Eastern Research Group, Inc.

Category 1 and 2 Commercial Marine Vessel 2020 Emissions Inventory

Prepared for:

U.S. Environmental Protection Agency
National Vehicle and Fuel Emissions Laboratory
2565 Plymouth Road
Ann Arbor, MI 48105

Prepared by:

Eastern Research Group, Inc.
1600 Perimeter Park Drive, Suite 200
Morrisville, NC 27312

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List of Abbreviations

AIS	Automatic Identification Systems
C1	Category 1
C1C2	Category 1 and 2
C1C2CMV	Category 1 and 2 commercial marine vessel components
C2	Category 2
C3CMV	Category 3 Commercial Marine Vessel
CMV	Commercial Marine Vessel
CO_2	Carbon Dioxide
ECA	Emissions Control Area
EF	Emission factor
FCC	Federal Communications Commission
GFW	Global Fishing Watch
HAP	Hazardous air pollutant
g/kWhr	Grams/kilowatt hour
kWhrs	Kilowatt-hours
GPS	Global Positioning System
GT	Gross Tonnage
IMO	International Maritime Organization
Kn	Knot
kW	Kilowatts
LF	Load factor
LLAF	Low load adjustment factor
LNG	Liquified natural gas
MDO	Marine diesel oil
MGO	Marine gas oil
MMSI	Maritime Mobile Service Identifier
NEI	National Emission Inventory
Nm	Nautical miles
PM	Particulate matter
PM_{10}	Particulate matter less than 10 microns in diameter
$PM_{2.5}$	Particulate matter less than 2.5 microns in diameter
Reefer	Refrigerated vessels
Ro Ro	Roll on/Roll off
S-AIS	Satellite automatic identification systems
SO_2	Sulfur dioxide
SOLAS	Safety of Life at Sea
T-AIS	Terrestrial automatic identification systems
TEU	Twenty-foot equivalent units
USACE	US Army Corps of Engineers
USCG	United States Coast Guard
USEPA	U.S. Environmental Protection Agency
ITU	International Telecommunications Union
VHF	Very High Frequency

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 U.S. Environmental Protection Agency (USEPA) 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 developed the Category 1 and 2 commercial marine vessel components (C1C2CMV) of the 2020 NEI. Category 1 (C1) engines are defined as having displacement below 7 liters per cylinder while Category 2 (C2) engines are defined as having displacement below 30 liters per cylinder and greater than or equal to 7 liters per cylinder.

Note this 2020 inventory builds upon the 2017 NEI which used a similar approach; where possible 2017 data files were updated to more accurately represent conditions in 2020, but as this work was implemented in 2021/22 during the covid pandemic, several data sources used to quality check the data had not been updated, so the most recent version of the data were used.

This report documents the development of the AIS preprocessor for all CMV modeling data (C1, C2 and Category 3 (C3)) and the application of the C1C2CMV model used for the 2020 NEI, including the conceptual framework, equations, data sources, assumptions, and limitations. A description of the development of the C3 CMV model, including the conceptual framework, equations, data sources, and assumptions, is provided in a separate report. This document is a deliverable under USEPA contract EP-C-17-0411, Work Assignment 4-19.

Automated Identification System (AIS) is a tracking system used by vessels to enhance navigation and avoid collision with other AIS transmitting vessels. This system integrates a vessel's Very High Frequency (VHF) radio transceiver with positioning systems such as a Global Positioning System (GPS) receiver and other electronic navigation sensors, such as gyrocompasses or rate of turn indicators. Each participating vessel transmits a signal that is picked up by onshore VHF towers, oil and gas platforms or offshore buoys equipped with AIS receivers, or satellites. VHF towers that receive these signals have a range of approximately 20-30 nautical miles (Nm), while a growing number of AIS satellites extend the range up to 2,000 miles from the coast.

The (IMO) International Convention for the Safety of Life at Sea requires AIS transmitters be fitted aboard all passenger ships as well as vessels with gross tonnage (GT) of 300 or more involved in international trips (IMO, 2002). As the cost of these transmitters have reduced over time, voluntary AIS usage has increased even for smaller vessels that do not trigger reporting requirements. In addition to the IMO requirements, the United States Coast Guard (USCG) has mandated that all commercial marine vessels continuously transmit AIS signals while transiting U.S. navigable waters.

The USEPA Office of Transportation and Air Quality received AIS data from USCG in order to quantify all ship activity which occurred between January 1 and December 31, 2020. The provided AIS data extends beyond 200 nautical miles from the U.S. coast. For the 2020 NEI inventory the boundary in the U.S Exclusive Economic Zone was used (solid line in Figure 1).

