO-RO	405,000	54,000	16,408,000	16,000	10,000	37,000	5,441,000
Tanker	645,000	86,000	26,126,000	25,000	17,000	59,000	8,662,000
Grand Total[1]	**5,089,000**	**686,000**	**206,638,000**	**198,000**	**131,000**	**463,000**	**68,555,000**

1. Global summary represents the global extent of all routes for the North American voyage data.

North America Domain Results

Figure 3 and Table 11 present domain estimates for 2002 shipping by vessel type. North American domain totals are three-quarters (~75%) of global estimation for emissions from shipping between North American ports and the origin or destination ports of the world. However, this is not the case among vessel types. Table 12 describes the average percent of global emissions falling within the North American domain by vessel type. Passenger, miscellaneous, and Roll-On/Roll-Off (RO-RO) ships spend more time within the region and bulk carriers and fishing vessels spend less time in the North American domain.

Figure 3. 2002 STEEM SOx comparisons for a) Bulk ships; b) General cargo ships; c) Tankers; d) Containerships; e) Roll-on/Roll-off (RORO) ships; g) Miscellaneous ships; f) Refrigerated cargo (Reefer) ships; g) Passenger ships (not including regional ferries); and j) Fishing vessels.

Units: grams/year by segment.

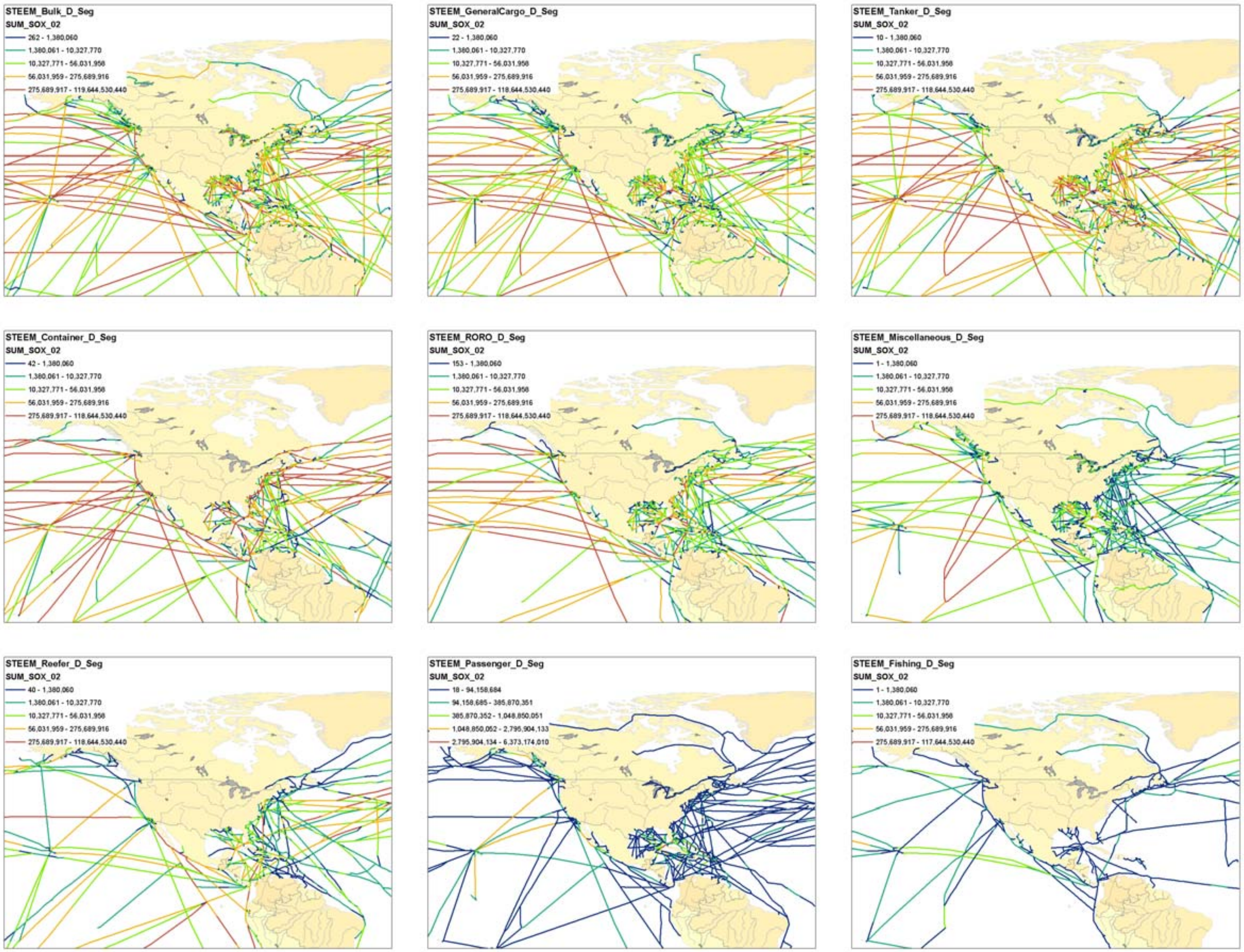


Table 11. North American estimates of 2002 STEEM results by nation and by vessel type.

