Proposal to Designate an Emission Control Area for Nitrogen Oxides, Sulfur Oxides and Particulate Matter

Technical Support Document

Chapter 2
Emission Inventory

Assessment and Standards Division
Office of Transportation and Air Quality
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2 Emission Inventory

2.1 Introduction

Ships (i.e., ocean-going vessels) are significant contributors to the total United States (U.S.) mobile source emission inventory. The U.S. ship inventory reported here focuses on Category 3 (C3) vessels, which use C3 engines for propulsion. C3 engines are defined as having displacement above 30 liters per cylinder (L/cyl). The resulting inventory includes emissions from both propulsion and auxiliary engines used on these vessels, as well as those on gas and steam turbine vessels.

Most of the vessels operating in U.S. ports that have propulsion engines less than 30 liters per cylinder are domestic and are already subject to strict national standards affecting NO_X, PM, and fuel sulfur content. As such, the inventory does not include any ships, foreign or domestic, powered by Category 1 or Category 2 (i.e., <30 L/cyl) engines. In addition, as discussed in Sections 2.3.2.3.9 and 2.3.3.3, this inventory is primarily based on activity data for ships that carry foreign cargo. Category 3 vessels carrying domestic cargo that operate only between U.S. ports are only partially accounted for in this inventory.[1] Emissions due to military vessels are also excluded.

The regional and national inventories for C3 vessels presented in this chapter are sums of independently constructed port and interport emissions inventories. Port inventories were developed for 89 deep water and 28 Great Lake ports in the U.S.[2] While there are more than 117 ports in the U.S., these are the top U.S. ports in terms of cargo tonnage. Port-specific emissions were calculated with a “bottom-up” approach, using data for vessel calls, emission factors, and activity for each port. Interport emissions and emissions for the remaining ports were obtained using the Waterway Network Ship Traffic, Energy and Environment Model (STEEM).[3,4] STEEM also uses a “bottom-up” approach, estimating emissions from C3 vessels using historical North American shipping activity, ship characteristics, and activity-based emission factors. STEEM was used to quantify and geographically (i.e., spatially) represent interport vessel traffic and emissions for vessels traveling generally within 200 nautical miles (nm) of the U.S.

The detailed port inventories were spatially merged into the STEEM gridded inventory to create a comprehensive inventory for Category 3 vessels. For the 117 ports, this involved removing the near-port portion of the STEEM inventory and replacing it with the detailed port inventories. For the remaining U.S. ports for which detailed port inventories are not available, the near-port portion of the STEEM inventory was simply retained. This was done for a base year of 2002. Inventories for 2020 were then projected using regional growth rates[5,6] and adjustment factors to account for the International Maritime Organization (IMO) Tier I and Tier II NO_X standards and NO_X retrofit program.[2] Inventories incorporating additional Tier III NO_X and fuel sulfur controls within the proposed Emission Control Area (ECA) were also developed for 2020.

The inventory estimates reported in this chapter include emissions out to 200 nm from the U.S. coastline, including Alaska and Hawaii, but not extending into the Exclusive Economic Zone (EEZ) of neighboring countries. Inventories are presented for the following pollutants: oxides of nitrogen (NO_X), particulate matter ($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2). The PM inventories include directly emitted PM only, although secondary sulfates and nitrates are taken into account in the air quality modeling.

2.2 Modeling Domain and Geographic Regions

The inventories described in this chapter reflect ship operations that occur within the area that extends 200 nautical miles (nm) from the official U.S. baseline but exclude operations in Exclusive Economic Zones of other countries. The official U.S. baseline is recognized as the low-water line along the coast as marked on the official U.S. nautical charts in accordance with the articles of the Law of the Sea. The boundary was mapped using geographic information system (GIS) shapefiles obtained from the National Oceanic and Atmospheric Administration, Office of Coast Survey.[7] The accuracy of the NOAA shapefiles was verified with images obtained from the U.S. Geological Survey. The confirmed NOAA shapefiles were then combined with a shapefile of the U.S. international border from the National Atlas.[8]

The resulting region was further subdivided for this analysis to create regions that were compatible with the geographic scope of the regional growth rates, which are used to project emission inventories for the years 2020, as described later in this document.

- The Pacific Coast region was split into separate North Pacific and South Pacific regions along a horizontal line originating from the Washington/Oregon border (Latitude 46° 15' North).
- The East Coast and Gulf of Mexico regions were divided along a vertical line roughly drawn through Key Largo (Longitude 80° 26' West).
- The Alaska region was divided into separate Alaska Southeast and Alaska West regions along a straight line intersecting the cities of Naknek and Kodiak. The Alaska Southeast region includes most of the State's population, and the Alaska West region includes the emissions from ships on a great circle route along the Aleutian Islands between Asia and the U.S. West Coast.
- For the Great Lakes domain, shapefiles were created containing all the ports and inland waterways in the near port inventory and extending out into the lakes to the international border with Canada. The modeling domain spanned from Lake Superior on the west to the point eastward in the State of New York where the St. Lawrence River parts from U.S. soil.
- The Hawaiian domain was subdivided so that a distance of 200 nm beyond the southeastern islands of Hawai'i, Maui, O'ahu, Moloka'i, Ni'ihau, Kaua'i, Lanai, and Kahoolawe was contained in Hawaii East. The remainder of the Hawaiian Region was then designated Hawaii West.

This methodology resulted in nine separate regional modeling domains that are identified below and shown in Figure 2-1. U.S. territories are not included in this analysis.

- South Pacific (SP)
- North Pacific (NP)
- East Coast (EC)
- Gulf Coast (GC)
- Alaska Southeast (AE)
- Alaska West (AW)
- Hawaii East (HE)

- Hawaii West (HW)
- Great Lakes (GL)

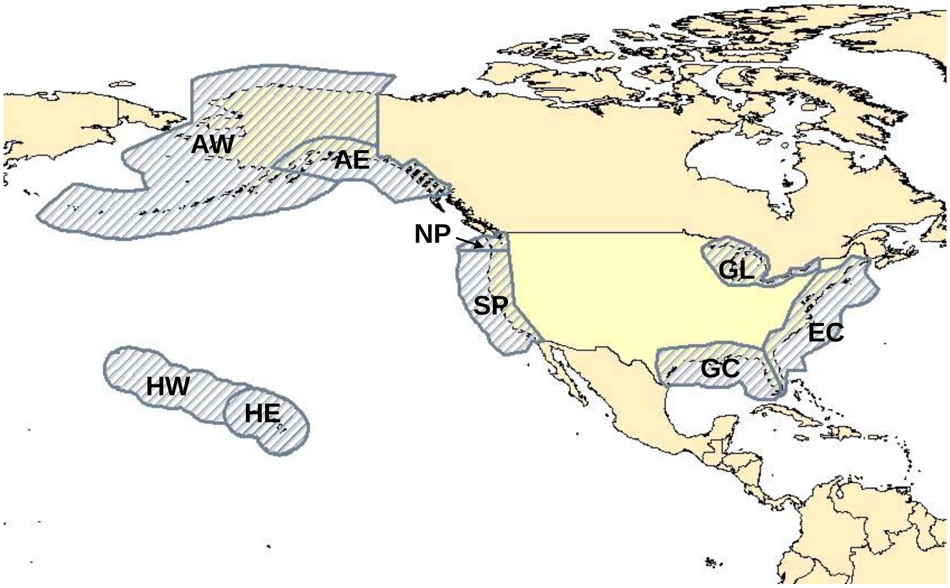


Figure 2-1 Regional Modeling Domains

2.3 Development of 2002 Inventories

This section describes the methodology and inputs, and presents the resulting inventories for the 2002 baseline calendar year. The first section describes the general methodology. The second section describes the methodology, inputs, and results for near port emissions. The third section describes the methodology and inputs for emissions when operating away from port (also referred to as “interport” emissions). The fourth section describes the method for merging the interport and near port portions of the inventory. Resulting total emissions for the U.S., as well as for nine geographic regions within the U.S., are then presented.

2.3.1 Outline of Methodology

The total inventory was created by summing emissions estimates for ships while at port (near port inventories) and while underway (interport inventories). Near port inventories for calendar year 2002 were developed for 117 U.S. commercial ports that engage in foreign trade. Based on an analysis of U.S. Government data, these 117 commercial ports encompass nearly all U.S. C3 vessel calls.[9]

The outer boundaries of the ports are defined as 25 nm from the terminus of the reduced speed zone for deep water ports and 7 nm from the terminus of the reduced speed zone for Great Lake ports. Port emissions are calculated for different modes of operation and then summed. Emissions for each mode are calculated using port-specific information for vessel calls, vessel characteristics, and activity, as well as other inputs that vary instead by vessel or engine type (e.g., emission factors).

The interport inventory is estimated using the Waterway Network Ship Traffic, Energy, and Environmental Model (STEEM).[3,4] The model geographically characterizes emissions from ships traveling along shipping lanes to and from individual ports, in addition to the emissions from vessels transiting near the ports. The shipping lanes were identified from actual ship positioning reports. The model then uses detailed information about ship destinations, ship attributes (e.g., vessel speed and engine horsepower), and emission factors to produce spatially allocated (i.e., gridded) emission estimates for ships engaged in foreign commerce.

The 117 near port inventories are an improvement upon STEEM's near port results in several ways. First, the precision associated with STEEM's use of ship positioning data may be less accurate in some locations, especially as the lanes approach shorelines where ships would need to follow more prescribed paths. Second, the STEEM model includes a maneuvering operational mode (i.e., reduced speed) that is generally assumed to occur for the first and last 20 kilometers of each trip when a ship is leaving or entering a port. In reality, the distance when a ship is traveling at reduced speeds varies by port. Also, the distance a ship traverses at reduced speeds often consists of two operational modes: a reduced speed zone (RSZ) as a ship enters or leaves the port area and actual maneuvering at a very low speed near the dock. Third, the STEEM model assumes that the maneuvering distance occurs at an engine load of 20 percent, which represents a vessel speed of approximately 60 percent of cruise speed. This is considerably faster than ships would maneuver near the docks. The single maneuvering speed assumed by STEEM also does not reflect the fact that the reduced speed zone, and therefore emissions, may vary by port. Fourth, and finally, the STEEM model does not include the emissions from auxiliary engines during hotelling operations at the port. The near-port inventories correct these issues.

The regional emission inventories produced by the current STEEM interport model are most accurate for vessels while cruising in ocean or Great Lakes shipping lanes; the near port inventories use more detailed local port information and are significantly more accurate near the ports. Therefore, the inventories in this analysis are derived by merging together: 1) the near port inventories, which extend 25 nautical miles and 7 nautical miles from the terminus of the RSZ for deep water ports and Great Lake ports, respectively, and 2) the remaining interport portion of the STEEM inventory, which extends from the endpoint of the near port inventories to the 200 nautical mile boundary or international border with Canada, as appropriate. Near some ports, a portion of the underlying STEEM emissions were retained if it was determined that the STEEM emissions included ships traversing the area near a port, but not actually entering or exiting the port.

2.3.2 Near Port Emissions

Near port inventories for calendar year 2002 were developed for ocean-going vessels at 89 deep water and 28 Great Lake ports in the U.S. The inventories include emissions from both propulsion and auxiliary engines on C3 vessels.

This section first describes the selection of the ports for analysis and then provides the methodology used to develop the near port inventories. This is followed by a description of the key inputs. Total emissions by port and pollutant for 2002 are then presented.

2.3.2.1 Selection of Individual Ports to be Analyzed

All 150 deep water and Great Lake ports in the Principal Ports of the United States dataset[10] were used as a starting point. Thirty ports which had no foreign traffic were eliminated because the dataset used to obtain port calls and other ship characteristics has no information about domestic traffic. Several California ports were also used because the California Air Resources Board (ARB) provided the necessary data and estimates for those ports. The final list of 117 deep water and Great Lake ports, along with their coordinates, is given in Appendix 2A.

2.3.2.2 Port Methodology

Near port emissions for each port are calculated for four modes of operation: 1) hotelling, 2) maneuvering, 3) reduced speed zone (RSZ), and 4) cruise. Hotelling, or dwelling, occurs while the vessel is docked or anchored near a dock, and only the auxiliary engine(s) are being used to provide power to meet the ship's energy needs. Maneuvering occurs within a very short distance of the docks. The RSZ varies from port to port, though generally the RSZ would begin and end when the pilots board or disembark, and typically occurs when the near port shipping lanes reach unconstrained ocean shipping lanes. The cruise mode emissions in the near ports analysis extend 25 nautical miles beyond the end of the RSZ lanes for deep water ports and 7 nautical miles for Great Lake ports.

Emissions are calculated separately for propulsion and auxiliary engines. The basic equation used is as follows:

Equation 2-1

$$Emissions_{\mathrm{mode}[eng]} = (calls) \times (P_{[eng]}) \times (hrs/call_{\mathrm{mode}}) \times (LF_{\mathrm{mode}[eng]}) \times (EF_{[eng]}) \times (Adj) \times (10^{-6}\ tonnes/g)$$

Where:

- Emissions$_{\text{mode [eng]}}$ = Metric tonnes emitted by mode and engine type
- Calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
- P$_{\text{[eng]}}$ = Total engine power by engine type, in kilowatts
- hrs/call$_{\text{mode}}$ = Hours per call by mode
- LF$_{\text{mode [eng]}}$ = Load factor by mode and engine type (unitless)
- EF$_{\text{[eng]}}$ = Emission factor by engine type for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
- Adj = Low load adjustment factor, unitless (used when the load factor is below 0.20)
- 10^{-6} = Conversion factor from grams to metric tonnes

Main engine load factors are calculated directly from the propeller curve based upon the cube of actual speed divided by maximum speed (at 100% maximum continuous rating [MCR]). In addition, cruise mode activity is based on cruise distance and speed inputs. Appendix 2B provides the specific equations used to calculate propulsion and auxiliary emissions for each activity mode.

2.3.2.3 Inputs for Port Emission Calculations

The following inputs are required to calculate emissions for the four modes of operation (cruise, RSZ, maneuvering, and hotelling):

- Number of calls
- Main engine power
- Cruise (vessel service) speed
- Cruise distance
- RSZ distance for each port
- RSZ speed for each port
- Auxiliary engine power
- Auxiliary load factors
- Main and auxiliary emission factors
- Low load adjustment factors for main engines
- Maneuvering time-in-mode (hours/call)
- Hotelling time-in-mode (hours/call)

Note that load factors for main engines are not listed explicitly, since they are calculated as a function of mode and/or cruise speed. This section describes the inputs in more detail, as well as the sources for each input.

2.3.2.3.1 Calls and Ship Characteristics (Propulsion Engine Power and Cruise Speed)

For this analysis, U.S. Army Corps of Engineers (USACE) entrance and clearance data for 2002,[11] together with Lloyd's data for ship characteristics,[12] were used to calculate average ship characteristics and calls by ship type for each port. Information for number of calls, propulsion engine power, and cruise speed were obtained from these data.

2.3.2.3.1.1 Bins by Ship Type, Engine Type, and DWT Range

The records from the USACE entrances and clearances data base were matched with Lloyd's data on ship characteristics for each port. Calls by vessels that have either Category 1 or 2 propulsion engines were eliminated from the data set. The data was then binned by ship type, engine type and dead weight tonnage (DWT) range. The number of entrances and clearances in each bin are counted, summed together and divided by two to determine the number of calls (i.e., one entrance and one clearance was considered a call). For Great Lake ports, there is a larger frequency of ships either entering the port loaded and leaving unloaded (light) or entering the port light and leaving loaded. In these cases, there would only be one record (the loaded trip into or out of the port) that would be present in the data. For Great Lake ports, clearances were matched with entrances by ship name. If there was not a reasonable match, the orphan entrance or clearance was treated as a call.

Propulsion power and vessel cruise speed are also averaged for each bin. Auxiliary engine power was computed from the average propulsion power using the auxiliary power to propulsion power ratios discussed in section 2.3.2.3.4.

2.3.2.3.1.2 Removal of Category 1 and 2 Ships

Since these inventories were intended to cover Category 3 propulsion engine ships only, the ships with Category 1 and 2 propulsion engines were eliminated. This was accomplished by matching all ship calls with information from Lloyd's Data, which is produced by Lloyd's Register-Fairplay Ltd.[12] Over 99.9 percent of the calls in the entrances and clearances data were directly matched with Lloyd's data. The remaining 0.1 percent was estimated based upon ships of similar type and size.

Engine category was determined from engine make and model. Engine bore and stroke were found in the Marine Engine 2005 Guide[13] and displacement per cylinder was calculated. Ships with Category 1 or 2 propulsion engines were eliminated from the data.

Many passenger ships and tankers have either diesel-electric or gas turbine-electric engines that are used for both propulsion and auxiliary purposes. Both were included in the current inventory.

2.3.2.3.2 Cruise Distance

Cruise mode emissions are calculated assuming a 25 nautical mile distance into and out of the port for deep water ports and 7 nautical miles into and out of the port for Great Lake ports outside of the reduced speed and maneuvering zones.

2.3.2.3.3 RSZ Distances and Speeds by Port

Reduced speed zone (RSZ) distance and speed were individually determined for each port. For deep water ports, the RSZ distances were developed from shipping lane information contained in the USACE National Waterway Network.[14] The database defines waterways as links or line segments that, for the purposes of this study, represent actual shipping lanes (i.e., channels, intracoastal waterways, sea lanes, and rivers). The sea-side endpoint for the RSZ was selected as the point along the line segment that was judged to be far enough into the ocean where ship movements were unconstrained by the coastline or other vessel traffic. The resulting RSZ distance was then measured for each deep water port. The final RSZ distances and endpoints for each port are listed in Appendix 2C. The RSZ for each Great Lake port was fixed at three nautical miles.

2.3.2.3.4 Auxiliary Engine Power and Load Factors

Since hotelling emissions are a large part of port inventories, it is important to distinguish propulsion engine emissions from auxiliary engine emissions. In the methodology used in this analysis, auxiliary engine maximum continuous rating power and load factors were calculated separately from propulsion engines and different emission factors (EFs) applied. All auxiliary engines were treated as Category 2 medium-speed diesel (MSD) engines for purposes of this analysis.

Auxiliary engine power is not contained in the USACE database and is only sparsely populated in the Lloyd's database; as a result, it must be estimated. The approach taken was to derive ratios of average auxiliary engine power to propulsion power based on survey data. The California Air Resources Board (ARB) conducted an Oceangoing Ship Survey of 327 ships in January 2005 that was principally used for this analysis.[15] Average auxiliary engine power to propulsion power ratios were estimated by ship type and are presented in Table 2-1. These ratios by ship type were applied to the propulsion power data to derive auxiliary power for the ship types at each port.

Table 2-1 Auxiliary Engine Power Ratios (ARB Survey, except as noted)

Ship Type	Average Propulsion Engine (kW)	Average Auxiliary Engines				Auxiliary to Propulsion Ratio
		Number	Power Each (kW)	Total Power (kW)	Engine Speed	
Auto Carrier	10,700	2.9	983	2,850	Medium	0.266
Bulk Carrier	8,000	2.9	612	1,776	Medium	0.222
Container Ship	30,900	3.6	1,889	6,800	Medium	0.220
Passenger Ship[a]	39,600	4.7	2,340	11,000	Medium	0.278
General Cargo	9,300	2.9	612	1,776	Medium	0.191
Miscellaneous[b]	6,250	2.9	580	1,680	Medium	0.269
RORO	11,000	2.9	983	2,850	Medium	0.259
Reefer	9,600	4.0	975	3,900	Medium	0.406
Tanker	9,400	2.7	735	1,985	Medium	0.211

[a] Many passenger ships typically use a different engine configuration known as diesel-electric. These vessels use large generator sets for both propulsion and ship-board electricity. The figures for passenger ships above are estimates taken from the Starcrest Vessel Boarding Program.

[b] Miscellaneous ship types were not provided in the ARB methodology, so values from the Starcrest Vessel Boarding Program were used.

Auxiliary engine to propulsion engine power ratios vary by ship type and operating mode roughly from 0.19 to 0.40. Auxiliary load, shown in Table 2-2, is used together with the total auxiliary engine power to calculate auxiliary engine emissions. Starcrest's Vessel Boarding Program[16] showed that auxiliary engines are on all of the time, except when using shoreside power during hotelling.

Table 2-2 Auxiliary Engine Load Factor Assumptions

Ship-Type	Cruise	RSZ	Maneuver	Hotel
Auto Carrier	0.13	0.30	0.67	0.24
Bulk Carrier	0.17	0.27	0.45	0.22
Container Ship	0.13	0.25	0.50	0.17
Passenger Ship	0.80	0.80	0.80	0.64
General Cargo	0.17	0.27	0.45	0.22
Miscellaneous	0.17	0.27	0.45	0.22
RORO	0.15	0.30	0.45	0.30
Reefer	0.20	0.34	0.67	0.34
Tanker	0.13	0.27	0.45	0.67

2.3.2.3.5 Fuel Types and Fuel Sulfur Levels

There are primarily three types of fuel used by marine engines: residual marine (RM), marine diesel oil (MDO), and marine gas oil (MGO), with varying levels of fuel sulfur.[5] MDO and MGO are generally described as distillate fuels. For this analysis, RM and MDO fuels are assumed to be used. Since PM and SO_2 emission factors are dependent on the fuel sulfur level, calculation of port inventories requires information about the fuel sulfur levels associated with each fuel type, as well as which fuel types are used by propulsion and auxiliary engines.

Based on an ARB survey,[15] average fuel sulfur level for residual marine was set to 2.5 percent for the west coast and 2.7 percent for the rest of the country. A sulfur content of 1.5 percent was used for MDO.[17] While a more realistic value for MDO used in the U.S. appears to be 0.4 percent, given the small proportion of distillate fuel used by ships relative to RM, the difference should not be significant. Sulfur levels in other areas of the world can be significantly higher for RM. Table 2-3, based on the ARB survey, provides the assumed mix of fuel types used for propulsion and auxiliary engines by ship type.

Table 2-3 Estimated Mix of Fuel Types Used by Ships

Ship Type	Fuel Used	
	Propulsion	**Auxiliary**
Passenger	100% RM	92% RM/8% MDO
Other	100% RM	71% RM/29% MDO

2.3.2.3.6 Propulsion and Auxiliary Engine Emission Factors

An analysis of emission data was prepared and published in 2002 by Entec.[17] The resulting Entec emission factors include individual factors for three speeds of diesel engines (slow-speed diesel (SSD), medium-speed diesel (MSD), and high-speed diesel (HSD)), steam turbines (ST), gas turbines (GT), and two types of fuel used here (RM and MDO). Table 2-4 lists the propulsion engine emission factors for NO_X and HC that were used for the 2002 port inventory development. The CO, PM, SO_2 and CO_2 emission factors shown in the table come from other data sources as explained below.

Table 2-4 Emission Factors for OGV Main Engines using RM, g/kWh

Engine	All Ports				West Coast Ports			Other Ports		
	NO_X	CO	HC	CO_2	PM_{10}	$PM_{2.5}$	SO_2	PM_{10}	$PM_{2.5}$	SO_2
SSD	18.1	1.40	0.60	620.62	1.4	1.3	9.53	1.4	1.3	10.29
MSD	14.0	1.10	0.50	668.36	1.4	1.3	10.26	1.4	1.3	11.09
ST	2.1	0.20	0.10	970.71	1.4	1.3	14.91	1.5	1.4	16.10
GT	6.1	0.20	0.10	970.71	1.4	1.3	14.91	1.5	1.4	16.10

CO emission factors were developed from information provided in the Entec appendices because they are not explicitly stated in the text. HC and CO emission factors were confirmed with a recent U.S. Government review.[18]

PM_{10}[A] values were determined based on existing engine test data in consultation with ARB.[19] GT PM_{10} emission factors were not part of the U.S. Government analysis but assumed here to be equivalent to ST PM_{10} emission factors. Test data shows PM_{10} emission rates as dependent upon fuel sulfur levels, with base PM_{10} emission rates of 0.23 g/kw-hr with distillate fuel (0.24% sulfur) and 1.35 g/kw-hr with residual fuel (2.46% sulfur).[20] The equation used to generate emission factors based on sulfur content is shown below. $PM_{2.5}$ is assumed to be 92 percent of PM_{10}. While the US Government NONROAD model uses 0.97 for such conversion based upon low sulfur fuels, a reasonable value seems to be closer to 0.92 because higher sulfur fuels in medium and slow speed engines would tend to produce larger particulates than high speed engines on low sulfur fuels.

Equation 2-2 Calculation of PM_{10} Emission Factors Based on Fuel Sulfur Levels

$$PM_{EF} = PM_{Nom} + [(S_{Act} - S_{Nom}) \times BSFC \times FSC \times MWR \times 0.0001]$$

where:

PM_{EF} = PM emission factor adjusted for fuel sulfur
PM_{Nom} = PM emission rate at nominal fuel sulfur level
= 0.23 g/kW-hr for distillate fuel, 1.35 g/kW-hr for residual fuel
S_{Act} = Actual fuel sulfur level (weight percent)
S_{Nom} = nominal fuel sulfur level (weight percent)
= 0.24 for distillate fuel, 2.46 for residual fuel
BSFC = fuel consumption in g/kW-hr
= 200 g/kW-hr used for this analysis
FSC = percentage of sulfur in fuel that is converted to direct sulfate PM
= 2.247% used for this analysis
MWR = molecular weight ratio of sulfate PM to sulfur
= 224/32 = 7 used for this analysis

SO_2 emission factors were based upon a fuel sulfur to SO_2 conversion formula which was supplied by ENVIRON.[21] Emission factors for SO_2 emissions were calculated using the formula assuming that 97.753 percent of the fuel sulfur was converted to SO_2.[22] The brake specific fuel consumption (BSFC)[B] that was used for SSDs was 195 g/kWh, while the BSFC that was used for MSDs was 210 g/kWh based upon Lloyds 1995. The BSFC that was used for STs and GTs was 305 g/kWh based upon Entec.[17]

Equation 2-3 Calculation of SO_2 Emission Factors, g/kWh

$$SO_2 \text{ EF} = \text{BSFC x } 64/32 \text{ x } 0.97753 \text{ x Fuel Sulfur Fraction}$$

CO_2 emission factors were calculated from the BSFC assuming a fuel carbon content of 86.7 percent by weight[17] and a ratio of molecular weights of CO_2 and C at 3.667.