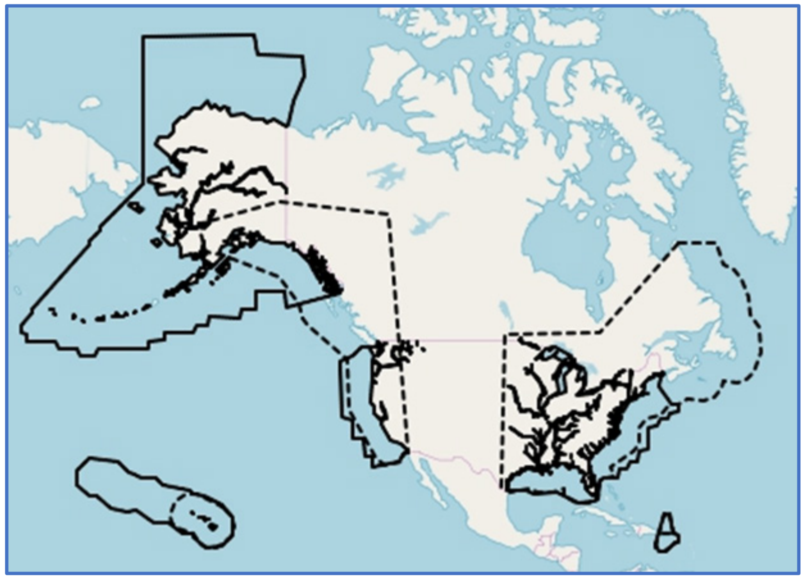


Figure 1. NEI Geographical Extent (Solid) and U.S. ECA (Dashed)

The preprocessed data were compiled into five-minute intervals by the USCG, providing a reasonably refined assessment of a vessel's movement. For example, using a five-minute average, a vessel traveling at 25 knots would be captured every two nautical miles that the vessel travels. For slower moving vessels, the distance between transmissions would be less. The ability to track vessel movements through AIS data and link them to vessel attribute data, has allowed for the development of an inventory of very accurate emission estimates. These AIS data were used to define the locations of individual vessel movements, estimate hours of operation, and quantify propulsion engine loads. The compiled AIS data also included the vessel's IMO number and Maritime Mobile Service Identifier (MMSI); which allowed each vessel to be matched to their characteristics obtained from the Clarksons ship registry (Clarksons, 2021).

The engine bore and stroke data reported in Clarksons for all vessel included in the AIS dataset, were used to calculate cylinder volume. Any vessel that had a calculated cylinder volume greater than 30 liters was flagged as a C3 vessel and incorporated into the USEPA's new Marine Emissions Tools. The remaining records were assumed to represent C1C2 or non-ship activity. This report focuses on data processing of the C1C2 vessels.

2.0 AIS Data Processing

USCG AIS data is often written in a format difficult to read by most common computing programs. To ensure success in preprocessing, AIS data were standardized by parsing records into comma separated columns, with erroneously written records removed. 99.99% of the 1,740,356,397 records received for C1C2 and C3 from the USCG for the 2020 annual dataset were retained and standardized through this process, with the removal of just 62,374 erroneous records.

AIS data are transmitted to both satellite (S-AIS) and terrestrial (T-AIS) receivers (Figure 2). Satellite receivers provide adequate coverage over open ocean, where T-AIS coverage is sparse. However, T-AIS data are more suitable for reporting close-to-shore activity. 1,286,119,698 T-AIS and 454,174,325 S-AIS records were retained from the standardization process. Duplicate records were identified and removed within each dataset, with 153,048,673 duplicates removed from T-AIS files and 898 removed from S-AIS files.