metric tons	NOx	SOx	CO_2	HC	PM	CO	Fuel Use
Bulk Carrier	560,000	330,000	19,400,000	19,000	47,000	44,000	6,430,000
Container	1,030,000	610,000	35,810,000	34,000	86,000	80,000	11,870,000
Fishing	1,100	900	54,000	40	120	90	18,000
General Cargo	250,000	150,000	8,550,000	8,000	21,000	19,000	2,840,000
Miscellaneous	46,000	36,000	2,220,000	1,600	4,900	3,600	720,000
Passenger	210,000	130,000	7,430,000	7,000	18,000	17,000	2,510,000
Reefer	62,000	36,000	2,150,000	2,100	5,000	4,800	720,000
RO-RO	240,000	140,000	8,460,000	8,000	20,000	19,000	2,810,000
Tanker	490,000	290,000	17,160,000	17,000	41,000	39,000	5,690,000
Domain Total	2,890,000	1,720,000	101,230,000	100,000	240,000	230,000	33,600,000

Table 12. Average contribution by vessel type within Domain, as percent of global estimates

Vessel Type	Average Percent in Domain
Bulk Carrier	64%
Container	75%
Fishing	64%
General Cargo	75%
Miscellaneous	86%
Passenger	97%
Reefer	71%
RO-RO	80%
Tanker	75%
Domain Percent	75%

Table 13 and Table 14 present future emissions by vessel type within the North American domain for Scenario 1. Similar to the global results, increased activity grows domain emissions and fuel use substantially, except where IMO Annex VI requirements modify growth in NOx and reduce SOx.

Table 13. North American estimates of 2010 Scenario 1 STEEM results by nation and by vessel type .

metric tons	NOx	SOx	CO_2	HC	PM	CO	Fuel Use
Bulk Carrier	580,000	340,000	20,290,000	20,000	49,000	46,000	6,730,000
Container	1,410,000	830,000	48,970,000	47,000	120,000	110,000	16,230,000
Fishing	1,100	880	54,000	40	120	90	18,000
General Cargo	250,000	150,000	8,810,000	8,000	21,000	20,000	2,920,000
Miscellaneous	47,000	37,000	2,250,000	1,700	5,000	3,700	730,000
Passenger	250,000	160,000	8,850,000	9,000	21,000	20,000	2,990,000
Reefer	80,000	47,000	2,780,000	2,700	7,000	6,000	930,000
RO-RO	290,000	170,000	10,080,000	10,000	24,000	23,000	3,340,000
Tanker	520,000	310,000	18,210,000	18,000	44,000	41,000	6,040,000
Domain Total	3,440,000	2,050,000	120,290,000	120,000	290,000	270,000	39,930,000

Table 14. North American estimates of 2020 Scenario 1 STEEM results by nation and by vessel type.

metric tons	NOx	SOx	CO_2	HC	PM	CO	Fuel
Bulk Carrier	580,000	77,000	23,550,000	23,000	15,000	53,000	7,810,000
Container	3,430,000	450,000	139,050,000	130,000	90,000	310,000	46,080,000
Fishing	1,100	170	54,000	40	30	90	18,000
General Cargo	240,000	32,000	9,730,000	9,000	6,000	22,000	3,230,000
Miscellaneous	49,000	7,000	2,360,000	1,700	1,400	3,800	770,000
Passenger	390,000	68,000	15,840,000	20,000	10,000	36,000	5,360,000
Reefer	160,000	23,000	6,590,000	6,000	4,200	15,000	2,190,000
RO-RO	450,000	59,000	18,050,000	17,000	11,000	41,000	5,980,000
Tanker	550,000	73,000	22,200,000	21,000	14,000	50,000	7,360,000
Domain Total	5,850,000	790,000	237,430,000	230,000	150,000	530,000	78,800,000

Discussion

Scenario estimates for increased activity, emissions reductions, and changing patterns of shipping can be compared in several contexts. National contributions to North American shipping are illustrated by comparing baseline 2002 shipping patterns with nation-by-nation data, in Figure 4. Figure 4a presents the 2002 results for this work, replicating the routes and estimates from the previous STEEM project. Given the year of this report (2010), Scenario 1 patterns shown in Figure 4b through Figure 4d represent 2010 results. For this report, all images report SOx using a common scale representing quantiles in 2010 for comparison with later figures.

