Eastern Research Group, Inc.

Category 3 Commercial Marine Vessel 2017 Emissions Inventory

Prepared for:

U.S. Environmental Protection Agency
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List of Abbreviations

AIS	Automatic Identification Systems
BSFC	Brake-Specific Fuel Consumption
C3	Category 3
CMV	Commercial Marine Vessel
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DWT	Deadweight tonnage
ECA	Environmental Control Area
ECA	Emissions Control Area
EF	Emission factor
FMI	Finnish Metrological Institute
FSC	Fuel Sulfur Content
GT	Gross Tonnage
GT	Gas turbine
GT-ED	Gas turbine-diesel-electric drive
Hb	Center of bulb above keel line
HFO	Heavy fuel oil
IHS	Information Handling Service
IMO	International Maritime Organization
Kn	Knot
kW	Auxiliary engine power
L/cyl	Liters per cylinder
LBP	Length along perpendicular
LCB	Longitudal position center of buoyancy
LLAF	Low load adjustment factor
LNG	Liquified natural gas
lwl	Waterline length
m	Meter
m^3	Cubic meter
MDO	Marine diesel oil
MGO	Marine gas oil
MMSI	Maritime Mobile Service Identifier
MSD	Medium speed diesel
MSD-ED	Medium speed-diesel-electric drive
MWR	Molecular weight ratio

MY	Model year
nm	Nautical miles
PM	Particulate matter
Reefer	Refrigerated vessels
RM	Residual marine
Ro Ro	Roll on/Roll off
RPM	Revolutions per minute
S-AIS	Satellite automatic identification systems
SO_2	Sulfur dioxide
SOLAS	Safety of Life at Sea
SSD	Slow speed diesel
ST	Steam turbine
T-AIS	Terrestrial automatic identification systems
TEU	Twenty-foot equivalent units
USCG	United States Coast Guard
VBP	Vessel Boarding Program

1.0 Introduction

The National Emission Inventory (NEI) assembles data that state, tribal, and local agencies need in order to evaluate and compare emissions trends within the United States. The NEI also serves as a basis for various EPA modeling and regulatory analyses. The NEI compiles comprehensive emissions data for criteria pollutants, hazardous air pollutants, and greenhouse gases for mobile, point, and nonpoint sources.

ERG has supported EPA in its development of a Category 3 commercial marine vessel (C3CMV) component of the 2017 NEI, where Category 3 engines are defined as having displacement above 30 liters per cylinder. This report documents the development of the C3CMV model, including the conceptual framework, equations, data sources, and assumptions. This document is a deliverable under EPA contract EP-C-17-0411, Work Assignment 2-19.

2.0 AIS Dataset

2.1 Temporal and Geographical Extent

The EPA received Automated Identification System (AIS) data from United States Coast Guard (USCG) in order to quantify all ship activity which occurred between January 1 and December 31, 2017. The International Maritime Organization's (IMO's) International Convention for the Safety of Life at Sea (SOLAS) requires AIS to be fitted aboard all international voyaging ships with gross tonnage of 300 or more, and all passenger ships regardless of size (IMO, 2002). In addition, the USCG has mandated that all commercial marine vessels continuously transmit AIS signals while transiting U.S. navigable waters. As the vast majority of C3 vessels meet these requirements, any omitted from the inventory due to lack of AIS adoption are deemed to have a negligible impact on national C3 emissions estimates.

The activity described by this inventory reflects ship operations within 200 nautical miles of the official U.S. baseline. This boundary is roughly equivalent to the border of the U.S Exclusive Economic Zone and the North American Emission Control Area (ECA), although some non-ECA activity is captured as well (Figure 1).

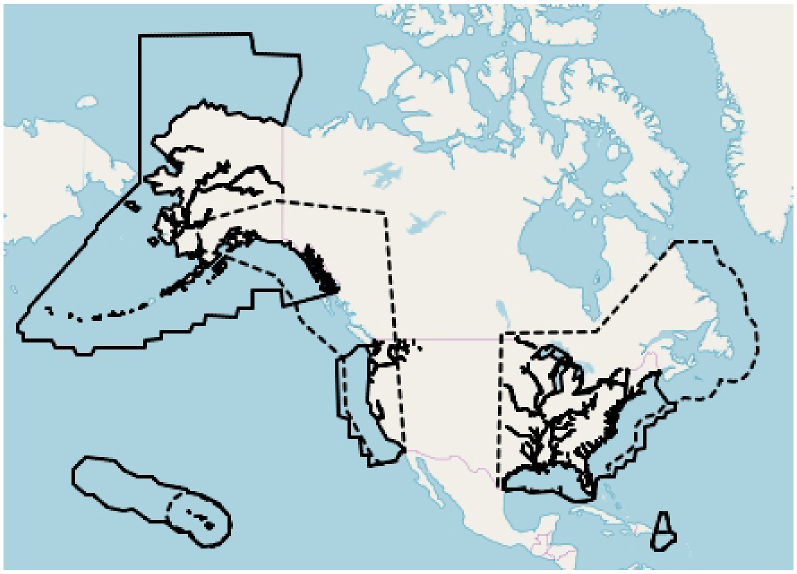

Figure 1. NEI Geographical Extent (Solid) and U.S. ECA (Dashed)

The compiled AIS data include the locations, speeds, drafts, and headings of all vessels with AIS transmitters operating within the specified geographical and time ranges. They also include vessel identifiers, such as the IMO number and Maritime Mobile Service Identifier (MMSI). These data were aggregated to five-minute intervals by the USCG.

2.2 Satellite and Terrestrial AIS Data

AIS data are transmitted to both satellite (S-AIS) and terrestrial (T-AIS) receivers. Satellite receivers provide adequate coverage over open ocean, where T-AIS coverage is sparse. The S-AIS and T-AIS datasets were merged by IMO number, MMSI, or both vessel identifiers. When both datasets reported activity for the same time stamp, the T-AIS messages were prioritized over the S-AIS messages, as T-AIS data are more suitable for the close-to-shore activity within this inventory.

3.0 Preparing Ship Registry Dataset

Ship parameter data were pulled primarily from the Clarksons ship registry and were supplemented and validated by smaller datasets (Clarksons, 2018; U.S. Coast Guard, 2017, 2018; U.S. Department of Transportation, 2017). The supplementary and Clarksons datasets were merged first on IMO number and then on the MMSI. All units were converted to metric units and all data for duplicate IMO numbers were merged. Expected ranges of ship parameter values were calculated for each ship type using the validated data. Where values differed between datasets, the parameter within the expected range was chosen. Vessel parameters required for emissions calculations are listed in Table 1.

Table 1. Ship Parameters

Vessel Identification Parameters	Vessel Category Parameters	Vessel Power Parameters	Vessel Grouping/Emission Factor Parameters
• IMO number • MMSI	• Engine bore • Engine stroke	• Hull displacement (m^3) • Length on perpendicular (m) • Summer load line draft (m) • Breadth (m) • Total installed propulsive power (kW) • Service speed (kn)	• Gross tonnage • Deadweight tonnage • Keel year • Propulsion type • Main stroke type • Engine revolutions per minute (rpm) • Twenty-foot equivalent units (TEU)

3.1 Ship Type

To fill gaps in vessel characteristics data and assign auxiliary and boiler loads, EPA matched vessel types to less granular ship type groups (see Appendix A-1). All barges and non-self-propelled vessels were removed from inventory calculations. The resulting database includes the following ship types:

- Bulk carrier
- Chemical tanker
- Container ship
- Cruise
- Ferry/roll-on/passenger vessel
- General cargo
- Liquified gas tanker
- Fishing
- Miscellaneous
- Oil tanker
- Offshore support vessel or drillship
- Other tanker
- Refrigerated vessel (Reefer)
- Roll-on/roll-off (Ro Ro)
- Tug
- Yacht

Figure 2 shows the 2017 AIS activity breakdown of these ship types.

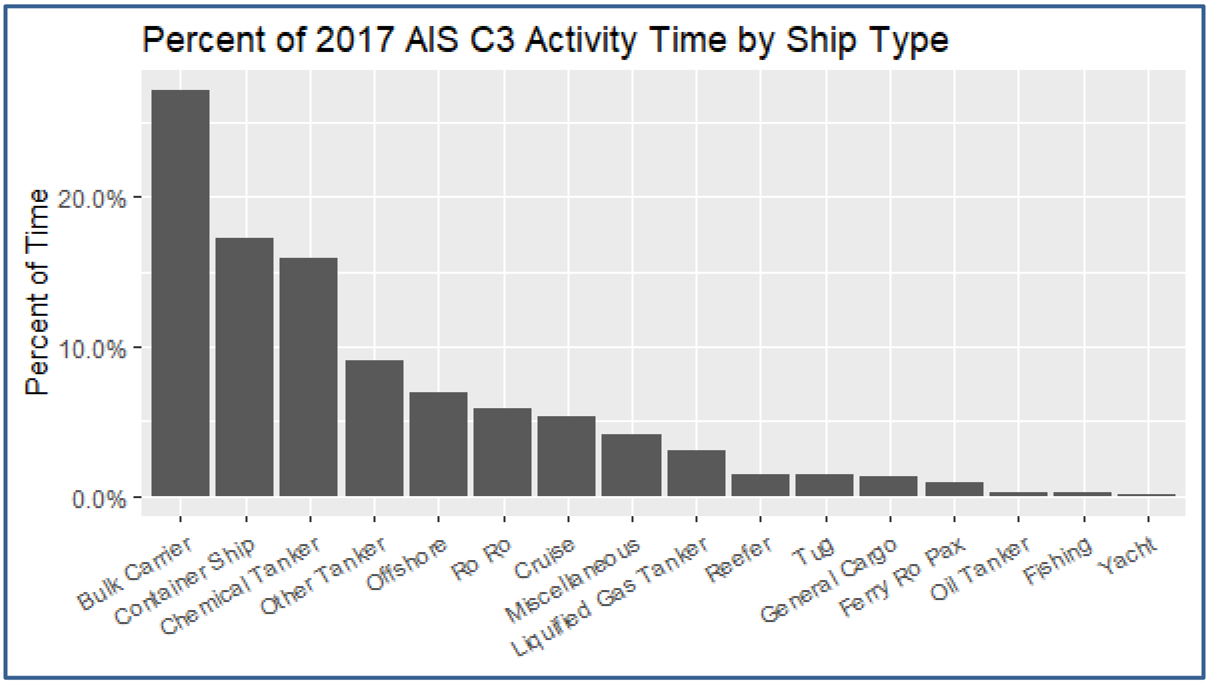

Figure 2. Category 3 AIS Activity Breakdown by Ship Type

3.2 Subtype

The EPA assigned subtypes to each vessel in the ship registry according to its ship type and size class (see Appendix A-2). Subtypes were primarily assigned to best fit with adopted auxiliary and auxiliary boiler engine loads (IMO, 2015). However, given the available data, certain adjustments were made in subtype characterization. As the number of vehicles per vehicle carrier was not available, vehicle carrier size classes were adopted from EPA (2009). All vehicle carrier auxiliary and auxiliary boiler loads are the same, regardless of subtype, and did not need to be altered for this process. Because cubic meter (m^3) size information was lacking, the EPA adopted chemical tanker deadweight tonnage (DWT) bins for liquified gas tankers.