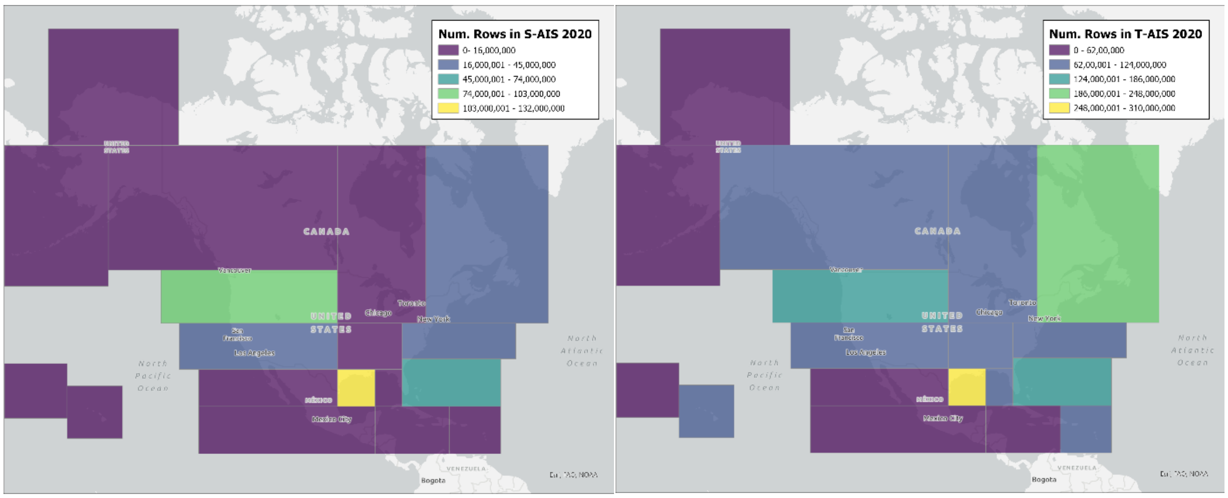


Figure 2. Distribution of Terrestrial and Satellite AIS Data

The S-AIS and T-AIS datasets were read in for the same month and geographic regions and merged by IMO number, MMSI, or both vessel identifiers. When both datasets reported activity for the same time stamp and vessel, the T-AIS messages were selected over the S-AIS messages, as T-AIS data are more suitable for the close-to-shore activity within this inventory. 341,974,594 records appeared in both T-AIS and S-AIS datasets and were subsequently removed from the S-AIS dataset.

Additionally, AIS transmitters unrelated to marine vessel combustion sources were identified and removed from the AIS dataset. These miscellaneous entities were identified using USCG-verified MMSI patterns, based on information obtained from the USCG Navigation center.[1] In total, 70,715 records were removed from the dataset. These records were associated with divers' radios, coastal stations, aids to navigation, search and rescue aircraft and transmitters, man overboard devices, and emergency position indicating radio beacon MMSI patterns. Easily identifiable pleasure craft vessels were also removed, further reducing the dataset by 435,650,562 records. This data cleaning reduced the size of the dataset by 51.6%, with 843,100,503 records retained out of the total 1,740,294,023 read in for all vessel categories, as noted in Figure 3.

[1] USCG Navigation Center, Maritime Mobile Service Identity, navcen.uscg.gov/?pageName=mtmmsi.

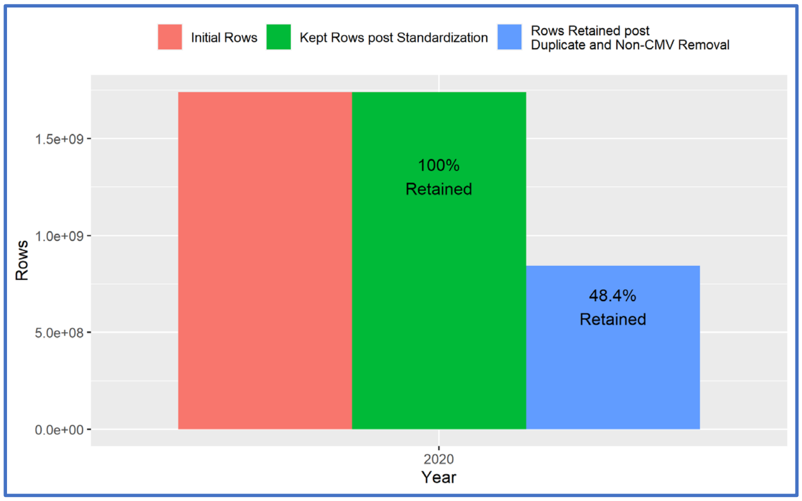
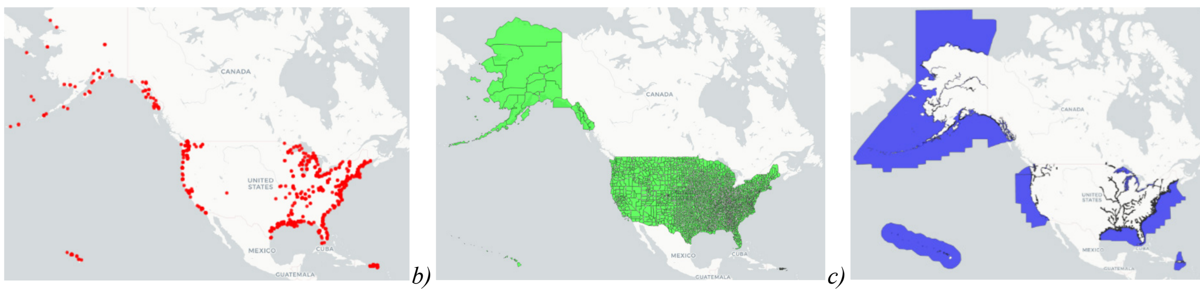