Figure 4e and Figure 4f illustrate the differences between 2020 and 2010 SOx emissions and fuel consumption, respectively; a minus sign percentage represents a decrease in emissions (SOx). Not surprisingly, the fastest growing shipping routes show the greatest growth in fuel use and the least reductions in SOx emissions from lower-sulfur fuels (or equivalent certified technologies meeting IMO Annex VI control requirements).

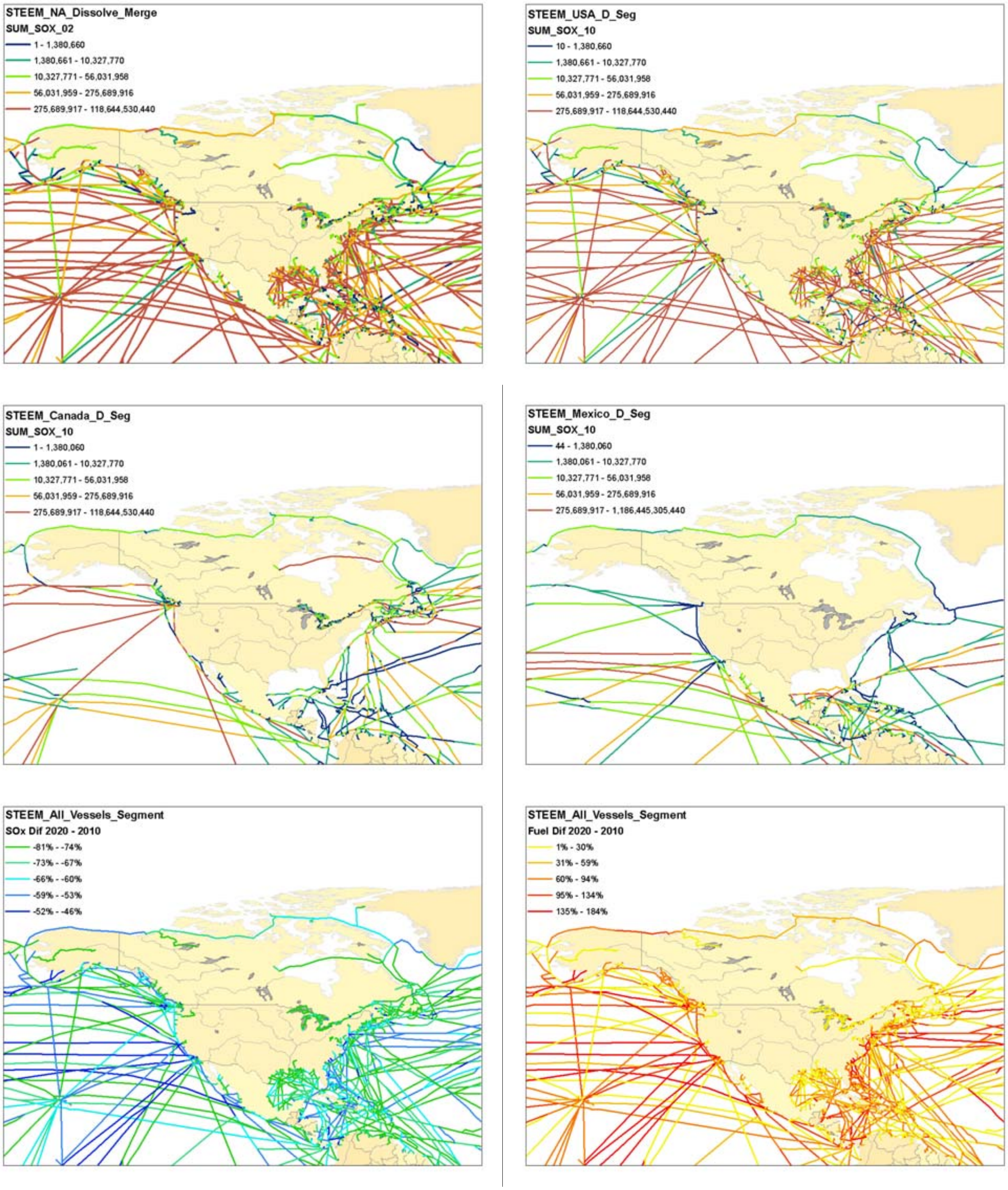
Overall, container shipping moving goods to and from North American ports contributes the greatest amount of emissions and uses the most fuel among all ship types. This is partly because of the higher installed power associated with liner shipping of containerized goods, and partly due to the nature of consumption of imported goods in North American communities. Importantly, under Scenario 1, these types of vessels grow fastest as well. Therefore, in future years the share of containerized shipping activity contributing to totals for emissions and fuel use increases.