3.3 Engine Type

Vessel engine type is required for the assignment of emission factors (EFs). The majority of the C3 fleet operated with slow-speed diesel (SSD) engines, which are identified as four-stroke engines. Medium-speed diesel (MSD) vessels were identified as those having two-stroke engines. While rpm classifications vary, 500 rpm was deemed to be the most appropriate cutoff between SSD and MSD engines, given the broad band of rpms separating the two groups (Diesel & Gas Turbine, 2013). EPA used rpm classifications to determine engine type only when engine stroke type information was unavailable. Gas turbine (GT) and steam turbine (ST) engines were determined by a descriptive propulsive type vessel characteristic field. This propulsive type field also allowed for the identification of electric-drive vessels (MSD-ED or GT-ED). Currently, no standardized identification methods are available for liquified natural gas (LNG) engines. All auxiliary engines were assumed to be MSD.

These propulsion type, main stroke type, and engine rpm fields either were not available in Clarkson's dataset or did not contain the needed information to complete the engine type classification. For this reason, an older Lloyds Information Handling Service (IHS) dataset was also used to determine engine type for the vessels represented in both datasets (IHS, 2014). The remaining vessels were assigned an engine type using the parameter gap-filling method described below.

3.4 Ship Parameter Gap Filling

Some vessel fields contain missing data. Waterline length (lwl) is typically calculated from length between perpendiculars (lbp). When lbp was missing, lwl was estimated based on a regression analysis using length overall. Missing twenty-foot equivalent (TEU) and DWT vessel size indicators were regressed from gross tonnage for the ship types that required these fields for their subtype assignments. Predicted values were only taken if they were within the expected range of that ship type. Ship types with a single subtype were given that subtype, regardless of whether their size fields were available.

A small portion of vessels could not be assigned subtypes, either because they were missing vessel type (and thus ship type information) or because their size fields could not be filled adequately. These represented 0.6% and 0.04% of the 2017 AIS fleet activity time, respectively; they were removed from the inventory, as these fields are required for the assignment of auxiliary and boiler engine power and the sensitivities to applying average subtypes have not been assessed.

The remaining fields were filled according to the most common parameters seen by vessels in the 2017 AIS vessel activity dataset. Annual time spent within the geographical extent was calculated for each vessel appearing in both the AIS and compiled ship registry datasets.

Missing keel year was estimated from build year (calculated from either the time-weighted or population-weighted average time difference between these dates by subtype). The most common ship category, engine type, and tier in the 2017 fleet were identified by ship type; subtype; and iterative groupings of ship category, engine type, and tier. The most common value at the most granular grouping was prioritized in gap-filling these fields, after which common values determined by less granular groupings were applied.

Similarly, time-weighted averages of the remaining numerical vessel characteristics were calculated at varying levels of granularity of subtype, ship category, engine type, and tier. The time-weighted average at the most granular grouping was prioritized in gap-filling these fields, after which averages determined by less granular groupings were applied. Block coefficients are a function of vessel hull displacement, waterline length, breadth, and draft. For vessels missing just one of these function inputs, values were back-calculated from the average applied block coefficient and the remaining input parameters. (Using an average block coefficient was determined to affect emissions estimates less than calculating one from average input parameters; see Brown & Aldridge, 2018.)

Analysis has shown that gap-filling parameters by vessel subtype averages produces a relatively small difference in estimated emissions (Brown & Aldridge, 2018). Roughly 60% of the AIS activity time was allocated to vessels missing hull displacement data. Due to this, 51% of the 2017 AIS activity time is allocated to vessels whose hull displacement was filled by back-calculating from block coefficients averaged by subtype, ship category, engine type, and tier. For the remaining vessel parameters, less than 6% of AIS activity time was allotted to missing data.

3.5 Merging AIS and Ship Registry Dataset

The IMO vessel identification code is a seven-digit vessel identifier assigned on behalf of the IMO to self-propelled, primarily commercial, seagoing cargo vessels with a gross tonnage of 300 or more or passenger vessels with a gross tonnage of 100 or more. The IMO vessel identification code remains linked to the vessel hull, regardless of changes in names, operations, or owners.

The MMSI is a nine-digit identifier associated with radio transmission of AIS messages. This means that every vessel in the AIS dataset has a unique identifier. However, because the MMSI ID is attached to the transmitter, an operator may fail to report a move of their radio transmitter between vessels. Therefore, the IMO number is prioritized as the matching identifier between the ship registry and AIS datasets. Those unmatched by this identifier were linked using the MMSI number. Each vessel in the linked dataset is assigned a unique ID.

3.6 Cleaning AIS Dataset

Before the emissions calculations, erroneous vessel activity messages were identified and removed from the dataset. Some duplicate messages, associated with the same vessel identifier and time stamp, were reported. These duplicates were removed. Erroneous speeds were deemed to be all speeds above 1.5 times the service speed of the vessel (IMO, 2015); these messages were also removed. Removing erroneous messages created gaps, which were filled in later processing steps. Activity messages report vessel draft, a parameter required for ship propulsive power modeling. Vessels were assumed to be operating at maximum draft when AIS-reported draft data were missing.

3.7 Temporal Gaps in AIS Activity

The AIS messages received from the USCG were typically aggregated to five-minute intervals. However, there were some intervals longer than five minutes between vessels' consecutive messages, suggesting cases in which transmissions were not sent or received, or in which a vessel left the study area and then returned. EPA analyzed these gaps to determine whether they reflected activity outside the geographical extent of the received AIS data. This analysis was completed by extrapolating vessel activity, assuming a constant speed and heading, from that of the previous message to gap, and comparing extrapolated positions to the AIS dataset boundaries. All gaps reflecting activity out of the AIS geographical area were omitted from the emissions inventory. The rest were filled in by linearly interpolated location, speed, and draft data at five-minute intervals.

3.8 Calculating Emissions

This inventory compiles emissions from each marine vessel represented in both the AIS activity and ship registry datasets. Emissions are calculated for each time interval between consecutive AIS messages for each vessel and allocated to the location of the message before the interval. Emissions are calculated according to Equation 1.

Equation 1

$$Emissions_{interval} = Time\ (hr)_{interval} \times\ Power(kW) \times EF(\frac{g}{kWh}) \times LLAF$$

where:

Power	=	calculated for the propulsive (main), auxiliary, and auxiliary boiler engines for each interval
EF	=	assigned emission factors for each engine (as described below)
LLAF	=	low load adjustment factor, a unitless factor that reflects increasing propulsive emissions during low load operations

3.9 Calculating Power

Past inventories have modeled main engine power with the Propeller Law. However, the Propeller Law does not account for hull resistance, which can significantly affect ship propulsive power (MAN Diesel & Turbo, 2011; Jalkanen et al., 2014; Molland et al., 2011). The availability of five-minute vessel speed and draft AIS activity data allows for use of more complex ship powering models, providing a significant improvement to the estimate's precision.

Propulsive power was calculated using the Holtrop & Mennen numerical ship power model, which follows the form of resistance-based methods, documented in Equation 2 (Holtrop & Mennen, 1982).

Equation 2

$$Power\ (kW) = \frac{\rho \times C_T \times \frac{1}{2} \times S \times V_{reported}{}^{3}}{\eta_T}$$

where:

ρ	=	sea water density
$V_{reported}$	=	AIS-reported speed before the message interval
C_T	=	vessel's hull resistance coefficient
S	=	hull surface area
η_T	=	engine efficiency

Where available vessel attributes were not sufficient to calculate certain Holtrop & Mennen parameters, such as transverse bulb area, transom area, longitudinal position center of buoyancy, and center of bulb above keel line, methodologies from Rakke (2016) were used. Vessels were assumed to be operating in calm, 15°C water conditions with clean and normal hulls. In accordance with this, a 15% service margin was applied, as is customary (MAN Diesel & Turbo; IMO, 2015). The midship section coefficient was assumed to be 0.995 for bulk and tankers, 0.95 for passenger vessels, 0.92 for tugs, and 0.98 for all other ship types (Kristensen & Lutzen, 2012). Passenger ship types were assumed to have two propellers and all other vessels were assumed to have one propeller. The waterplane area coefficient was calculated according to methodologies in Kristensen & Lutzen (2012). EPA adopted upper and lower bounds from SARC Maritime Software and Services (2018) and applied them to these waterplane area coefficients in order to ensure the values were within a realistic range.

Brown & Aldridge (2018) compared the effects of two resistance-based, and two load-factor-based, power modeling methods on a regional AIS ship emissions inventory with parameter gap filling. Analyzed power models included the load-factor-based Propeller Law (EPA, 2009) and Admiralty Law (IMO, 2015) models, as well as the resistance-based Kristensen & Lutzen (2012) and Holtrop & Mennen (1982) models. For that sample, emissions resulting from a Holtrop & Mennen inventory were shown to be affected less than 1.5% by the use of subtype averaged parameters for gap filling. Holtrop & Mennen's model was less sensitive to the use of averaged displacement than the Kristensen model. Because of this, and because of the heavy reliance on gap-filled hull displacement values in this fleet, the Holtrop & Mennen model was chosen for this inventory.

3.10 Assigning Operating Mode

Operating mode is determined according to the propulsive load factor and speed associated with each vessel's AIS message. Table 2 shows the requirements for these operating mode assignments.

Table 2. Operational Mode Speed and Load Factor Requirements

Operating Mode	Speed Range Requirements	Engine Load Factor Requirements	Source
Berth	≤ 1 kn	None	IMO, 2015
Anchorage	> 1 kn and ≤ 3 kn	None	IMO, 2015
Maneuvering	> 3 kn	≤ 20%	EPA, 2009
Transit	> 3 kn	> 20%	EPA, 2009

3.11 Calculating Auxiliary and Boiler Power

Auxiliary engines support electrical generators for auxiliary vessel power. Auxiliary engine power cannot be calculated directly using AIS data and is not estimated in Clarkson's ship registry dataset; rather, defaults must be used. Auxiliary engine power defaults were adopted from those used by the IMO's Third Greenhouse Gas Report (2015). These values incorporate data collected by Starcrest's Vessel Boarding Program (VBP) in the Port of Los Angeles, the Port of Long Beach, the Port Authority of New York & New Jersey, the Port of Houston Authority, the Port of Seattle, and the Port of Tacoma. They also incorporation data from the Finnish Metrological Institute. Slight adjustments were made to accommodate missing size field data. Subtypes *liquified gas tanker 5000* and *liquified gas tanker 10000* were assigned the IMO (2015) supplied auxiliary power of liquified gas tankers of size 0-49,999 m^3. The applied auxiliary engine power (kW) is presented in Table 3.