Equation 2-4 Calculation of CO_2 Emission Factors, g/kWh

$$CO_2 \text{ EF} = \text{BSFC x } 3.667 \text{ x } 0.867$$

[A] PM_{10} is particulate matter of 10 micrometers or less.

[B] Brake specific fuel consumption is sometimes called specific fuel oil consumption (SFOC).

The most current set of auxiliary engine emission factors also comes from Entec except as noted below for PM and SO_2. Table 2-5 provides these auxiliary engine emission factors.

Table 2-5 Auxiliary Engine Emission Factors by Fuel Type, g/kWh

Engine	Fuel	All Ports				West Coast Ports			Other Ports		
		NO_X	CO	HC	CO_2	PM_{10}	$PM_{2.5}$	SO_2	PM_{10}	$PM_{2.5}$	SO_2
MSD	RM	14.70	1.10	0.40	668.36	1.4	1.3	10.26	1.4	1.3	11.09
	MDO	13.90	1.10	0.40	668.36	0.6	0.55	6.16	0.6	0.55	6.16

SO_2 emission factors were calculated using Equation 2-3 while PM emissions were determined using Equation 2-2.

Using the ratios of RM versus MDO use[15] as given in Table 2-3 together with the emission factors shown in Table 2-5, the auxiliary engine emission factor averages by ship type are listed in Table 2-6. As discussed above, this fuel sulfur level may be too high for the U.S. However, we do not believe this emission factor has a significant effect on the total emission inventory estimates.

Table 2-6 Auxiliary Engine Emission Factors by Ship Type, g/kWh

Ship Type	All Ports				West Coast Ports			Other Ports		
	NO_x	CO	HC	CO_2	PM_{10}	$PM_{2.5}$	SO_2	PM_{10}	$PM_{2.5}$	SO_2
Passenger	14.64	1.10	0.40	668.36	1.3	1.2	9.93	1.4	1.3	10.70
Others	14.47	1.10	0.40	668.36	1.1	1.0	9.07	1.2	1.1	9.66

2.3.2.3.7 Low Load Adjustment Factors for Propulsion Engines

Emission factors are considered to be constant down to about 20 percent load. Below that threshold, emission factors tend to increase as the load decreases. This trend results because diesel engines are less efficient at low loads and the brake specific fuel consumption (BSFC) tends to increase. Thus, while mass emissions (grams per hour) decrease with low loads, the engine power tends to decrease more quickly, thereby increasing the emission factor (grams per engine power) as load decreases. Energy and Environmental Analysis Inc. (EEA) demonstrated this effect in a study prepared for the U.S. Government in 2000.[23] In the EEA report, equations have been developed for the various emissions. The low-load emission factor adjustment factors were developed based upon the concept that the BSFC increases as load decreases below about 20 percent load.

Using these algorithms, fuel consumption and emission factors versus load were calculated. By normalizing emission factors to 20% load, low-load multiplicative adjustment factors were calculated for propulsion engines and presented in Table 2-7. Due to how they are operated, there is no need for a low load adjustment factor for auxiliary engines.

Table 2-7 Calculated Low Load Multiplicative Adjustment Factors

Load (%)	NO_X	HC	CO	PM	SO_2	CO_2
1	11.47	59.28	19.32	19.17	5.99	5.82
2	4.63	21.18	9.68	7.29	3.36	3.28
3	2.92	11.68	6.46	4.33	2.49	2.44
4	2.21	7.71	4.86	3.09	2.05	2.01
5	1.83	5.61	3.89	2.44	1.79	1.76
6	1.60	4.35	3.25	2.04	1.61	1.59
7	1.45	3.52	2.79	1.79	1.49	1.47
8	1.35	2.95	2.45	1.61	1.39	1.38
9	1.27	2.52	2.18	1.48	1.32	1.31
10	1.22	2.20	1.96	1.38	1.26	1.25
11	1.17	1.96	1.79	1.30	1.21	1.21
12	1.14	1.76	1.64	1.24	1.18	1.17
13	1.11	1.60	1.52	1.19	1.14	1.14
14	1.08	1.47	1.41	1.15	1.11	1.11
15	1.06	1.36	1.32	1.11	1.09	1.08
16	1.05	1.26	1.24	1.08	1.07	1.06
17	1.03	1.18	1.17	1.06	1.05	1.04
18	1.02	1.11	1.11	1.04	1.03	1.03
19	1.01	1.05	1.05	1.02	1.01	1.01
20	1.00	1.00	1.00	1.00	1.00	1.00

2.3.2.3.8 Use of Detailed Typical Port Data for Other Inputs

There is currently not enough information to readily calculate time-in-mode (hours/call) for all 117 ports during the maneuvering and hotelling modes of operation. As a result, it was necessary to review and select available detailed emission inventories that have been estimated for selected ports to date. These ports are referred to as typical ports. The typical port information for maneuvering and hotelling time-in-mode (as well as maneuvering load factors for the propulsion engines) was then used for the typical ports and also assigned to the other modeled ports. A modeled port is the port in which emissions are to be estimated. The methodology that was used to select the typical ports and match these ports to the other modeled ports is briefly described in Appendix 2D, and more fully described in an ICF report.[2]

2.3.2.3.9 Port Domestic Traffic

One of the concerns with using USACE entrances and clearances data is that it only contains foreign cargo movements moved by either a foreign flag vessel or a U.S. flag vessel. As a result, U.S. flag ships carrying domestic cargo (i.e., Jones Act) ships are not included in the USACE data. Determining the contribution of Jones Act ships is difficult as most data sources include Category 1 and 2 Jones Act ship movements with Category 3 ships and do not provide either enough data or a method for separating them.

Under contract to the U.S. Government, ICF conducted an analysis to estimate the amount of Category 3 Jones Act ships calling at the 117 U.S. ports. This was done by analyzing marine exchange data obtained from port authorities for eleven typical ports and using this information to estimate the Jones Act ship contribution for the remaining ports. Based on this limited analysis, Jones Act ships are estimated to account for 9.2% of the total installed power calling on U.S. ports. Approximately 30% of these ships, largely in the Alaska and Pacific regions, have been included in the 2002 baseline inventory. Based on this analysis, Jones Act ships excluded from this inventory constitute roughly 6.5% of total installed power.[24] This results in an underestimation of the port ship inventory and therefore the benefits of the ECA program reported in this chapter are also underestimated.

2.3.2.4 2002 Near Port Inventories

This section provides a summary of the total port emissions for 2002. Table 2-8 provides a breakout of the total port emissions by auxiliary and propulsion engines. Table 2-9 provides the breakout by mode of operation, while Table 2-10 provides a summary of port emissions by ship type.

Table 2-8 2002 Port Emissions Summary by Engine and Port Type (metric tonnes)

Engine Type	Port Type	Metric Tonnes						
		NO_X	PM_{10}	$PM_{2.5}$	HC	CO	SO_2	CO_2
Propulsion	Deep Water	64,288	5,478	5,034	2,532	6,329	52,676	2,360,435
	Great Lakes	248	25	23	11	22	187	11,267
	Total	64,536	5,503	5,057	2,543	6,351	52,863	2,371,702
Auxiliary	Deep Water	57,317	5,052	4,597	1,615	4,306	41,232	2,635,436
	Great Lakes	302	25	23	8	23	202	13,944
	Total	57,619	5,077	4,620	1,624	4,328	41,433	2,649,380
All	Deep Water	121,606	10,530	9,631	4,148	10,635	93,908	4,995,871
	Great Lakes	549	50	46	19	45	389	25,210
	Grand Total	122,155	10,580	9,677	4,167	10,680	94,297	5,021,082

Auxiliary emissions at ports are responsible for 39-48% of the total port inventory, depending on the pollutant. Hotelling, cruise, and RSZ modes of operation are all important contributors to emissions.

Table 2-9 2002 Port Emissions Summary by Mode and Port Type (metric tonnes)

Mode	Port Type	Metric Tonnes						
		NO_X	PM_{10}	$PM_{2.5}$	HC	CO	SO_2	CO_2
Cruise	Deep Water	34,193	2,826	2,623	1,141	2,651	21,186	1,314,146
	Great Lakes	183	17	16	6	14	137	8,313
	Total	34,376	2,843	2,639	1,148	2,665	21,323	1,322,459
RSZ	Deep Water	34,427	2,887	2,657	1,280	3,804	35,148	1,318,897
	Great Lakes	45	4	4	2	4	33	2,052
	Total	34,472	2,891	2,661	1,281	3,808	35,181	1,320,950
Maneuvering	Deep Water	7,383	758	625	440	724	4,356	266,262
	Great Lakes	70	7	7	4	8	50	3,213
	Total	7,452	765	632	444	732	4,406	269,476
Hotelling	Deep Water	45,603	4,060	3,726	1,287	3,456	33,218	2,096,566
	Great Lakes	252	21	19	7	19	168	11,631
	Total	45,855	4,081	3,745	1,294	3,475	33,386	2,108,197
All	Deep Water	121,606	10,530	9,631	4,148	10,635	93,908	4,995,871
	Great Lakes	549	50	46	19	45	389	25,210
	Grand Total	122,155	10,580	9,677	4,167	10,680	94,297	5,021,082

Table 2-10 2002 Port Emissions Summary by Ship Type and Port Type (metric tonnes)

Ship Type	Port Type	Metric Tonnes						
		NO_X	PM_{10}	$PM_{2.5}$	HC	CO	SO_2	CO_2
Auto Carrier	Deep Water	5,125	421	384	185	577	3,676	198,637
	Great Lakes	0	0	0	0	0	0	0
	Total	5,125	421	384	185	577	3,676	198,637
Barge Carrier	Deep Water	148	13	12	5	12	141	6,364
	Great Lakes	0	0	0	0	0	0	0
	Total	148	13	12	5	12	141	6,364
Self-Unloading Bulk Carrier	Deep Water	0	0	0	0	0	0	0
	Great Lakes	276	27	25	10	23	210	13,273
	Total	276	27	25	10	23	210	13,273
Other Bulk Carrier	Deep Water	19,373	1,570	1,431	633	1,732	14,945	767,825
	Great Lakes	227	19	17	7	18	147	9,807
	Total	19,600	1,589	1,448	640	1,750	15,092	777,632
Container	Deep Water	33,990	2,733	2,494	1,282	2,833	22,628	1,288,596
	Great Lakes	0	0	0	0	0	0	0
	Total	33,990	2,733	2,494	1,282	2,833	22,628	1,288,596
General Cargo	Deep Water	7,402	630	576	251	684	6,208	302,338
	Great Lakes	22	2	2	1	2	15	969
	Total	7,424	631	578	252	686	6,223	303,307
Miscellaneous	Deep Water	179	16	15	6	35	128	8,209
	Great Lakes	0	0	0	0	0	0	0

Ship Type	Port Type	Metric Tonnes						
		NO_X	PM_{10}	$PM_{2.5}$	HC	CO	SO_2	CO_2
	Total	179	16	15	6	35	128	8,209
Passenger	Deep Water	19,165	1,819	1,668	578	1,470	14,184	893,157
	Great Lakes	0	0	0	0	0	0	0
	Total	19,165	1,819	1,668	578	1,470	14,184	893,157
Refrigerated Cargo	Deep Water	3,027	247	226	98	313	1,968	130,060
	Great Lakes	0	0	0	0	0	0	0
	Total	3,027	247	226	98	313	1,968	130,060
Roll-On/Roll-Off	Deep Water	3,391	281	259	113	278	2,193	139,396
	Great Lakes	0	0	0	0	0	0	0
	Total	3,391	281	259	113	278	2,193	139,396
Tanker	Deep Water	29,758	2,796	2,562	994	2,695	27,802	1,259,107
	Great Lakes	22	2	2	1	2	15	1,012
	Total	29,780	2,798	2,564	995	2,697	27,817	1,260,119
Ocean Going Tug	Deep Water	48	5	4	2	6	34	2,182
	Great Lakes	0	0	0	0	0	0	0
	Total	48	5	4	2	6	34	2,182
Integrated Tug-Barge	Deep Water	0	0	0	0	0	0	0
	Great Lakes	3	0	0	0	0	2	149
	Total	3	0	0	0	0	2	149
All	Deep Water	121,606	10,530	9,631	4,148	10,635	93,908	4,995,871
	Great Lakes	549	50	46	19	45	389	25,210
	Grand Total	122,155	10,580	9,677	4,167	10,680	94,297	5,021,082

2.3.3 Interport Emissions

This section presents our nationwide analysis of the methodology and inputs used to estimate interport emissions from main propulsion and auxiliary engines used by Category 3 ocean-going vessels for the 2002 calendar year. The modeling domain for vessels operating in the ocean extends from the U.S. coastline to a 200 nautical mile boundary. For ships operating in the Great Lakes, it extends out to the international boundary with Canada. The emission results are divided into nine geographic regions of the U.S. (including Alaska and Hawaii), and then totaled to provide a national inventory.

The interport emissions described in this section represent total interport emissions prior to any adjustments made to incorporate near-port inventories. The approach used to replace the near-port portion of the interport emissions is provided in Section 2.3.4.

2.3.3.1 Interport Methodology

The interport emissions were estimated using the Waterway Network Ship Traffic, Energy, and Environmental Model (STEEM).[3,4] STEEM was developed by the University of Delaware as a comprehensive approach to quantify and geographically represent interport ship traffic, emissions, and energy consumption from large vessels calling on U.S. ports or transiting the U.S. coastline to other destinations, and shipping activity in Canada and Mexico. The model estimates emissions from main propulsion and auxiliary marine engines used on Category 3 vessels that engage in foreign commerce using historical North American shipping activity, ship attributes (i.e., characteristics), and activity-based emission factor information. These inputs are assembled using a GIS platform that also contains an empirically derived network of shipping lanes. It includes the emissions for all ship operational modes from cruise in unconstrained shipping lanes to maneuvering in a port. The model, however, excludes hotelling operations while the vessel is docked or anchored, and very low speed maneuvering close to a dock. For that reason, STEEM is referred to as an “interport” model, to easily distinguish it from the near ports analysis.

STEEM uses advanced ArcGIS tools and develops emission inventories in the following way. The model begins by building a spatially-defined waterway network based on empirical shipping location information from two global ship reporting databases. The first is the International Comprehensive Ocean-Atmosphere Data Set (ICOADS), which contains reports on marine surface and atmospheric conditions from the Voluntary Observing Ships (VOS) fleet.[25] There are approximately 4,000 vessels worldwide in the VOS system. The ICOADS project is sponsored by the National Oceanic and Atmospheric Administration and National Science Foundation's National Center for Atmospheric Research (NCAR). The second database is the Automated Mutual-Assistance Vessel Rescue (AMVER) system.[26] The AMVER data set is based on a ship search and rescue reporting network sponsored by the U.S. Coast Guard. The AMVER system is also voluntary, but is generally limited to ships over 1,000 gross tons on voyages of 24 hours or longer. About 8,600 vessels reported to AMVER in 2004.

The latitude and longitude coordinates for the ship reports in the above databases are used to statistically create and spatially define the direction and width of each shipping lane in the waterway network. Each statistical lane (route and segment) is given a unique identification number for computational purposes. For the current analysis, STEEM used 20 years of ICOADS data (1983-2002) and about one year of AMVER data (part of 2004 and part of 2005) (Figure 2-2).

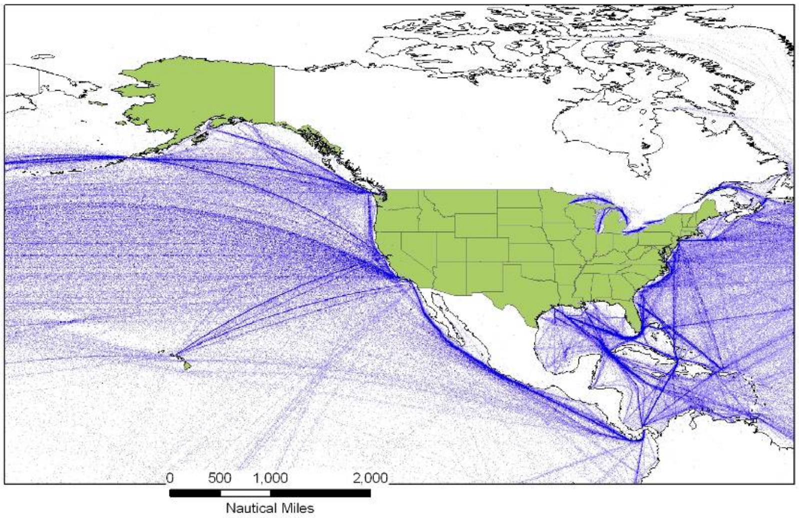


Figure 2-2 AMVER and ICOADS data

Every major ocean and Great Lake port is also spatially located in the waterway network using ArcGIS software. For the U.S., the latitude and longitude for each port is taken from the USACE report on vessel entrances and clearances.[11] Each port also has a unique identification number for computational purposes.

As illustrated in Figure 2-3, the waterway network represented by STEEM resembles a highway network on land. It is composed of ports, which are origins and destinations of shipping routes: junctions where shipping routes intersect, and segments that are shipping lanes between two connected junctions. Each segment can have only two junctions or ports, and ship traffic flow can enter and leave a segment only through a junction or at a port. The figure represents only a sample of the many routes contained in the model.

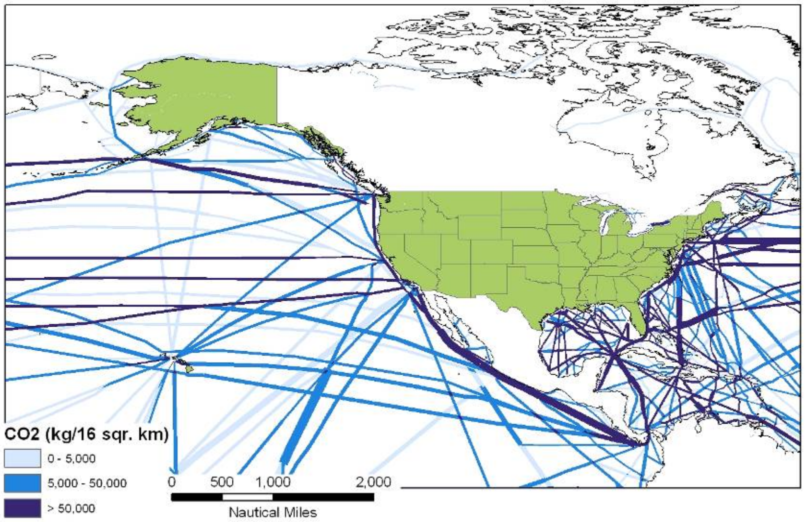


Figure 2-3 Illustration of STEEM Modeling Domain and Spatial Distribution of Shipping Lanes

The STEEM interport model also employs a number of databases to identify the movements for each vessel (e.g., trips), individual ship attributes (e.g., vessel size and horsepower), and related emission factor information (e.g., emission rates) that are subsequently used in the inventory calculations.

To allocate ships to the statistical lanes, STEEM uses ArcGIS Network Analyst tools along with specific information on each individual ship movement to solve the most probable path on the network between each pair of ports (i.e., a trip) for a certain ship size. This is assumed to represent the least-energy path, which in most cases is the shortest distance unless prevented by weather or sea conditions, water depth, channel width, navigational regulations, or other constraints that are beyond the model's capability to forecast.

After identifying the shipping route and resulting distance associated with each unique trip, the emissions are simply calculated for each operational mode using the following generalized equation along with information from the ship attributes and emission factor databases:

Equation 2-5

Emissions per trip = distance (nautical miles) / speed (nautical miles/hour) x horsepower (kW) x
fractional load factor x emission factor (g/kW-hour)

In STEEM, emissions are calculated separately for distances representing cruise and maneuvering operational modes. Maneuvering occurs at slower speeds and load factors than during cruise conditions. In STEEM, maneuvering is assumed to occur for the first and last

20 kilometers of each trip when a ship is entering or leaving a port. A ship is assumed to move at maneuvering speed for an entire trip if the distance is less than 20 kilometers.

Finally, the emissions along each shipping route (i.e., segment) for all trips are proportioned among the respective cells that are represented by the gridded modeling domain. For this work, emissions estimates were produced at a cell resolution of 4 kilometers by 4 kilometers, which is appropriate for most atmospheric air quality models. The results for each cell are then summed, as appropriate, to produce emission inventories for the various geographic regions of interest in this analysis.

2.3.3.2 Inputs for Interport Emission Calculations

The STEEM model includes detailed information about ship routes and destinations in order to provide spatially allocated emissions of ships in transit. The shipping lanes and directions were empirically derived from ship positioning data in several datasets. The International Comprehensive Ocean-Atmosphere Data Set (ICOADS) contains reports on marine surface and atmospheric conditions from the Voluntary Observing Ships (VOS) fleet.[27] STEEM also uses a dataset derived from the Automated Mutual-Assistance Vessel Rescue (AMVER) system,[28] which is based on a ship search and rescue reporting network sponsored by the U.S. Coast Guard. Traffic along each of these lanes is derived from USACE entrance and clearance data for 2002,[29] together with Lloyd's Register-Fairplay Ltd's data for ship characteristics. Information for number of calls, ship characteristics, propulsion engine power, and cruise speed were obtained from these data.

The emission factors and load factors used as inputs to STEEM are very similar to those used for the ports analysis. Additional adjustments were made to interport emission results for PM_{10} and SO_2 in order to reflect recent U.S. Government review of available engine test data and fuel sulfur levels. Details of the STEEM emission inputs and adjustments are located in Appendix 2E.

2.3.3.3 Interport Domestic Traffic

As previously noted, STEEM includes the emissions associated with ships that are engaged in foreign commerce. As a result, U.S. flag vessels carrying domestic cargo (Jones Act ships) are not included. The STEEM interport analysis also roughly estimated the emissions associated with these ships that are engaged solely in domestic commerce.[1,4] Specifically, the interport analysis estimated that the large ocean-going vessels carrying only domestic cargo excluded from STEEM represent approximately 2-3 percent of the total U.S. emissions.

In section 2.3.2.3.9 in the estimation of port inventories, the estimate of excluded installed power was roughly 6.5 percent. It is not inconsistent that the STEEM estimate of excluded emissions is lower than the excluded power estimated from calls to U.S. ports, since the STEEM model includes ships that are transiting without stopping at U.S. ports. Since most of the Jones Act ships tend to travel closer along the coast line, most of the Jones Act ship traffic is expected to fall within the proposed ECA. Therefore, the results presented in this chapter are expected to underpredict the benefits of the proposed ECA.

2.3.4 Combining the Near Port and Interport Inventories

The national and regional inventories in this study are a combination of the results from the near ports analysis described in Section 2.3.2 and the STEEM interport modeling described in Section 2.3.3. The two inventories are quite different in form. As previously presented, the STEEM modeling domain spans the Atlantic and Pacific Oceans in the northern hemisphere. The model characterizes emissions from vessels while traveling between ports. That includes when a vessel is maneuvering a distance of 20 kilometers to enter or exit a port, cruising near a port as it traverses the area, or moving in a shipping lane across the open sea. For the U.S., STEEM includes the emissions associated with 251 ports. The results are spatially reported in a gridded format that is resolved to a cell dimension of 4 kilometers by 4 kilometers.

The near port results, however, are much more geographically limited and are not reported in a gridded format. The analysis includes the emissions associated with ship movements when entering or exiting each of 117 major U.S. ports. For deep water ports that include when a vessel is hotelling and maneuvering in the port, operating in the RSZ that varies in length for each port, and cruising 25 nautical miles between the end of the RSZ and an unconstrained shipping lane. For Great Lakes ports that includes hotelling and maneuvering, three nautical miles of RSZ operation, and cruising 7 nautical miles between the end of the RSZ and open water. The results are reported for each port and mode of operation.

To precisely replace only the portion of the STEEM interport inventory that is represented in the near port inventory results, it is necessary to spatially allocate the emissions in a format that is compatible with the STEEM 4 kilometers by 4 kilometers gridded output. Once that has been accomplished, the two inventories can be blended together. Both of these processes are described below. This work was conducted by ENVIRON International as a subcontractor under the U.S. Government contract with ICF.[2]

2.3.4.1 Spatial Location of the Near Port Inventories

The hotelling, maneuvering, RSZ, and cruise emissions from the near port inventories were spatially located by their respective latitude and longitude coordinates using ArcGIS software. For this study, shapefiles were created that depicted the emission locations as described above. Additional shapefiles were also obtained to locate other geographic features such as the coastline and rivers of the U.S. These shapefiles and the STEEM output can be layered upon each other, viewed in ArcMap, and analyzed together. The following sections provide a more detailed description of how the shapefiles representing the ports, RSZ lanes, and cruise lanes were developed.

2.3.4.1.1 Ports

Each port, and thus the designated location for hotelling and maneuvering emissions, is modeled as a single latitude/longitude coordinate point using the port center as defined by USACE in the Principal Ports of the United States dataset.[10] The hotelling and maneuvering emissions represented by the latitude/longitude coordinate for each port were subsequently assigned to a single cell in the gridded inventory where that point was located. It should be noted that modeling a port as a point will over specify the location of the emissions associated with that port if it occupies an area greater than one grid cell, or 4 kilometers by 4 kilometers. The coordinates of all of the 117 ports used in this work are shown in Appendix 2A.