Figure 5 illustrates the change from roughly 35% to nearly 60% of total emissions attributed to containerized vessels by 2020, under high-growth scenarios. Under lower-growth scenarios these ship types still increase their activity faster relative to other ship types, contributing more than 40% to 2020 totals.

While the data discussed represent annual totals, the monthly variation is also important to environmental and air quality assessments. Fishing vessels are the major type that exhibits seasonal variation of more than about 1% either more or less than a uniform pattern. Figure 6 and Table 15 illustrate these patterns using 2002 vessel arrival and departure data.

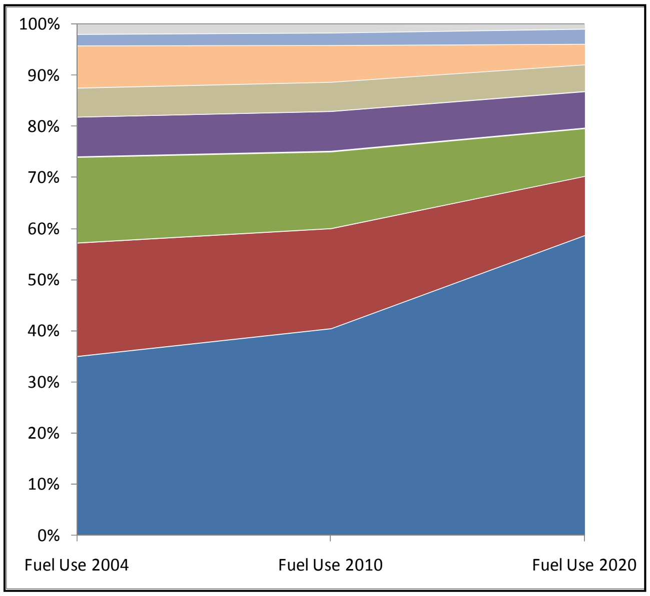
Figure 4. STEEM results for a) 2002 data provided for all ships; and 2010 results under Scenario 1 for b) US data; c) Canada data; and d) Mexico data; and comparison of 2020 and 2010 for e) SOx and f) Fuel use.

Units: grams/year by segment.

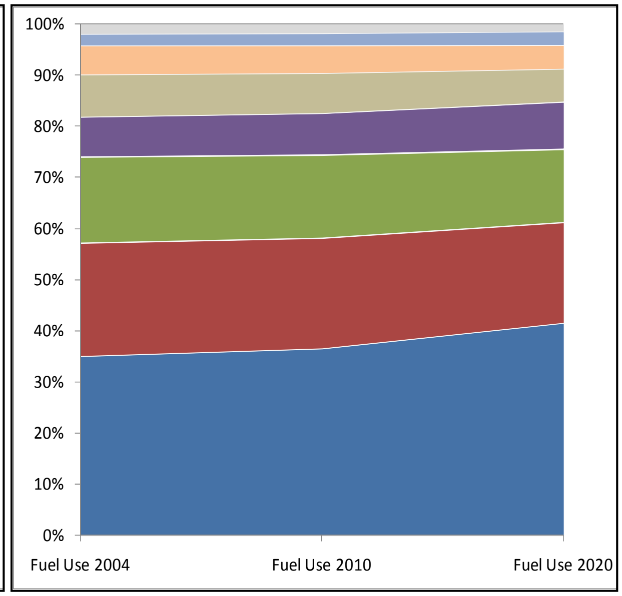


Note: All images report SOx using a common scale representing quantiles in 2010 for comparison with later figures. In plate (e), the minus sign percentages represent a decrease in SOx emissions relative to 2010.