Table 3. Auxiliary Engine Power (kW)

Subtype	Transit (kW)	Maneuvering (kW)	Berth (kW)	Anchorage (kW)
Bulk carrier small	190	310	280	190
Bulk carrier handy size	190	310	280	190
Bulk carrier handy max	260	420	370	260
Bulk carrier pana max	420	680	600	420
Bulk carrier cape size	420	680	600	420
Bulk carrier cape size largest	420	680	600	420
Chemical tanker smallest	80	110	160	80
Chemical tanker small	230	330	490	230
Chemical tanker handy size	230	330	490	230
Chemical tanker handy max	550	780	1,170	550
Container ship 1000	300	550	340	300
Container ship 2000	820	1,320	600	820
Container ship 3000	1,230	1,800	700	1,230
Container ship 5000	1,390	2,470	940	1,390
Container ship 8000	1,420	2,600	970	1,420
Container ship 12000	1,630	2,780	1,000	1,630
Container ship 14500	1,960	3,330	1,200	1,960

Table 3. Auxiliary Engine Power (kW)

Subtype	Transit (kW)	Maneuvering (kW)	Berth (kW)	Anchorage (kW)
Container ship largest	2,160	3,670	1,320	2,160
General cargo 5000	60	90	120	60
General cargo 10000	170	250	330	170
General cargo largest	490	730	970	490
Liquified gas tanker 5000	240	360	240	240
Liquified gas tanker 10000	240	360	240	240
Liquified gas tanker 20000	1,710	2,565	1,710	1,710
Liquified gas tanker largest	1,710	2,565	1,710	1,710
Oil tanker smallest	250	375	250	250
Oil tanker small	375	563	375	375
Oil tanker handy size	625	938	625	625
Oil tanker handy max	750	1,125	750	750
Oil tanker pana max	750	1,125	750	750
Oil tanker afra max	1,000	1,500	1,000	1,000
Oil tanker suez max	1,250	1,875	1,250	1,250
Oil tanker vlcc	1,500	2,250	1,500	1,500
Other tanker	500	750	500	500
Ferry pax 2000	186	186	186	186
Ferry pax largest	524	524	524	524
Cruise 2000	450	580	450	450
Cruise 10000	450	580	450	450
Cruise 60000	3,500	5,460	3,500	3,500
Cruise 100000	11,480	14,900	11,480	11,480
Cruise largest	11,480	14,900	11,480	11,480
Ferry Ro pax 2000	105	105	105	105
Ferry Ro pax largest	710	710	710	710
Reefer	1,170	1,150	1,080	1,170
RoRo 5000	600	1,700	800	600
RoRo largest	950	2,720	1,200	950
Vehicle carrier 10000	500	1,125	800	500
Vehicle carrier 20000	500	1,125	800	500
Vehicle carrier 30000	500	1,125	800	500
Vehicle carrier largest	500	1,125	800	500
Yacht	130	130	130	130
Tug	50	50	50	50
Fishing	200	200	200	200
Offshore	320	320	320	320
Service other	220	220	220	220
Miscellaneous	190	190	190	190

Auxiliary boiler engines supply steam and hot water for heating and other auxiliary requirements on marine vessels. As with auxiliary engine power, auxiliary boiler engine power varies according to operational mode and no boiler engine power information was available through the Clarkson's ship registry or AIS activity datasets. Values were adopted from the IMO's Third Greenhouse Gas Report (2015), which used Starcrest's VBP data. Slight adjustments were applied to account for missing size field data. Subtypes *liquified gas tanker 5000* and *liquified gas tanker 10000* were assigned the IMO (2015) supplied auxiliary boiler power of liquified gas tankers of size 0–49,999 m^3. The applied auxiliary boiler power is presented in Table 4. Transiting operational modes have low auxiliary engine loads because heat is typically scavenged from the main engine exhaust instead of boiler engines during these operations.

Table 4. Auxiliary Boiler Engine Loads (kW)

Subtype	Transit (kW)	Maneuvering (kW)	Berth (kW)	Anchorage (kW)
Bulk carrier small	190	310	280	190
Bulk carrier handy size	190	310	280	190
Bulk carrier handy max	260	420	370	260
Bulk carrier pana max	420	680	600	420
Bulk carrier cape size	420	680	600	420
Bulk carrier cape size largest	420	680	600	420
Chemical tanker smallest	80	110	160	80
Chemical tanker small	230	330	490	230
Chemical tanker handy size	230	330	490	230
Chemical tanker handy max	550	780	1,170	550
Container ship 1000	300	550	340	300
Container ship 2000	820	1,320	600	820
Container ship 3000	1,230	1,800	700	1,230
Container ship 5000	1,390	2,470	940	1,390
Container ship 8000	1,420	2,600	970	1,420
Container ship 12000	1,630	2,780	1,000	1,630
Container ship 14500	1,960	3,330	1,200	1,960
Container ship largest	2,160	3,670	1,320	2,160
General cargo 5000	60	90	120	60
General cargo 10000	170	250	330	170
General cargo largest	490	730	970	490
Liquified gas tanker 5000	240	360	240	240
Liquified gas tanker 10000	240	360	240	240
Liquified gas tanker 20000	1,710	2,565	1,710	1,710
Liquified gas tanker largest	1,710	2,565	1,710	1,710
Oil tanker smallest	250	375	250	250
Oil tanker small	375	563	375	375
Oil tanker handy size	625	938	625	625
Oil tanker handy max	750	1,125	750	750

Table 4. Auxiliary Boiler Engine Loads (kW)

Subtype	Transit (kW)	Maneuvering (kW)	Berth (kW)	Anchorage (kW)
Oil tanker pana max	750	1,125	750	750
Oil tanker afra max	1,000	1,500	1,000	1,000
Oil tanker suez max	1,250	1,875	1,250	1,250
Oil tanker vlcc	1,500	2,250	1,500	1,500
Other tanker	500	750	500	500
Ferry pax 2000	186	186	186	186
Ferry pax largest	524	524	524	524
Cruise 2000	450	580	450	450
Cruise 10000	450	580	450	450
Cruise 60000	3,500	5,460	3,500	3,500
Cruise 100000	11,480	14,900	11,480	11,480
Cruise largest	11,480	14,900	11,480	11,480
Ferry Ro pax 2000	105	105	105	105
Ferry Ro pax largest	710	710	710	710
Reefer	1,170	1,150	1,080	1,170
RoRo 5000	600	1,700	800	600
RoRo largest	950	2,720	1,200	950
Vehicle carrier 10000	500	1,125	800	500
Vehicle carrier 20000	500	1,125	800	500
Vehicle carrier 30000	500	1,125	800	500
Vehicle carrier largest	500	1,125	800	500
Yacht	130	130	130	130
Service tug	50	50	50	50
Miscellaneous fishing	200	200	200	200
Offshore	320	320	320	320
Service other	220	220	220	220
Miscellaneous other	190	190	190	190

4.0 Emission Factors

EFs are assigned according to engine type, engine group, tier and fuel sulfur level below. MSD-ED and GT-ED adopt MSD and GT EFs, respectively.

4.1 CO, HC, and VOC

CO (carbon monoxide) and HC (hydrocarbon) EFs are reported in Table 5 for propulsive, auxiliary, and auxiliary boiler engines along with the sources from which they originated. LNG EFs were adopted from Kristensen (2012), as they were in IMO (2015).

Table 5. CO and HC EFs

Engine Type	Engine	CO EF (g/kWh)	HC EF (g/kWh)	Source
SSD	Propulsive	1.4	0.6	EPA, 2009
MSD	Propulsive	1.1	0.5	EPA, 2009
GT	Propulsive	0.2	0.1	EPA, 2009
ST	Propulsive	0.2	0.1	EPA, 2009
LNG	Propulsive	1.3	0	Kristensen, 2012
MSD	Auxiliary	1.1	0.4	Starcrest Consulting Group, 2015
HSD	Auxiliary	0.9	0.4	Starcrest Consulting Group, 2015
LNG	Auxiliary	1.3	0	Kristensen, 2012
Boiler	Auxiliary boiler	0.2	0.1	Starcrest Consulting Group, 2015

Note for C3 engines, HC emissions were converted into VOC values using a multiplier of 1.053 (VOC/HC) based on the approach used in the 2014 National Emission Inventory (EPA 2018a).

4.2 Fuel Use Assignment

All C3 marine vessels are assumed to use distillate marine gas oil (MGO) or marine diesel oil (MDO) fuel during operations within the North American ECA in order to comply with fuel sulfur regulations. All those outside the ECA are assumed to use residual marine (RM) or heavy fuel oil (HFO). Some uncertainty exists in this assignment, as the usage of blended fuels, or of scrubber adoption with high sulfur fuels, within these regions, is not known.

4.3 NO_x

NO_x (nitrogen oxides) EFs are applied according to engine type, fuel type, and engine tier and are presented in Tables 6–8 for main, auxiliary, and auxiliary boiler engines. The IMO has established NO_x standards for marine diesel engines that depend on the keel year of the vessel. All vessels for which the keel-laid date was before model year (MY) 2000, as well as all ST, GT, and LNG vessels, are considered Tier 0. Tier 1 NO_x standards were applied to all remaining marine diesel engines from MY 2000 and 2010. Tier 2 standards were applied to all vessels from MY 2011 through 2015, and Tier 3 standards were applied to all vessels with a keel-laid date MY 2016 and later.

Table 6. Propulsive NO_x EFs (g/kWh)

Engine Type	Fuel Type	Tier	NO_x EF (g/kWh)	Source
SSD	MGO/MDO	Tier 0	17	ENTEC, 2002
MSD	MGO/MDO	Tier 0	13.2	ENTEC, 2002
ST	MGO/MDO	Tier 0	2	ENTEC, 2002

Table 6. Propulsive NO_x EFs (g/kWh)

Engine Type	Fuel Type	Tier	NO_x EF (g/kWh)	Source
GT	MGO/MDO	Tier 0	5.7	ENTEC, 2002
SSD	MGO/MDO	Tier 1	16	Starcrest Consulting Group, 2015
MSD	MGO/MDO	Tier 1	12.2	Starcrest Consulting Group, 2015
SSD	MGO/MDO	Tier 2	14.4	Starcrest Consulting Group, 2015
MSD	MGO/MDO	Tier 2	10.5	Starcrest Consulting Group, 2015
SSD	MGO/MDO	Tier 3	3.4	Starcrest Consulting Group, 2015
MSD	MGO/MDO	Tier 3	2.6	Starcrest Consulting Group, 2015
SSD	RM/HFO	Tier 0	18.1	ENTEC, 2002
MSD	RM/HFO	Tier 0	14	ENTEC, 2002
ST	RM/HFO	Tier 0	2.1	ENTEC, 2002
GT	RM/HFO	Tier 0	6.1	ENTEC, 2002
SSD	RM/HFO	Tier 1	17	Buhaug et al., 2009
MSD	RM/HFO	Tier 1	13	Buhaug et al., 2009
SSD	RM/HFO	Tier 2	15.3	Buhaug et al., 2009
MSD	RM/HFO	Tier 2	11.2	Buhaug et al., 2009
SSD	RM/HFO	Tier 3	3.4	Starcrest Consulting Group, 2015
MSD	RM/HFO	Tier 3	2.6	Starcrest Consulting Group, 2015
LNG	LNG	Tier 0	1.3	Kristensen, 2012

Table 7. Auxiliary NO_x EFs (g/kWh)

Engine Type	Fuel Type	Tier	NO_x EF (g/kWh)	Source
MSD	RM/HFO	Tier 0	14.7	IMO, 2015
MSD	RM/HFO	Tier 1	13	IMO, 2015
MSD	RM/HFO	Tier 2	11.2	IMO, 2015
MSD	RM/HFO	Tier 3	2	Starcrest Consulting Group, 2015
MSD	MGO/MDO	Tier 0	10.9	Starcrest Consulting Group, 2015
MSD	MGO/MDO	Tier 1	9.8	Starcrest Consulting Group, 2015
MSD	MGO/MDO	Tier 2	7.7	Starcrest Consulting Group, 2015
MSD	MGO/MDO	Tier 3	2	Starcrest Consulting Group, 2015
LNG	LNG	Tier 0	1.3	IMO, 2015
HSD	RM/HFO	Tier 0	11.6	IMO, 2015
HSD	RM/HFO	Tier 1	10.4	IMO, 2015
HSD	RM/HFO	Tier 2	8.2	IMO, 2015
HSD	RM/HFO	Tier 3	2.6	Starcrest Consulting Group, 2015
HSD	MGO/MDO	Tier 0	13.8	Starcrest Consulting Group, 2015
HSD	MGO/MDO	Tier 1	12.2	Starcrest Consulting Group, 2015
HSD	MGO/MDO	Tier 2	10.5	Starcrest Consulting Group, 2015
HSD	MGO/MDO	Tier 3	2.6	Starcrest Consulting Group, 2015

Table 8. Boiler NO_x EFs (g/kWh)

Engine Type	Fuel Type	Tier	NO_x EF (g/kWh)	Source
Boiler	RM/HFO	Tier 0	2.1	ENTEC, 2002
Boiler	MGO/MDO	Tier 0	2	ENTEC, 2002

4.4 Brake-Specific Fuel Consumption

The remaining pollutants (particulate matter [PM], sulfur dioxide [SO_2], and carbon dioxide [CO_2]) are calculated according to assumed brake-specific fuel consumption (BSFC). The applied BSFC rates are supplied in Tables 9–11. Sources reflect those used by IMO (2015).