2.3.4.2 Reduced Speed Zone Operation

The RSZ routes associated with each of the 117 ports were modeled as lines. Line shapefiles were constructed using the RSZ distance information described in Section 2.3.2 and the USACE National Waterway Network (NWN) geographic database of navigable waterways in and around the U.S.[14] The coordinates of RSZ endpoints for all of the 117 ports used in this work are shown in Appendix 2C.

The RSZ emissions were distributed evenly along the length of the line. The latitude/longitude coordinates for each point along the line were subsequently used to assign the emissions to a grid cell based on the proportion of the line segment that occurred in the respective cell.

2.3.4.2.1 Cruise Operations

The cruise mode links that extend 25 nautical miles for deep water ports or 7 nautical miles for Great Lake ports from the end of the RSZ end point were also modeled with line shapefiles. These links were spatially described for each port following the direction of the shipping lane evident in the STEEM data. Again, as with RSZ emissions, the latitude/longitude coordinates for each point along the line were subsequently used to assign the emissions to a grid cell based on the proportion of the line segment that occurred in the respective cell.

2.3.4.3 Combining the Near Port and STEEM Emission Inventories in Port Areas

After spatially defining the geographic location of the near port emissions, but before actually inserting them into the gridded STEEM inventory, it was necessary to determine if all of the STEEM emissions within an affected cell should be replaced, or if some of the emissions should be retained. In this latter case, ships would be traversing the area near a port, but not actually entering or exiting the port.

The percentage of STEEM emissions that are attributable to a port, and should be removed and replaced, were approximated by dividing the STEEM emissions in the isolated portion of the route that lead only to the port, with the STEEM emissions in the major shipping lane.

The actual merging of the two inventories was performed by creating a number of databases that identified the fraction of the near port inventory for each pollutant species and operating mode that should be added to the grid cells for each port. A similar database was also created that identified how much of the original STEEM emissions should be reduced to account for ship movements associated directly with a port, while preserving those that represented transient vessel traffic. These databases were subsequently used to calculate the new emission results for each affected cell in the original STEEM gridded inventory, resulting in the combined inventory results for this study.

In a few cases, the outer edges of the port inventories fell outside the international boundary; that portion outside the U.S. boundary was removed. As a result, the port totals presented in the next section are slightly less than those reported in Section 2.3.2.4. The removed portion represents less than 2 percent of the total port emissions.

Since STEEM includes emissions associated with 251 ports, the 117 ports do not cover all the ports identified by the shipping lane paths evident in the STEEM data. In the remaining ports, the STEEM model output was used.

2.3.5 2002 Baseline Inventories

The modeling domain of the new combined emission inventory described above is the same as the original STEEM domain, i.e., the Atlantic and Pacific Oceans, the Gulf of Mexico, the Great Lakes, Alaska, and Hawaii. Inventories for the nine geographic regions of the U.S. specified in Section 2.2 were created using ArcGIS software to intersect the regional shapefiles with the 4 kilometers by 4 kilometers gridded domain. Any grid cell split by a regional boundary was considered to be within a region if over 50 percent of its area was within the region. The emissions from the cells within a region were then summed. The final emission inventories for 2002 are shown in Table 2-11 for each of the nine geographic regions and the nation. The geographic scope of these regions was previously displayed in Figure 2-1.

Table 2-11 2002 Regional and National Emissions from Category 3 Vessel Main and Auxiliary Engines

Region	**Metric Tonnes**						
	NO_X	**PM_{10}**	**$PM_{2.5}$ [a]**	**HC**	**CO**	**SO_2**	**CO_2**
Alaska East (AE)	18,051	1,425	1,311	597	1,410	10,618	657,647
Alaska West (AW)	60,019	4,689	4,313	1,989	4,685	34,786	2,143,720
East Coast (EC)	219,560	17,501	16,101	7,277	17,231	145,024	8,131,553
Gulf Coast (GC)	172,897	14,043	12,920	5,757	14,169	104,852	6,342,139
Hawaii East (HE)	22,600	1,775	1,633	749	1,765	13,182	818,571
Hawaii West (HW)	31,799	2,498	2,297	1,053	2,484	18,546	1,151,725
North Pacific (NP)	26,037	2,154	1,982	938	2,090	15,295	990,342
South Pacific (SP)	104,155	8,094	7,447	3,464	8,437	60,443	3,796,572
Great Lakes (GL)	15,019	1,179	1,085	498	1,174	8,766	541,336
Total Metric Tonnes	*670,135*	*53,358*	*49,089*	*22,324*	*53,444*	*411,511*	*24,573,605*

[a] Estimated from PM_{10} using a multiplicative adjustment factor of 0.92.

The relative contributions of the near port and interport emission inventories to the total U.S. ship emissions are presented in Table 2-12 and Table 2-13. As expected, based on the geographic scope of the two types of inventories, the interport and near port inventories are about 80 percent and 20 percent of the total, respectively.

Table 2-12 2002 Contribution of Near Port and Interport Emissions to the Total C3 Inventory

Region	Metric Tonnes								
	NO_X			PM_{10}			$PM_{2.5}$ [a]		
	Port	Interport	Total	Port	Interport	Total	Port	Interport	*Total*
Alaska East (AE)	833	17,218	18,051	80	1,345	1,425	74	1,237	*1,311*
Alaska West (AW)	0	60,019	60,019	0	4,689	4,689	0	4,313	*4,313*
East Coast (EC)	48,313	171,247	219,560	4,126	13,375	17,501	3,796	12,305	*16,101*
Gulf Coast (GC)	33,637	139,260	172,897	3,169	10,874	14,043	2,916	10,004	*12,920*
Hawaii East (HE)	2,916	19,684	22,600	251	1,524	1,775	231	1,402	*1,633*
Hawaii West (HW)	0	31,799	31,799	0	2,498	2,498	0	2,297	*2,297*
North Pacific (NP)	14,015	12,022	26,037	1,216	938	2,154	1,119	863	*1,982*
South Pacific (SP)	20,079	84,076	104,155	1,525	6,569	8,094	1,403	6,044	*7,447*
Great Lakes (GL)	491	14,528	15,019	44	1,135	1,179	41	1,044	*1,085*
Total Metric Tonnes	*120,285*	*549,852*	*670,137*	*10,413*	*42,945*	*53,358*	*9,580*	*39,510*	49,089

[a] Estimated from PM_{10} using a multiplicative adjustment factor of 0.92.

Table 2-13 2002 Contribution of Near Port and Interport Emissions to the Total C3 Inventory (Cont'd)

Region	Metric Tonnes								
	HC			CO			SO_2		
	Port	Interport	Total	Port	Interport	Total	Port	Interport	*Total*
Alaska East (AE)	27	570	597	66	1,344	1,410	641	9,977	*10,618*
Alaska West (AW)	0	1,989	1,989	0	4,685	4,685	0	34,786	*34,786*
East Coast (EC)	1,603	5,674	7,277	3,864	13,367	17,231	45,952	99,072	*145,024*
Gulf Coast (GC)	1,142	4,615	5,757	3,305	10,864	14,169	24,187	80,665	*104,852*
Hawaii East (HE)	96	653	749	230	1,535	1,765	1,891	11,291	*13,182*
Hawaii West (HW)	0	1,053	1,053	0	2,484	2,484	0	18,546	*18,546*
North Pacific (NP)	540	398	938	1,152	938	2,090	8,329	6,966	*15,295*
South Pacific (SP)	678	2,786	3,464	1,876	6,561	8,437	11,715	48,728	*60,443*
Great Lakes (GL)	17	481	498	40	1,134	1,174	346	8,420	*8,766*
Total Metric Tonnes	*4,103*	*18,219*	*22,322*	*10,533*	*42,912*	*53,445*	*93,062*	*318,450*	411,512

As noted previously, these inventories exclude a portion of traffic from U.S. flag ships carrying domestic cargo. Estimates range from roughly 2 to 7 percent of installed power, which indicates that the inventories may be underestimated by 2 to 7 percent.

2.4 Development of 2020 Inventories

2.4.1 Outline of Methodology

The emissions from Category 3 ocean-going vessels (main propulsion and auxiliary engines) are projected to 2020 by applying certain growth factors to the 2002 emission inventories to account for the expected change in ship traffic over these time periods due to growth in trade.

The remaining sections describe the derivation of the growth adjustment factors for each of the modeling regions described in Section 2.2. Emission control program related adjustments to the

2020 inventories are then described. A baseline inventory and an inventory within the proposed ECA are then presented.

2.4.2 Growth Factors by Geographic Region

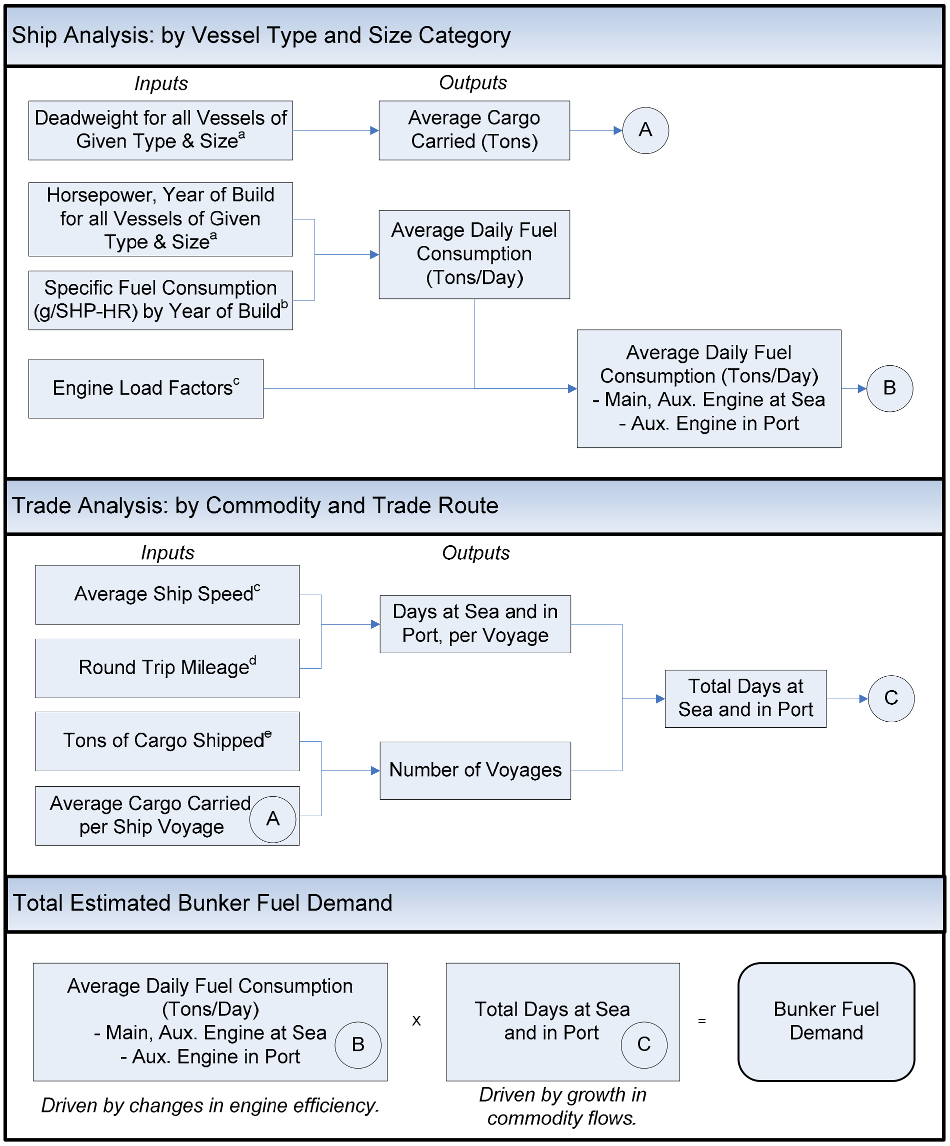
The growth factors that are used to estimate future year emission inventories are based on the expected demand for marine bunker fuels that is associated with shipping goods, i.e., commodities, into and out of the U.S. This section describes the growth factors that are used to project the emissions to 2020 for each of the nine geographic regions evaluated in this analysis. The use of bunker fuel as a surrogate for estimating future emissions is appropriate because the quantity of fuel consumed by C3 engines is highly correlated with the amount of combustion products, i.e., pollutants that are emitted from those vessels. The term bunker fuel in this report also includes marine distillate oil and marine gas oil that are used in some auxiliary power engines.

The remainder of this section first summarizes the development of growth rates by RTI International (RTI) for five geographic regions of the U.S., as performed under contract to the U.S. government.[5,6] This is followed by the derivation of the growth factors that are used in this study for the nine geographic regions of interest.

2.4.2.1 Summary of Regional Growth Rate Development

RTI developed fuel consumption growth rates for five geographic regions of the U.S. These regions are the East Coast, Gulf Coast, North Pacific, South Pacific, and Great Lakes. The amount of bunker fuel required in any region and year is based on the demand for transporting various types of cargo by Category 3 vessels. This transportation demand is in turn driven by the demand for commodities that are produced in one location and consumed in another, as predicted by an econometric model. The flow of commodities is matched with typical vessels for trade routes (characterized according to cargo capacity, engine horsepower, age, specific fuel consumption, and engine load factors). Typical voyage parameters are then assigned to the trade routes that include average ship speed, round trip mileage, tons of cargo shipped, and days in port. Fuel consumption for each trade route and commodity type thus depends on commodity projections, ship characteristics, and voyage characteristics. Figure 2-4 illustrates the approach to developing baseline projections of marine fuel consumption.

As a means of comparison, the IMO Secretary General's Informal Cross Government/Industry Scientific Group of Experts presented a growth rate that ranged from 3.3% to 3.7%.[30] RTI's overall U.S. growth rate was projected at 3.4%, which is consistent with that range.



a – Clarksons Ship Register Database
b – Engine Manufacturers' Data, Technical Papers
c – Corbett and Wang (2005) "Emission Inventory Review: SECA Inventory Progress Discussion"
d - Combined trade routes and heavy leg analysis
e – Global Insight Inc. (GII) Trade Flow Projections

Figure 2-4 Illustration of Method for Estimating Bunker Fuel Demand

2.4.2.2 Trade Analysis

The trade flows between geographic regions of the world, as illustrated by the middle portion of Figure 2-4 were defined for the following eight general types of commodities:

- liquid bulk – crude oil
- liquid bulk – refined petroleum products
- liquid bulk – residual petroleum products
- liquid bulk – chemicals (organic and inorganic)
- liquid bulk –gas (including LNG and LPG)
- dry bulk (e.g., grain, coal, steel, ores and scrap)
- general cargo (e.g., lumber/forest products)

- containerized cargo

The analysis specifically evaluated trade flows between 21 regions of the world. Table 2-14 shows the countries associated with each region.

Table 2-14 Aggregate Regions and Associated Countries

Aggregate Regions	Base Countries / Regions
U.S. Atlantic Coast	U.S. Atlantic Coast
U.S. Great Lakes	U.S. Great Lakes
U.S. Gulf Coast	U.S. Gulf Coast
E. Canada[a]	Canada[a]
W. Canada[a]	Canada[a]
U.S. Pacific North	U.S. Pacific North
U.S. Pacific South	U.S. Pacific South
Greater Caribbean	Colombia, Mexico, Venezuela, Caribbean Basin, Central America
South America	Argentina, Brazil, Chile, Peru, Other East Coast of S. America, Other West Coast of S. America
Africa – West	Western Africa
Africa-North/East-Mediterranean	Mediterranean Northern Africa, Egypt, Israel,
Africa-East/South	Kenya, Other Eastern Africa, South Africa, Other Southern Africa
Europe-North	Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Netherlands, Norway, Sweden, Switzerland, United Kingdom
Europe-South	Greece, Italy, Portugal, Spain, Turkey, Other Europe
Europe-East	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovak Republic
Caspian Region	Southeast CIS
Russia/FSU	The Baltic States, Russia Federation, Other Western CIS
Middle East Gulf	Jordan, Saudi Arabia, UAE, Other Persian Gulf
Australia/NZ	Australia, New Zealand
Japan	Japan
Pacific-High Growth	Hong Kong S.A.R., Indonesia, Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand
China	China
Rest of Asia	Viet Nam, India, Pakistan, Other Indian Subcontinent

[a] Canada is treated as a single destination in the GI model. Shares of Canadian imports from and exports to regions of the world in 2004 are used to divide Canada trade into shipments to/from Eastern Canada ports and shipments to/from Western Canada ports.[31]

The overall forecast of demand for shipping services and bunker fuel was determined for each of the areas using information on commodity flows from Global Insight's (GI) World Trade Service. Specifically, GI provided a specialized forecast that reports the flow of each commodity type for the period 1995–2024, based on a proprietary econometric model. The general structure of the GI model for calculating trade flows assumes a country's imports from another country are driven by the importing country's demand forces (given that the exporting country possesses enough supply capacity), and affected by exporting the country's export price and importing country's import cost for the commodity. The model then estimates demand forces, country-specific exporting capacities, export prices, and import costs.

The GI model included detailed annual region-to-region trade flows for eight composite commodities from 1995 to 2024, in addition to the total trade represented by the commodities. Table 2-15 illustrates the projections for 2012 and 2020, along with baseline data for 2005. In 2005, dry bulk accounted for 41 percent of the total trade volume, crude oil accounted for 28 percent, and containers accounted for 12 percent. Dry bulk and crude oil shipments are expected to grow more slowly over the forecast period than container shipments. By 2020, dry bulk represents 39 percent of the total, crude oil is 26 percent, and containers rise to 17 percent.

Table 2-15 Illustration of World Trade Estimates for Composite Commodities, 2005, 2012, and 2020

Commodity Type	Cargo (millions of tons)		
	2005	2012	2020
Dry Bulk	2,473	3,051	3,453
Crude Oil	1,703	2,011	2,243
Container	714	1,048	1,517
Refined Petroleum	416	471	510
General Cargo	281	363	452
Residual Petroleum and Other Liquids	190	213	223
Chemicals	122	175	228
Natural Gas	79	91	105
Total International Cargo Demand	5,979	7,426	8,737

2.4.2.3 Ship Analysis by Vessel Type and Size

Different types of vessels are required to transport the different commodities to the various regions of the world. Profiles of these ships were developed to identify the various vessel types and size categories that are assigned to transport commodities of each type along each route. These profiles include attributes such as ship size, engine horsepower, engine load factors, age, and engine fuel efficiency. This information was subsequently used to estimate average daily fuel consumption for each typical ship type and size category.

The eight GI commodity categories were mapped to the type of vessel that would be used to transport that type of cargo using information from Clarkson's Shipping Database.[32] These assignments are shown in Table 2-16.

Table 2-16 Assignment of Commodities to Vessel Types

Commodity	Ship Category	Vessel Type
Liquid bulk – crude oil	Crude Oil Tankers	Tanker
Liquid bulk – refined petroleum products	Product Tankers	Product Carrier
Liquid bulk – residual petroleum products	Product Tankers	Product Carrier
Liquid bulk – chemicals (organic and inorganic)	Chemical Tankers	Chemical & Oil Carrier
Liquid bulk – natural gas (including LNG and LPG)	Gas Carriers	LNG Carrier, LPG Carrier, Chemical & LPG Carrier, Ethylene/LPG, Ethylene/LPG/Chemical, LNG/Ethylene/LPG, LNG/Regasification, LPG/Chemical, LPG/Oil, Oil & Liquid Gas Carrier
Dry bulk (e.g. grain, coal, steel, ores and scrap)	Dry Bulk Carriers	Bulk Carrier
General cargo (including neobulk, lumber/forest products)	General Cargo	General Cargo Liner, Reefer, General Cargo Tramp, Reefer Fish Carrier, Ro-Ro, Reefer/Container, Ro-Ro Freight/Passenger, Reefer/Fleet Replen., Ro-Ro/Container, Reefer/General Cargo, Ro-Ro/Lo-Lo, Reefer/Pallets Carrier, Reefer/Pass./Ro-Ro, Reefer/Ro-Ro Cargo
Containerizable cargo	Container Ships	Fully Cellular Container

Each of the vessel types were classified by their cargo carrying capacity or deadweight tons (DWT). The size categories were identified based on both industry definitions and natural size breaks within the data. Table 2-17 summarizes the size categories that were used in the analysis and provides other information on the general attributes of the vessels from Clarkson's Shipping Database. The vessel size descriptions are also used to define shipping routes based on physical limitations that are represented by canals or straits through which ships can pass. Very large crude oil tankers are the largest by DWT rating, and the biggest container ships (Suezmax) are also very large.

Table 2-17 Fleet Characteristics

Ship Type	Size by DWT	Maximum Size (DWT)	Maximum Size (DWT)	Number of Ships	Total DWT (millions)	Total Horse Power (millions)	Total Kilowatts (millions)
Container	Suezmax	83,000	140,000	101	9.83	8.56	6.38
	PostPanamax	56,500	83,000	465	30.96	29.3	21.85
	Panamax	42,100	56,500	375	18.04	15.04	11.21
	Intermediate	14,000	42,100	1,507	39.8	32.38	24.14
	Feeder	0	14,000	1,100	8.84	7.91	5.90
General Cargo	All	All		3,214	26.65	27.07	20.18
Dry Bulk	Capesize	79,000	0	715	114.22	13.81	10.30
	Panamax	54,000	79,000	1,287	90.17	16.71	12.46
	Handymax	40,000	54,000	991	46.5	10.69	7.97
	Handy	0	40,000	2,155	58.09	19.58	14.60
Crude Oil Tanker	VLCC	180,000	0	470	136.75	15.29	11.40
	Suezmax	120,000	180,000	268	40.63	5.82	4.34
	AFRAmax	75,000	120,000	511	51.83	8.58	6.40
	Panamax	43,000	75,000	164	10.32	2.17	1.62
	Handymax	27,000	43,000	100	3.45	1.13	0.84
	Coastal	0	27,000	377	3.85	1.98	1.48
Chemical Tanker	All	All		2,391	38.8	15.54	11.59
Petroleum Product Tanker	AFRAmax	68,000	0	226	19.94	3.6	2.68
	Panamax	40,000	68,000	352	16.92	4.19	3.12
	Handy	27,000	40,000	236	7.9	2.56	1.91
	Coastal	0	27,000	349	3.15	1.54	1.15
Natural Gas Carrier	VLGC	60,000	0	157	11.57	5.63	4.20
	LGC	35,000	60,000	140	6.88	2.55	1.90
	Midsize	0	35,000	863	4.79	3.74	2.79
Other	All	All		7,675	88.51	53.6	39.96
Total	--	--	--	26,189	888.4	308.96	230.36

The average fuel consumption for each vessel type and size category was estimated in a multi-step process using individual vessel data on engine characteristics. Clarkson's Shipping Database Register provides each ship's total installed horsepower (HP), type of propulsion (diesel or steam), and year of build. These characteristics are then matched to information on typical specific fuel consumption (SFC), which is expressed in terms of grams of bunker fuel burned per horsepower-hour (g/HP-hr, which is equivalent to 1.341 g/kW-hr).

The SFC values are based on historical data from Wartsila Sulzer, a popular manufacturer of diesel engines for marine vessels. RTI added an additional 10 percent to the reported "test bed" or "catalogue" numbers to account for the guaranteed tolerance level and an in-service SFC differential. Overall, the 10 percent estimate is consistent with other analyses that show some variation between the “test bed” SFC values reported in the manufacturer product catalogues and those observed in actual service. This difference is explained by the fact that old, used engines consume more fuel than brand new engines and in-service fuels may be different than the test bed fuels.[33]

Figure 2-5 shows SFC values that were used in the model regarding the evolution of specific fuel oil consumption rates for diesel engines over time. Engine efficiency in terms of SFC has improved over time, most noticeably in the early 1980s in response to rising fuel prices. However, there is a tradeoff between improving fuel efficiency and reducing emissions. Conversations with engine manufacturers indicate that it is reasonable to assume SFC will remain constant for the projection period of this study, particularly as they focus on meeting NO_X emission standard as required by MARPOL Annex VI, or other potential pollution control requirements. Post-2000 SFC values are constant at approximately 135 g/hp-hr (180 g/kW-hr).

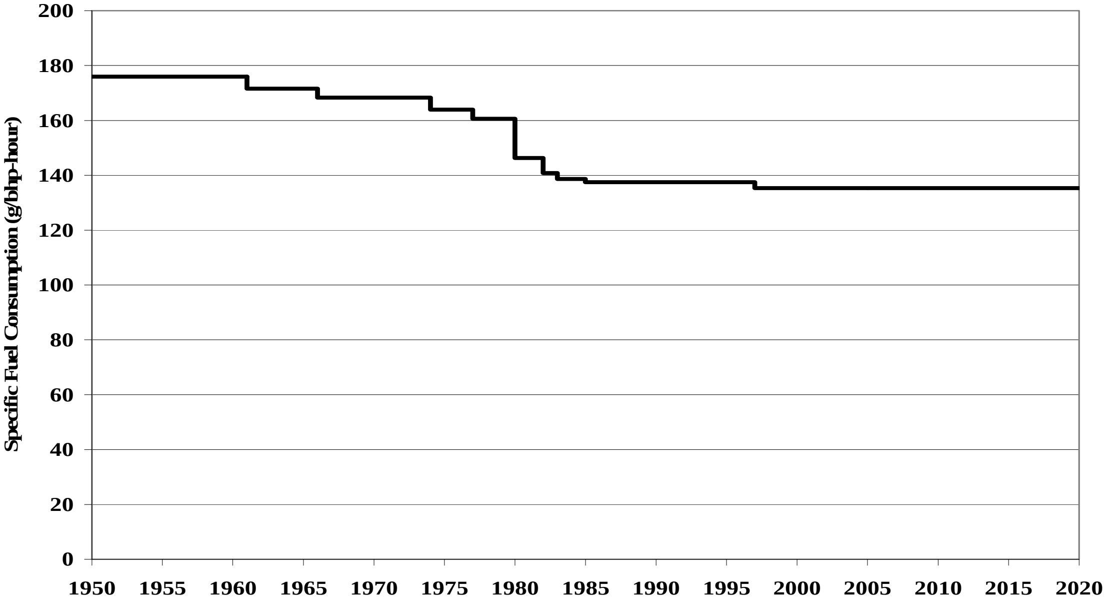


Figure 2-5 Diesel Engine Specific Fuel Consumption

RTI assumed a fixed SFC of 220 g/HP-hr (295 g/kW-hr) for steam engines operating on bunker fuel.