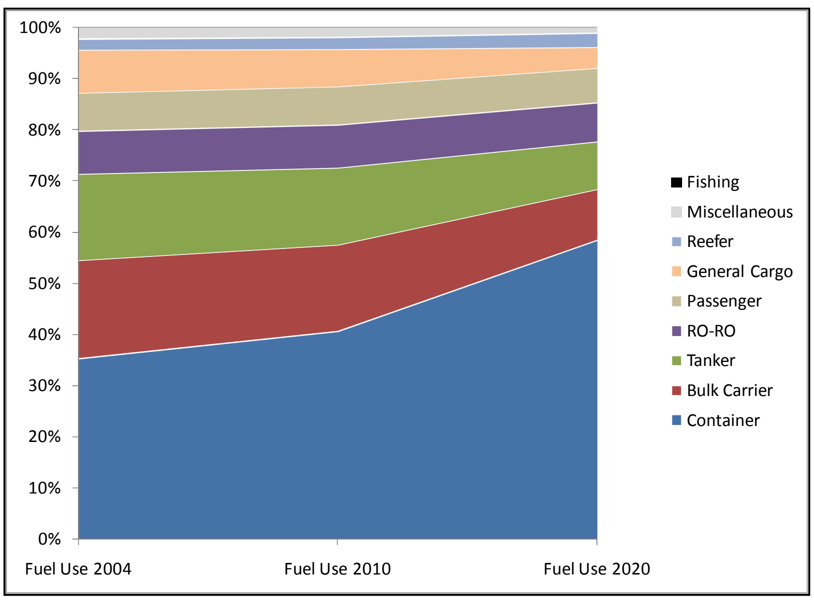
Figure 5. Comparison of vessel-type specific percent contributions to using a) global domain and Scenario 1; b) global domain and Scenario 2; and c) North American domain and Scenario 1.



(a)



(b)



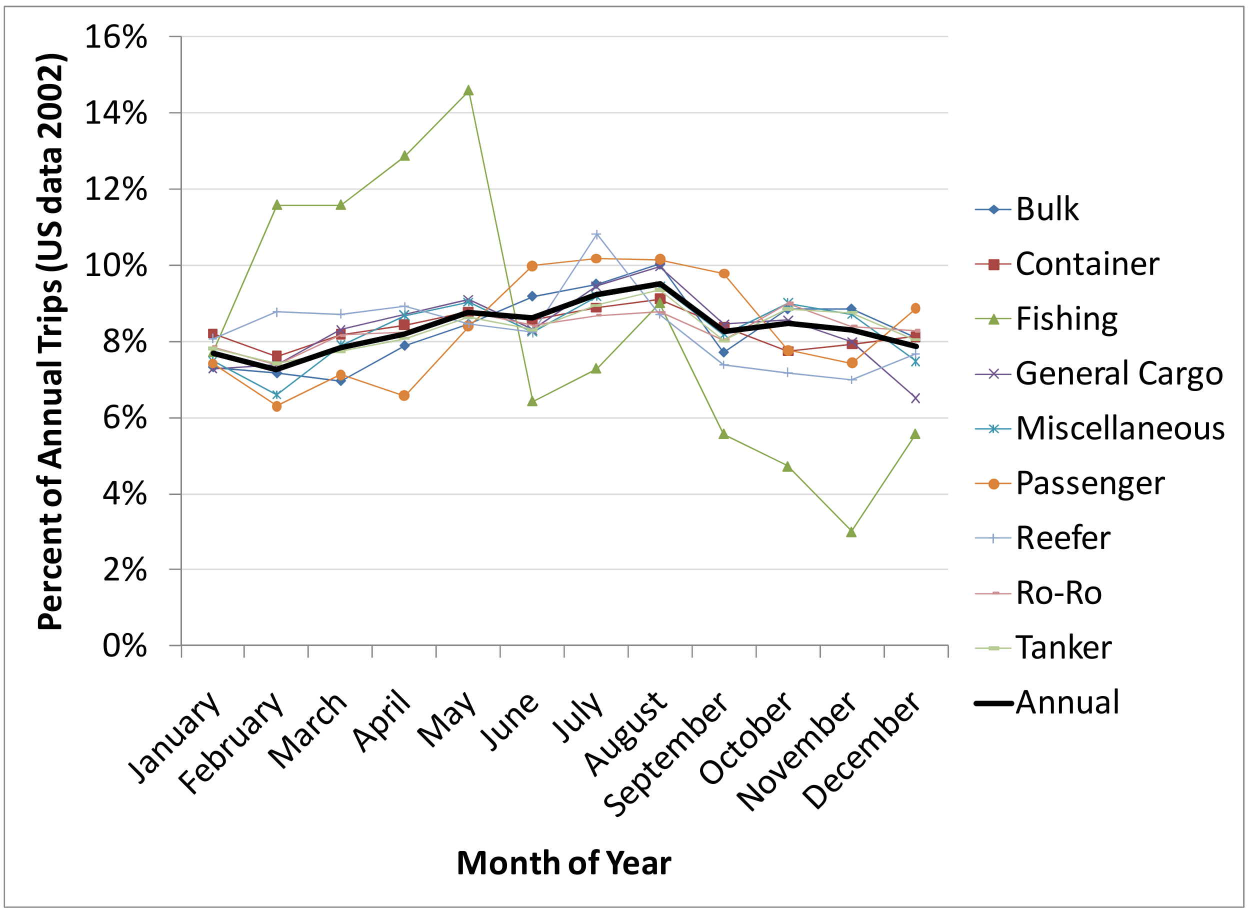
(c)

Table 15. Summary of monthly traffic patterns by vessel type, based on US data.