Table 9. Propulsive Engine BSFC Rates (g/kWh)

Engine Type	Fuel Type	BSFC (g/kWh)	Source[a]
SSD	MGO/MDO	185	Cooper & Gustafsson, 2004
MSD	MGO/MDO	205	Cooper & Gustafsson, 2004
ST	MGO/MDO	300	Cooper & Gustafsson, 2004
GT	MGO/MDO	300	Cooper & Gustafsson, 2004
SSD	RM/HFO	195	Cooper & Gustafsson, 2004
MSD	RM/HFO	215	Cooper & Gustafsson, 2004
ST	RM/HFO	305	Cooper & Gustafsson, 2004
GT	RM/HFO	305	Cooper & Gustafsson, 2004
LNG	LNG	166	Wärtsila, 2014

[a] References used in the IMO 2015 study are noted.

Table 10. Auxiliary Engine BSFC Rates (g/kWh)

Engine Type	Fuel Type	BSFC (g/kWh)	Source[a]
HSD	RM/HFO	227	Cooper & Gustafsson, 2004
MSD	RM/HFO	227	Cooper & Gustafsson, 2004
HSD	MGO/MDO	217	Cooper & Gustafsson, 2004
MSD	MGO/MDO	217	Cooper & Gustafsson, 2004
LNG	LNG	166	Wärtsila, 2014

[a] References used in the IMO 2015 study are noted.

Table 11. Auxiliary Boiler Engine BSFC Rates (g/kWh)

Engine Type	Fuel Type	BSFC (g/kWh)	Source[a]
Boiler	RM/HFO	305	Cooper & Gustafsson, 2004
Boiler	MGO/MDO	300	Cooper & Gustafsson, 2004

[a] References used in the IMO 2015 study are noted.

4.5 PM

Past inventories have calculated PM using Equation 3 (EPA, 2009).

Equation 3

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

where:

EF(PM)	=	PM emission factor adjusted for fuel sulfur (g/kWh)
PM_{Nom}	=	PM emission rate at nominal fuel sulfur level
	=	0.23 g/kWh for distillate fuel, 1.35 g/kWh 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/kWh
FSC	=	percentage of sulfur in fuel that is converted to direct sulfate PM
	=	2.247% applied for this inventory
MWR	=	molecular weight ratio of sulfate PM to sulfur
	=	224/32 = 7 applied for this inventory

While Equation 3 is representative of marine vessels operating with fuel sulfur levels greater than the nominal given values, it does not accurately represent the effect of varying BSFC values when fuel sulfur is below nominal levels. Where $S_{Act} << S_{Nom}$ and BSFC is variable (Tables 9–11), it is possible for Equation 3 to output decreasing PM EFs with increasing BSFC, which is not accurate. To resolve this issue, a base PM rate was first estimated at zero fuel sulfur content for the assumed fuel consumption rate (Equation 4).

Equation 4

$$PM_{Base} = PM_{Nom} + [(0 - S_{Nom}) \times BSFC \times FSC \times MWR \times 0.0001]$$

The equation was then refactored from Equation 4 to use PM_{Base} instead of PM_{Nom}, and $S_{Nom} = 0$ (Equation 5).

Equation 5

$$EF(PM_{10}) = PM_{Base} + [S_{Act} \times BSFC \times FSC \times MWR \times 0.0001]$$

FSC and MWR values reflect those in Equation 3, and PM_{Base} is set to 0.1545 (g/kWh) for distillate (MGO/MDO) fuel and 0.5761 (g/kWh) for residual (RM/HFO) fuel.

This updated equation assumes a base emission rate for zero fuel sulfur and increases the rate as a function of fuel sulfur content and fuel consumption rate. This method avoids generating negative emission rates for low fuel sulfur and high fuel consumption.

For the current inventory, fuel sulfur values are set to 0.1% for all vessel activity within the ECA in accordance with fuel sulfur regulations (EPA, 2010). Marine vessels are assumed to use fuel with 2.7% fuel sulfur levels outside of the ECA.[1] BSFC values (Tables 9–11) are applied in Equation 5 according to the assigned fuel and engine types per vessel activity message for this calculation.

Equation 5 is not effective for ST, GT, and LNG vessels, whose PM EFs were adopted from IMO (2015) and are reported in Table 12.

Table 12. ST, GT, and LNG PM EFs (g/kWh)

Engine Type	Fuel Type	PM_{10} EF (g/kWh)	Source[a]
ST	MGO/MDO	0.16	Cooper & Gustafsson, 2004
GT	MGO/MDO	0.01	Cooper & Gustafsson, 2004
ST	RM/HFO	0.93	Cooper & Gustafsson, 2004
GT	RM/HFO	0.06	Cooper & Gustafsson, 2004
LNG	LNG	0.03	Kristensen, 2012

[a] References used in the IMO 2015 study are noted.

$PM_{2.5}$ EFs are calculated as 92% of PM_{10} EFs (EPA, 2009).

4.6 SO_2

SO_2 is calculated by Equation 6, where S_{Act} represents the assigned fuel sulfur level according to the vessel's activity location.

Equation 6

$$EF(SO_2) = BSFC \times 2 \times 0.97753 \times (S_{Act} \div 100)$$

4.7 CO_2

CO_2 is dependent on fuel type and is calculated as the linear function represented in Equation 7.

Equation 7

$$EF(CO_2) = BSFC \times Carbon\ Content\ Factor$$

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[1] The non-ECA fuel sulfur content reflects that applied in EPA (2009) and in the development of EFs in ENTEC (2002). More recent inventories suggest the adoption of the international, 2012 non-ECA fuel sulfur level of 2.51% (IMO, 2015). However, this inventory primarily reflects ECA activity and therefore the effect of a 2.7% fuel sulfur level is deemed to be negligible. More research is needed on up-to-date non-ECA fuel sulfur levels as marine vessels approach the 2020 0.5% fuel sulfur regulations.

The BSFC to CO_2 conversion factors were adopted from IMO (2015) and are reported in Table 13.

Table 13. BSFC to CO_2 Conversion Factor

Fuel Type	BSFC to CO_2 Carbon Content Factor	Source[a]
MGO/MDO	3.206	IMO, 2012
RM/HFO	3.114	IMO, 2012
LNG	2.75	IMO, 2012

[a] References used in the IMO 2015 study are noted.

4.8 Low Load Adjustment Factor

EFs are considered to be constant when a vessel's modeled propulsive engine load represents more than 20% of its total installed propulsive power. Below that threshold, EFs tend to increase as the engine load decreases. This trend results because diesel engines are less efficient at low loads and the BSFC tends to increase. To account for this, low load adjustment factors (LLAFs) are calculated and applied in Equation 1 (EPA, 2009).

Modeled emissions from vessels with electric-drive engines (MSD-ED or GT-ED) were assigned LLAFs of one for all pollutants. These vessels generate power with several smaller engines, some of which, it is assumed, shut down as power demand decreases to ensure that no engines are operating at lower inefficient loads, enhancing overall efficiency and reducing fuel consumption.

Equation 8 is used to calculate this adjustment factor, according to the pollutant-specific parameters suppled in Table 14 for all non-SO_2 pollutants.

Equation 8

$$LLAF = a(Fractional\ Engine\ Load)^{-x} + b$$

Table 14. LLAF Parameters

Pollutant	A	X	B
NO_x	0.1255	1.5	10.4496
HC	0.0667	1.5	0.3859
CO	0.8378	1	0.1548
PM_{10}	0.0059	1.5	0.2551
$PM_{2.5}$	0.0059	1.5	0.2551
SO_2	2.3735		-0.4792
CO_2	44.1	1	648.6

Equations 9 and 10 are designed to calculate this adjustment factor using the SO_2 parameters suppled in Table 11.

Equation 9

$$Fuel\ Consumption\ (g/kWh)\ =\ 14.1205\ (1 \div Fractional\ Load)\ +\ 205.7169$$

Equation 10

$$Emission\ Rate\ (g/kWh)\ =\ a\ (Fuel\ Consumption\ \times\ Fuel\ Sulfur\ Fraction)\ +\ b$$

4.9 HAP Specific Profiles

The EPA recently updated HAP speciation profiles in order to calculate HAPs from the criteria pollutants estimated by the above-described methodology. The fractions reported in Table 15 were multiplied by the emissions of their assigned basis pollutant to complete this calculation.