Figure 3. Comparison of Record Retention During Preliminary Processing

After this data cleaning step, the AIS data were parsed into daily files so that AIS messages could be analyzed consecutively. Entities that reported only a single AIS record throughout the year were removed, because at minimum two records are needed per ship to calculate activity durations. Consecutive hoteling activity of each ship were aggregated in the dataset in order to reduce size. Hoteling records were aggregated to no more than an hour, in order to ensure that hourly rasterized emissions properly represented hoteling activity. Time and distances were calculated between each consecutive record of each vessel's annual transit and allocated to the record following the activity duration, with time calculated in hours and distance calculated in meters using the haversine method. Activity intervals exceeding 24 hours were omitted from emissions estimates as this would suggest that the transmitter may have been turned off or the vessel was docked with the engine off.

Though AIS reports speed over ground (SOG), an additional speed was calculated using the calculated duration and distance intervals between consecutive records. Records associated with a calculated speed greater than 40 kn helped identify AIS messages that had erroneously reported their location and/or time, as the activity needed to transit to that location at that time for that vessel would have been impossible. These records were removed, and time and distance were recalculated across their gap. Erroneous vessels were identified if 30% or more of their daily records were associated with erroneous calculated speeds. These erroneous vessels were removed from that day's emissions estimates. Where time, distance, and calculated speed were considered within reason, but SOG was greater than 40 kn, SOG was replaced by calculated speed, otherwise SOG was used for all emissions estimations calculations. 67.9% of all 2020 AIS records were retained after removal of single record filtering, hoteling aggregation, or erroneous speed calculations.

Each remaining AIS record was assigned a FIPS for NEI aggregation purposes. FIPS were assigned using three shapefiles: the NEI Port Shapefile, the 2020 TIGER County Shapefile, and the NEI Shipping Lane Shapefiles (Figure 4). If an AIS record reported from a location within an NEI Port Shapefile, it would receive the FIPS associated with that port polygon. In addition, these records with port polygons were assigned port SCCs, and all others were assigned underway SCCs. Otherwise, if an AIS message did not report from a port but did report from within a TIGER County shapefile, it would receive the FIPS associated with that county shape. Finally, if an AIS message reported from within the shipping lane shapefiles, but not within the TIGER County or port shapefiles (i.e., federal waters), the message would be assigned the FIPS associated with that federal waters shipping lane shape. All records reporting outside United States territorial waters were assigned a FIPS of 98001. Additional codes were used to differentiate Canadian and Mexican waters.



a) *b)* *c)*

Figure 4. Shapefiles Used for Assigning FIPS including a) NEI Port Shapefile; b) TIGER County Shapefile; c) NEI Shipping Lane Shapefile

3.0 Emissions Calculation

This inventory represents emissions from each self-propelled, and non-pleasure-craft, marine vessel included in the cleaned AIS activity dataset. Emissions are calculated for each time interval between consecutive AIS messages for each vessel and allocated to the location of the message following to the interval. Emissions are calculated according to Equation 1.

$$Emissions_{interval} = Time\ (hr)_{interval} \times\ Power(kW) \times EF(\frac{g}{kWh}) \times LLAF \qquad (1)$$

Power is calculated for the propulsive (main), auxiliary, and auxiliary boiler engines for each interval and emission factor (EF) reflects the assigned emission factors for each engine, as described below. LLAF represents the low load adjustment factor, a unitless factor which reflects increasing propulsive emissions during low load operations. Time indicates the activity duration time between consecutive intervals.

4.0 Vessel Identification

After the AIS dataset was cleaned, the MMSIs were compiled for vessel identification. Vessels must be identified to determine their vessel type, and thus their vessel group, power rating, and engine tier information which are required for emissions calculations. Ship characteristics information were compiled from Clarksons 2021 Ship Registry and Global Fishing Watch's (GFW) Version 2 Fishing Vessels dataset, with a preference for Clarksons reported data when the same vessels were reported across multiple datasets. GFW determines ship type information by analyzing processed 2012 to 2020 AIS data through machine learning classifiers, which identify activity patterns by ship and gear type.