Using the above information, the average daily fuel consumption (AFC), expressed in metric tons of fuel at full engine load, for each vessel type and size category is found using the following equation:

Equation 2-6

$$\text{Fleet AFC}_{v,s} = \frac{1}{N}\sum\left[SFC_{v,s} \times HP_{v,s} \times 10^{-6} tonnes/g\right]$$

Where:

- Fleet AFC = Average daily fuel consumption in metric tonnes at full engine load
- *v* = Vessel type
- *s* = Vessel size category
- N = Number of vessels in the fleet
- SFC = Specific fuel consumption in grams of bunker fuel burned per horsepower-hour in use(g/HP-hr)
- HP = Total installed engine power, in horsepower (HP)
- 10^6 tonnes/g = Conversion from grams to metric tonnes

As previously noted, AFC values calculated in the above equation are based on total horsepower; therefore, they must be scaled down to reflect typical operation using less than 100 percent of the horsepower rating, i.e., actual engine load. Table 2-18 shows the engine load factors that were used to estimate the typical average daily fuel consumption (tons/day) for the main propulsion engine and the auxiliary engines when operated at sea and in port.[34]

Table 2-18 Main and Auxiliary Engine Load Factors

Vessel Type	Main Engine Load Factor (%)	Auxiliary Engine as Percent of Main Engine	Auxiliary Engine as Percent of Main Engine at Sea
Container Vessels	80	22.0	11.0
General Cargo Carriers	80	19.1	9.5
Dry Bulk Carriers	75	22.2	11.1
Crude Oil Tankers	75	21.1	10.6
Chemical Tankers	75	21.1	10.6
Petroleum Product Tankers	75	21.1	10.6
Natural Gas Carrier	75	21.1	10.6
Other	70	20.0	10.0

The RTI analysis also assumed that the shipping fleet changes over time as older vessels are scrapped and replaced with newer ships. Specifically, vessels over 25 years of age are retired and replaced by new ships of the most up-to-date configuration. This assumption leads to the following change in fleet characteristics over the projection period:

- New ships have engines rated at the current SFC, so even though there are no further improvements in specific fuel consumption, the fuel efficiency of the fleet as a whole will improve over time through retirement and replacement.
- New ships will weigh as much as the average ship built in 2005, so the total cargo capacity of the fleet will increase over time as smaller ships retire and are replaced.
- Container ships will increase in size over time on the trade routes between Asia to either North America or Europe.

2.4.2.4 Trade Analysis by Commodity Type and Trade Route

Determining the total number of days at sea and in port requires information on the relative amount of each commodity that is carried by the different ship type size categories on each of the trade routes. For example, to serve the large crude oil trade from the Middle East Gulf region to the

Gulf Coast of the U.S., 98 percent of the deadweight tonnage is carried on very large oil tankers, while the remaining 2 percent is carried on smaller Suezmax vessels. After the vessel type size distribution was found, voyage parameters were estimated. Specifically, these are days at sea and in port for each voyage (based on ports called, distance between ports, and ship speed**)**, and the number of voyages (based on cargo volume projected by GI and the DTW from Clarkson's Shipping Database). The length of each voyage and number of voyages were used to estimate the total number of days at sea and at port, which is a parameter used later to calculate total fuel consumption for each vessel type and size category over each route and for each commodity type. (More information on determining the round trip distance for each voyage that is associated with cargo demand for the U.S. is provided in Section 2.4.2.5.)

The days at sea were calculated by dividing the round trip distance by the average vessel speed:

Equation 2-7

$$\text{Days at Sea Per Voyage}_{v,s,route} = \frac{\text{round trip distance route}}{\text{speed}_{v,s} \times 24\,\text{hrs}}$$

Where:

v = Vessel type
s = Vessel size category
$route$ = Unique trip itinerary
round trip route distance = Trip length in nautical miles
speed = Vessel speed in knots or nautical miles per hour
24 hrs = Number of hours in one day

Table 2-19 presents the speeds by vessel type that were used in the analysis.[34] These values are the same for all size categories, and are assumed to remain constant over the forecast period.

Table 2-19 Vessel Speed by Type

Vessel Type	Speed (knots)
Crude Oil Tankers	13.2
Petroleum Product Tankers	13.2
Chemical Tankers	13.2
Natural Gas Carriers	13.2
Dry Bulk Carriers	14.1
General Cargo Vessels	12.3
Container Vessels	19.9
Other	12.7

The number of voyages along each route for each trade was estimated for each vessel type v and size category s serving a given route by dividing the tons of cargo moved by the amount of cargo (DTW) per voyage:

Equation 2-8

$$\text{Number of Voyages}_{v,s,trade} = \frac{\text{total metric tonnes of cargo moved}}{\text{fleet average DWT}_{v,s} \times \text{utilization rate}}$$

Where:

v = Vessel type
s = Vessel size category
trade = Commodity type
Fleet average DWT = Median dead weight tonnage carrying capacity in metric tons
Utilization rate = Fraction of total ship DWT capacity used

The cargo per voyage is based on the fleet average ship size from the vessel profile analysis. For most cargo, a utilization rate of 0.9 is assumed to be constant throughout the forecast period. Lowering this factor would increase the estimated number of voyages required to move the forecasted cargo volumes, which would lead to an increase in estimated fuel demand.

In addition to calculating the average days at sea per voyage, the average days in port per voyage was also estimated by assuming that most types of cargo vessels spend four days in port per voyage. RTI notes, however, that this can vary somewhat by commodity and port.

2.4.2.5 Worldwide Estimates of Fuel Demand

This section describes how the information from the vessel and trade analyses were used to calculate the total annual fuel demand associated with international cargo trade. Specifically, for each year *y* of the analysis, the total bunker fuel demand is the sum of the fuel consumed on each route of each trade (commodity). The fuel consumed on each route of each trade is in turn the sum of the fuel consumed for each route and trade for that year by propulsion main engines and auxiliary engines when operated at sea and in port. These steps are illustrated by the following equations:

Equation 2-9

$$\begin{aligned} \text{FC}_{\text{y}} &= \underset{\text{trade}}{\Sigma}\ \underset{\text{route}}{\Sigma}\ \text{FC}_{\text{trade, route, year}} \\ &= \underset{\text{trade}}{\Sigma}\ \underset{\text{route}}{\Sigma} \left[\text{AFC}_{\text{trade, route, y at sea}} \text{ x Days at Sea}_{\text{trade, route, y}} + \text{AFC}_{\text{trade, route, y at port}} \text{ x Days at Port}_{\text{trade, route, y}} \right] \end{aligned}$$

Where:

FC = Fuel consumed in metric tonnes
y = calendar year
trade = Commodity type
route = Unique trip itinerary
AFC = Average daily fuel consumption in metric tonnes
yatsea = Calendar year main and auxiliary engines are operated at sea
yatport = Calendar year main and auxiliary engines are operated in port

Equations 2-10

$$\text{AFC}_{\text{trade, route, y at sea}} = \sum_{\text{v,s,t,r}} (\text{Percent of trade along route})_{\text{v,s}} \left[\text{Fleet AFC}_{\text{v,s}} \text{ x} \left(\text{MELF} + \text{AE at sea LF}\right)\right]$$

$$\text{AFC}_{\text{trade, route, y at port}} = \sum_{\text{v,s,t,r}} (\text{Percent of trade along route})_{\text{v,s}} \left[\text{Fleet AFC}_{\text{v,s}} \text{ x AE import LF}\right]$$

$$\text{Days at Sea}_{\text{trade, route, y}} = \sum_{\text{v,s,t,r}} (\text{Percent of trade along route})_{\text{v,s}} \left[\text{Days at sea per voyage}_{\text{v,s}} \text{ x Number of voyages}_{\text{v,s}}\right]$$

$$\text{Days at Port}_{\text{trade, route, y}} = \sum_{\text{v,s,t,r}} (\text{Percent of trade along route})_{\text{v,s}} \left[\text{Days at port per voyage x Number of voyages}\right]$$

Where:

- AFC = Average daily fuel consumption in metric tones
- *trade* = Commodity type
- *route* = Unique trip itinerary
- *yatsea* = Calendar year main and auxiliary engines are operated at sea
- *yatport* = Calendar year main and auxiliary engines are operated in port
- *y* = calendar year
- *v* = Vessel type
- *s* = Vessel size category
- *t* = Trade
- *r* = Route
- Fleet AFC = Average daily fuel consumption in metric tonnes at full engine load
- MELF = main engine load factor, unitless
- AE at sea LF = auxiliary engine at-sea load factor, unitless
- AE in port LF = auxiliary engine in-port load factor, unitless

The inputs for these last four equations are all derived from the vessel analysis in Section 2.4.2.3 and the trade analysis in Section 2.4.2.2.

2.4.2.6 Worldwide Bunker Fuel Consumption

Based on the methodology outlined above, estimates of global fuel consumption over time were computed, and growth rates determined from these projections.

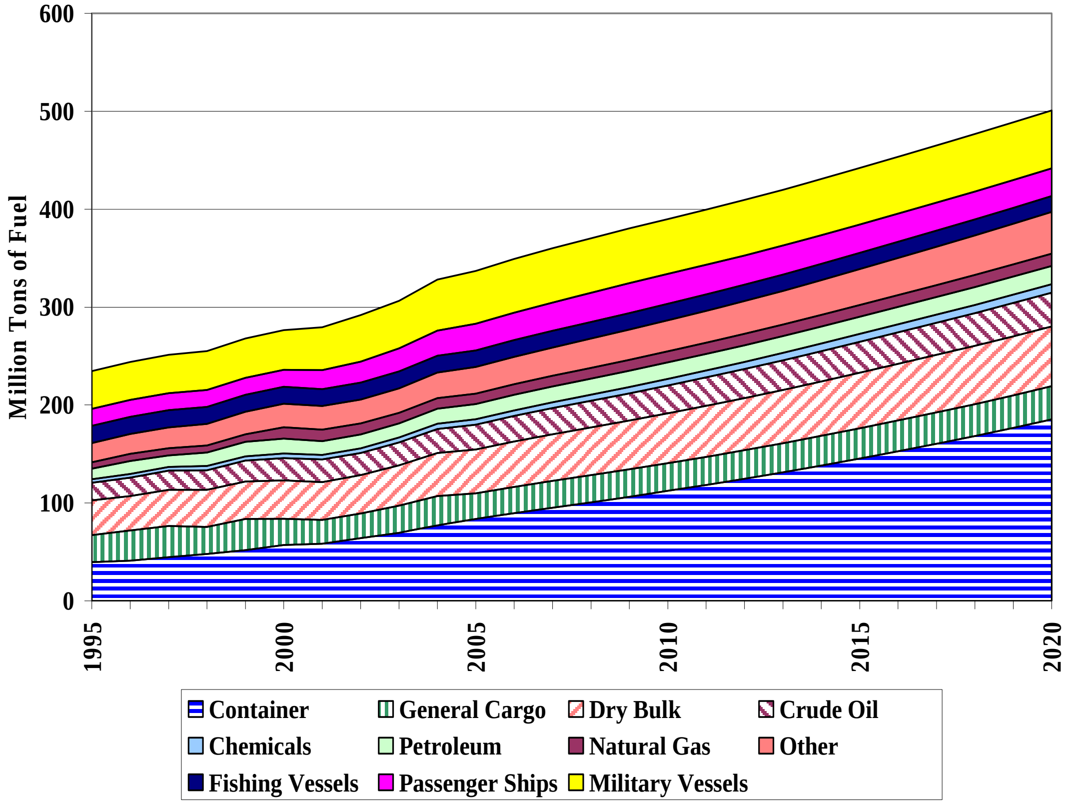


Figure 2-6 Worldwide Bunker Fuel Consumption

Figure 2-6 shows estimated world-wide bunker fuel consumption by vessel type. Figure 2-7 shows the annual growth rates by vessel-type/cargo that are used in the projections shown in Figure 2-6. Total annual growth is generally between 2.5 percent and 3.5 percent over the time period between 2006 and 2020 and generally declines over time, resulting in an average annual growth of around 2.6 percent.

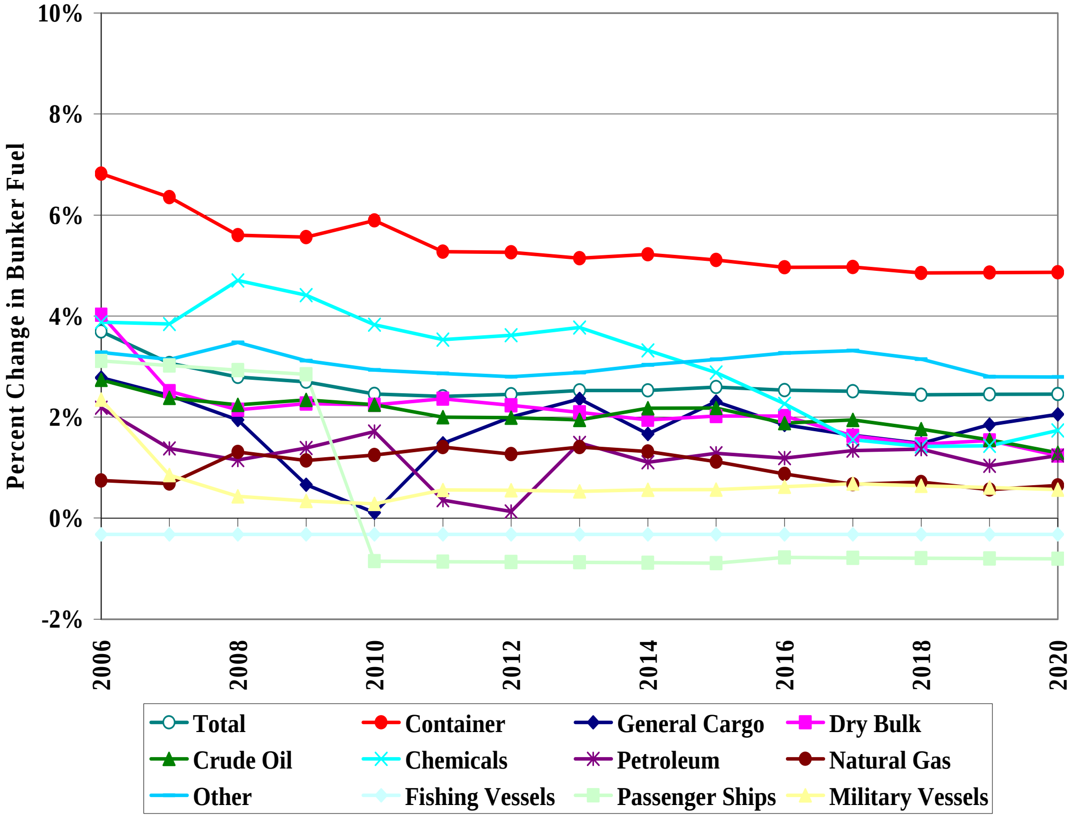


Figure 2-7 Annual Growth Rate in World-Wide Bunker Fuel Use by Commodity Type

2.4.2.7 Fuel Demand Used to Import and Export Cargo for the United States

The methodology described above provides an estimate of fuel consumption for international cargo worldwide. RTI also estimated the subset of fuel demand for cargo imported to and exported from five regions of the U.S. The five regions are:

- North Pacific
- South Pacific
- Gulf
- East Coast
- Great Lakes

For this analysis, the same equations were used, but were limited to routes that carried cargo between specific cities in Asia, Europe and Middle East to the various ports in the specific regions of the U.S.

The trip distances for non-container vessel types were developed from information from Worldscale Association and Maritime Chain.[35,36] The data from Worldscale is considered to be the industry standard for measuring port-to-port distances, particularly for tanker traffic. The reported distances account for common routes through channels, canals, or straits. This distance information was supplemented by data from Maritime Chain, a web service that provides port-to-port distances along with some information about which channels, canals, or straits must be passed on the voyage.

Voyage distances for container vessels are based on information from Containerization International Yearbook (CIY)[37] and calculations by RTI. That reference provides voyage information for all major container services. Based on the frequency of the service, number of vessels assigned to that service, and the number of days in operation per year, RTI estimated the average length of voyages for the particular bilateral trade routes in the Global Insights trade forecasts.

The distance information developed above was combined with the vessel speeds previously shown in Table 2-19 to find the length of a voyage in days. Table 2-20 presents the day lengths for non-containerized vessel types and Table 2-21 shows the same information for container vessels.

Table 2-20 Day Length for Voyages for Non-Container Cargo Ship (approximate average)

Global Insights Trade Regions	**Days per Voyage** US South Pacific	US North Pacific	US East Coast	US Great Lakes	US Gulf
Africa East-South	68	75	57	62	54
Africa North-Mediterranean	49	56	37	43	47
Africa West	56	63	36	46	43
Australia-New Zealand	48	47	65	81	63
Canada East	37	46	7	18	19
Canada West	11	5	40	58	39
Caspian Region	95	89	41	46	48
China	41	36	73	87	69
Europe Eastern	61	68	38	45	46
Europe Western-North	53	60	24	32	34
Europe Western-South	54	61	30	37	37
Greater Caribbean	26	33	16	29	17
Japan	35	31	65	81	62
Middle East Gulf	77	72	56	65	83
Pacific High Growth	52	48	67	76	88
Rest of Asia	68	64	66	64	73
Russia-FSU	64	71	38	46	48
Rest of South America	51	30	41	46	44

Table 2-21 Day Length for Voyages for Container-Ship Trade Routes

Origin – Destination Regions	**Days per Voyage**
Asia – North America (Pacific)	37
Europe – North America (Atlantic)	37
Mediterranean – North America	41
Australia/New Zealand – North America	61
South America – North America	48
Africa South – North America (Atlantic)	54
Africa West – North America (Atlantic)	43

Origin – Destination Regions	Days per Voyage
Asia – North America (Atlantic)	68
Europe – North America (Pacific)	64
Africa South – North America (Pacific)	68
Africa West – North America (Pacific)	38
Caspian Region – North America (Atlantic)	42
Caspian Region – North America (Pacific)	38
Middle East/Gulf Region – North America (Atlantic)	63
Middle East/Gulf Region – North America (Pacific)	80

2.4.2.8 Bunker Fuel Consumption for the United States

Figure 2-8 and Figure 2-9 present the estimates of fuel use for delivering trade goods to and from the U.S. The results in Figure 2-8 show estimated historical bunker fuel use in year 2001 of around 47 million tonnes (note: while this fuel is used to carry trade goods to and from the U.S., it is not necessarily all purchased in the U.S. and is not all burned in U.S. waters). This amount grows to over 90 million tonnes by 2020 with the most growth occurring on trade routes from the East Coast and the "South Pacific" region of the West Coast.

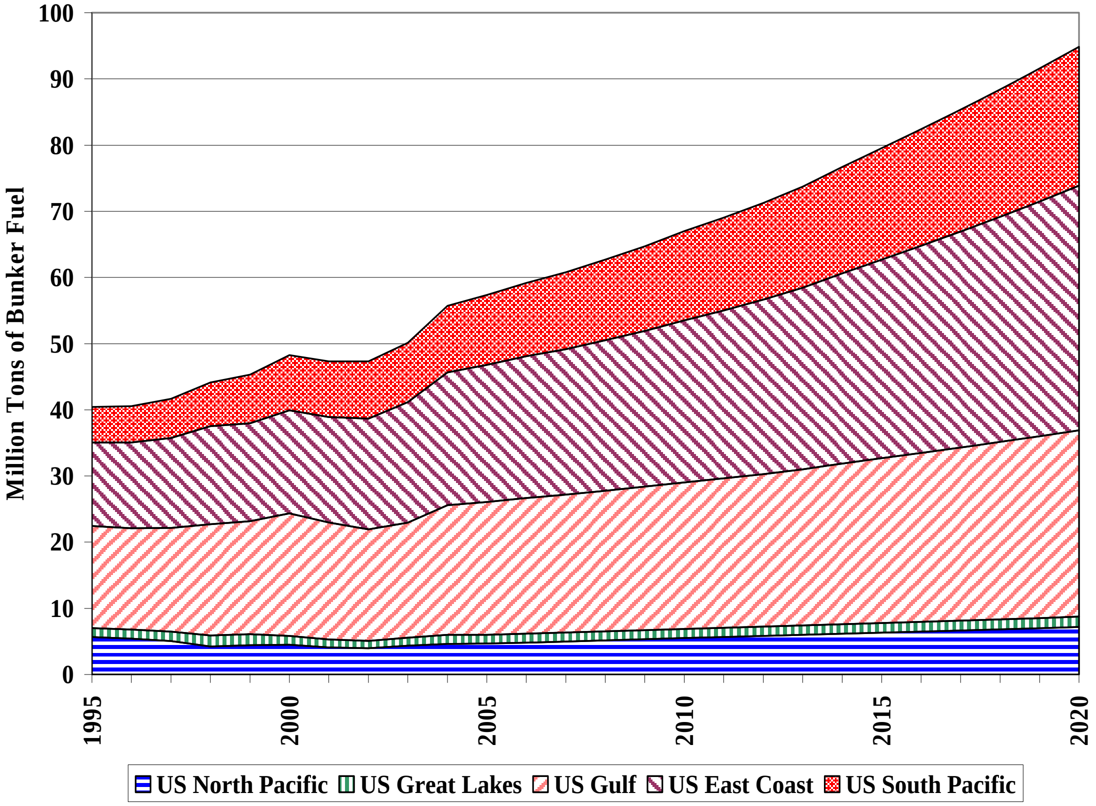


Figure 2-8 Bunker Fuel Used to Import and Export Cargo by Region of the United States

Figure 2-9 shows the estimated annual growth rates for the fuel consumption that are used in the projections shown in Figure 2-8. Overall, the average annual growth rate in marine bunkers associated with future U.S. trade flows is 3.4 percent between 2005 and 2020.

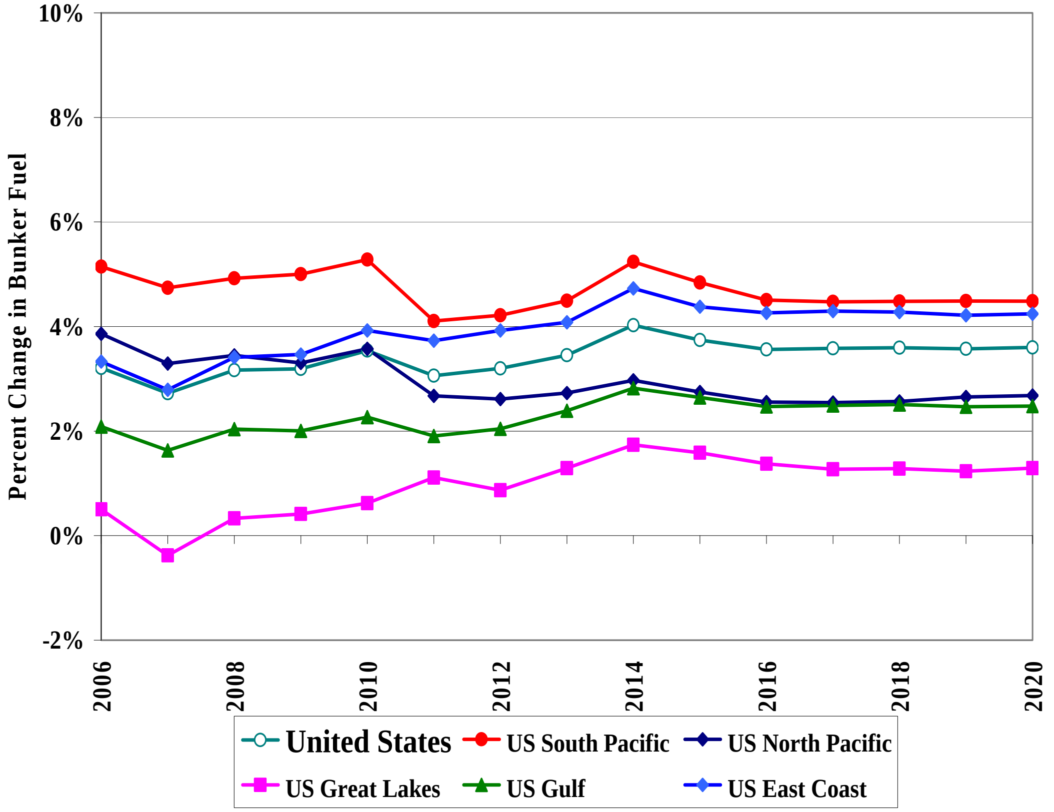


Figure 2-9 Annual Growth Rates for Bunker Fuel Used to Import and Export Cargo by Region of the United States

2.4.2.9 2020 Growth Factors for Nine Geographic Regions

The results of the RTI analysis described above are used to develop the growth factors that are necessary to project the 2002 base year emissions inventory to 2020. The next two sections describe how the five RTI regions were associated with the nine regions analyzed in this report, and how the specific growth rates for each of the nine regions were developed.

2.4.2.9.1 Mapping the RTI Regional Results to the Nine Region Analysis

The nine geographic regions analyzed in this study were designed to be consistent with the five RTI regional modeling domains. More specifically, four of the nine geographic areas in this study, i.e., Alaska East, Alaska West, Hawaii East, and Hawaii West are actually subsets of two broader regional areas that were analyzed by RTI, i.e., the North Pacific for both Alaska regions and South Pacific for Hawaii. Therefore, the growth rate information from the related larger region was assumed to be representative for that state.