Table 15. HAP Speciation Profile

Pollutant	Pollutant Code	Basis	Fraction
1,3-Butadiene[a]	106990	VOC	0.001013
2,2,4-Trimethylpentane[b]	540841	VOC	0.00712
Acenaphthene[a]	83329	VOC	5.09E-05
Acenaphthylene[a]	208968	VOC	0.000118
Acetaldehyde[a]	75070	VOC	0.009783
Acrolein[a]	107028	VOC	0.001848
Ammonia[c]	NH_3	$PM_{2.5}$	0.019247
Anthracene[a]	120127	VOC	0.000344
Antimony[a]	7440360	$PM_{2.5}$	0.000615
Arsenic[c]	7440382	$PM_{2.5}$	2.59E-05
Benz[a]Anthracene[a]	56553	$PM_{2.5}$	8.82E-06
Benzene[a]	71432	VOC	0.004739
Benzo[a]Pyrene[c]	50328	$PM_{2.5}$	4.18E-06
Benzo[b]Fluoranthene[c]	205992	$PM_{2.5}$	8.35E-06
Benzo[k]Fluoranthene[c]	207089	$PM_{2.5}$	4.18E-06
Benzo(g,h,i)Perylene[a]	203123	$PM_{2.5}$	0.000132
Cadmium[a]	7440439	$PM_{2.5}$	0.000236
Chrysene[a]	218019	$PM_{2.5}$	1.63E-05
Chromium (VI)[b]	18540299	$PM_{2.5}$	7.24E-09
Dibenzo[a,h]anthracene[a]	53703	$PM_{2.5}$	8.65E-06
Ethyl Benzene[a]	100414	VOC	0.000439
Fluoranthene[a]	206440	$PM_{2.5}$	8.97E-05
Fluorene[a]	86737	VOC	0.000164

Table 15. HAP Speciation Profile

Pollutant	Pollutant Code	Basis	Fraction
Formaldehyde[a]	50000	VOC	0.042696
Indeno[1,2,3-c,d]Pyrene[c]	193395	$PM_{2.5}$	8.35E-06
Lead[c]	7439921	$PM_{2.5}$	0.000125
Manganese[b]	7439965	$PM_{2.5}$	3.22E-06
Mercury[c]	7439976	$PM_{2.5}$	4.18E-08
Naphthalene[a]	91203	VOC	0.00273
Hexane[b]	110543	VOC	0.00279
Nickel[c]	7440020	$PM_{2.5}$	0.000687
Polychlorinated Biphenyls[c]	1336363	$PM_{2.5}$	4.18E-07
Phenanthrene[a]	85018	VOC	0.001356
Propionaldehyde[a]	123386	VOC	0.001517
Pyrene[a]	129000	$PM_{2.5}$	3.37E-05
Selenium[c]	7782492	$PM_{2.5}$	4.38E-08
Toluene[a]	108883	VOC	0.002035
Xylenes (Mixed Isomers)[a]	1330207	VOC	0.001422
o-Xylene[a]	95476	VOC	0.000513

[a] Agrawal, Harshit, William A Welch, J Wayne Miller, and David R Cocker. 2008. 'Emission Measurements from a Crude Oil Tanker at Sea,' Environmental Science & Technology, 42, no. 19: 7098-103. DOI: 10.1021/es703102y. Used data for auxiliary engine which burned marine gas oil with 0.06 wt % sulfur and 0.01 wt,% ash content.

[b] Speciation Profiles and toxic Emission Factors for Nonroad Engines in MOVES2014b, EPA-420-R-18-011, July 2018b.

[c] Swedish Environmental Protection Agency, Swedish Methodology for Environmental Data; Methodology for Calculating Emissions from Ships: 1. Update of Emission Factors, 2004.

5.0 Rasterization

In order to include the results of the inventory in the national air quality modeling platform, ERG developed daily rasters from the estimated C3 emissions. After emissions were calculated and allocated to the latitude and longitude coordinates of the message prior to the associated activity interval, they were split into daily files and read into the rasterization function. Throughout the function's processing, these emissions were then additionally split by hour and SCC category. After this, the R rasterize function was used to overlay the points with a grid cell box and sum emissions per grid cell to create a raster. An example of this process can be seen in Figure 3.

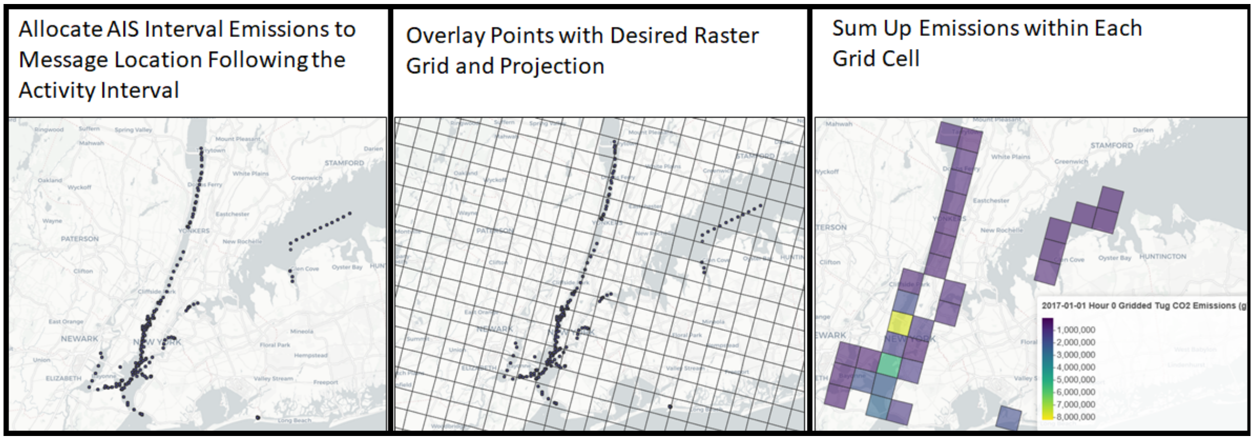

Figure 3. C1C2 NEI AIS Activity Hours by Vessel Group

In order to rasterize the data as needed, multiple rasterization grids were developed to cover the continental US (CONUS) and give more granular depictions of Alaska, Hawaii, Puerto Rico, the Great Lakes and the Long Island regions. These grids were created with rectangular polygon shapefiles which outline the extent of the desired raster grid and are imbedded with the necessary projection information for that area. For each desired raster, these polygons and the desired grid resolution were used as inputs for the rasterization function.

The resulting rasters were outputted as netCDF files, each of which represent a single day and SCC combination. Each netCDF file has 24 layers, with the first layer representing the first hour of the day (00:00:00 – 01:00:00 UTC), and seven variables which represent the modelled pollutants (VOC, CO_2, CO, NO_X, $PM_{2.5}$, SO_2, PM_{10}).

5.1 Masking Raster

The C3CMV model includes interpolated data points between all AIS messages associated with non-hoteling activity intervals greater than five minutes. This was done with the intention that each underway emissions estimation should represent the same activity duration. However, some messages were interpolated in locations that cannot contain C3 activity, like narrow inland waterways and shallow water bodies. Therefore, because interpolated messages were included in the rasterization process described above, a masking raster was required in order to define likely and unlikely C3 locations. This masking raster was then used to remove all emissions from grid cells in unlikely C3 locations.

ERG developed an R function to create the initial masking raster. This function creates a single, annual raster of non-interpolated C3 activity with the intention to remove all emissions from the daily rasters that were in unlikely C3 locations. Unlikely C3 locations were grid cells in which exclusively interpolated messages existed.

However, an analysis of the 12km CONUS masking raster brought to light certain anomalies in non-interpolated data which may also result in unlikely emissions locations. The non-interpolated masking raster reported odd inland activity such as that near Gainesville, FL and up the Mississippi river where C3 activity is not likely. These emissions were determined to be the result of "rogue" messages within the raw AIS dataset initially received from the US Coast Guard. Rogue messages can easily be identified by analyzing a single vessel's path. Figure 4 shows an example of a single vessel transiting along the west coast of Mexico, with red dots signifying the message associated with the timestamp reported above the image and the purple dots signifying past messages. Within the span of 45 minutes, AIS reports activity messages for this vessel inland near Gainesville, FL, in the Atlantic Ocean, and back in its likely true position along the west coast of Mexico.

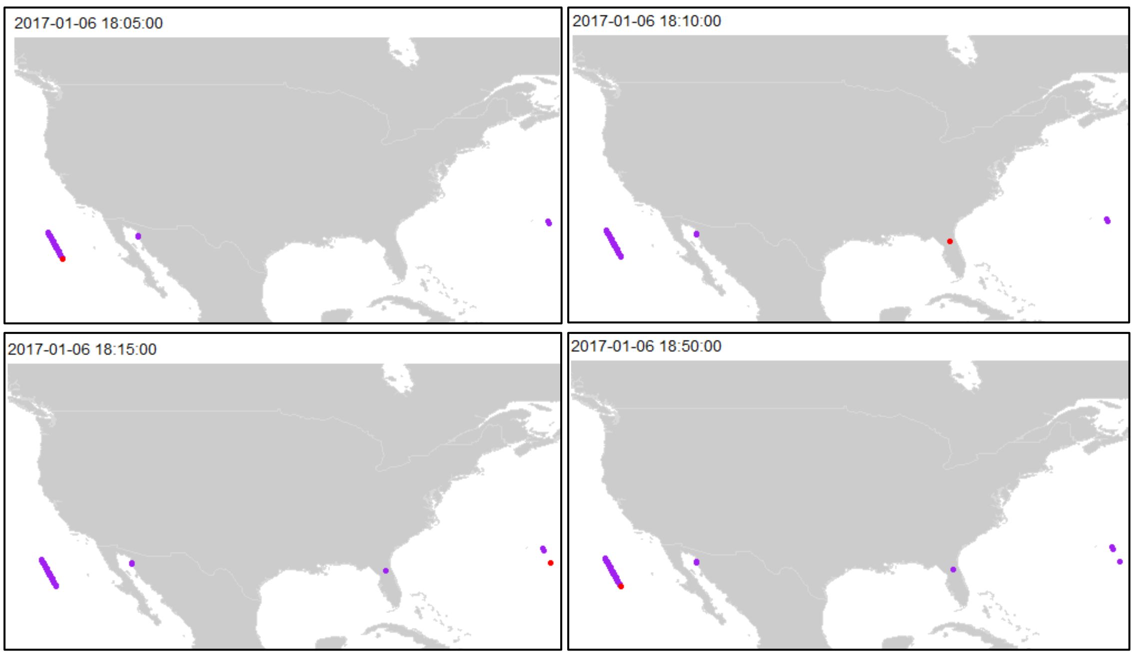

Figure 4. Example of Rogues Messages (Current Activity Message in Red and Past Messages in Purple)

Given that a single vessel reported a non-interpolated message near Gainesville, FL, and given the rouge nature of this message, it is evident that C3 activity is not likely near Gainesville, FL. Similar analysis was done to determine the unlikelihood of C3 activity up the Mississippi River and near Cape Coral, FL.

An analysis of the Gulf of California made it clear that, while activity was sparse, legitimate and non-rouge message were reported there by C3 vessels. Gaps between emissions-filled grid cells in the non-interpolated raster were likely caused by gaps in AIS messages which were longer than five-minute intervals. These intervals would eventually be filled in by the interpolation code described above. Therefore, it seemed better to assume the remaining grid cells in the Gulf of California, that had not been filled by the non-interpolated raster, to be likely C3 areas as well.

This manual adjustment allowed for those Gulf of California interpolated points to be accounted for.

Thus, the non-interpolated masking raster was altered to account for the findings in this analysis. ERG developed an R function for this purpose, which reads in the annual, non-interpolated raster described above and converts all raster values to either NA, to represent unlikely C3 activity areas, or 1, to represent likely C3 activity locations. It also reads in a table, such as Table 16 which was created for altering the 12km CONUS raster according to the above findings. This function creates a box for each row of Table 16, using the longitude and latitude minimum and maximum, and assigns all grid cell values within that box the value in the "Assign Grid Values" field. This allows for manual adjustments of likely and unlikely activity areas. The function then outputs a single raster, with only values of 1 or NA, to show likely and unlikely C3 activity areas. All emissions in the daily rasters which were in unlikely grid cells in the masking raster were set to 0.

Table 16. 12km CONUS Masking Raster Adjustments

lngMin	lngMax	latMin	latMax	Description	Assign Grid Values
-95.8008	-88.6816	31.1282	44.9337	Middle US	NA
-82.2162	-81.6724	29.3343	29.7453	Gainesville, FL	NA
-114.312	-113.137	29.81205	31.15641	Gulf of California	1
-114.494	-113.676	30.77488	31.46615	Second Gulf of California	1
-92.45	-91.6919	28.09137	28.70022	Gulf of Mexico	1
-82.4799	-81.7603	26.13571	26.55414	Cape Coral	NA

However, while the resulting submissions to the air quality modeling platform did use this masking raster, the NEI county-level submissions did not. Instead, counties which exclusively reported interpolated messages were assumed to be unlikely C3 areas and all C3 emissions were set to zero for those counties. Thus, because masks were applied at the grid-cell level for the air quality modeling platform, but the county level for the NEI platform, certain differences will exist between them.