Vessel-specific information were linked to AIS records by matching the AIS fleet MMSIs and IMOs with those in the compiled ship registry dataset. C3 vessels that could not be matched on both identifiers were matched on IMO and then MMSI, in that order. In contrast, C1C2 vessels were matched on MMSI before IMO if it could not match on both identifiers.

The received AIS data included ship and cargo type information, but because these data are entered by the user, there might be issues with regards to the accuracy of this field. The current version of the Marine Cadastre AIS data includes updated vessel type information that tries to address some of these quality issues (Marine Cadastre, 2018). The Marine Cadastre vessel types associated with the AIS ship and cargo type number were used for the remaining vessels unidentified by both the Clarksons and GFW datasets.

5.0 Vessel Group Assignments

In combining the different data sources, 236 different vessel types were match to the C1C2 vessels (Table A-1, Appendix A). Surrogate vessel attribute data is not available for all vessel types, so vessel types were aggregated into 16 different vessel groups for which surrogate data were available (Table 1). Note in comparing vessel counts between 2017 and 2020, coverage remained the same or were larger in 2020, suggesting increased use of AIS transponders. The decline for miscellaneous vessels suggests that vessel type codes used between the two years are improving. Table 2 provides a list of vessel types removed. To determine these groups, the vessel types identified in the above-described datasets were compared to the Marine Cadastre ship types associated with each of the vessels' Ship and Cargo Type number. Additionally, all vessels with Ship and Cargo Type numbers associated with the "Tug Tow" Vessel Group were assigned "Tug" vessel types. Between the non-tug vessels that adopted vessel types from the Marine Cadastre assignments out of necessity and the tug vessels that were specified to adopt these, 17,910 vessels were directly identified by their ship and cargo number. The miscellaneous group represent 1.5 % of the AIS vessels (excluding recreational vessels) for which a specific vessel type could not be assigned.

Table 1. C1C2 Inventory Ship Counts in Entire AIS Data

Vessel Group	2017 Entire Area Ship Count	2020 Entire Area Ship Count
Bulk Carrier	45	44
Commercial Fishing	1,686	4,262
Container Ship	8	16
Ferry Excursion	482	724
General Cargo	1,555	3,451
Government	1,368	1,192
Miscellaneous	1,810	269
Offshore support	1,203	1,337
Pilot	NA	17
Reefer	15	13
Ro Ro	27	218
Tanker	144	555
Tug	4,203	5,661
Work Boat	83	151
Total in Inventory:	**12,629**	**17,910**

Table 2. C1C2 Vessels Removed

Vessel Group	Ship Count
Pleasure Craft (Removed)	9,798
Non-Propelled (Removed)	55
Total (Including Table 1 Inventory Ships)	**9,853**

The aggregated vessel counts were evaluated to ensure they were reasonable using publicly available data sources. For example, the US Army Corps of Engineers (USACE 2020) reported that there are 6,386 US flagged tugs operating in the US in 2020. This suggests that the 2020 NEI-AIS value of 5,661, though less than the USACE estimate, represents more of the fleet than was accounted for in the 2017 inventory.

The latest BOEM (2017) Gulf of Mexico emissions inventory identified 1,007 support vessels that provide services to oil and gas platforms in federal waters. The USACE reported 1,846 vessels in this category. The 2020 NEI-AIS C1C2 fleet included 1,337 offshore support vessels. Both the USACE and NEI estimates would include vessels that support offshore platforms located in federal and state waters in the Gulf of Mexico, as well as California and Alaska. The NEI data would also include Canada and Mexico.

The USACE documented that there were 76 domestic flagged tankers. This stands in comparison to the 2020 NEI-AIS estimate of 555 tankers which includes non-US flagged vessels operating in the US, Canadian, or Mexican waters.

The 2020 NEI-AIS estimate of 724 ferry-excursion vessels is comparable to the USACE's 2020 estimate of 1,181 passenger-ferry vessels. Note, the threshold for required participation in AIS for excursion ferries is 150 passengers, suggesting that AIS may not be including the smaller vessels; conversely some of the vessels included in the USACE may be Category 3 vessels; further study may be needed to better understand these vessel counts.

Other comparisons are more problematic. For example, the USACE estimates that there are 845 U.S flagged dry cargo vessels operating in the U.S., however 3,451 general cargo ships were identified in the 2020 NEI-AIS fleet is much larger than the USACE number. It should be noted that the general cargo vessel type is vaguely defined, such that some of these vessels may be mapped to other vessel groups if more detailed data were available. Even accounting for foreign registered vessels, AIS indicates that the dry cargo fleet may be larger than what is reported by the USACE.