The nine geographic regions represented in the emission inventory study are presented in Figure 2-1. The association of the RTI regions to the emission inventory regions is shown in Table 2-22.

Table 2-22 Association of the RTI Regions to the Nine Emission Inventory Regions

Consumption Region	Corresponding Emission Inventory Region
North Pacific	North Pacific (NP)
North Pacific	Alaska East (AE)
North Pacific	Alaska West (AW)
South Pacific	South Pacific (SP)
South Pacific	Hawaii East (HE)
South Pacific	Hawaii West (HW)
Gulf	Gulf Coast (GC)
East Coast	East Coast (EC)
Great Lakes	Great Lakes (GL)

2.4.2.9.2 Growth Factors for the Emission Inventory Analysis

Emission inventories for 2020 are estimated by multiplying the 2002 baseline inventory for each region by a corresponding growth factor that was developed from the RTI regional results. Specifically, the average annual growth rate from 2002-2020 was calculated for each of the five regions. Each regional growth rate was then compounded over the inventory projection time period for 2020, i.e., 18 years. The resulting multiplicative growth factors for each emission inventory region and the associated RTI average annual growth rates are presented in Table 2-23 for 2020.

Table 2-23 Regional Emission Inventory Growth Factors for 2020

Emission Inventory Region	2002-2020 Average Annualized Growth Rate (%)	Multiplicative Growth Factor Relative to 2002
Alaska East (AE)	3.3	1.79
Alaska West (AW)	3.3	1.79
East Coast (EC)	4.5	2.21
Gulf Coast (GC)	2.9	1.67
Hawaii East (HE)	5.0	2.41
Hawaii West (HW)	5.0	2.41
North Pacific (NP)	3.3	1.79
South Pacific (SP)	5.0	2.41
Great Lakes (GL)	1.7	1.35

2.4.3 Emission Controls in 2020 Baseline and Control Scenarios

This section describes the control programs present in the 2020 baseline and control scenarios. Section 2.4.4 describes the process of incorporating these programs into the 2020 emission inventories.

The baseline scenario includes the International Marine Organization's (IMO) Tier I NO_X standard for marine diesel engines that became effective in 2000, as well as the Tier II standard that will become effective in 2011. Also included in the baseline inventories is the NO_X retrofit program for pre-controlled engines proposed by IMO.

Although the 0.1% fuel sulfur requirement goes into place for all vessels operating in ECAs beginning in 2015, the use of 2020 as the analytic year will still provide a representative scenario for the impact of the 0.1% fuel sulfur requirement on human health and the environment. This is because the fuel requirements of the ECA go into effect all at once; there is no phase-in. So the impacts of the fuel requirement in 2020 are expected to be the same as in 2015, with a small increase due to growth. With regard to the NO_X impacts, while 2020 will include five years of turnover to the Tier III standards, the long service lives of engines on ocean-going vessels mean that these impacts will be small and affect less than 25% of the total fleet, assuming an average 20-year service life. These NO_X reductions would not inflate the benefits of the program by very much, if any. Note that the global fuel sulfur standard does not go into effect until 2020. We did not include this in the 2020 analysis, to provide a better estimate of benefits in the early (pre-2020) years of the program

The effects of these controls are reflected in the 2020 emission inventories by applying appropriate adjustment factors that reflect the percentage of the vessel fleet in those years that are estimated to comply with the controls. Adjustment factors are ratios of 2020 to 2002 calendar year (CY) emission factors (EFs). Adjustment factors are derived separately by engine type for propulsion and auxiliary engines. The adjustment factors for propulsion engines are applied to the propulsion portion of the port inventory and the interport portion of the inventory. The adjustment factors for auxiliary engines are applied to the auxiliary portion of the port inventory.

The control scenario includes an Emission Control Area (ECA) within a distance of 200 nautical miles (nm) from shore. Outside this distance, baseline controls were applied (i.e., the Tier I and Tier II NO_X standards, the NO_X retrofit program, and current fuel sulfur content levels). The ECA NO_X controls include the baseline controls above, plus Tier II NO_X standards. Fuel sulfur content is also assumed to be controlled to 1,000 ppm within the ECA. Note that gas and steam turbine engines are not subject to any of the NO_x standards; however, these engines are not a large part of the inventory.

The retrofit program for Tier 0 (pre-control) engines was modeled as 11 percent control from Tier 0 for 80 percent of 1990 thru 1999 model year (MY) engines greater than 90 liters per cylinder (L/cyl) starting in 2011. The retrofit program was also modeled with a five year phase-in. The current Tier I controls, which also are modeled as achieving an 11 percent reduction from Tier 0, apply to the 2000 thru 2010 MY engines. In 2011 thru 2015, Tier II controls are applied. Tier II controls are modeled as a 2.5 g/kW-hr reduction from Tier I. In the ECA area only, for 2016 MY engines and beyond, Tier III controls are applied. Tier III controls are modeled as achieving an 80 percent reduction from Tier I levels. Control of fuel sulfur content within the ECA area affects SO_2 and PM emissions.

ECA controls were applied to the 48 state region as well as Alaska East (AE) and Hawaii East (HE). Alaska West (AW) and Hawaii West (HW) are baseline cases only.

2.4.4 2020 Emission Factors

This section describes the emission factors that are used in the 2020 scenarios. HC and CO emission factors are assumed to remain unchanged from the 2002 scenario. NO_x and fuel sulfur controls are anticipated to lower NO_X, SO_2 and PM emission factors. The switch to lower sulfur distillate fuel use is also assumed to lower CO_2 emissions slightly.

The NO_X emission factors (EFs) by engine/ship type and tier are provided in Table 2-24. Tier 0 refers to pre-control. There are separate entries for Tier 0/1/2 base and Tier 0/1/2 control, since the control engines would be using distillate fuel, and there are small NO_X emission reductions assumed when switching from residual to distillate fuel.[17] The NO_X control EFs by tier were derived using the assumptions described in section 2.4.3.

Table 2-24 Modeled NO_X Emission Factors by Tier

Engine/ Ship Type	**NO_X EF (g/kW-hr)**								
	Baseline				**Control Areas**				
	Tier 0	**T0 retrofit**	**Tier I**	**Tier II**	**Tier 0**	**T0 retrofit**	**Tier I**	**Tier II**	**Tier III**
Main									
SSD	18.1	16.1	16.1	13.6	17	15.1	15.1	12.6	3
MSD	14	12.5	12.5	10.0	13.2	11.7	11.7	9.2	2.3
ST	2.1	n/a	n/a	n/a	2	n/a	n/a	n/a	n/a
GT	6.1	n/a	n/a	n/a	5.7	n/a	n/a	n/a	n/a
Aux									
Pass	14.6	n/a[a]	13.0	10.5	14.6	n/a[a]	13.0	10.5	2.6
Other	14.5	n/a[a]	12.9	10.4	14.5	n/a[a]	12.9	10.4	2.6

[a] The retrofit program applies to engines over 90 L/cyl; auxiliary engines are smaller than this cutpoint and would therefore not be subject to the program.

The NO_X EFs by tier were then used with the vessel age distributions (Table 2-25 & Table 2-26) to generate calendar year NO_X EFs by engine/ship type for the base and control areas included in the scenarios. These calendar year NO_X EFs are provided in Table 2-27 below. Since the age distributions are different for vessels in the Great Lakes, NO_X EFs were determined separately for the Great Lakes.

Table 2-25 Vessel Age Distribution for Deep Sea Ports by Engine Type

Age Group (years old)	Propulsion Engine Type [a] (Fraction of Total)				All Auxiliary Engines
	MSD	SSD	GT	ST	
0	0.00570	0.02667	0.00000	0.00447	0.01958
1	0.07693	0.07741	0.07189	0.12194	0.07670
2	0.10202	0.07512	0.14045	0.16464	0.08426
3	0.08456	0.07195	0.05608	0.05321	0.07489
4	0.08590	0.05504	0.67963	0.00000	0.07831
5	0.06427	0.05563	0.04165	0.00000	0.05685
6	0.06024	0.04042	0.00000	0.00000	0.04455
7	0.07867	0.07266	0.00626	0.00000	0.07150
8	0.06730	0.05763	0.00000	0.00000	0.05764
9	0.04181	0.04871	0.00000	0.00000	0.04475
10	0.04106	0.04777	0.00000	0.00000	0.04364
11	0.03100	0.03828	0.00000	0.00000	0.03538
12	0.04527	0.03888	0.00000	0.04873	0.04160
13	0.03583	0.02787	0.00000	0.00000	0.02909
14	0.03519	0.02824	0.00000	0.00000	0.02935
15	0.02921	0.01466	0.00000	0.00000	0.01869
16	0.00089	0.01660	0.00000	0.00000	0.01189
17	0.01326	0.01582	0.00000	0.00000	0.01462
18	0.00847	0.02414	0.00000	0.00000	0.01966
19	0.00805	0.01982	0.00000	0.00000	0.01550
20	0.00566	0.02258	0.00000	0.00000	0.01756
21	0.00495	0.02945	0.00000	0.00000	0.02260
22	0.00503	0.01883	0.00000	0.00875	0.01467
23	0.00676	0.01080	0.00000	0.00883	0.00943
24	0.00539	0.01091	0.00000	0.00883	0.00900
25	0.01175	0.01099	0.00000	0.18029	0.01224
26	0.00803	0.01045	0.00000	0.11065	0.01130
27	0.00522	0.00835	0.00000	0.01395	0.00738
28	0.00294	0.00788	0.00000	0.08657	0.00659
29	0.00285	0.00370	0.00034	0.02907	0.00349
30	0.00254	0.00106	0.00370	0.05126	0.00193
31	0.00084	0.00113	0.00000	0.00605	0.00096
32	0.00023	0.00367	0.00000	0.07105	0.00322
33	0.00117	0.00582	0.00000	0.00000	0.00419
34	0.00132	0.00092	0.00000	0.00000	0.00098
35+	0.01967	0.00013	0.00000	0.03172	0.00598

[a] MSD is medium speed diesel, SSD is slow speed diesel, GT is gas turbine, ST is steam turbine.

Table 2-26 Vessel Age Distribution for Great Lake Ports by Engine Type

Age Group (years old)	Propulsion Engine Type[a] (Fraction of Total)			
	MSD	SSD	ST	All Auxiliary Engines
0	0.01610	0.03913	0.00000	0.02399
1	0.02097	0.03489	0.00000	0.02243
2	0.01370	0.04644	0.00000	0.02544
3	0.02695	0.03040	0.00000	0.02511
4	0.01571	0.04547	0.00000	0.02497
5	0.04584	0.01498	0.00000	0.02442
6	0.01494	0.02180	0.00000	0.01528
7	0.01327	0.01857	0.00000	0.01391
8	0.00099	0.04842	0.00000	0.02107
9	0.00027	0.03376	0.00000	0.01454
10	0.01085	0.01177	0.00000	0.01076
11	0.00553	0.01183	0.00000	0.00782
12	0.00739	0.00546	0.00000	0.00626
13	0.02289	0.02557	0.00000	0.02242
14	0.00000	0.00286	0.00000	0.00121
15	0.00275	0.00510	0.00000	0.00361
16	0.00069	0.00073	0.00000	0.00078
17	0.00000	0.00104	0.00000	0.00041
18	0.00342	0.01967	0.00000	0.01059
19	0.00219	0.01220	0.00000	0.00645
20	0.00867	0.06140	0.00000	0.03034
21	0.00000	0.05638	0.00000	0.02503
22	0.03375	0.02108	0.00000	0.02279
23	0.04270	0.02051	0.00000	0.02606
24	0.08161	0.01010	0.00000	0.03744
25	0.02935	0.05217	0.00000	0.03480
26	0.18511	0.00522	0.00000	0.07701
27	0.01870	0.00389	0.00000	0.01083
28	0.13815	0.01438	0.00000	0.06181
29	0.05487	0.01160	0.00000	0.02697
30	0.00000	0.00114	0.00000	0.00047
31	0.03986	0.00000	0.00000	0.01611
32	0.03654	0.00282	0.00000	0.01631
33	0.03358	0.00000	0.00000	0.01358
34	0.00295	0.00123	0.00000	0.00165
35+	0.06974	0.30796	1.00000	0.31734

[a] MSD is medium speed diesel, SSD is slow speed diesel, GT is gas turbine, ST is steam turbine.

[b] Fleet average weighted by installed power (ship port calls x main propulsion engine power).

Table 2-27 Modeled NO_X Emission Factors by Calendar Year and Control Type

Engine/ Ship Type	CY NO_X EF (g/kW-hr)				
	2002	2020 Base		2020 ECA Control	
		DSP	GL	DSP	GL
Main					
SSD	18.1	14.7	15.9	10.8	13.1
MSD	14	10.9	13.1	7.7	11.8
ST	2.1	2.1	2.1	2.0	2.0
GT	6.1	6.1	n/a	5.7	n/a
Aux					
Pass	14.6	11.7	13.6	8.6	12.0
Other	14.5	11.5	13.4	8.6	12.0

DSP = Deep water ports and areas other than the Great Lakes
GL = Great Lakes

The PM and SO_2 EFs are a function of fuel sulfur level. For the baseline portions of the inventory, there are two residual fuel sulfur levels modeled: 25,000 ppm for the West Coast and 27,000 ppm for the rest of the U.S. The baseline distillate fuel sulfur level assumed for all areas is 15,000 ppm. As discussed in section 2.3.2.3.5, for the baseline, main engines use residual fuel and auxiliary engines use a mix of residual and distillate fuel. For the control areas, there is one level of distillate fuel sulfur assumed to be used by all engines: 1,000 ppm for the ECA control areas.

Table 2-28 provides the PM_{10} EFs by engine/ship type and fuel sulfur level. For modeling purposes, $PM_{2.5}$ is assumed to be 92 percent of PM_{10}. The PM EFs are adjusted to reflect the appropriate fuel sulfur levels using Equation 2-2.

Table 2-29 provides the modeled SO_2 EFs. SO_2 emission reductions are directly proportional to reductions in fuel sulfur content.

CO_2 is directly proportional to fuel consumed. Table 2-30 provides the modeled CO_2 and brake specific fuel consumption (BSFC) EFs. Due to the higher energy content of distillate fuel on a mass basis, the switch to distillate fuel for the control areas results in a small reduction to BSFC and, correspondingly, CO_2 emissions.[17]

Table 2-28 Modeled PM_{10} Emission Factors

Engine/ Ship Type	PM_{10} EF (g/kW-hr)		
	Baseline		Control Areas
	Other than West Coast 27,000 ppm S	West Coast[a] 25,000 ppm S	ECA 1,000 ppm S
Main			
SSD	1.40	1.40	0.19
MSD	1.40	1.40	0.19
ST	1.50	1.40	0.17
GT	1.50	1.40	0.17
Aux			
Pass	1.40	1.30	0.19
Other	1.20	1.10	0.19

[a] For the base cases, the West Coast fuel is assumed to be used in the following regions: Alaska East (AE), Alaska West (AW), Hawaii East (HE), Hawaii West (HW), North Pacific (NP), and South Pacific (SP).

Table 2-29 Modeled SO_2 Emission Factors*

Engine/ Ship Type	SO_2 EF (g/kW-hr)		
	Baseline		Control Areas
	Other than West Coast 27,000 ppm S	West Coast[a] 25,000 ppm S	ECA Control 1,000 ppm S
Main			
SSD	10.29	9.53	0.36
MSD	11.09	10.26	0.39
ST	16.10	14.91	0.57
GT	16.10	14.91	0.57
Aux			
Pass	10.70	9.93	0.39
Other	9.66	9.07	0.39

[a] For the base cases, the West Coast fuel is assumed to be used in the following regions: Alaska East (AE), Alaska West (AW), Hawaii East (HE), Hawaii West (HW), North Pacific (NP), and South Pacific (SP).

Table 2-30 Modeled Fuel Consumption and CO_2 Emission Factors

Engine/ Ship Type	EF (g/kW-hr)			
	Baseline		Control Areas	
	BSFC	CO_2	BSFC	CO_2
Main				
SSD	195	620	185	589
MSD	210	668	200	637
ST	305	970	290	923
GT	305	970	290	923
Aux				
Pass	210	668	200	636
Other	210	668	200	636

2.4.5 Calculation of 2020 Near Port and Interport Inventories

Based on the emission factors described in Section 2.4.4, appropriate adjustments were applied to the NO_X, PM (PM_{10} and $PM_{2.5}$), SO_2, and CO_2 inventory of each 2020 scenario. This section describes the development and application of the adjustment factors to the port and interport inventories, and the methodology for combining the port and interport portions.

2.4.5.1 Port Methodology

2.4.5.1.1 Non-California Ports

For the non-California ports, 2002 emissions for each port are summed by engine/ship type. Propulsion and auxiliary emissions are summed separately, since the EF adjustment factors differ. The appropriate regional growth factor, as provided in Table 2-23, is then applied, along with EF adjustment factors by engine/ship type. The EF adjustment factors are a ratio of the control EF to the 2002 EF. Table 2-31 through Table 2-35 provide the EF adjustment factors for each pollutant and control area. The ports will be subject to ECA controls in the control scenario. These tables are also used as input for the California ports and interport control inventory development, discussed in subsequent sections.

Table 2-31 NO_X EF Adjustment Factors by Engine/Ship Type and Control Type[a]

Engine/ Ship Type	2020 Base		2020 ECA Control	
	DSP	GL	DSP	GL
Main				
SSD	0.8130	0.8783	0.5967	0.7219
MSD	0.7804	0.9366	0.5515	0.8423
ST	1.0000	1.0000	0.9524	0.9524
GT	1.0000	n/a	0.9344	n/a
Aux				
Pass	0.7985	0.9296	0.5869	0.8196
Other	0.7972	0.9292	0.5940	0.8295

[a] NO_X adjustment factors are a ratio of future base or control EFs to 2002 EFs
DSP = deep water ports and areas other than the Great Lakes; GL = Great Lakes

Table 2-32 PM_{10} EF Adjustment Factors by Engine/Ship Type and Control Type[a]

Engine/ Ship Type	2020 Base		2020 ECA Control	
	Other	WC	Other	WC
Main				
SSD	1.0000	1.0000	0.1352	0.1352
MSD	1.0000	1.0000	0.1328	0.1328
ST	1.0000	1.0000	0.1108	0.1187
GT	1.0000	1.0000	0.1108	0.1187
Aux				
Pass	1.0000	1.0000	0.1328	0.1430
Other	1.0000	1.0000	0.1550	0.1691

[a] PM_{10} adjustment factors are a ratio of the control EFs to the 2002 EFs. PM is not adjusted for the future baseline because fuel sulfur levels are only assumed to change within the ECA.
Other = Other than West Coast
WC = Ports/areas within the West Coast. This includes the regions of Alaska, Hawaii, North Pacific, and South Pacific.

Table 2-33 $PM_{2.5}$ EF Adjustment Factors by Engine/Ship Type and Control Type[a]

Engine/ Ship Type	2020 Base		2020 ECA Control	
	Other	WC	Other	WC
Main				
SSD	1.0000	1.0000	0.1339	0.1339
MSD	1.0000	1.0000	0.1316	0.1316
ST	1.0000	1.0000	0.1092	0.1176
GT	1.0000	1.0000	0.1092	0.1176
Aux				
Pass	1.0000	1.0000	0.1316	0.1426
Other	1.0000	1.0000	0.1555	0.1711

[a] $PM_{2.5}$ adjustment factors are a ratio of the control EFs to the 2002 EFs. PM is not adjusted for the future baseline because fuel sulfur levels are only assumed to change within the ECA. The $PM_{2.5}$ adjustment factors are slightly different from those for PM_{10} due to rounding.
Other = Other than West Coast
WC = Ports/areas within the West Coast. This includes the regions of Alaska, Hawaii, North Pacific, and South Pacific.

Table 2-34 SO_2 EF Adjustment Factors by Engine/Ship Type and Control Type[a]

Engine/ Ship Type	2020 Base		2020 ECA Control	
	Other	WC	Other	WC
Main				
SSD	1.0000	1.0000	0.0351	0.0380
MSD	1.0000	1.0000	0.0353	0.0381
ST	1.0000	1.0000	0.0352	0.0380
GT	1.0000	1.0000	0.0352	0.0380
Aux				
Pass	1.0000	1.0000	0.0365	0.0394
Other	1.0000	1.0000	0.0405	0.0431

[a] SO_2 adjustment factors are a ratio of the control EFs to the 2002 EFs. SO_2 is not adjusted for the future baseline because fuel sulfur levels are only assumed to change within the ECA.
Other = Other than West Coast
WC = Ports/areas within the West Coast. This includes the regions of Alaska, Hawaii, North Pacific, and South Pacific.

Table 2-35 CO_2 EF Adjustment Factors by Engine/Ship Type and Control Type[a]

Engine/ Ship Type	2020 Base		2020 ECA Control	
	Other	WC	Other	WC
Main				
SSD	1.0000	1.0000	0.9488	0.9488
MSD	1.0000	1.0000	0.9531	0.9531
ST	1.0000	1.0000	0.9509	0.9509
GT	1.0000	1.0000	0.9509	0.9509
Aux				
Pass	1.0000	1.0000	0.9525	0.9593
Other	1.0000	1.0000	0.9525	0.9683

[a] CO_2 adjustment factors are a ratio of the control EFs to the 2002 EFs. CO_2 is not adjusted for the future baseline because fuel consumption (BSFC) is only assumed to change within the ECA.
Other = Other than West Coast
WC = Ports/areas within the West Coast. This includes the regions of Alaska, Hawaii, North Pacific, and South Pacific.

2.4.5.1.2 California Ports

For the California ports, 2002 emissions for each port are summed by ship type. Propulsion and auxiliary emissions are summed separately, since the EF adjustment factors differ. The EF adjustment factors by engine/ship type, provided in the previous section, are consolidated by ship type, using the CARB assumption that engines on all ships except passenger ships are 95 percent slow speed diesel (SSD) engines and 5 percent medium speed diesel engines (MSD) based upon a 2005 ARB survey.[C] All passenger ships were assumed to be medium speed diesel engines with electric drive propulsion (MSD-ED). Steam turbines (ST) and gas-turbines (GT) are not included in

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[C] California Air Resources Board, *2005 Oceangoing Ship Survey, Summary of Results*, September 2005.

the CARB inventory. The EF adjustment factors by ship type are then applied, along with ship-specific growth factors supplied by CARB. The ship-specific growth factors relative to 2002 are provided in Table 2-36 below.

Table 2-36 Growth Factors by Ship Type for California Ports Relative to 2002

Ship Type	Calendar Year	
	2002	**2020**
Auto	1.0000	1.5010
Bulk	1.0000	0.2918
Container	1.0000	2.5861
General	1.0000	0.7331
Passenger	1.0000	7.5764
Reefer	1.0000	1.0339
RoRo	1.0000	1.5010
Tanker	1.0000	2.0979

2.4.5.2 Interport Methodology

The interport portion of the inventory is not segregated by engine or ship type. As a result, regional EF adjustment factors were developed based on the assumed mix of main (propulsion) engine types in each region. The mix of main engine types by region was developed using the ship call data and is presented in Table 2-37. Main engines are considered a good surrogate for interport emissions, since the majority of emissions while underway are due to the main engines. The EF adjustment factors by main engine type in Section 2.4.5.1were used together with the mix of main engine types by region to develop the EF regional adjustment factors for each control area. The resulting EF regional adjustment factors for each pollutant and control area are provided in Table 2-38 through Table 2-42 below. These EF regional adjustment factors, together with the regional growth factors in Table 2-23, were applied to calculate the future inventories for each control area.

Table 2-37 Installed Power by Main Engine Type and Region

Region	2020 Installed Power (%)				
	MSD	**SSD**	**GT**	**ST**	**Total**
Alaska East (AE)	19.1%	18.4%	0.3%	62.2%	100%
Alaska West (AW)	19.1%	18.4%	0.3%	62.2%	100%
East Coast (EC)	25.6%	72.5%	0.9%	1.0%	100%
Gulf Coast (GC)	13.7%	85.5%	0.0%	0.8%	100%
Hawaii East (HE)	66.2%	18.5%	7.4%	8.0%	100%
Hawaii West (HW)	66.2%	18.5%	7.4%	8.0%	100%
North Pacific (NP)	5.1%	83.5%	1.6%	9.7%	100%
South Pacific (SP)	29.2%	70.8%	0.0%	0.0%	100%
Great Lakes (GL)	48%	44%	0%	8%	100%

Table 2-38 NO_X EF Adjustment Factors by Region and Control Type[a]

U.S. Region	2002	2020	
		Base	ECA Control
Alaska East (AE)	1.0000	0.9237	0.8104
Alaska West (AW)	1.0000	0.9237	n/a
East Coast (EC)	1.0000	0.8082	0.5917
Gulf Coast (GC)	1.0000	0.8102	0.5935
Hawaii East (HE)	1.0000	0.8202	0.6201
Hawaii West (HW)	1.0000	0.8202	n/a
North Pacific (NP)	1.0000	0.8325	0.6343
South Pacific (SP)	1.0000	0.8036	0.5837
Great Lakes (GL)	1.0000	0.8131	0.7989
Out of Region[b]	1.0000	0.8095	n/a

[a] NO_X adjustment factors are a ratio of future base or control EFs to 2002 EFs. These regional adjustment factors are used to adjust the interport portion of the 2002 inventory.

[b] Out of Region refers to areas outside the 200 nm US modeling boundary, but within the air quality modeling domain. The out of region adjustment factors are derived by weighting the regional adjustment factors by the main propulsion power in each region.