5.2 2016 Adjustments

ERG also adjusted the resulting raster to estimate emissions for the 2016 air quality modeling platform. For this process, the geographic distribution of emissions was assumed to be equivalent to that of 2017, but the quantity of emissions were adjusted by a ship-type specific multiplier. ERG developed this multiplier by analyzing the ratio of total US Army Corps of Engineers Entrance and Clearance inbound calls between 2016 and 2017 by ship type (USACE, 2018). The annual ratios reported in Table 17 were multiplied by the emissions of their associated ship type to adjust for 2016 and then emissions were summed by day, hour and SCC to fit the format of non-adjusted raster outputs.

Table 17. 2017 to 2016 Adjustment Ratios

Ship Type	Annual Ratio[a]
Barge	1.550607
Bulk Carrier	1.066936
Chemical Tanker	1.031006
Container Ship	1.03415
Cruise	1.008228
Ferry Ro Pax	1.429229
General Cargo	0.887673
Liquified Gas Tanker	1.192548
Miscellaneous Fishing	0.932203
Miscellaneous Other	1.015071
Offshore	0.860101
Oil Tanker	1.10119
Other Tanker	1.037261
Reefer	0.867657
Ro	1.006726
Service Tug	1.074369
Yacht	0.98

[a] Ratios are to be applied to the 2017 values to estimate 2016 values (2016/2017 ratios).

6.0 Summary

Table 18 presents the total estimated emissions due to Category 3 marine vessels in the NEI area throughout 2017 and Figure 5 shows the geographic distribution of NO_x emissions in U.S. waters.

VOC	CO_2	CO	NO_X	$PM_{2.5}$	SO_2	PM_{10}	kWhrs	Time (hr)
35,092.93	31,181,884	66,491.61	633,965.9	26,978.41	182,324.2	29,324.36	2.63E+10	7,884,514

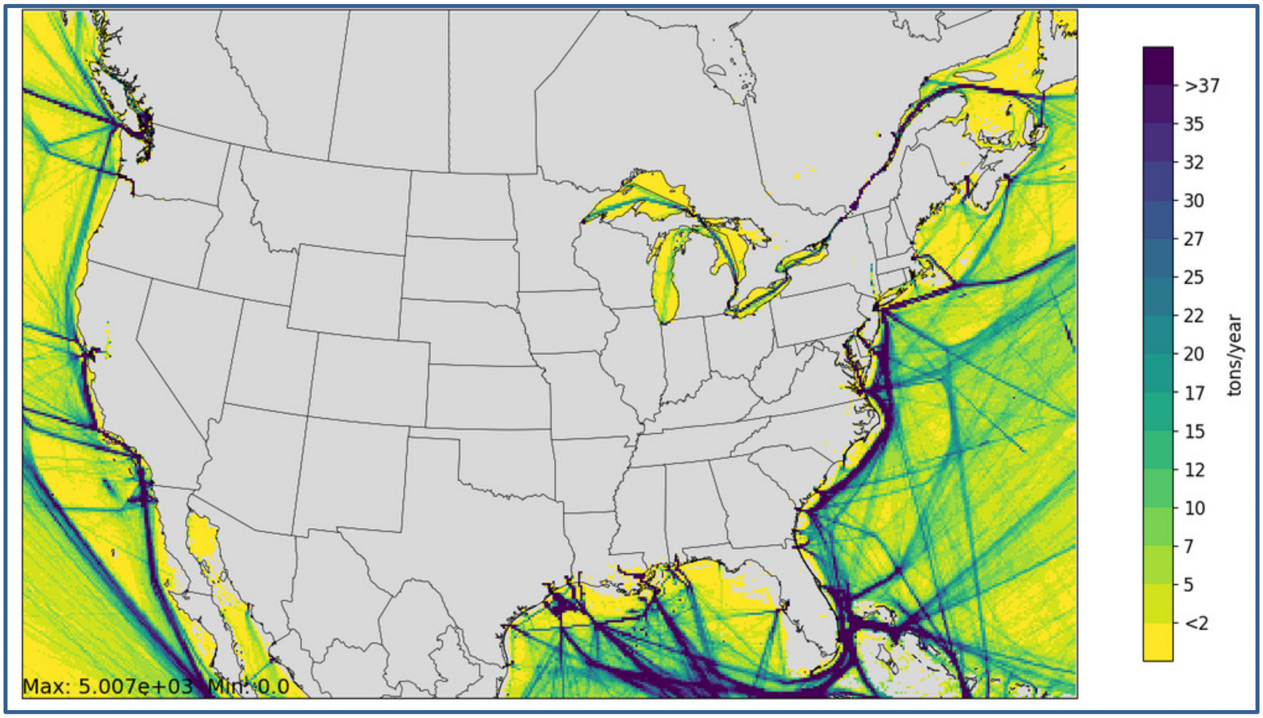

Figure 5. C3 2017 Annual NO_x Emissions

Table 19 presents the total C3 NEI emissions by ship type in 2017 and Figure 6 shows the relative distribution of NO_x emissions by vessel type.

Table 18. Category 3 NEI Emissions by Vessel Group (tons unless otherwise indicated)

Ship Type	VOC	CO_2	CO	NO_X	$PM_{2.5}$	SO_2	PM_{10}	kWhrs	Time (hr)
Bulk Carrier	6,627.04	5,568,626.88	12,550.05	122,562.80	6,079.37	42,995.08	6,608.01	4.01E+09	2,687,880.42
Chemical Tanker	2,928.83	2,724,014.56	5,588.63	52,202.71	1,487.37	8,150.39	1,616.70	3.00E+09	1,052,696.33
Container Ship	13,895.70	10,717,255.35	26,290.70	249,314.48	12,020.12	85,393.01	13,065.34	7.41E+09	1,369,816.17
Cruise	1,836.53	2,936,544.14	4,476.00	44,461.23	1,026.97	4,685.89	1,116.27	3.52E+09	183,975.33
Ferry Ro Pax	51.35	55,923.04	97.36	989.91	21.07	90.11	22.90	7.75E+07	18,101.42
General Cargo	187.50	165,041.52	324.63	2,856.02	78.10	398.26	84.89	1.77E+08	82,450.00
Liquified Gas Tanker	1,363.27	1,908,508.56	2,819.11	27,281.53	1,553.44	11,324.53	1,688.53	1.48E+09	302,105.00
Miscellaneous Fishing	24.70	21,656.49	43.24	445.17	33.49	242.87	36.40	9.48E+(	26,905.25
Miscellaneous Other	569.71	484,638.91	1,048.66	10,415.91	390.67	2,539.62	424.64	4.63E+08	326,918.92
Offshore	1,268.47	753,215.58	2,036.25	17,772.44	504.35	2,733.12	548.21	7.63E+08	476,475.33
Oil Tanker	100.56	122,790.99	161.85	1,354.78	31.97	87.35	34.75	1.32E+08	27,033.33
Other Tanker	3,445.09	2,822,430.09	5,434.49	46,418.47	1,393.32	7,447.45	1,514.48	2.77E+09	722,848.50
Reefer	292.86	320,605.51	610.42	7,001.55	438.25	3,291.97	476.36	1.71E+08	91,159.83

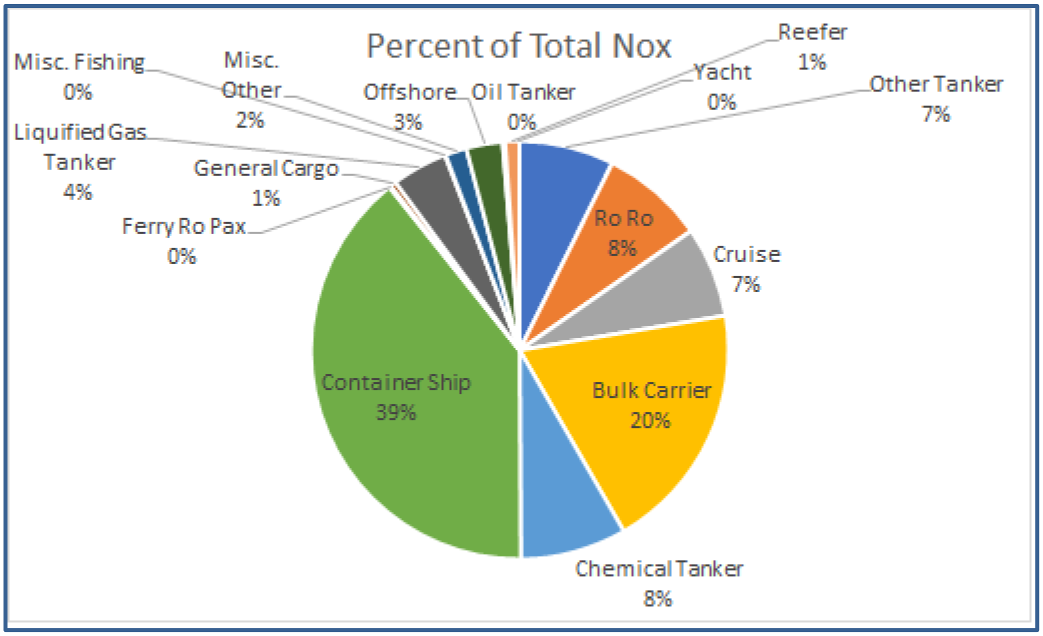

Figure 6. Relative Distribution of C3 NO_X Emissions by Vessel Type

As noted earlier, Kilowatt-hours (kWhrs) were calculated by multiplying the activity durations per AIS interval and the assigned power estimation based on AIS reported speed, and Clarksons installed power ratings and service speed. kWhrs were summed by ship type as well as by SCC. Each ship type's total kWhrs were analyzed by the percentages allotted to each SCC category (Figure 7).