4,262 commercial fishing vessels were identified in the AIS dataset. The national fisherman trade association estimated that nearly 2,900 commercial fishing vessels are required to comply with the AIS reporting standard (National Fisherman, 2015). In addition, the estimated size of the U.S. commercial fishing vessel fleet is approximately 27,000 vessels (OECD, 2019). Though the 2020 NEI-AIS commercial fishing vessels data is three times larger than in 2017, the inventory is still under reporting commercial fishing vessels. This under reporting may indicate that most of the fleet is composed of smaller vessels that do not trigger reporting requirements. The cost of AIS transmitter installation and the desire to keep fishing sites and activities secret may contribute to this under reporting of AIS data for commercial fishing vessels.

6.0 Power Assignments

6.1 Propulsive Power

Power ratings are required per vessel in order to calculate emissions. Propulsive power consumption is calculated using the Propeller Law, which requires each vessel's total installed propulsive power in addition to their optimal service speed, as shown in Equation 2.

$$P = \mathrm{LF} \times P_{ref} = \left(\frac{V}{V_{ref}}\right)^3 \times P_{ref} \qquad (2)$$

Where:

P	=	Power per AIS message interval (kW)
LF	=	Load Factor
P_{ref}	=	Total Installed Propulsive Power (kW)
V	=	AIS reported speed (kn)
V_{ref}	=	Service Speed (kn)

Equation 2 is used to estimate the likely propulsive power applied for each vessel between consecutive AIS messages. The cubic ratio of the AIS reported speed following the message interval and the vessel's optimal service speed is calculated to estimate a load factor (LF). The load factor represents the percentage of the vessel's total installed propulsive power assumed to be used during that activity interval.

Vessel-specific installed propulsive power ratings and service speeds were pulled from Clarksons ship registry and adopted from GFW's dataset when available. However, as noted, there is limited vessel-specific attribute data for most of the C1C2 2020 NEI fleet. This necessitated the use of surrogate engine power and vessel service speeds. Propulsive surrogate power and vessel service speeds are reported in Table 3. Surrogate total installed propulsive power values were compiled through analysis of C1C2 vessels using propulsive power data reported in Clarksons. Vessels missing propulsive power data were assigned the surrogate values associated with their vessel group.

Table 3. C1C2 Propulsive Power and Load Factor Surrogates

Vessel Group	Surrogate Total Installed Propulsive Power (kW)	Surrogate Service Speed (kn)	Number of Vessels from which Average Service Speed was Calculated
Bulk Carrier	7,505.32	14	22
Commercial Fishing	519.67	12	31
Container Ship	2,700	15	2
Ferry Excursion	5,322.14	20	102
General Cargo	2,395.58	12	35
Government	2,124.82	16	27
Miscellaneous	2,336.58	13	77
Offshore support	3,949.33	14	557
Reefer	5,876.7	13	4
Ro Ro	3,792.7	14	24
Tanker	6,577.66	14	58
Tug	2,395.11	11	485
Work Boat	3,546.08	12	44

Vessels missing service speed information adopted the surrogate service speed reported in Table 3 in order to calculate a surrogate LF to be used as described in Equation 2. Surrogate service speed was compiled by calculating the time-weighted, ship type average service speed based on vessel information grouped by type for the 2020 AIS C1C2 fleet. The number of vessels with service speed data used to calculate these averages varied by vessel group and are reported in Table 3. Given this variation in sample sizes, the uncertainty surrounding the load factors which used surrogate service speed also varies. For this reason, vessel-group specific upper bounds provided by the EPA were used to cap all surrogate load factors. A lower bound of 2% was placed on all load factors, both surrogate and non-surrogate.

After data cleaning there was a small percentage of AIS messages missing AIS-reported speed. In these cases, vessels were assumed to be operating at a 20% load. This assumption is supported by the fact that the vast majority of C1C2 vessels have been shown to operate close to shore at lower than optimal loads. All vessels operating below 0.5 kn were assumed to be non-active, drifting vessels whose AIS-reported speed reflected the effect of the wind, wave actions, tides and currents which move the ship slightly. Thus, all vessels reporting speeds below 0.5 kn were assumed not to be in transit and assigned 0 propulsive power during these events. The percent of activity time associated with propulsive power and load factor surrogates can be seen in Figure 5. A comparison of Figure 5 and Figure 6, which displays the C1C2 NEI AIS activity hours by vessel group, suggest the effect of these surrogates have on the resulting C1C2 NEI emission estimates. For example, tugs represent a large amount of operating hours and are one of the categories that require extensive use of surrogates, compared to bulk carriers where vessel specific attributes are available but have considerably less operating hours.