Table 2-39 PM_{10} EF Adjustment Factors by Region and Control Type[a]

U.S. Region	2002	2020	
		Base	ECA Control
Alaska East (AE)	1.0000	1.0000	0.1244
Alaska West (AW)	1.0000	1.0000	n/a
East Coast (EC)	1.0000	1.0000	0.1341
Gulf Coast (GC)	1.0000	1.0000	0.1347
Hawaii East (HE)	1.0000	1.0000	0.1311
Hawaii West (HW)	1.0000	1.0000	n/a
North Pacific (NP)	1.0000	1.0000	0.1332
South Pacific (SP)	1.0000	1.0000	0.1345
Great Lakes (GL)	1.0000	1.0000	0.1320
Out of Region[b]	1.0000	1.0000	n/a

[a] PM_{10} adjustment factors are a ratio of future base or control EFs to 2002 EFs. These regional adjustment factors are used to adjust the interport portion of the 2002 inventory.

[b] Out of Region refers to areas outside the 200 nm US modeling boundary, but within the air quality modeling domain. The out of region adjustment factors are derived by weighting the regional adjustment factors by the main propulsion power in each region.

Table 2-40 $PM_{2.5}$ EF Adjustment Factors by Region and Control Type[a]

U.S. Region	2002	2020	
		Base	ECA Control
Alaska East (AE)	1.0000	1.0000	0.1233
Alaska West (AW)	1.0000	1.0000	n/a
East Coast (EC)	1.0000	1.0000	0.1329
Gulf Coast (GC)	1.0000	1.0000	0.1334
Hawaii East (HE)	1.0000	1.0000	0.1299
Hawaii West (HW)	1.0000	1.0000	n/a
North Pacific (NP)	1.0000	1.0000	0.1320
South Pacific (SP)	1.0000	1.0000	0.1332
Great Lakes (GL)	1.0000	1.0000	0.1307
Out of Regionb	1.0000	1.0000	n/a

[a] $PM_{2.5}$ adjustment factors are a ratio of future base or control EFs to 2002 EFs. These regional adjustment factors are used to adjust the interport portion of the 2002 inventory.

[b] Out of Region refers to areas outside the 200 nm US modeling boundary, but within the air quality modeling domain. The out of region adjustment factors are derived by weighting the regional adjustment factors by the main propulsion power in each region.

Table 2-41 SO_2 EF Adjustment Factors by Region and Control Type[a]

U.S. Region	2002	2020	
		Base	ECA Control
Alaska East (AE)	1.0000	1.0000	0.0380
Alaska West (AW)	1.0000	1.0000	n/a
East Coast (EC)	1.0000	1.0000	0.0352
Gulf Coast (GC)	1.0000	1.0000	0.0352
Hawaii East (HE)	1.0000	1.0000	0.0381
Hawaii West (HW)	1.0000	1.0000	n/a
North Pacific (NP)	1.0000	1.0000	0.0380
South Pacific (SP)	1.0000	1.0000	0.0380
Great Lakes (GL)	1.0000	1.0000	0.0352
Out of Region[b]	1.0000	1.0000	n/a

[a] SO_2 adjustment factors are a ratio of future base or control EFs to 2002 EFs. These regional adjustment factors are used to adjust the interport portion of the 2002 inventory.

[b] Out of Region refers to areas outside the 200 nm US modeling boundary, but within the air quality modeling domain. The out of region adjustment factors are derived by weighting the regional adjustment factors by the main propulsion power in each region are derived by weighting the regional adjustment factors by the main propulsion power in each region.

Table 2-42 CO_2 EF Adjustment Factors by Region and Control Type[a]

U.S. Region	2002	2020	
		Base	ECA Control
Alaska East (AE)	1.0000	1.0000	0.9509
Alaska West (AW)	1.0000	1.0000	n/a
East Coast (EC)	1.0000	1.0000	0.9499
Gulf Coast (GC)	1.0000	1.0000	0.9494
Hawaii East (HE)	1.0000	1.0000	0.9519
Hawaii West (HW)	1.0000	1.0000	n/a
North Pacific (NP)	1.0000	1.0000	0.9493
South Pacific (SP)	1.0000	1.0000	0.9501
Great Lakes (GL)	1.0000	1.0000	0.9510
Out of Region[b]	1.0000	1.0000	n/a

[a] CO_2 adjustment factors are a ratio of future base or control EFs to 2002 EFs. These regional adjustment factors are used to adjust the interport portion of the 2002 inventory.

[b] Out of Region refers to areas outside the 200 nm US modeling boundary, but within the air quality modeling domain. The out of region adjustment factors are derived by weighting the regional adjustment factors by the main propulsion power in each region.

2.4.5.3 Estimating and Combining the Near Port and Interport Control Inventories

To produce future year control scenarios, the interport inventories were scaled by a growth factor to 2020, as previously described. An ECA boundary line was drawn so that each point on it was at a 200 nm distance from the nearest point on land. Adjustment factors, as described in section 2.4.4, were then applied to interport emissions within the ECA boundary.

To create control scenarios in the near port inventories, growth and control factors were applied to the 2002 near port inventories (described in sections 2.4.2 and 2.4.4). The near port inventories were then converted into a gridded format (section 2.3.4). Using this grid, STEEM values were removed from near port cells and near port emissions were used as replacement values. In cases where the emissions near ports were only partially attributable to port traffic, the STEEM inventory was reduced rather than removed.

Interport and near port emissions were then aggregated to form regional totals.

2.4.6 2020 Baseline and Control Inventories and Fuel Consumption

The baseline emission inventories for 2020 are presented in Table 2-43.

Table 2-43 2020 Baseline Inventory

U.S. Region	Metric Tonnes per Year						
	NOx	PM10	PM2.5[a]	HC	CO	SO_2	CO_2
Alaska East (AE)	27,982	2,561	2,356	1,073	2,534	19,084	1,182,047
Alaska West (AW)	89,826	8,118	7,469	3,444	8,112	60,227	3,711,596
East Coast (EC)	391,995	39,003	35,882	16,216	38,382	323,038	18,121,202
Gulf Coast (GC)	232,114	23,403	21,531	9,590	23,628	174,751	10,567,512
Hawaii East (HE)	42,935	4,185	3,850	1,765	4,161	31,075	1,930,172
Hawaii West (HW)	60,409	5,888	5,417	2,483	5,855	43,722	2,715,741
North Pacific (NP)	38,051	3,916	3,603	1,706	3,799	27,807	1,800,743
South Pacific (SP)	208,294	20,148	18,536	8,585	20,686	149,751	9,490,502
Great Lakes (GL)	18,768	1,613	1,484	681.914	1,607	11,993	740,624
Total U.S. Metric Tonnes	**1,110,375**	**108,835**	**100,128**	**45,544**	**108,762**	**841,447**	**50,260,140**

[a] Estimated from PM_{10} using a multiplicative conversion factor of 0.92.

The ECA control case inventories for each of the nine geographic regions and the U.S. domain total are presented in Table 2-44. The regional and total inventories include all emissions within the 200 nm US modeling domain. Controls are applied to all regions included in the proposed ECA.

Table 2-44 Category 3 Vessel Inventories for 2020 Proposed ECA Control Case[a]

U.S. Region	Metric Tonnes per Year						
	NOx	PM10	PM2.5[a]	HC	CO	SO_2	CO_2
Alaska East (AE)	25,978	322	296	1,073	2,534	728	1,124,652
Alaska West (AW)	89,826	8,118	7,469	3,444	8,112	60,227	3,711,596
East Coast (EC)	289,671	5,286	4,863	16,216	38,382	11,514	17,233,800
Gulf Coast (GC)	170,861	3,201	2,945	9,590	23,628	6,255	10,034,946
Hawaii East (HE)	32,952	551	507	1,765	4,161	1,187	1,838,832
Hawaii West (HW)	60,409	5,888	5,417	2,483	5,855	43,722	2,715,741
North Pacific (NP)	29,105	539	496	1,706	3,799	1,076	1,715,210
South Pacific (SP)	150,461	2,753	2,533	8,585	20,686	5,786	9,009,986
Great Lakes (GL)	16,420	207	190	681	1,607	420	704,390
Total U.S. Metric Tonnes	**865,684**	**26,864**	**24,715**	**45,544**	**108,762**	**130,914**	**48,089,152**

[a] This scenario assumes ECA controls apply within 200 nautical miles of all U.S. regions. Alaska West and Hawaii West are not subject to ECA controls.

The fuel consumption by fuel type in the baseline and ECA cases is also presented in Table 2-45.

Table 2-45 Fuel Consumption by Category 3 Vessels in Baseline and ECA Scenarios.

U.S. Region	Baseline			With ECA		
	Metric Tonnes Fuel			Metric Tonnes Fuel		
	Distillate	Residual	Total	Distillate	Residual	Total
Alaska East (AE)	3,386	367,977	371,363	353,331	0	353,331
Alaska West (AW)	0	1,166,068	1,166,068	0	1,166,068	1,166,068
East Coast (EC)	202,139	5,490,981	5,693,120	5,414,326	0	5,414,326
Gulf Coast (GC)	96,428	3,223,557	3,319,985	3,152,669	0	3,152,669
Hawaii East (HE)	10,529	595,871	606,400	577,704	0	577,704
Hawaii West (HW)	0	853,202	853,202	0	853,202	853,202
North Pacific (NP)	28,532	537,206	565,738	538,866	0	538,866
South Pacific (SP)	83,576	2,898,045	2,981,622	2,830,658	0	2,830,658
Great Lakes (GL)	1,269	231,412	232,681	221,297	0	221,297
Total U.S. Metric Tonnes	**425,860**	**15,364,319**	**15,790,179**	**13,088,852**	**2,019,270**	**15,108,122**

2.5 Projected Emission Reductions

The projected reduction (tonnes) for the 2020 control case relative to the 2020 baseline is presented in Table 2-46. Reductions by region, for the total U.S., and for the total 48-states, are provided by pollutant in each table.

Table 2-46 Reductions for 2020 Proposed ECA Control Case[a]

U.S. Region	Metric Tonnes per Year						
	NO_X	PM_{10}	$PM_{2.5}$[a]	HC	CO	SO_2	CO_2
Alaska East (AE)	2,004	2,239	2,060	0	0	18,356	57,395
Alaska West (AW)	0	0	0	0	0	0	0
East Coast (EC)	102,324	33,717	31,019	0	0	311,524	887,402
Gulf Coast (GC)	61,253	20,202	18,586	0	0	168,496	532,566
Hawaii East (HE)	9,983	3,634	3,343	0	0	29,888	91,340
Hawaii West (HW)	0	0	0	0	0	0	0
North Pacific (NP)	8,946	3,377	3,107	0	0	26,731	85,533
South Pacific (SP)	57,833	17,395	16,003	0	0	143,965	480,516
Great Lakes (GL)	2,348	1,406	1,294	0	0	11,573	36,234
Total U.S. Metric Tonnes	244,690	81,971	75,413	0	0	710,534	2,170,987

[a] The emission reductions are relative to the 2020 baseline.

2.6 Conclusion

An emission inventory for ships in the U.S. was developed based on the latest state of the art models and inputs, using a "bottom-up" methodology. The inventory includes emissions for 117 ports, as well as emissions for ships while underway in U.S. waters. The analysis clearly demonstrates that emissions from ships in the proposed ECA are contributing to U.S. air pollution. The inventory data were used as an input for the air quality modeling analysis.

Appendices

Appendix 2A: Port Coordinates

Table 2A-1 Port Coordinates

Port Name	US ACE Code	Port Coordinates	
		Longitude	Latitude
Albany, NY	C0505	-73.7482	42.64271
Alpena, MI	L3617	-83.4223	45.0556
Anacortes, WA	C4730	-122.6	48.49617
Anchorage, AK	C4820	-149.895	61.23778
Ashtabula, OH	L3219	-80.7917	41.91873
Baltimore, MD	C0700	-76.5171	39.20899
Barbers Point, Oahu, HI	C4458	-158.109	21.29723
Baton Rouge, LA	C2252	-91.1993	30.42292
Beaumont, TX	C2395	-94.0881	30.08716
Boston, MA	C0149	-71.0523	42.35094
Bridgeport, CT	C0311	-73.1789	41.172
Brownsville, TX	C2420	-97.3981	25.9522
Brunswick, GA	C0780	-81.4999	31.15856
Buffalo, NY	L3230	-78.8953	42.8783
Burns Waterway Harbor, IN	L3739	-87.1552	41.64325
Calcite, MI	L3620	-83.7756	45.39293
Camden-Gloucester, NJ	C0551	-75.1043	39.94305
Carquinez, CA	CCA01	-122.123	38.03556
Catalina, CA	CCA02	-118.496	33.43943
Charleston, SC	C0773	-79.9216	32.78878
Chester, PA	C0297	-75.3222	39.85423
Chicago, IL	L3749	-87.638	41.88662
Cleveland, OH	L3217	-81.6719	41.47852
Conneaut, OH	L3220	-80.5486	41.96671
Coos Bay, OR	C4660	-124.21	43.36351
Corpus Christi, TX	C2423	-97.3979	27.81277
Detroit, MI	L3321	-83.1096	42.26909
Duluth-Superior, MN and WI	L3924	-92.0964	46.77836
El Segundo, CA	CCA03	-118.425	33.91354
Erie, PA	L3221	-80.0679	42.15154
Escanaba, MI	L3795	-87.025	45.73351
Eureka, CA	CCA04	-124.186	40.79528
Everett, WA	C4725	-122.229	47.98476
Fairport Harbor, OH	L3218	-81.2941	41.76666
Fall River, MA	C0189	-71.1588	41.72166
Freeport, TX	C2408	-95.3304	28.9384
Galveston, TX	C2417	-94.8127	29.31049
Gary, IN	L3736	-87.3251	41.61202
Georgetown, SC	C0772	-79.2896	33.36682
Grays Harbor, WA	C4702	-124.122	46.91167
Gulfport, MS	C2083	-89.0853	30.35216
Hilo, HI	C4400	-155.076	19.72861

Port Name	US ACE Code	Port Coordinates	
		Longitude	Latitude
Honolulu, HI	C4420	-157.872	21.31111
Hopewell, VA	C0738	-77.2763	37.32231
Houston, TX	C2012	-95.2677	29.72538
Indiana Harbor, IN	L3738	-87.4455	41.67586
Jacksonville, FL	C2017	-81.6201	30.34804
Kahului, Maui, HI	C4410	-156.473	20.89861
Kalama, WA	C4626	-122.863	46.02048
Lake Charles, LA	C2254	-93.2221	30.22358
Long Beach, CA	C4110	-118.21	33.73957
Longview, WA	C4622	-122.914	46.14222
Lorain, OH	L3216	-82.1951	41.48248
Los Angeles, CA	C4120	-118.241	33.77728
Manistee, MI	L3720	-86.3443	44.25082
Marblehead, OH	L3212	-82.7091	41.52962
Marcus Hook, PA	C5251	-75.4042	39.81544
Matagorda Ship Channel, TX	C2410	-96.5641	28.5954
Miami, FL	C2164	-80.1832	25.78354
Milwaukee, WI	L3756	-87.8997	42.98824
Mobile, AL	C2005	-88.0411	30.72527
Morehead City, NC	C0764	-76.6947	34.71669
Muskegon, MI	L3725	-86.3501	43.19492
Nawiliwili, Kauai, HI	C4430	-159.353	21.96111
New Bedford, MA	C0187	-70.9162	41.63641
New Castle, DE	C0299	-75.5616	39.65668
New Haven, CT	C1507	-72.9047	41.29883
New Orleans, LA	C2251	-90.0853	29.91414
New York, NY and NJ	C0398	-74.0384	40.67395
Newport News, VA	C0736	-76.4582	36.98522
Nikishka, AK	C4831	-151.314	60.74793
Oakland, CA	C4345	-122.308	37.82152
Olympia, WA	C4718	-122.909	47.06827
Other Puget Sound, WA	C4754	-122.72	48.84099
Palm Beach, FL	C2162	-80.0527	26.76904
Panama City, FL	C2016	-84.1993	30.19009
Pascagoula, MS	C2004	-88.5588	30.34802
Paulsboro, NJ	C5252	-75.2266	39.82689
Penn Manor, PA	C0298	-74.7408	40.13598
Pensacola, FL	C2007	-87.2579	30.40785
Philadelphia, PA	C0552	-75.2022	39.91882
Plaquemines, LA, Port of	C2255	-89.6875	29.48
Port Angeles, WA	C4708	-123.453	48.1305
Port Arthur, TX	C2416	-93.9607	29.83142
Port Canaveral, FL	C2160	-80.6082	28.41409
Port Dolomite, MI	L3627	-84.3128	45.99139
Port Everglades, FL	C2163	-80.1178	26.09339
Port Hueneme, CA	C4150	-119.208	34.14824
Port Inland, MI	L3803	-85.8628	45.95508

Port Name	US ACE Code	Port Coordinates	
		Longitude	Latitude
Port Manatee, FL	C2023	-82.5613	27.63376
Portland, ME	C0128	-70.2513	43.64951
Portland, OR	C4644	-122.665	45.47881
Presque Isle, MI	L3845	-87.3852	46.57737
Providence, RI	C0191	-71.3984	41.81178
Redwood City, CA	CCA05	-122.21	37.51306
Richmond, CA	C4350	-122.374	37.92424
Richmond, VA	C0737	-77.4194	37.45701
Sacramento, CA	CCA06	-121.544	38.56167
San Diego, CA	C4100	-117.178	32.70821
San Francisco, CA	C4335	-122.399	37.80667
Sandusky, OH	L3213	-82.7123	41.47022
Savannah, GA	C0776	-81.0954	32.08471
Searsport, ME	C0112	-68.925	44.45285
Seattle, WA	C4722	-122.359	47.58771
South Louisiana, LA, Port of	C2253	-90.6179	30.03345
St. Clair, MI	L3509	-82.4941	42.82663
Stockton, CA	C4270	-121.316	37.9527
Stoneport, MI	L3619	-83.4703	45.28073
Tacoma, WA	C4720	-122.452	47.28966
Tampa, FL	C2021	-82.5224	27.78534
Texas City, TX	C2404	-94.9181	29.36307
Toledo, OH	L3204	-83.5075	41.66294
Two Harbors, MN	L3926	-91.6626	47.00428
Valdez, AK	C4816	-146.346	61.12473
Vancouver, WA	C4636	-122.681	45.62244
Wilmington, DE	C0554	-75.507	39.71589
Wilmington, NC	C0766	-77.954	34.23928

Appendix 2B: Port Methodology and Equations

Near port emissions for each port are calculated for four modes of operation: 1) hotelling, 2) maneuvering, 3) reduced speed zone (RSZ), and 4) cruise. Hotelling, or dwelling, occurs while the vessel is docked or anchored near a dock, and only the auxiliary engine(s) are being used to provide power to meet the ship's energy needs. Maneuvering occurs within a very short distance of the docks. The RSZ varies from port to port, though generally the RSZ would begin and end when the pilots board or disembark, and typically occurs when the near port shipping lanes reach unconstrained ocean shipping lanes. The cruise mode emissions in the near ports analysis extend 25 nautical miles beyond the end of the RSZ lanes for deep water ports and 7 nautical miles for Great Lake ports.

Emissions are calculated separately for propulsion and auxiliary engines. The basic equation used is as follows:

Equation 2B-1

$$Emissions_{\mathrm{mod}\,e[eng]} = (calls) \times (P_{[eng]}) \times (hrs/call_{\mathrm{mod}\,e}) \times (LF_{\mathrm{mod}\,e[eng]}) \times (EF_{[eng]}) \times (Adj) \times (10^{-6}\ tonnes/g)$$

Where:
Emissions$_{\text{mode [eng]}}$ = Metric tonnes emitted by mode and engine type
Calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
P$_{\text{[eng]}}$ = Total engine power by engine type, in kilowatts
hrs/call$_{\text{mode}}$ = Hours per call by mode
LF$_{\text{mode [eng]}}$ = Load factor by mode and engine type (unitless)
EF$_{\text{[eng]}}$ = Emission factor by engine type for the pollutant of interest, in g/kW-hr
(these vary as a function of engine type and fuel used, rather than activity mode)
Adj = Low load adjustment factor, unitless (used when the load factor is below 0.20)
10^{-6} = Conversion factor from grams to metric tonnes

Main engine load factors are calculated directly from the propeller curve based upon the cube of actual speed divided by maximum speed (at 100% maximum continuous rating [MCR]). In addition, cruise mode activity is based on cruise distance and speed inputs. The following sections provide the specific equations used to calculate propulsion and auxiliary emissions for each activity mode.

Cruise

Cruise emissions are calculated for both propulsion (main) and auxiliary engines. The basic equation used to calculate cruise mode emissions for the main engines is:

Equation 2B-2

$$Emissions_{cruise[main]} = (calls) \times (P_{[main]}) \times (hrs/call_{cruise}) \times (LF_{cruise[main]}) \times (EF_{[main]}) \times (10^{-6}\ tonnes/g)$$

Where:
Emissions$_{\text{cruise [main]}}$ = Metric tonnes emitted from main engines in cruise mode
Calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)

$P_{[main]}$ = Total main engine power, in kilowatts
$hrs/call_{cruise}$ = Hours per call for cruise mode
$LF_{cruise\ [main]}$ = Load factor for main engines in cruise mode (unitless)
$EF_{[main]}$ = Emission factor for main engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
10^{-6} = Conversion factor from grams to metric tonnes

In addition, the time in cruise is calculated as follows:

Equation 2B-3

$$Hrs\ /\ call_{cruise} = Cruise\ Distance\,[nmiles]\,/\,Cruise\ Speed\ [knots] \times 2\,trips\ /\ call$$

Where:
Cruise distance = one way distance (25 nautical miles for deep sea ports, and 7 nautical miles for Great Lake ports)
Cruise speed = vessel service speed, in knots
2 trips/call = Used to calculate round trip cruise distance

Main engine load factors are calculated directly from the propeller curve based upon the cube of actual speed divided by maximum speed (at 100% maximum continuous rating [MCR]):

Equation 2B-4

$$LoadFactor_{cruise\ [main]} = \left(Cruise\ Speed\ [knots]\,/\,Maximum\ Speed\ [knots]\right)^3$$

Since cruise speed is estimated at 94 percent of maximum speed[38], the load factor for main engines at cruise is 0.83.

Substituting Equation 2B-3 for time in cruise into Equation 2B-2, and using the load factor of 0.83, the equation used to calculate cruise mode emissions for the main engines becomes the following:

Equation 2B-5 Cruise Mode Emissions for Main Engines

$$Emissions_{cruise[main]} = (calls) \times (P_{[main]}) \times (CruiseDistance/CruiseSpeed) \times (2\,trips/call) \times 0.83 \times (EF_{[main]}) \times (10^{-6}\ tonne$$

Where:
$Emissions_{cruise\ [main]}$ = Metric tonnes emitted from main engines in cruise mode
calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
$P_{[main]}$ = Total main engine power, in kilowatts
Cruise distance = one way distance (25 nautical miles for deep sea ports, and 7 nautical miles for Great Lake ports)
Cruise speed = vessel service speed, in knots
2 trips/call = Used to calculate round trip cruise distance
0.83 = Load factor for main engines in cruise mode, unitless
$EF_{[main]}$ = Emission factor for main engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
10^{-6} = Conversion factor from grams to metric tonnes

The equation used to calculate cruise mode emissions for the auxiliary engines is:

Equation 2B-6 Cruise Mode Emissions for Auxiliary Engines

$$Emissions_{cruise[aux]} = (calls) \times (P_{[aux]}) \times (Cruise\ Distance/Cruise\ Speed) \times (2\,trips/call) \times (LF_{cruise[aux]}) \times (EF_{[aux]}) \times (10^{-6}\ tonnes\ /$$

Where:
Emissions$_{cruise[aux]}$ = Metric tonnes emitted from auxiliary engines in cruise mode
calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
P$_{[aux]}$ = Total auxiliary engine power, in kilowatts
Cruise distance = one way distance (25 nautical miles for deep sea ports, and 7 nautical miles for Great Lake ports)
Cruise speed = vessel service speed, in knots
2 trips/call = Used to calculate round trip cruise distance
LF$_{cruise\ [aux]}$ = Load factor for auxiliary engines in cruise mode, unitless (these vary by ship type and activity mode)
EF$_{[aux]}$ = Emission factor for auxiliary engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
10^{-6} = Conversion factor from grams to metric tonnes

The inputs of calls, cruise distance, and vessel speed are the same for main and auxiliary engines. Relative to the main engines, auxiliary engines have separate inputs for engine power, load factor, and emission factors. The activity-related inputs, such as engine power, vessel speed, and calls, can be unique to each ship calling on a port, if ship-specific information is available. For this analysis, these inputs were developed by port for bins that varied by ship type, engine type, and dead weight tonnage (DWT) range.

Reduced Speed Zone

RSZ emissions are calculated for both propulsion (main) and auxiliary engines. The basic equation used to calculate RSZ mode emissions for the main engines is:

Equation 2B-7

$$Emissions_{RSZ[main]} = (calls) \times (P_{[main]}) \times (hrs/call_{RSZ}) \times (LF_{RSZ[main]}) \times (EF_{[main]}) \times (Adj) \times (10^{-6}\ tonnes/g)$$

Where:
Emissions$_{RSZ[main]}$ = Metric tonnes emitted from main engines in RSZ mode
calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
P$_{[main]}$ = Total main engine power, in kilowatts
hrs/call$_{RSZ}$ = Hours per call for RSZ mode
LF$_{RSZ\ [main]}$ = Load factor for main engines in RSZ mode, unitless
EF$_{[main]}$ = Emission factor for main engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
Adj = Low load adjustment factor, unitless (used when the load factor is below 0.20)
10^{-6} = Conversion factor from grams to metric tonnes

In addition, the time in RSZ mode is calculated as follows:

Equation 2B-8

$$Hrs\ /\ call_{RSZ}\ =\ \ RSZ\ \ Dis\tan ce\,[nmiles\ ]\,/\ RSZ\ \ Speed\ \ [knots\ ]\times 2\,trips\ \ /\ call$$

Load factor during the RSZ mode is calculated as follows:

Equation 2B-9

$$LoadFactor_{RSZ\,[main]} = \left(RSZ\ Speed\ /\ Maximum\,Speed\right)^{3}$$

In addition:

Equation 2B-10

$$Maximum\,Speed\ =\ Cruise\,Speed\ /\ 0.94$$

Where:
0.94 = Fraction of cruise speed to maximum speed

Substituting Equation 2B-10 into Equation 2B-9, the equation to calculate load factor becomes:

Equation 2B-11

$$LoadFactor_{RSZ\,[main]} = \left(RSZ\ Speed \times 0.94\,/\,Cruise\,Speed\right)^{3}$$

Where:
0.94 = Fraction of cruise speed to maximum speed

Load factors below 2 percent were set to 2 percent as a minimum.