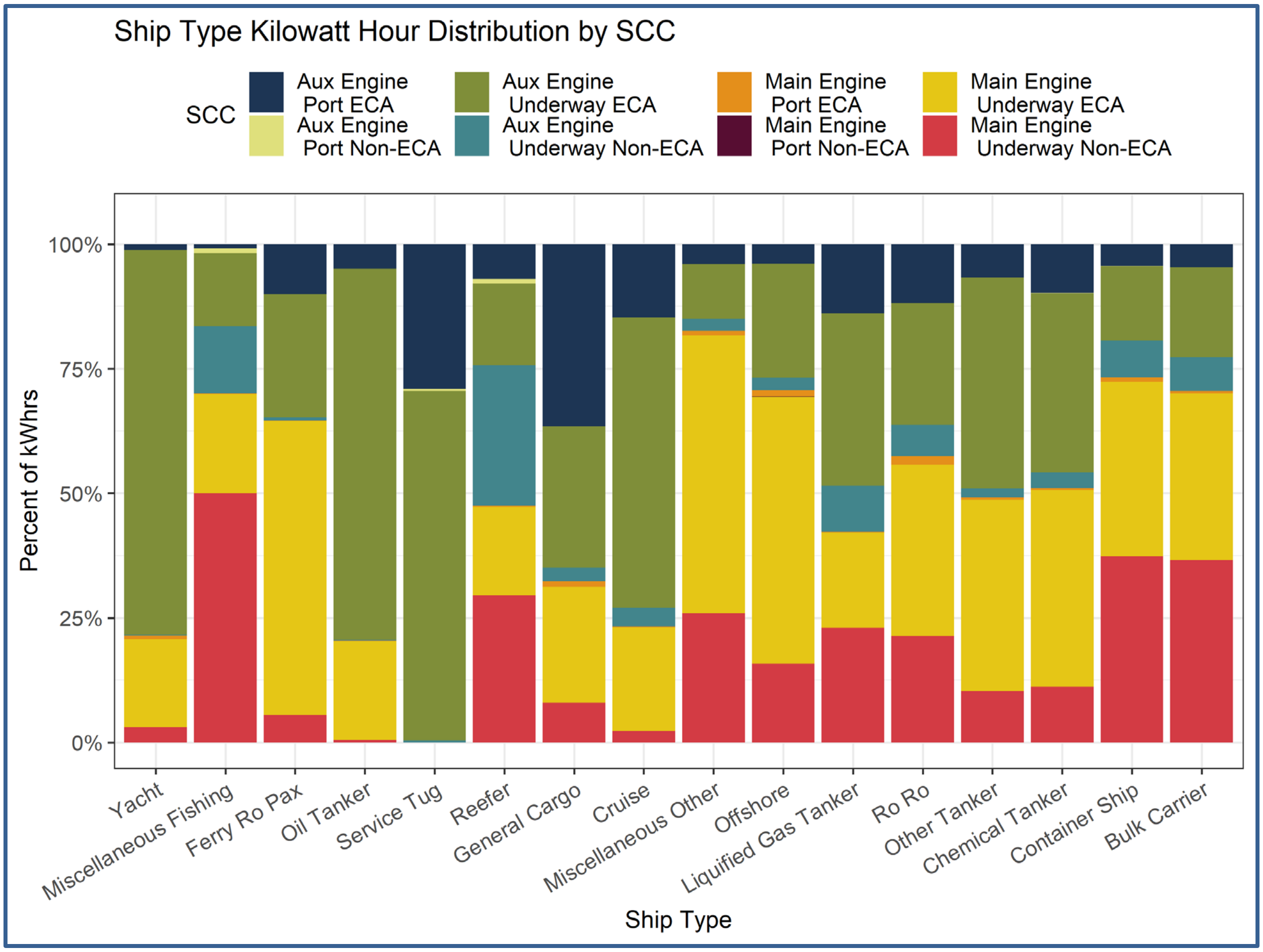

Figure 7. Ship Type Kilowatt Hour Distribution by SCC

Total emissions can be seen by SCC in Table 20.

Table 19. Category 3 NEI Emissions by SCC (tons)

SCC	FuelType	Port/ Underway	Engine	VOC	CO_2	CO	NO_X	$PM_{2.5}$	SO_2	PM_{10}
2280002103	MGO/MDO	Port	Main	1,255.54	237,953.96	1,268.01	6,990.48	127.37	146.53	138.45
228002104	MGO/MDO	Port	Aux	1,029.44	2,336,528.90	2,627.92	23,580.50	538.94	1,424.85	585.81
2280002203	MGO/MDO	Underway	Main	18,822.11	10,449,301.00	30,584.70	267,142.46	3,347.98	6,383.46	3,639.11
2280002204	MGO/MDO	Underway	Aux	3,871.62	8,165,379.69	9,942.53	88,131.74	1,914.66	4,979.35	2,081.15
2280003103	RM/HFO	Port	Main	6.42	1,082.34	6.60	39.85	4.76	18.51	5.17
2280003104	RM/HFO	Port	Aux	6.71	15,058.10	17.14	209.03	29.29	255.26	31.83
2280003203	RM/HFO	Underway	Main	9,093.22	8,104,928.98	19,430.04	217,493.61	17,306.18	137,389.16	18,811.06
2280003204	RM/HFO	Underway	Aux	1,007.87	1,871,651.52	2,614.67	30,378.20	3,709.23	31,727.09	4,031.77

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APPENDIX A

Ship Type and Subtype Assignments

A-1 Ship Type Map

Clarkson's Vessel Type	**Ship Type**
Offshore Launch Barge/Pontoon	Barge
Crane Barge	Barge
Derrick Lay Barge	Barge
Deck Cargo Barge	Barge
Split Hopper Barge	Barge
General Cargo Barge	Barge
Products Tank Barge	Barge
Deck Cargo Pontoon	Barge
Covered Bulk Cargo Barge	Barge
Crane Pontoon	Barge
Maintenance Platform	Barge
Chemical Tank Barge	Barge
Maintenance Pontoon	Barge
Chemical/Products Tank Barge	Barge
Barge (Function Unknown)	Barge
Bulk Aggregates Barge	Barge
Hopper Barge	Barge
Oil Storage Barge	Barge
Bulk Dry Storage Barge	Barge
Water Tank Barge	Barge
Open Bulk Cargo Barge	Barge
Deck Cargo Pontoon, Semi Sub	Barge
Cement Storage Barge	Barge
Bulk Cement Barge	Barge
Drill Barge	Barge
Bitumen Tank Barge	Barge
Trans Shipment Barge	Barge
Vehicle Carrying Barge	Barge
Liquid Mud Barge	Barge
Cement Mixing Barge	Barge
Inland Drilling Barge	Barge
Freight Barge	Barge
Tank Barge	Barge
Public Tankship/Barge	Barge
Barge Carrier, Naval Auxiliary	Barge
Barge Carrier	Barge
Training Barge	Barge
Bulk Carrier	Bulk carrier
Cement Carrier	Bulk carrier

Clarkson's Vessel Type	Ship Type
Limestone Carrier	Bulk carrier
Ore Carrier	Bulk carrier
Urea Carrier	Bulk carrier
Open Hatch Carrier	Bulk carrier
Chip Carrier	Bulk carrier
Forest Product Carrier	Bulk carrier
Stone Chip Carrier	Bulk carrier
Gypsum Carrier	Bulk carrier
Ore & Sulphuric Acid Carrier	Bulk carrier
Miscellaneous Dry Bulk	Bulk carrier
Slurry Carrier	Bulk carrier
Salt Carrier	Bulk carrier
Fully Cellular Container	Container ship
Container Ship (Inland)	Container ship
Cruise Ship	Cruise
Cruise (Inland)	Cruise
Passenger (Uninspected)	Cruise
Passenger (Inspected)	Cruise
Pass /Car Ferry	Ferry Ro pax
Passenger Catamaran Vessel	Ferry Ro pax
Passenger (Inland)	Ferry Ro pax
Passenger Vessel	Ferry Ro pax
Passenger/Ro-Ro (Inland)	Ferry Ro pax
Passenger/Cargo Vessel	Ferry Ro pax
Ferry	Ferry Ro pax
Passenger Barge (Uninspected)	Ferry Ro pax
Passenger Barge (Inspected)	Ferry Ro pax
Air Cushion Ferry	Ferry Ro pax
Pass /Car Catamaran Vessel	Ferry Ro pax
General Cargo	General cargo
General Cargo (Inland)	General cargo
Deck Cargo Carrier	General cargo
Landing Craft	General cargo
Trans Shipment Vessel	General cargo
Ore/Oil Carrier	General cargo
Industrial Vessel	General cargo
Freight Ship	General cargo
Livestock Carrier	General cargo
Aggregate Carrier	General cargo
Palletised Cargo Carrier	General cargo

Clarkson's Vessel Type	**Ship Type**
Log Tipping Ship	General cargo
Miscellaneous Cargo	General cargo
Heavy Lift Cargo Vessel	General cargo
General Cargo/Passenger (Inland)	General cargo
LPG Carrier	Liquified gas tanker
LPG Tank Barge	Liquified gas tanker
Lng Tanker (Inland)	Liquified gas tanker
LPG Carrier (Inland)	Liquified gas tanker
Lng Tank Barge	Liquified gas tanker
Ethylene/LPG	Liquified gas tanker
LNG Carrier	Liquified gas tanker
LNG Bunkering Vessel	Liquified gas tanker
CO2 Carrier	Liquified gas tanker
LNG/Ethylene/LPG	Liquified gas tanker
LNG/Regasification	Liquified gas tanker
Ethane/LPG	Liquified gas tanker
Tug, Naval Auxiliary	Tug
Multi-Purpose	Miscellaneous
Work/Repair Vessel	Miscellaneous
Pontoon (Function Unknown)	Barge
Landing Ship (Dock Type)	Miscellaneous
Electricity Generating Pontoon	Barge
Submarine Tender	Miscellaneous
Munitions Carrier	Miscellaneous
Attack Vessel, Naval	Miscellaneous
Salvage Vessel	Miscellaneous
Destroyer	Miscellaneous
Patrol Vessel, Naval	Miscellaneous
Electricity Generating Vessel	Miscellaneous
Unknown Function, Naval/Auxiliary	Miscellaneous
Search & Rescue	Miscellaneous
Frigate	Miscellaneous
Corvette	Miscellaneous
Minehunter	Miscellaneous
Replenishment Dry Cargo Vessel	Bulk carrier
Training Ship, Naval Auxiliary	Miscellaneous
Torpedo Boat	Miscellaneous
Floating Crane	Miscellaneous
Minelayer	Miscellaneous
Weapons Trials Vessel	Miscellaneous

Clarkson's Vessel Type	Ship Type
Training Ship	Miscellaneous
Torpedo Recovery Vessel	Miscellaneous
Anti-Pollution Vessel	Miscellaneous
Other Activities (Inland)	Miscellaneous
Icebreaker	Miscellaneous
Crane Vessel, Naval Auxiliary	Miscellaneous
Replenishment Tanker	Other tanker
Permanent Shore Facility	Miscellaneous
Oilfield Pollution Control	Miscellaneous
ERRV	Miscellaneous
Unclassified	Miscellaneous
UNSPECIFIED	Miscellaneous
Unknown	Miscellaneous
Public Vessel, Unclassified	Miscellaneous
School Ship	Miscellaneous
Public Freight	Miscellaneous
Motor Lifeboat	Miscellaneous
Aids to Navigation Boat	Miscellaneous
Cutter	Miscellaneous
Motor Surf Boat	Miscellaneous
Transportable Port Security Boat	Miscellaneous
Response Boat-Medium	Miscellaneous
Special Purpose Craft - Heavy Weather	Miscellaneous
Special Purpose Craft - Near Shore Lifeboat	Miscellaneous
Special Purpose Craft - Screening Vessel	Miscellaneous
Utility Boat - Big	Miscellaneous
Patrol Boat - Island Class	Miscellaneous
Medium Endurance Cutter	Miscellaneous
High Endurance Cutter	Miscellaneous
Coastal Patrol Boat - Marine Protector Class	Miscellaneous
Inland Construction Tenders	Miscellaneous
National Security Cutter	Miscellaneous
Icebreaking Tug - Bay Class	Miscellaneous
Unique	Miscellaneous
Fast Response Cutter - Sentinel Class	Miscellaneous
Defender Class Boat	Miscellaneous
Tank Landing Craft	Miscellaneous