Month	Bulk	Container	Fishing	General Cargo	Misc.	Passenger	Reefer	Ro-Ro	Tanker	Annual
January	7.3%	8.2%	7.7%	7.3%	7.5%	7.4%	8.1%	7.9%	7.8%	7.7%
February	7.2%	7.6%	11.6%	7.4%	6.6%	6.3%	8.8%	7.4%	7.4%	7.3%
March	7.0%	8.2%	11.6%	8.3%	7.9%	7.1%	8.7%	8.2%	7.7%	7.8%
April	7.9%	8.4%	12.9%	8.7%	8.7%	6.6%	8.9%	8.2%	8.1%	8.2%
May	8.5%	8.8%	14.6%	9.1%	9.0%	8.4%	8.5%	8.8%	8.6%	8.8%
June	9.2%	8.6%	6.4%	8.3%	8.3%	10.0%	8.2%	8.4%	8.3%	8.6%
July	9.5%	8.9%	7.3%	9.4%	9.2%	10.2%	10.8%	8.7%	8.9%	9.2%
August	10.0%	9.1%	9.0%	10.0%	9.5%	10.2%	8.7%	8.8%	9.4%	9.5%
September	7.7%	8.4%	5.6%	8.5%	8.2%	9.8%	7.4%	8.0%	8.0%	8.3%
October	8.8%	7.7%	4.7%	8.6%	9.0%	7.8%	7.2%	9.0%	8.9%	8.5%
November	8.9%	7.9%	3.0%	8.0%	8.7%	7.4%	7.0%	8.4%	8.8%	8.3%
December	8.1%	8.1%	5.6%	6.5%	7.5%	8.9%	7.7%	8.3%	8.0%	7.9%

Source: [17].

Figure 6. Monthly variation in emissions from North American Ship Traffic



Strengths and Limitations of Current Work

Technical issues related to the reuse of the STEEM model included challenges realigning by vessel-type the many-to-many data relationships underlying prior STEEM modeling work. Now that the STEEM network architecture was merged into the GIFT Model [10-13], there is no requirement to maintain and run two networks; this alone will enable origin-destination pairs to be entered without the same data management needs as the STEEM model requires. This section describes some of the strengths and limitations of vessel-type specific and other features of this project.

Analytical Strengths of the Vessel-type specific Analysis:

1. Delivering vessel-type specific shapefiles for the North American domain, based on vessel-type specific activity estimates and growth rates, enables independent updates to be made to modify and create new scenarios.

2. National resolution of domains, illustrated in Figure 7 for the Great Lakes region, provide opportunity for jurisdictional and national market-based policy analyses in aggregate and by vessel type. This also provides one means of comparing with earlier studies. For example, a 2000 study of waterborne commerce vessels in United States continental and inland waterways estimated Great Lakes shipping to emit about ~12,000 tons of NOx [18]; the current STEEM results for US data only estimate these emissions to be ~19,000 tons NOx, a difference of about 50% mostly attributed to bottom-up activity-based inventory methods used in STEEM. However, including Canada traffic would increase this estimate by another ~9,000 tons NOx.

3. Shape file delivery with a full attribute tables for pollutants and fuel usage enables analysts to use these to produce inventories in multiple formats for modeling and policy analysis.