Substituting Equation 2B-8 for time in mode and Equation 2B-11 for load factor into Equation 2B-7 , the expression used to calculate RSZ mode emissions for the main engines becomes:

Equation 2B-12 RSZ Mode Emissions for Main Engines

$$\begin{aligned} Emissions\ _{RSZ\,[aux\,]} &= (calls\,)\times(P_{[aux\,]})\times(RSZ\ \ Dis\tan ce/\ RSZ\ \ Speed\ )\times(2\,trips\,/call\,) \\ &\times\left(RSZ\ \ Speed\ \times 0.94\,/\,Cruise\ \ Speed\ \right)^{3}\times(EF_{[aux\,]})\times\left(Adj\,\right)\times(10^{-6}\ tonnes\ \ /\ g\,) \end{aligned}$$

Where:
$Emissions_{RSZ[main]}$ = Metric tonnes emitted from main engines in RSZ mode
calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
$P_{[main]}$ = Total main engine power, in kilowatts
RSZ distance = one way distance, in nautical miles (specific to each port)
RSZ speed = speed, in knots (specific to each port)
2 trips/call = Used to calculate round trip RSZ distance
Cruise speed = vessel service speed, in knots
$EF_{[main]}$ = Emission factor for main engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
Adj = Low load adjustment factor, unitless (used when the load factor is below 0.20)

10^{-6} = Conversion factor from grams to tons
0.94 = Fraction of cruise speed to maximum speed

Emission factors are considered to be relatively constant down to about 20 percent load. Below that threshold, emission factors tend to increase significantly as the load decreases. During the RSZ mode, load factors can fall below 20 percent. Low load multiplicative adjustment factors were developed and applied when the load falls below 20 percent (0.20). If the load factor is 0.20 or greater, the low load adjustment factor is set to 1.0.

The equation used to calculate RSZ mode emissions for the auxiliary engines is:

Equation 2B-13 RSZ Mode Emissions for Auxiliary Engines

$$Emissions_{RSZ[aux]} = (calls) \times (P_{[aux]}) \times (RSZ\ Distance / RSZ\ Speed) \times (2\ trips/call) \times (LF_{RSZ[aux]}) \times (EF_{[aux]}) \times (10^{-6}\ tonnes / g)$$

Where:
$Emissions_{RSZ[aux]}$ = Metric tonnes emitted from auxiliary engines in RSZ mode
calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
$P_{[aux]}$ = Total auxiliary engine power, in kilowatts
RSZ distance = one way distance, in nautical miles (specific to each port)
RSZ speed = speed, in knots (specific to each port)
2 trips/call = Used to calculate round trip cruise distance
$LF_{RSZ\ [aux]}$ = Load factor for auxiliary engines in RSZ mode, unitless (these vary by ship type and activity mode)
$EF_{[aux]}$ = Emission factor for auxiliary engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
10^{-6} = Conversion factor from grams to metric tonnes

Unlike main engines, there is no need for a low load adjustment factor for auxiliary engines, because of the way they are generally operated. When only low loads are needed, one or more engines are shut off, allowing the remaining engines to maintain operation at a more efficient level.

The inputs of calls, RSZ distance, and RSZ speed are the same for main and auxiliary engines. Relative to the main engines, auxiliary engines have separate inputs for engine power, load factor, and emission factors. The RSZ distances vary by port rather than vessel or engine type. Some RSZ speeds vary by ship type, while others vary by DWT. Mostly, however, RSZ speed is constant for all ships entering the harbor area. All Great Lake ports have reduced speed zone distances of three nautical miles occurring at halfway between cruise speed and maneuvering speed.

Maneuvering

Maneuvering emissions are calculated for both propulsion (main) and auxiliary engines. The basic equation used to calculate maneuvering mode emissions for the main engines is:

Equation 2B-14

$$Emissions_{man[main]} = (calls) \times (P_{[main]}) \times (hrs / call_{man}) \times (LF_{man[main]}) \times (EF_{[main]}) \times (Adj) \times (10^{-6}\ tonnes / g)$$

Where:

$\text{Emissions}_{\text{man[main]}}$ = Metric tonnes emitted from main engines in maneuvering mode
calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
$P_{\text{[main]}}$ = Total main engine power, in kilowatts
$\text{hrs/call}_{\text{man}}$ = Hours per call for maneuvering mode
$LF_{\text{man [main]}}$ = Load factor for main engines in maneuvering mode, unitless
$EF_{\text{[main]}}$ = Emission factor for main engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
Adj = Low load adjustment factor, unitless (used when the load factor is below 0.20)
10^{-6} = Conversion factor from grams to metric tonnes

Maneuvering time-in-mode is estimated based on the distance a ship travels from the breakwater or port entrance to the pier/wharf/dock (PWD). Maneuvering times also include shifts from one PWD to another or from one port within a greater port area to another. Average maneuvering speeds vary from 3 to 8 knots depending on direction and ship type. For consistency, maneuvering speeds were assumed to be the dead slow setting of approximately 5.8 knots.

Load factor during maneuvering is calculated as follows:

Equation 2B-15

$$LoadFactor_{man[main]} = \left(Man\,Speed[knots] / Maximum\,Speed[knots]\right)^3$$

In addition:

Equation 2B-16

$$Maximum\,Speed = Cruise\,Speed[knots] / 0.94$$

Where:
0.94 = Fraction of cruise speed to maximum speed

Also, the maneuvering speed is 5.8 knots. Substituting Equation 2B-16 into Equation 2B-15, and using a maneuvering speed of 5.8 knots, the equation to calculate load factor becomes:

Equation 2B-17

$$LoadFactor_{man[main]} = \left(5.45 / Cruise\,Speed\right)^3$$

Load factors below 2 percent were set to 2 percent as a minimum.

Substituting Equation 2B-17 for load factor into Equation 2B-14, the expression used to calculate maneuvering mode emissions for the main engines becomes:

Equation 2B-18 Maneuvering Mode Emissions for Main Engines

$$Emissions_{man[main]} = (calls) \times (P_{[main]}) \times (hrs / call_{man}) \times (5.45 / Cruise\ Speed)^3 \times (EF_{[main]}) \times (Adj) \times (10^{-6}\ tonnes\ /\ g)$$

Where:
$\text{Emissions}_{\text{man[main]}}$ = Metric tonnes emitted from main engines in maneuvering mode
calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
$P_{\text{[main]}}$ = Total main engine power, in kilowatts

$hrs/call_{man}$ = Hours per call for maneuvering mode
Cruise speed = Vessel service speed, in knots
$EF_{[main]}$ = Emission factor for main engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
Adj = Low load adjustment factor, unitless (used when the load factor is below 0.20)
10^{-6} = Conversion factor from grams to metric tonnes

Since the load factor during maneuvering usually falls below 20 percent, low load adjustment factors are also applied accordingly. Maneuvering times are not readily available for all 117 ports. For this analysis, maneuvering times and load factors available for a subset of the ports were used to calculate maneuvering emissions for the remaining ports. This is discussed in more detail in section 2.3.2.3.8.

The equation used to calculate maneuvering mode emissions for the auxiliary engines is:

Equation 2B-19 Maneuvering Mode Emissions for Auxiliary Engines

$$Emissions_{man[aux]} = (calls) \times (P_{[aux]}) \times (hrs / call_{man}) \times (LF_{man[aux]}) \times (EF_{[aux]}) \times (10^{-6}\ tonnes / g)$$

Where:
$Emissions_{man[aux]}$ = Metric tonnes emitted from auxiliary engines in maneuvering mode
calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
$P_{[aux]}$ = Total auxiliary engine power, in kilowatts
$hrs/call_{man}$ = Hours per call for maneuvering mode
$LF_{man\ [aux]}$ = Load factor for auxiliary engines in maneuvering mode, unitless (these vary by ship type and activity mode)
$EF_{[aux]}$ = Emission factor for auxiliary engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)
10^{-6} = Conversion factor from grams to metric tonnes

Low load adjustment factors are not applied for auxiliary engines.

Hotelling

Hotelling emissions are calculated for auxiliary engines only, as main engines are not operational during this mode. The equation used to calculate hotelling mode emissions for the auxiliary engines is:

Equation 2B-20 Hotelling Mode Emissions for Auxiliary Engines

$$Emissions_{hotel[aux]} = (calls) \times (P_{[aux]}) \times (hrs / call_{hotel}) \times (LF_{hotel[aux]}) \times (EF_{[aux]}) \times (10^{-6}\ tonnes / g)$$

Where:
$Emissions_{hotel[aux]}$ = Metric tonnes emitted from auxiliary engines in hotelling mode
calls = Round-trip visits (i.e., one entrance and one clearance is considered a call)
$P_{[aux]}$ = Total auxiliary engine power, in kilowatts
$hrs/call_{hotel}$ = Hours per call for hotelling mode
$LF_{hotel\ [aux]}$ = Load factor for auxiliary engines in hotelling mode, unitless (these vary by ship type and activity mode)

$EF_{[aux]}$ = Emission factor for auxiliary engines for the pollutant of interest, in g/kW-hr (these vary as a function of engine type and fuel used, rather than activity mode)

10^{-6} = Conversion factor from grams to metric tonnes

Hotelling times are not readily available for all 117 ports. For this analysis, hotelling times available for a subset of the ports were used to calculate hotelling emissions for the remaining ports.

Appendix 2C: Port Reduced Speed Zone (RSZ) Information

Table 2C-1 Port RSZ Information

Port Name	RSZ Speed (knts)	RSZ distance (naut mi)	Final RSZ End Point(s)	
			Longitude	Latitude
Albany, NY	c	142.5	-73.8929	40.47993
Alpena, MI	e	3	-83.2037	44.99298
Anacortes, WA	a	108.3	-124.771	48.49074
Anchorage, AK	14.5	143.6	-152.309	59.5608
Ashtabula, OH	e	3	-80.8097	42.08549
Baltimore, MD	c	157.1	-75.8067	36.8468
Barbers Point, Oahu, HI	10	5.1	-158.132	21.21756
Baton Rouge, LA	10	219.8	-89.4248	28.91161
			-89.137	28.98883
Beaumont, TX	7	53.5	-93.7552	29.55417
Boston, MA	10	14.3	-70.7832	42.37881
Bridgeport, CT	10	2	-73.1863	41.13906
Brownsville, TX	8.8	18.7	-97.0921	26.06129
Brunswick, GA	13	38.8	-80.9345	31.29955
			-81.1357	30.68935
Buffalo, NY	e	3	-79.0996	42.81683
Burns Waterway Harbor, IN	e	3	-87.1032	41.80625
Calcite, MI	e	3	-83.5383	45.39496
Camden-Gloucester, NJ	c	94	-75.0095	38.79004
Carquinez, CA	12	39	-122.632	37.76094
Catalina, CA	12	11.9	-118.465	33.63641
Charleston, SC	12	17.3	-79.6452	32.62557
Chester, PA	c	78.2	-75.0095	38.79004
Chicago, IL	e	3	-87.4141	41.86971
Cleveland, OH	e	3	-81.765	41.63079
Conneaut, OH	e	3	-80.5639	42.13361
Coos Bay, OR	6.5	13	-124.359	43.35977
Corpus Christi, TX	d	30.1	-96.8753	27.74433
Detroit, MI	e	3	-83.1384	42.10308
Duluth-Superior, MN and WI	e	3	-91.8536	46.78916
El Segundo, CA	12	23.3	-118.926	33.91252
			-118.465	33.63641
Erie, PA	e	3	-80.115	42.3151
Escanaba, MI	e	3	-86.9224	45.58297
Eureka, CA	12	9	-124.347	40.75925
Everett, WA	a	123.3	-124.771	48.49074
Fairport Harbor, OH	e	3	-81.3917	41.91401
Fall River, MA	9	22.7	-71.3334	41.41708
Freeport, TX	c	2.6	-95.2949	28.93323
Galveston, TX	c	9.3	-94.6611	29.3247
Gary, IN	e	3	-87.2824	41.77658
Georgetown, SC	12	17.6	-79.0779	33.1924

Port Name	RSZ Speed (knts)	RSZ distance (naut mi)	Final RSZ End Point(s)	
			Longitude	Latitude
Grays Harbor, WA	a	4.9	-124.24	46.89509
Gulfport, MS	10	17.4	-88.9263	30.11401
Hilo, HI	10	7.1	-154.985	19.76978
Honolulu, HI	10	10	-157.956	21.17658
			-157.785	21.23827
Hopewell, VA	10	91.8	-75.8067	36.8468
Houston, TX	c	49.6	-94.6611	29.3247
Indiana Harbor, IN	e	3	-87.4007	41.8401
Jacksonville, FL	10	18.6	-81.3649	30.39769
Kahului, Maui, HI	10	7.5	-156.44	21.01066
Kalama, WA	b	68.2	-124.137	46.22011
Lake Charles, LA	6	38	-93.3389	29.73094
Long Beach, CA	12	18.1	-118.465	33.63641
			-118.13	33.45211
Longview, WA	b	67.3	-124.137	46.22011
Lorain, OH	e	3	-82.2701	41.64023
Los Angeles, CA	12	20.6	-118.465	33.63641
			-118.13	33.45211
Manistee, MI	e	3	-86.3819	44.41573
Marblehead, OH	e	3	-82.7293	41.69638
Marcus Hook, PA	c	94.7	-75.0095	38.79004
Matagorda Ship Channel, TX	7.3	24	-96.2287	28.33472
Miami, FL	12	3.8	-80.1201	25.75787
Milwaukee, WI	e	3	-87.6718	42.97343
Mobile, AL	11	36.1	-88.0644	30.1457
Morehead City, NC	10	2.2	-76.6679	34.68999
Muskegon, MI	e	3	-86.5377	43.29151
Nawiliwili, Kauai, HI	10	7.3	-159.266	21.87705
New Bedford, MA	9	22.4	-71.1013	41.38499
New Castle, DE	c	60.5	-75.0095	38.79004
New Haven, CT	10	2.1	-72.9121	41.26588
New Orleans, LA	10	104.2	-89.4248	28.91161
			-89.137	28.98883
New York, NY and NJ	c	15.7	-73.8929	40.47993
Newport News, VA	14	24.3	-75.8067	36.8468
Nikishka, AK	14.5	90.7	-152.309	59.5608
Oakland, CA	12	18.4	-122.632	37.76094
Olympia, WA	a	185.9	-124.771	48.49074
Other Puget Sound, WA	a	106	-124.771	48.49074
Palm Beach, FL	3	3.1	-79.9973	26.77129
Panama City, FL	10	10	-84.1797	30.0818
Pascagoula, MS	10	17.5	-88.4804	30.09597
Paulsboro, NJ	c	83.5	-75.0095	38.79004
Penn Manor, PA	c	114.5	-75.0095	38.79004
Pensacola, FL	12	12.7	-87.298	30.27777
Philadelphia, PA	c	88.1	-75.0095	38.79004

Port Name	RSZ Speed (knts)	RSZ distance (naut mi)	Final RSZ End Point(s)	
			Longitude	Latitude
Plaquemines, LA, Port of	10	52.4	-89.4248	28.91161
			-89.137	28.98883
Port Angeles, WA	a	65	-124.771	48.49074
Port Arthur, TX	7	21	-93.7552	29.55417
Port Canaveral, FL	10	4.4	-80.5328	28.41439
Port Dolomite, MI	e	3	-84.2445	45.83181
Port Everglades, FL	7.5	2.1	-80.082	26.08627
Port Hueneme, CA	12	2.8	-119.238	34.10859
Port Inland, MI	e	3	-85.6524	45.87553
Port Manatee, FL	9	27.4	-83.0364	27.59078
Portland, ME	10	11.4	-70.1077	43.54224
Portland, OR	b	105.1	-124.137	46.22011
Presque Isle, MI	e	3	-87.082	46.5804
Providence, RI	9	24.9	-71.3334	41.41708
Redwood City, CA	12	36	-122.632	37.76094
Richmond, CA	12	22.6	-122.632	37.76094
Richmond, VA	10	106.4	-75.8067	36.8468
Sacramento, CA	12	90.5	-122.632	37.76094
San Diego, CA	12	11.7	-117.315	32.62184
San Francisco, CA	12	14.4	-122.632	37.76094
Sandusky, OH	e	3	-82.5251	41.56193
Savannah, GA	13	45.5	-78.0498	33.83598
Searsport, ME	9	22.2	-68.7645	44.1179
Seattle, WA	a	133.3	-124.771	48.49074
South Louisiana, LA, Port of	10	142.8	-89.4248	28.91161
			-89.137	28.98883
St. Clair, MI	e	3	-82.5838	42.55923
Stockton, CA	12	86.9	-122.632	37.76094
Stoneport, MI	e	3	-83.2355	45.25919
Tacoma, WA	a	150.5	-124.771	48.49074
Tampa, FL	9	30	-83.0364	27.59078
Texas City, TX	c	15.1	-94.6611	29.3247
Toledo, OH	e	3	-83.3034	41.7323
Two Harbors, MN	e	3	-91.4414	46.93391
Valdez, AK	10	27.2	-146.881	60.86513
Vancouver, WA	b	95.7	-124.137	46.22011
Wilmington, DE	c	65.3	-75.0095	38.79004
Wilmington, NC	10	27.6	-80.325	31.84669

[a] Cruise speed through Strait of Juan de Fuca, then varies by ship type for remaining journey

[b] Inbound on Columbia River at 6.5 knots, outbound at 12 knots

[c] Speed varies by ship type similar to typical like port

[d] Speed varies by ship DWTs

[e] All Great Lake ports have reduced speed zone distances of 3 nautical miles with speeds halfway between service speed and maneuvering speed.

Appendix 2D: Use of Detailed Typical Port Data for Other Inputs

There is currently not enough information to readily calculate time-in-mode (hours/call) for all 117 ports during the maneuvering and hotelling modes of operation. As a result, it was necessary to review and select available detailed emission inventories that have been estimated for selected ports to date. These ports are referred to as typical ports. The typical port information for maneuvering and hotelling time-in-mode (as well as maneuvering load factors for the propulsion engines) was then used for the typical ports and also assigned to the other modeled ports. A modeled port is the port in which emissions are to be estimated. The methodology that was used to select the typical ports and match these ports to the other modeled ports is briefly described in this appendix, and more fully described in the ICF documentation.[39]

2.6.1 Selection of Typical Ports

In 1999, the U.S. Government published two guidance documents[40,41] to calculate marine vessel activity at ports. These documents contained detailed port inventories of eight deep sea ports, two Great Lake ports and two inland river ports. The detailed inventories were developed by obtaining ship call data from Marine Exchanges/Port Authorities (MEPA) at the various ports for 1996 and matching the various ship calls to data from Lloyds Maritime Information Services to provide ship characteristics. The ports for which detailed inventories were developed are shown in Table 2D-1 for deep sea ports and Table 2D-2 for Great Lake ports along with the level of detail of shifts for each port. Most ports provided the ship name, Lloyd's number, the vessel type, the date and time the vessel entered and left the port, and the vessel flag. Inland river ports were developed from US Army Corps of Engineers (USACE) Waterborne Commerce Statistics Center data.

Table 2D-1 Deep Sea MEPA Vessel Movement and Shifting Details

MEPA Area and Ports	MEPA Data Includes
Lower Mississippi River including the ports of New Orleans, South Louisiana, Plaquemines, and Baton Rouge	Information on the first and last pier/wharf/dock (PWD) for the vessel (gives information for at most one shift per vessel). No information on intermediate PWDs, the time of arrival at the first destination PWD, or the time of departure from the River.
Consolidated Port of New York and New Jersey and other ports on the Hudson and Elizabeth Rivers	All PWDs or anchorages for shifting are named. Shifting arrival and departure times are not given. Hotelling time is based upon the entrance and clearance times and dates, subtracting out maneuvering times. Maneuvering times were calculated based upon the distance the ship traveled at a given maneuvering speed.
Delaware River Ports including the ports of Philadelphia, Camden, Wilmington and others	All PWDs or anchorages for shifting are named. Shifting arrival and departure times are not given. Hotelling time is based upon the entrance and clearance times and dates, subtracting out maneuvering times. Maneuvering times were calculated based upon the distance the ship traveled at a given maneuvering speed.
Puget Sound Area Ports including the ports of Seattle, Tacoma, Olympia, Bellingham, Anacortes, and Grays Harbor	All PWDs or anchorages for shifting are named. Arrival and departure dates and times are noted for all movements, allowing calculation of maneuvering and hotelling both for individual shifts and the overall call on port.
The Port of Corpus Christi, TX	Only has information on destination PWD and date and time in and out of the port area. No shifting details.

MEPA Area and Ports	MEPA Data Includes
The Port of Coos Bay, OR	Only has information on destination PWD and date and time in and out of the port area. No shifting details.
Patapsco River Ports including the port of Baltimore Harbor, MD	All PWDs or anchorages for shifting are named. Shifting arrival and departure times are not given. Hotelling time is based upon the entrance and clearance times and dates, subtracting out maneuvering times. Maneuvering times were calculated based upon the distance the ship traveled at a given maneuvering speed.
The Port of Tampa, FL	All PWDs or anchorages for shifting are named. Arrival and departure dates and times are noted for all movements, allowing calculation of maneuvering and hotelling both for individual shifts and the overall call.

Table 2D-2 Great Lake MEPA movements and shifts

MEPA Area and Ports	MEPA Data Includes
Port of Cleveland, OH	Information on the first and last PWD for the vessel (gives information for at most one shift per vessel). No information on intermediate PWDs..
Port of Burns Harbor, IN	No shifting details, No PWDs listed..

Since 1999, several new detailed emissions inventories have been developed and were reviewed for use as additional or replacement typical ports: These included:

- Port of Los Angeles[38,42]
- Puget Sound Ports[43]
- Port of New York/New Jersey[44]
- Port of Houston/Galveston[45]
- Port of Beaumont/Port Arthur[46]
- Port of Corpus Christi[47]
- Port of Portland[48]
- Ports of Cleveland, OH and Duluth-Superior, MN&WI[49]

Based on the review of these newer studies, some of the previous typical ports were replaced with newer data and an additional typical port was added. Data developed for Cleveland and Duluth-Superior for LADCO was used in lieu of the previous typical port data for Cleveland and Burns Harbor because it provided more detailed information and better engine category definitions. The Port of Houston/Galveston inventory provided enough data to add an additional typical port. All three port inventories were adjusted to reflect the current methodology used in this study.

The information provided in the current inventory for Puget Sound Ports[43] was used to calculate RSZ speeds, load factors, and times for all Puget Sound ports. As described in Section

2.6.3.2, an additional modeled port was also added to account for the considerable amount of Jones Act tanker ship activity in the Puget Sound area that is not contained in the original inventory.

The newer Port of New York/New Jersey inventory provided a check against estimates made using the 1996 data. All other new inventory information was found to lack sufficient detail to prepare the detailed typical port inventories needed for this project.

The final list of nine deep sea and two Great Lake typical ports used in this analysis and their data year is as follows:

- Lower Mississippi River Ports [1996]
- Consolidated Ports of New York and New Jersey and Hudson River [1996]
- Delaware River Ports [1996]
- Puget Sound Area Ports [1996]
- Corpus Christi, TX [1996]
- Houston/Galveston Area Ports [1997]
- Ports on the Patapsco River [1996]
- Port of Coos Bay, OR [1996]
- Port of Tampa, FL [1996]
- Port of Cleveland, OH on Lake Erie [2005]
- Duluth-Superior, MN & WI on Lake Michigan [2005]

The maneuvering and hotelling time-in-modes, as well as the maneuvering load factors for these typical ports, were binned by ship type, engine type, and DWT type, using the same bins described in the section entitled “Bins by Ship Type, Engine Type, and DWT Range.”

2.6.2 Matching Typical Ports to Modeled Ports

The next step in the process was to match the ports to be modeled with the typical port which was most like it. Three criteria were used for matching a given port to a typical port: regional differences[D], maximum vessel draft, and the ship types that call on a specific port. One container port, for instance, may have much smaller bulk cargo and reefer ships number of calls on that port than another. Using these three criteria and the eleven typical ports that are suitable for port matching, the 89 deep sea ports and 28 Great Lake ports were matched to the typical ports. For a typical port, the modeled and typical port is the same (i.e., the port simply represents itself). For California ports, we used data provided by ARB as discussed in Section 2.6.3. The matched ports for the deep sea ports are provided in Table 2D-3.

[D] The region in which a port was located was used to group top ports as it was considered a primary influence on the characteristics (size and installed power) of the vessels calling at those ports.