Clarkson's Vessel Type	**Ship Type**
Standby Safety/Guard	Miscellaneous
Troopship	Miscellaneous
Repair Vessel, Naval Auxiliary	Miscellaneous
Pearl Shells Carrier	Miscellaneous
Mining Vessel	Miscellaneous
Diving Vessel, Naval Auxiliary	Miscellaneous
Naval Small Craft	Miscellaneous
Hospital Vessel, Naval Auxiliary	Miscellaneous
Car Park	Miscellaneous
Submarine Salvage Vessel	Miscellaneous
Minesweeper	Miscellaneous
Cruiser	Miscellaneous
Torpedo Trials Vessel	Miscellaneous
Multi-Purpose/Heavy Lift Cargo	Miscellaneous
Salvage Vessel, Naval Auxiliary	Miscellaneous
Infantry Landing Craft	Miscellaneous
Mooring	Miscellaneous
Shopping Complex	Miscellaneous
Pollution Control Vessel	Miscellaneous
Amphibious Assault Ship LHA	Miscellaneous
Command Vessel	Miscellaneous
Helicopter Carrier	Miscellaneous
Heavy Load Carrier	Miscellaneous
Icebreaker AGB	Miscellaneous
Live Fish Carrier (Well Boat)	Fishing
Fishing Vessel	Fishing
Fish Feed Carrier	Fishing
Stern Trawler	Fishing
Fishery Patrol Vessel	Fishing
Trawler	Fishing
Fishery Research Vessel	Fishing
Fishery Support Vessel	Fishing
Commercial Fishing Vessel	Fishing
Fish Processing Vessel	Fishing
Fishing Tender	Fishing
Whale Catcher	Fishing
Fish Factory Ship	Fishing
Seal Catcher	Fishing
Factory Stern Trawler	Fishing
Pipe Laying Barge	Offshore

Clarkson's Vessel Type	**Ship Type**
Cutter Suction/Bucket Wheel Dredger	Offshore
Backhoe/Dipper/Grab Dredger	Offshore
Barge Unloading Dredger	Offshore
Crew Boat	Offshore
Seismic Support	Offshore
Utility/Workboat	Offshore
Derrick/Lay Vessel	Offshore
Bucket Ladder Dredger	Offshore
Special Equipment Dredger	Offshore
Suction Dredger	Offshore
Hydrographic Survey	Offshore
Cable, Umbilicals & FP/Flowline Lay	Offshore
Cable Layer (Fibre Optic)	Offshore
Dredger (Unspecified)	Offshore
Other Dredger	Offshore
Crew Tender	Offshore
Crew/Fast Supply Vessel	Offshore
Suction Hopper Dredger	Offshore
Dredging Pontoon	Offshore
Windfarm Crew/Supply Tender	Offshore
Oceanographic Survey	Offshore
Dredging (Inland)	Offshore
Transport (Heavy Lift)	Offshore
Supply Tender	Offshore
Trailing Suction Hopper Dredger	Offshore
Grab Dredger Pontoon	Offshore
Tension Leg Platform	Offshore
SPAR	Offshore
Dredgers (Stone Dumping, Fallpipe)	Offshore
Platform Supply	Offshore
Geophysical Survey	Offshore
Oil Recovery	Offshore
Offshore Supply Vessel	Offshore
Arctic Survey Boat	Offshore
Inland Buoy Tender	Offshore
Seagoing Buoy Tender	Offshore
Coastal Buoy Tender - Keeper Class	Offshore
River Buoy Tenders	Offshore
Seagoing Buoy Tender/ Icebreaker	Offshore
River Buoy Tender	Offshore

Clarkson’s Vessel Type	Ship Type
Buoy/Lighthouse Tender	Offshore
Diving Support	Offshore
Seismic Survey	Offshore
Multi-Functional Support	Offshore
Maintenance	Offshore
Miscellaneous Offshore Service	Offshore
Offshore Crew Tender	Offshore
Rov/Submersible Support	Offshore
Pipe Layer	Offshore
Cable Layer, Naval Auxiliary	Offshore
Crew Boat, Naval Auxiliary	Offshore
Gravel/Stone Discharge	Offshore
Steam Supply Pontoon	Offshore
Reefer Fish Carrier	Reefer
Reefer	Reefer
Reefer/General Cargo	Reefer
Reefer/Pallets Carrier	Reefer
Reefer/Ro-Ro Cargo	Reefer
Reefer/Pass /Ro-Ro	Reefer
Research Vessel	Miscellaneous
Research Vessel, Naval Auxiliary	Miscellaneous
Marine Research	Miscellaneous
Research (Inland)	Miscellaneous
Ro-Ro Cargo (Inland)	RoRo
Pure Car Carrier	RoRo
Ro-Ro Freight/Passenger	RoRo
Logistics Vessel (Naval RoRo Cargo)	RoRo
Ro-Ro	RoRo
Ro-Ro/Lo-Lo	RoRo
Ro-Ro/Container	RoRo
Tug	Tug
Fire-fighting Tug	Tug
Towing/Pushing (Inland)	Tug
Towing Vessel	Tug
Small Harbor Tug	Tug
Ocean-going Salvage Tug	Tug
Ocean-going Tug	Tug
Self Elevating Install Barge	Other Tanker
Accommodation Barge	Offshore
Chemical & Oil Carrier	Chemical tanker

Clarkson's Vessel Type	Ship Type
Asphalt & Bitumen Carrier	Other tanker
Chemical/Products Tanker (Inland)	Chemical tanker
Bunkering Vessel	Other tanker
FPSO	Offshore
Product Carrier	Offshore
Oil Tanker (Inland)	Oil tanker
Tug, Anchor Hoy	Other tanker
Crude Oil Tank Barge	Oil tanker
Waste Disposal Carrier	Other tanker
Chemical Tanker (Inland)	Chemical tanker
Water Carrier	Other tanker
Edible Oil Carrier	Other tanker
Well Stimulation	Offshore
Accommodation Unit - Self Elevating	Offshore
Mini Tension Leg Platform	Offshore
Jack-up Production Unit	Offshore
Semi-Submersible Production Unit	Offshore
Floating Production Unit	Offshore
Heavy Lift/Crane Ship	Offshore
FSO	Offshore
Self Elevating Install Vessel	Offshore
Buoyant Tower	Offshore
Jack-up Drilling Rig	Offshore
Semi-Submersible Heavy Lift	Offshore
Supply	Offshore
Tank Ship	Other tanker
Mobile Offshore Drilling Unit	Offshore
Drillship	Offshore
Tanker	Other tanker
Wine Carrier	Other tanker
Accommodation Vessel	Offshore
Anchor Handling Tug/Supply	Offshore
Anchor Handling Tug	Offshore
FSU	Offshore
FSRU	Offshore
LNG/FPSO	Offshore
Slop Reception Vessel	Oil tanker
Water Tanker (Inland)	Other tanker
Semi-Submersible Drilling Rig	Offshore
LNG/FSU	Offshore

Clarkson's Vessel Type	**Ship Type**
Water Tanker, Naval Auxiliary	Other tanker
Bulk/Oil Carrier	Oil tanker
Drilling Tender	Offshore
LPG/FSO	Offshore
Accommodation Unit - Semi Sub	Offshore
Oil & Liquid Gas Carrier	Oil tanker
FPDSO	Offshore
Cylindrical Floating Drill Unit	Offshore
Methanol Carrier	Other tanker
Sulphuric Acid Carrier	Other tanker
Molten Sulphur Carrier	Other tanker
Shuttle Tanker	Oil tanker
Fruit Juice Carrier	Other tanker
Extended Well Test Vessel	Offshore
Chemical & LPG Carrier	Chemical tanker
Phosphoric Acid Carrier	Other tanker
LPG/FPSO	Offshore
Product Carrier/Ro-Ro	Other tanker
Cylindrical Floating Prod Unit	Offshore
Oil Recovery Tanker	Oil tanker
Products/Multi-Purpose Cargo	Other tanker
Cylindrical Floating Accom Unit	Offshore
Motor Yacht	Yacht
Yacht (Sailing)	Yacht
Recreational	Yacht

A-2 Subtype Map

ShipType	SizeUnits	SizeMin	SizeMax	SubType
Bulk Carrier	Deadweight	0	10,000	Bulk carrier small
		10,000	35,000	Bulk carrier handy size
		35,000	60,000	Bulk carrier handy max
		60,000	1 00E+05	Bulk carrier pana max
		100,000	2 00E+05	Bulk carrier cape size
		200,000	Inf	Bulk carrier cape size largest
Chemical Tanker	Deadweight	0	5,000	Chemical tanker smallest
		5,000	10,000	Chemical tanker small
		10,000	20,000	Chemical tanker handy size
		20,000	Inf	Chemical tanker handy max
Container Ship	TEU	0	1,000	Container ship 1000
		1,000	2,000	Container ship 2000
		2,000	3,000	Container ship 3000
		3,000	5,000	Container ship 5000
		5,000	8,000	Container ship 8000
		8,000	12,000	Container ship 12000
		12,000	14,500	Container ship 14500
		14,500	Inf	Container ship largest
General Cargo	Deadweight	0	5,000	General cargo 5000
		5,000	10,000	General cargo 10000
		10,000	Inf	General cargo largest
Liquified Gas Tanker	Deadweight	0	5,000	Liquified gas tanker 5000
		5,000	10,000	Liquified gas tanker 10000
		10,000	20,000	Liquified gas tanker 20000
		20,000	Inf	Liquified gas tanker largest
Oil Tanker	Deadweight	0	5,000	Oil tanker smallest
		5,000	10,000	Oil tanker small
		10,000	20,000	Oil tanker handy size
		20,000	60,000	Oil tanker handy max
		60,000	80,000	Oil tanker pana max
		80,000	120,000	Oil tanker afra max
		120,000	2 00E+05	Oil tanker suez max
		200,000	Inf	Oil tanker vlcc
Other Tanker	Deadweight	0	Inf	Other tanker
Ferry Pax	Gross Tonnage	0	2,000	Ferry pax 2000
		2,000	Inf	Ferry pax largest
Cruise	Gross Tonnage	0	2,000	Cruise 2000
		2,000	10,000	Cruise 10000
		10,000	60,000	Cruise 60000
		60,000	1 00E+05	Cruise 100000
		100,000	Inf	Cruise largest
Ferry Ro Pax	Gross Tonnage	0	2,000	Ferry Ro pax 2000
		2,000	Inf	Ferry Ro pax largest
Reefer	Deadweight	0	Inf	Reefer
Ro Ro	Gross Tonnage	0	5,000	RoRo 5000
		5,000	Inf	RoRo largest
Vehicle Carrier	Deadweight	0	10,000	Vehicle carrier 10000
		10,000	20,000	Vehicle carrier 20000
		20,000	30,000	Vehicle carrier 30000

ShipType	SizeUnits	SizeMin	SizeMax	SubType
		30,000	Inf	Vehicle carrier largest
Yacht	Gross Tonnage	0	Inf	Yacht
Service Tug	Gross Tonnage	0	Inf	Tug
Miscellaneous Fishing	Gross Tonnage	0	Inf	Fishing
Offshore	Gross Tonnage	0	Inf	Offshore
Service Other	Gross Tonnage	0	Inf	Service other
Miscellaneous Other	Gross Tonnage	0	Inf	Miscellaneous