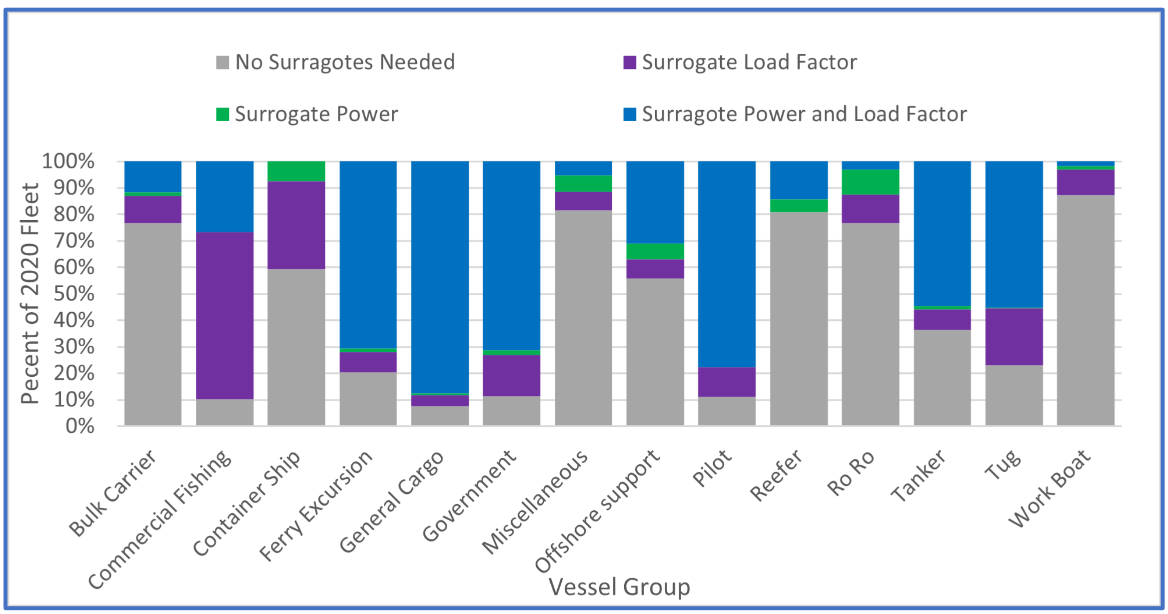


Figure 5. Use of Propulsion Surrogates for the 2020 Vessel Fleet (percent)