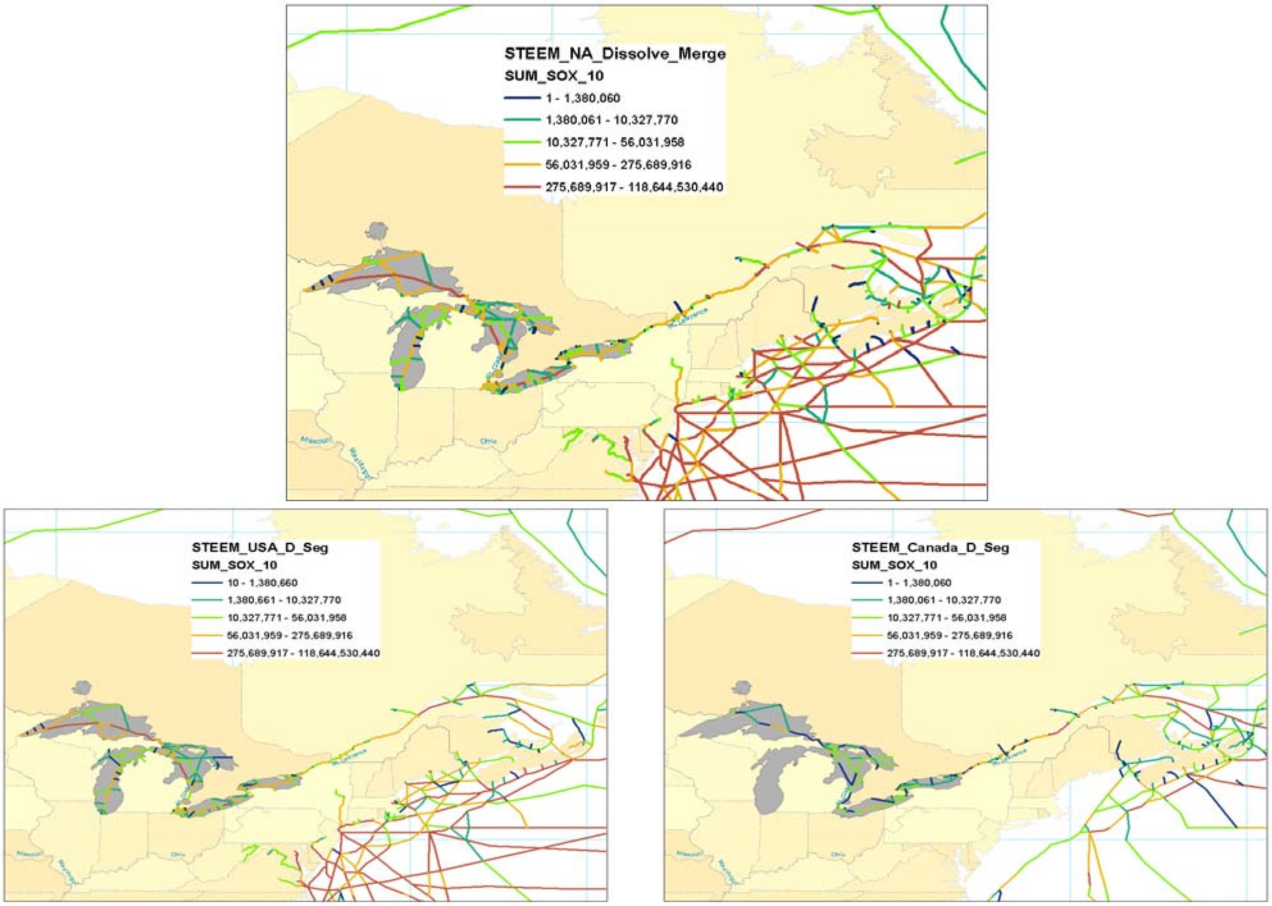
Analytical Limitations of the Vessel-type specific Analysis:

1. Under this project, STEEM could not successfully rematch the buffered routes and grid calculations to the segments. This project delivers the domain shapefiles that place emissions along the STEEM network.

2. Given the many-to-many relationships and dual network design of STEEM, merging the segments for this work created the potential for redundant or duplicative data reporting. In other words, segments not collocated were sometimes identified by the same identifying value. This is a problem of the matrices used and the many-to-many relationships that assigned similar but not reconciled segment numbering among the networks for Atlantic and Pacific projections. This could account for some of the ~4% difference in the work reported here versus the previous STEEM project. By bringing the STEEM architecture into the GIFT model, this can be avoided in future projects.

3. Potential remains to improve segment locations, particularly within port regions and for specific terminals. This limitation was addressed by meta-analyses funded by U.S. EPA in previous work to support the ECA application, and some of these improvements are still to be implemented within STEEM (or GIFT).

Figure 7. Example of complementary data from Canada and the U.S. for the Great Lakes region.



Summary and Conclusions

This work reveals the expected change in patterns of shipping that would result solely from asymmetric growth among vessel types. Unless port choices change, coastwise impacts (near-shore shipping lanes) will continue to grow because they accommodate all ship types during port entrances and clearances. The intensities of future emissions offshore within the North American study domain may contribute to shifting sources of transport of air pollution, and modeling of these changes could assess whether impacts will change to affected communities.

Global totals previously estimated by STEEM are well replicated in this work, and North American domain totals are three-quarters (~75%) of global estimation for emissions from shipping between North American ports and the origin or destination ports of the world. However, this is not the case among vessel types. Passenger, miscellaneous, and RO-RO ships spend more time within the region and bulk carriers and fishing vessels spend less time in the North American domain. This information is relevant to understanding which vessels are more likely to operate within national domains; this could indicate which vessel groups will evaluate cost-effective controls similarly – e.g., capital investments and operating costs would be distributed across greater periods of control strategy operation, perhaps incentivizing some technologies and operational changes more than others.