Table 2D-3 Matched Ports for the Deep Sea Ports

Modeled Port Name	Typical Like Port
Anacortes, WA	Puget Sound
Barbers Point, HI	Puget Sound
Everett, WA	Puget Sound
Grays Harbor, WA	Puget Sound
Honolulu, HI	Puget Sound
Kalama, WA	Puget Sound
Longview, WA	Puget Sound
Olympia, WA	Puget Sound
Port Angeles, WA	Puget Sound
Portland, OR	Puget Sound
Seattle, WA	Puget Sound
Tacoma, WA	Puget Sound
Vancouver, WA	Puget Sound
Valdez, AK	Puget Sound
Other Puget Sound	Puget Sound
Anchorage, AK	Coos Bay
Coos Bay, OR	Coos Bay
Hilo, HI	Coos Bay
Kahului, HI	Coos Bay
Nawiliwili, HI	Coos Bay
Nikishka, AK	Coos Bay
Beaumont, TX	Houston
Freeport, TX	Houston
Galveston, TX	Houston
Houston, TX	Houston
Port Arthur, TX	Houston
Texas City, TX	Houston
Corpus Christi, TX	Corpus Christi
Lake Charles, LA	Corpus Christi
Mobile, AL	Corpus Christi
Brownsville, TX	Tampa
Gulfport, MS	Tampa
Manatee, FL	Tampa
Matagorda Ship	Tampa
Panama City, FL	Tampa
Pascagoula, MS	Tampa
Pensacola, FL	Tampa
Tampa, FL	Tampa
Everglades, FL	Tampa
New Orleans, LA	Lower Mississippi
Baton Rouge, LA	Lower Mississippi

Modeled Port Name	Typical Like Port
South Louisiana, LA	Lower Mississippi
Plaquemines, LA	Lower Mississippi
Albany, NY	New York/New Jersey
New York/New Jersey	New York/New Jersey
Portland, ME	New York/New Jersey
Georgetown, SC	Delaware River
Hopewell, VA	Delaware River
Marcus Hook, PA	Delaware River
Morehead City, NC	Delaware River
Paulsboro, NJ	Delaware River
Chester, PA	Delaware River
Fall River, MA	Delaware River
New Castle, DE	Delaware River
Penn Manor, PA	Delaware River
Providence, RI	Delaware River
Brunswick, GA	Delaware River
Canaveral, FL	Delaware River
Charleston, SC	Delaware River
New Haven, CT	Delaware River
Palm Beach, FL	Delaware River
Bridgeport, CT	Delaware River
Camden, NJ	Delaware River
Philadelphia, PA	Delaware River
Wilmington, DE	Delaware River
Wilmington, NC	Delaware River
Richmond, VA	Delaware River
Jacksonville, FL	Delaware River
Miami, FL	Delaware River
Searsport, ME	Delaware River
Boston, MA	Delaware River
New Bedford/Fairhaven, MA	Delaware River
Baltimore, MD	Patapsco River
Newport News, VA	Patapsco River
Savannah, GA	Patapsco River
Catalina, CA	ARB Supplied
Carquinez, CA	ARB Supplied
El Segundo, CA	ARB Supplied
Eureka, CA	ARB Supplied
Hueneme, CA	ARB Supplied
Long Beach, CA	ARB Supplied
Los Angeles, CA	ARB Supplied
Oakland, CA	ARB Supplied

Modeled Port Name	Typical Like Port
Redwood City, CA	ARB Supplied
Richmond, CA	ARB Supplied
Sacramento, CA	ARB Supplied
San Diego, CA	ARB Supplied
San Francisco, CA	ARB Supplied
Stockton, CA	ARB Supplied

Great Lake ports were matched to either Cleveland or Duluth as shown in Table 2D-4.

Table 2D-4 Great Lake Match Ports

Port Name	Typical Like Port
Alpena, MI	Cleveland
Buffalo, NY	Cleveland
Burns Waterway, IN	Cleveland
Calcite, MI	Cleveland
Cleveland, OH	Cleveland
Dolomite, MI	Cleveland
Erie, PA	Cleveland
Escanaba, MI	Cleveland
Fairport, OH	Cleveland
Gary, IN	Cleveland
Lorain, OH	Cleveland
Marblehead, OH	Cleveland
Milwaukee, WI	Cleveland
Muskegon, MI	Cleveland
Presque Isle, MI	Cleveland
St Clair, MI	Cleveland
Stoneport, MI	Cleveland
Two Harbors, MN	Cleveland
Ashtabula, OH	Duluth-Superior
Chicago, IL	Duluth-Superior
Conneaut, OH	Duluth-Superior
Detroit, MI	Duluth-Superior
Duluth-Superior, MN&WI	Duluth-Superior
Indiana, IN	Duluth-Superior
Inland Harbor, MI	Duluth-Superior
Manistee, MI	Duluth-Superior
Sandusky, OH	Duluth-Superior
Toledo, OH	Duluth-Superior

Once a modeled port was matched to a typical port, the maneuvering and hotelling time-in-mode values, as well as the maneuvering load factors by bin for the typical ports, were used directly for the modeled ports, with no adjustments.

2.6.2.1 Bin Mismatches

In some cases, the specific DWT range bin at the modeled port was not in the typical like port data. In those cases, the next nearest DWT range bin was used for the calculations. In a few cases, the engine type for a given ship type might not be in the typical like port data. In these cases, the closest engine type at the typical like port was used. Also in a few cases, a specific ship type in the modeled port data was not in the typical like port data. In this case, the nearest like ship type at the typical port was chosen to calculate emissions at the modeled port.

2.6.3 Stand Alone Ports

In a few cases, the USACE entrances and clearances data was not used to calculate emissions at the modeled port. These include the California ports for which we received data from ARB, the Port of Valdez, Alaska, and a conglomerate port within the Puget Sound area, as described below.

2.6.3.1 California Ports

The California Air Resources Board (ARB) supplied inventories for 14 California ports for 2002. The data received from ARB for the California ports were modified to provide consistent PM and SO_2 emissions to those calculated in this report. In addition, cruise and RSZ emissions were calculated directly based upon average ship power provided in the ARB methodology document[50] and number of calls, because ARB did not calculate cruise emissions, and transit (RSZ) emissions were allocated to counties instead of ports. ARB provided transit distances for each port to calculate the RSZ emissions. Ship propulsion and auxiliary engine power were calculated based upon the methodology previously described for use in computing cruise and RSZ emissions. For maneuvering and hotelling emissions, the ARB values were used and adjusted as discussed below. The data supplied by ARB included domestic traffic as well as foreign cargo traffic.

For PM emission calculations, ARB used an emission factor of 1.5 g/kWh to calculate total PM emissions and factors of 0.96 and 0.937 to convert total PM to PM_{10} and $PM_{2.5}$ respectively. Since an emission factor of 1.4 g/kWh was used in our calculations for PM_{10} and an emission factor of 1.3 g/kWh for $PM_{2.5}$, ARB PM_{10} and $PM_{2.5}$ emissions were multiplied by factors of 0.972 and 0.925, respectively to get consistent PM_{10} and $PM_{2.5}$ emissions for propulsion engines.

For auxiliary engines, ARB used the same emission factors as above, while we used PM_{10} and $PM_{2.5}$ emission factors of 1.3 and 1.2 g/kWh, respectively for passenger ships and 1.1 and 1.0 g/kWh, respectively for all other ships. In the ARB inventory, all passenger ships are treated as electric drive and all emissions are allocated to auxiliary engines. ARB auxiliary engine emissions were thus multiplied by factors of 0.903 and 0.854 respectively for passenger ships and 0.764 and 0.711 respectively for other ships to provide consistent PM emission calculations.

SO_2 emissions were also different between the ARB and these analyses. ARB used a composite[E] propulsion engine SO_2 emission factor of 10.55 g/kWh while we used a composite SO_2 emission factor of 9.57 g/kWh. Thus, ARB SO_2 propulsion emissions were multiplied by a factor of 0.907 to be consistent with our emission calculations. For auxiliary engines, ARB used SO_2 emission factors of 11.48 and 9.34 g/kWh, respectively for passenger and other ships, while we use emission factors of 9.93 and 9.07 g/kWh, respectively. Thus, ARB auxiliary SO_2 emissions were multiplied by factors of 0.865 and 0.971, respectively for passenger and other ships to provide consistent SO_2 emissions.

2.6.3.2 Port in Puget Sound

In the newest Puget Sound inventory[43], it was found that a considerable amount of tanker ships stop at Cherry Point, Ferndale, March Point and other areas which are not within the top 89 U.S. deep sea ports analyzed in this analysis. In addition, since they are ships carrying U.S. cargo (oil from Alaska) from one U.S. port to another, they are not documented in the USACE entrances and clearances data. To compensate for this anomaly, an additional port was added which encompassed these tanker ships stopping within the Puget Sound area but not at one of the Puget Sound ports analyzed in this analysis. Ship calls in the 1996 typical port data to ports other than those in the top 89 U.S. deep sea ports were analyzed separately. There were 363 ship calls by tankers to those areas in 1996. In the inventory report for 2005, there were 468 calls. For 2002, it was estimated there were 432 calls. The same ship types and ship characteristics were used as in the 1996 data, but the number of calls was proportionally increased to 432 calls to represent these ships. The location of the “Other Puget Sound” port was approximately at Cherry Point near Aberdeen.

2.6.3.3 Port of Valdez

In a recent Alaska port inventory,[51] it was found that significant Category 3 domestic tanker traffic enters and leaves the Port of Valdez on destination to West Coast ports. Since the USACE entrances and clearances data did not contain any tanker calls at Valdez in 2002, the recent Alaska inventory data was used to calculate emissions at that port. In this case, the number of calls and ship characteristics for 2002 were taken directly from the Alaska inventory and used in determining emissions for the modeled port with the Puget Sound area typical port being used as the like port.

[E] Based upon ARB assuming 95 percent of the engines were SSD and 5 percent were MSD. The composite SO_2 EF of 9.57 g/kW-hr was calculated using this weighting, along with the SSD and MSD SO_2 EFs for the West Coast ports reported in Table 2-4.

Appendix 2E: Emission Inputs to STEEM

The STEEM waterway network model relies on a number of inputs to identify the movements for each vessel, individual ship attributes, and related emission factor information. Each of these databases is described separately below.

2.6.4 Shipping Movements

The shipping activity and routes database provides information on vessel movements or trips. It is developed using port entrances and clearances information from the USACE report for the U.S. and the Lloyd's Maritime Intelligence Unit (LMIU) for Canada and Mexico.[52] These sources contain information for each vessel carrying foreign cargo at each major port or waterway that, most importantly for this analysis, includes:

- Vessel name
- Last port of call (entrance record) or next port of call (clearance record)

The database then establishes unique identification numbers for each ship, each port pair, and each resulting trip.

2.6.5 Ship Attributes

The ship attributes data set contains the important characteristics of each ship that are necessary for the STEEM interport model to calculate the emissions associated with each trip. The information in this data set is matched to each previously assigned ship identification number. The following information comes from the USACE entrances and clearances report for each ship identification number:

- Ship type
- Gross registered tonnage (GRT)
- Net registered tonnage (NRT)

The ship attributes data set contains the following information from Lloyd's Register-Fairplay for each ship identification number.

- Main propulsion engine installed power (horsepower)
- Service speed (cruise speed)
- Ship size (length, wide, and draft)

Sometimes data was lacking from the above references for ship speed. In these instances, the missing information was developed for each of nine vessel types and the appropriate value was applied to each individual ship of that type. Specifically, the missing ship speeds for each ship category were obtained from the average speeds used in a Lloyd's Register study of the Baltic Sea and from an Entec UK Limited study for the European Commission.[53,54] The resulting vessel cruise speeds for ships with missing data are shown in Table 2E-1.

Table 2E-1 Average Vessel Cruise Speed by Ship Type[a]

Ship Type	Average Cruise Speed (knots)
Bulk Carrier	14.1
Container Ship	19.9
General Cargo	12.3
Passenger Ship	22.4
Refrigerated Cargo	16.4
Roll On-Roll Off	16.9
Tanker	13.2
Fishing	11.7
Miscellaneous	12.7

[a] Used only when ship specific data were missing from the commercial database references.

The average speed during maneuvering is approximately 60 percent of a ship's cruise speed based on using the propeller law described earlier and the engine load factor for maneuvering that is presented later in this section.

As with vessel cruise speed, main engine installed power was sometimes lacking in the Lloyd's Register-Fairplay data set. Here again, the missing information was developed for nine different vessel types and the appropriate value was applied to each individual ship of that type when the data were lacking. In this case, the missing main engine horsepower was estimated by regressing the relationships between GRT and NRT, and between installed power and GRT for each category. This operation is performed internally in the model and the result applied to each individual ship, as appropriate.

The ship attributes database also contains information on the installed power of engines used for auxiliary purposes. However, this information is usually lacking in the Lloyds data set, so an alternative technique was employed to estimate the required values. In short, the STEEM model uses a ratio of main engine horsepower to auxiliary engine horsepower that was determined for eight different vessel types using information primarily from ICF International.[55] (The ICF report attributed these power values to a study for the Port of Los Angeles by Starcrest Consulting.[38]) The auxiliary engine power for each individual vessel of a given ship type is then estimated by multiplying the appropriate main power to auxiliary power ratio and the main engine horsepower rating for that individual ship. The main and auxiliary power values and the resulting auxiliary engine to main engine ratios are shown in Table 2E-2.

Table 2E-2 Auxiliary Engine Power Ratios

Vessel Type	Average Main Engine Power (kW)	Average Auxiliary Engine Power (kW)	*Auxiliary to Main Engine Power Ratio*
Bulk Carrier	7,954	1,169	*0.147*
Container Ship	30,885	5,746	*0.186*
General Cargo	9,331	1,777	*0.190*
Passenger Ship	39,563	39,563 [a]	*1.000*
Refrigerated Cargo	9,567	3,900 [b]	*0.136*
Roll On-Roll Off	10,696 [c]	2,156 [c]	*0.202*
Tanker	9,409	1,985	*0.211*
Miscellaneous	*6,252*	*1,680*	*0.269*

[a] The ICF reference reported a value of 11,000 for auxiliary engines used on passenger vessels.[55]

[b] The STEEM used auxiliary engine power as reported in the ARB methodology document.[50]

[c] The STEEM purportedly used values for Roll On-Roll Off main and auxiliary engines that represent a trip weighted average of the Auto Carrier and Cruise Ship power values from the ICF reference.

Finally, the ship attributes database provides information on the load factors for main engines during cruise and maneuvering operation, in addition to load factors for auxiliary marine engines. Main engine load factors for cruise operation were taken from a study of international shipping for all ship types, except passenger vessels.[56] For this analysis, the STEEM model used a propulsion engine load factor for passenger ship engines at cruise speed of 55 percent of the total installed power. This is based on engine manufacturer data contained in two global shipping studies.[56,57] During maneuvering, it was assumed that all main engines, including those for passenger ships, operate at 20 percent of the installed power. This is consistent with a study done by Entec UK for the European Commission. The main engine load factors at cruise speed by ship type are shown in Table 2E-3.

Auxiliary engine load factors, except for passenger ships, were obtained from the ICF International study referenced above. These values are also shown in Table 2E-. For cruise mode, neither port nor interport portions of the inventory were adjusted for low load operation, as the low load adjustments are only applied to propulsion engines with load factors below 20%.

Table 2E-3 Main and Auxiliary Engine Load Factors at Cruise Speed by Ship Type

Ship Type	Average Main Engine Load Factor (%)	Average Auxiliary Engine Load Factor (%)
Bulk Carrier	75	17
Container Ship	80	13
General Cargo	80	17
Passenger Ship	55	25
Refrigerated Cargo	80	20
Roll On-Roll Off	80	15
Tanker	75	13
Miscellaneous	70	17

2.6.6 Emission Factor Information

The emission factor data set contains emission rates for the various pollutants in terms of grams of pollutant per kilowatt-hour (g/kW-hr). The main engine emission factors are shown in Table 2E-4. The speed specific factors for NO_X, HC, and SO_2 were taken from several recent analyses of ship emissions in the U.S., Canada, and Europe.50’55’56’ [58] The PM factor was based on discussions with the California Air Resources Board (ARB) staff. The fuel specific CO emission factor was taken from a report by ENVIRON International.[59] The STEEM study used the composite emission factors shown in the table because the voyage data used in the model do not explicitly identify main engine speed ratings, i.e., slow or medium, or the auxiliary engine fuel type, i.e., marine distillate or residual marine. The composite factor for each pollutant is determined by weighting individual emission factors by vessel engine population data from a 2005 survey of ocean-going vessels that was performed by ARB.[60]

Table 2E-4 Main Engine Emission Factors by Ship and Fuel Type

Engine Type	Main Engine Emission Factors (g/kW-hr)						
	Fuel Type	NO_X	PM_{10}	$PM_{2.5}$ [a]	HC	CO	SO_2
Slow Speed	Residual Marine	18.1	1.5	1.4	0.6	1.4	10.5
Medium Speed	Residual Marine	14	1.5	1.4	0.5	1.1	11.5
Composite EF	Residual Marine	17.9	1.5	1.4	0.6	1.4	10.6

[a] Estimated from PM_{10} using a multiplicative adjustment factor of 0.92.

The emission factors for auxiliary engines are shown in Table 2E-5. The fuel specific main emission factors for NO_X and HC were taken from several recent analyses of ship emissions in the U.S., Canada, and Europe, as referenced above for the main engine load factors. The PM factor for marine distillate was taken from a report by ENVIRON International, which was also referenced above. The PM factor for residual marine was based on discussions with the California Air Resources Board (ARB) staff. The CO factors are from the Starcrest Consulting study of the Port of Los Angeles.[38] For SO_2, the fuel specific emission factors were obtained from Entec and Corbett and Koehler.’[56] The composite emission factors displayed in the table are discussed below.

Table 2E-5 Auxiliary Engine Emission Factors by Ship and Fuel Type

Engine Type	Auxiliary Engine Emission Factors (g/kW-hr)						
	Fuel Type	NO_X	PM_{10}	$PM_{2.5}$ [a]	HC	CO	SO_2
Medium Speed	Marine Distillate	13.9	0.3	0.3	0.4	1.1	4.3
Medium Speed	Residual Marine	14.7	1.5	1.4	0.4	1.1	12.3
Composite EF	Residual Marine	14.5	1.2	1.1	0.4	1.1	**

[a] Estimated from PM_{10} using a multiplicative adjustment factor of 0.92.
[b] See Table 2E-6 for composite SO_2 emission factors by vessel type.

As for main engines, the STEEM study used the composite emission factors for auxiliary engines. For all pollutants other than SO_2, underlying data used in the model do not explicitly identify auxiliary engine voyages by fuel type, i.e., marine distillate or residual marine. Again, the composite factor for those pollutants was determined by weighting individual emission factors by vessel engine population data from a 2005 survey of ocean-going vessels that was performed by ARB.[61]

For SO_2, composite emission factors for auxiliary engines were calculated for each vessel type. These composite factors were determined by taking the fuel specific emission factors from Table 2E-5 and weighting them with an estimate of the amount of marine distillate and residual marine that is used by these engines. The relative amount of each fuel type consumed was taken from the 2005 ARB survey. The relative amounts of each fuel type for each vessel type and the resulting SO_2 emission factors are shown in Table 2E-6.

Table 2E-6 Auxiliary Engine SO_2 Composite Emission Factors by Vessel Type

Vessel Type	**Residual Marine (%)**	**Marine Distillate (%)**	***Composite Emission Factor (g/kW-hr)***
Bulk Carrier	71	29	*9.98*
Container Ship	71	29	*9.98*
General Cargo	71	29	*9.98*
Passenger Ship	92	8	*11.66*
Refrigerated Cargo	71	29	*9.98*
Roll On-Roll Off	71	29	*9.98*
Tanker	71	29	*9.98*
Miscellaneous	*0*	*100*	*4.3*

2.6.7 Adjustments to STEEM PM and SO_2 Emission Inventories

The interport emission results contained in this study for PM_{10} and SO_2 were taken from the STEEM inventories and then adjusted to reflect the U.S. Government's recent review of available engine test data and fuel sulfur levels for the near port analysis. In the near ports work, a PM emission factor of 1.4 g/kW-hr was used for most main engines, e.g., slow speed diesel and medium speed diesel engines, all of which are assumed to use residual marine. A slightly higher value was used for steam turbine and gas turbine engines, and a slightly lower value was used for most auxiliary engines. However, these engines represent only a small fraction of the total emissions inventory. As shown in Section 2.6.6, the STEEM study used an emission factor of 1.5 g/kW-hr for all main engines and a slightly lower value for auxiliary engines. Here again, the auxiliary engines comprise only a small fraction of the total emissions from these ships. Therefore, for simplicity, the interport PM inventories were adjusted by multiplying the STEEM results by the ratio of the two primary emission factors, i.e., 1.4/1.5 or 0.933, to approximate the difference in fuel effects.

Appendix 2F: Inventories Used for Air Quality Modeling

The emission inventories presented in this chapter are slightly different from the emissions inventories used in the air quality modeling presented in Chapter 3. Specifically, the inventories used in the air quality modeling reflect a slightly different boundary for the proposed ECA that was based on a measurement error. Due to the nature of the measurement error, the corrections to the ECA boundaries are not uniform, but are different by coastal area. As seen in Table 2F-1, the changes are not expected to have a significant impact on the results of our analysis. The measurement error affects only those portions that are farthest from shore.

The inventories used for air quality modeling also only contain Tier I NO_X controls, as opposed to the Tier I and Tier II controls contained in the final inventories.

A comparison of the air quality and final inventories by region for the 2020 baseline scenarios is provided in Table 2F-1. Results are provided only for NO_X, $PM_{2.5}$, and SO_2, since the air quality modeling is focused on ozone and $PM_{2.5}$. As shown, the inventory provided for air quality modeling generally understates the inventory reductions and air quality benefits produced by the ECA.

Table 2F-1 Comparison of Air Quality Inventories vs Final Inventories for 2020 Baseline Case

U.S. Region	Metric Tonnes per Year								
	NO_X			$PM_{2.5}$			SO_X		
	AQ	Final	% Diff	AQ	Final	% Diff	AQ	Final	% Diff
East Coast (EC)	439,713	391,995	12%	35,891	35,882	0%	323,108	323,038	0%
Gulf Coast (GC)	261,024	232,114	12%	21,669	21,531	1%	175,862	174,751	1%
North Pacific (NP)	42,291	38,051	11%	3,575	3,603	-1%	27,580	27,807	-1%
South Pacific (SP)	216,849	208,294	4%	17,092	18,536	-8%	138,102	149,751	-8%
Great Lakes (GL)	19,842	18,768	6%	1,484	1,484	0%	11,993	11,993	0%
Total 48-State	**979,719**	**889,222**	10%	**79,711**	**81,037**	-2%	**676,645**	**687,339**	-2%

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[1] ICF International (March 2009). Inventory Contribution of U.S. Flagged Vessels, prepared for the U.S. Environmental Protection Agency, EPA Report Number EPA-420-R-09-005.

[2] ICF International (October 2007). Commercial Marine Port Inventory Development, prepared for the U.S. Environmental Protection Agency, EPA Report Number EPA-420-R-07-012c, Docket ID EPA-HQ-OAR-2007-0121-0063.1.

[3] Corbett, J. et al. (April 2007). Estimation, Validation and Forecasts of Regional Commercial Marine Vessel Inventories, Final Report, prepared by University of Delaware for the California Air Resource Board, Contract Number 04-346, and the Commission for Environmental Cooperation in North America, Contract Number 113.111, Docket ID EPA-HQ-OAR-2007-0121-0063.2.

[4] Corbett, J. et al. (May 2006). Estimation, Validation and Forecasts of Regional Commercial Marine Vessel Inventories, Tasks 1 and 2: Baseline Inventory and Ports Comparison, Final Report, prepared by University of Delaware for the California Air Resource Board, Contract Number 04-346, and the Commission for Environmental Cooperation in North America, Contract Number 113.111, May 2006, Docket ID EPA-HQ-OAR-2007-0121-0013.

[5] RTI International (December 2006). Global Trade and Fuels Assessment – Future Trends and Effects of Designation Requiring Clean Fuels in the Marine Sector: Task Order No. 1, Draft Report, prepared for the U.S. Environmental Protection Agency, EPA Report Number EPA420-D-07-006, Docket ID EPA-HQ-OAR-2007-0121-0063.3.

[6] RTI International (April 24, 2006). RTI Estimates of Growth in Bunker Fuel Consumption, Memorandum with spreadsheet from Michael Gallaher and Martin Ross, RTI, to Barry Garelick and Russ Smith, U.S. Environmental Protection Agency, Docket ID EPA-HQ-OAR-2007-0121-0063.4.

[7] National Oceanic and Atmospheric Administration, *Exclusive Economic Zone,* Available online at http://nauticalcharts.noaa.gov/csdl/eez.htm.

[8] U.S. Department of Interior, *North American Atlas – Political Boundaries*, Available online at http://www.nationalatlas.gov/mld/bound0m.html.

[9] US Department of Transportation Maritime Administration, *U.S. Water Transportation Statistical Snapshot*, May 2008, available from www.marad.dot.gov

[10] U.S. Army Corps of Engineers Navigation Data Center, *Principal Ports of the United States*, 2002, available at http://www.iwr.usace.army.mil/ndc/db/pport/dbf/pport02.dbf.

[11] U.S. Army Corps of Engineers Navigation Data Center, *Vessel Entrances and Clearances*, 2002, available at http://www.iwr.usace.army.mil/ndc/db/entclrn/data/entrclrn02/

[12] ICF International (October 2007). Commercial Marine Port Inventory Development, prepared for the U.S. Environmental Protection Agency, EPA Report Number EPA-420-R-07-012c, Docket ID EPA-HQ-OAR-2007-0121-0063.1.

[13] Nexus Media Communications, *The Motor Ship's Guide to Marine Diesel Engines 2005,* available at http://www.motorship.com/

[14] U.S. Army Corps of Engineers, *National Waterway Network,* Available online at http://www.iwr.usace.army.mil/ndc/data/datanwn.htm, Downloaded April 2006.

[15] California Air Resources Board (September 2005). 2005 Oceangoing Ship Survey, Summary of Results.

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