Scenario 2 suggests more modest growth in shipping activity if recession and recovery trends are substantially altered for North American goods movement by ships. Both scenarios reveal the important mitigation measures of IMO Annex VI, in which some NOx controls will be implemented and global emissions of sulfur will reduce substantially. Compared to 2002 baseline, Scenario 1 change in SOx in

2020 is a *net reduction by ~55% despite growth in shipping.* Scenario 2 change in SOx in 2020 is a *net reduction by ~70% reflecting more modest growth in future shipping*.

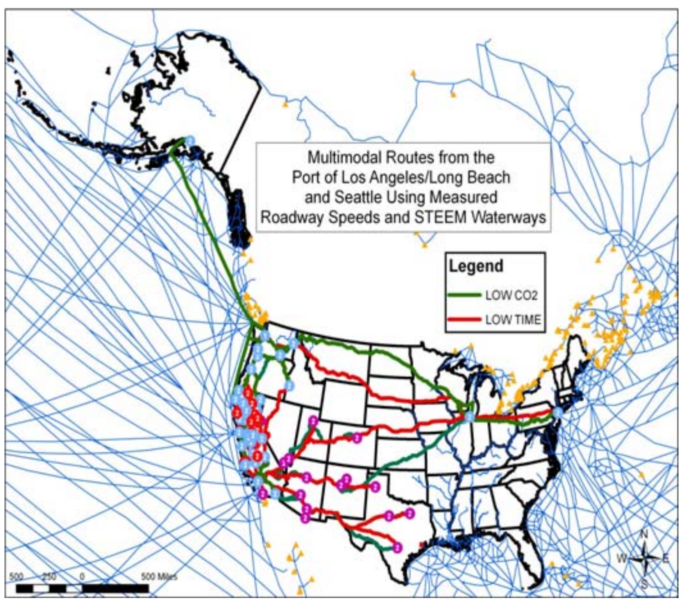
Overall, container shipping moving goods to and from North American ports contributes the greatest amount of emissions and uses the most fuel among all ship types. This is partly because of the higher installed power associated with liner shipping of containerized goods, and partly due to the nature of consumption of imported goods in North American communities. In any growth scenario evaluated for this project, the future share of containerized shipping activity contributing to totals for emissions and fuel use increases. Given that containerized shipping is intrinsically intermodal (connecting with rail and road), this leads to a conclusion that international goods movement will be linked with domestic goods movement decisions.

Recommendations

Four key recommendations emerge from this work. Several of them are related to the challenge of rerunning STEEM compared with new GIS techniques to achieve the functions STEEM can perform with less redundant networks and more transparent database integration. These are listed here:

1. Integrate into the Geospatial Intermodal Freight Transportation (GIFT) Model to enable multimodal modeling. This has already been accomplished, structurally, during the development of GIFT, as shown in Figure 8.

Figure 8. Example of the GIFT network, including the STEEM architecture.



2. Construct common data set for origins and destinations to identify potential redundancy, and correct it. This would presumably include updating the baseline year from 2002 to a more current year.
3. Validate and improve the segment location, especially within port regions. This was done generally for North America during the first STEEM project, and it is an ongoing task globally.
4. Develop origin-destination pairs that are assigned to specific port terminals or more accurate waterfront locations to enable better integration in multimodal models (GIFT). This is especially important for port complexes that span large regions, e.g., the Port of Houston waterfront spans tens of miles, and the Port Authority of New York/New Jersey spans three states (New York, New Jersey, Connecticut).

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Glossary of terms, abbreviations and symbols

Abbreviation	Term
BAU	Business as usual
CO_2	Carbon dioxide
CO	Carbon monoxide
CMV	Commercial marine vessel
CEC	Commission on Environmental Cooperation
CAGR	Compound Annual Growth Rate
ECA	Emission Control Area (defined in IMO Anne VI revisions)
GIFT	Geospatial Intermodal Freight Transportation
GHG	Greenhouse gas
GRT	Gross Registered Tons
HC	Hydrocarbons
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LMIU	Lloyd's Maritime Intelligence Unit
MW	Megawatts
NOx	Oxides of nitrogen
SOx	Oxides of sulfur
PM	Particulate Matter
RO-RO	Roll-on/Roll-off
STEEM	Ship Traffic, Energy, and Emissions Model
USACE	United States Army Corps of Engineers
U.S.EPA	United States Environmental Protection Agency