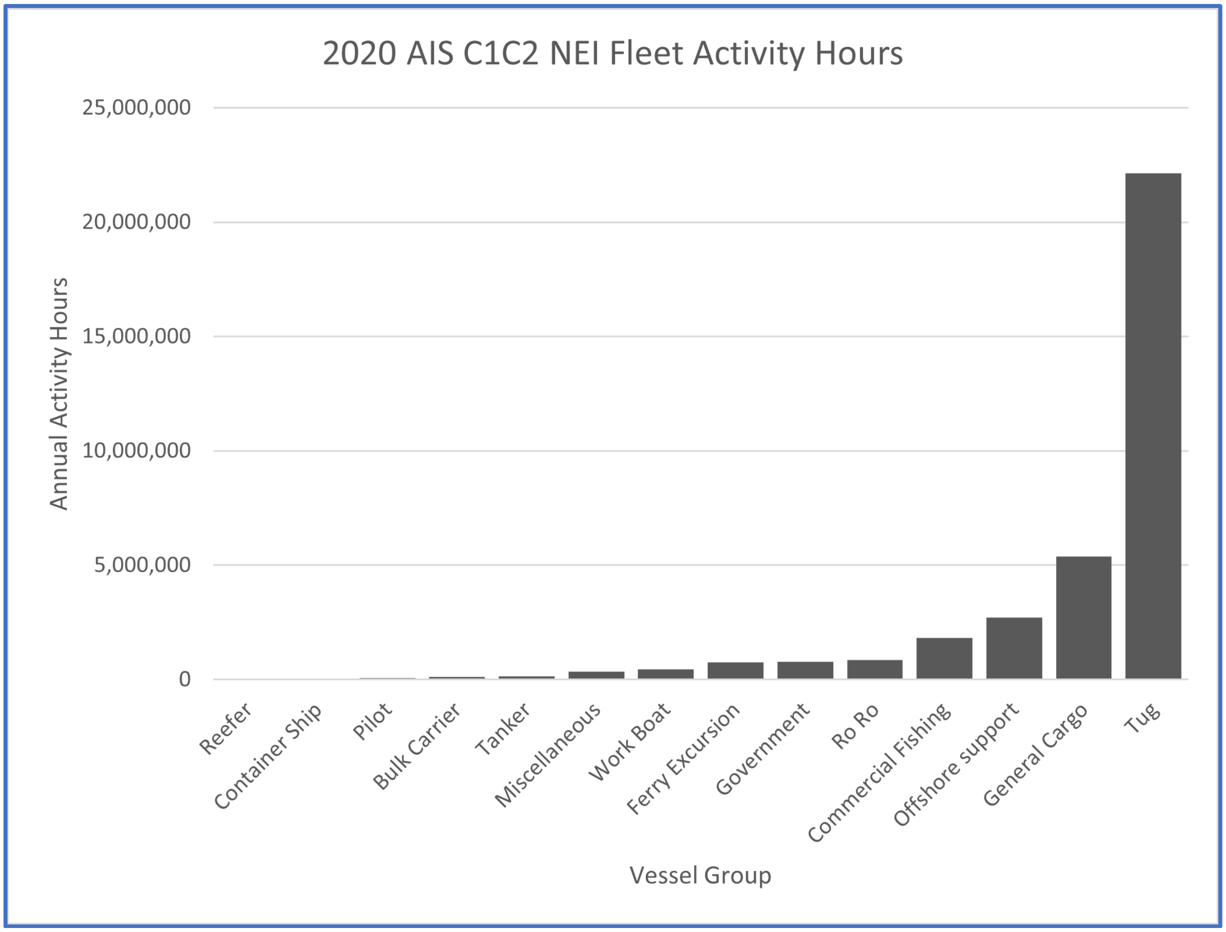


Figure 6. C1C2 Activity Hours by Vessel Group

6.2 Auxiliary and Boiler Power

Auxiliary engine power ratings are rarely documented in ship registry datasets, and auxiliary boiler power is not included at all. Therefore, to calculate auxiliary engine and boiler emissions, power surrogates are required, as shown in Table 4. Auxiliary power ratings were developed from analysis of C1C2 vessels with auxiliary data available in the Clarksons ship registry dataset. Similar to propulsive engines, auxiliary power is applied to each AIS observation by multiplying the auxiliary LF to the auxiliary total installed power rating. Surrogate auxiliary kWs were developed by adjusting the average auxiliary power rating by the load factors presented in Table 4. Additional auxiliary LFs were compiled from USEPA's (2009) *Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories* in addition to EPA provided values.

Table 4. C1C2 Auxiliary and Boiler Power Surrogates

Vessel Group	Aux Operating Load Factor	Auxiliary Power Rated at Load (kW)	Boiler Power Rating at Load (kW)
Bulk Carrier	0.1	100.9	109
Commercial Fishing	0.43	243.7	0
Container Ship	0.19	112.9	506
Ferry Excursion	0.43	595.5	0
General Cargo	0.22	246.3	106
Government	0.43	994.4	0
Miscellaneous	0.43	459.8	0
Offshore support	0.56	605.2	0
Pilot	0.43	8.7	0
Reefer	0.32	913.3	464
Ro Ro	0.26	180.8	109
Tanker	0.26	623.7	346
Tug	0.43	69.5	0
Work Boat	0.43	641.6	0

Boilers are used on commercial marine vessels to provide hot water and steam for different applications. Previously heat from boilers was used to elevate the temperature of storage tanks and fuel system to allow residual fuels to flow, but with a requirement to use low sulfur residual blends that do not have the viscosity of residual fuels, this need for heat may be reduced. Boiler emissions were estimated for vessels that typically are equipped with boilers (e.g., bulk carriers, containerships, general cargo ships, Roll on/Roll off (Ro Ros), refrigerated vessels (Reefers), and tankers). The boiler power ratings reported in Table 4 were adopted from USEPA's (2009) *Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories* and reflect boiler usages at common boiler engine loads. Therefore, a load factor is not needed for boiler power assignments and the values reported in Table 4 are used as-is.

7.0 Emission Factors

The emission factors used in this inventory take into consideration the EPA's marine vessel fuel regulations as well as exhaust standards based on the year that the vessel was manufactured appropriate regulatory tier. These values are reported as g/kWh in Table 5 and were developed using engine tier factors reported in Appendix H of the USEPA's (2020) Port Emissions Inventory Guidance (2020). To compile these emissions factors, population-weighted average emission factors were calculated by engine tier based on C1C2 population distributions grouped by engine displacement. Boiler emission factors were obtained from an earlier Entec study (Entec, 2004).

If the year of manufacture was unknown then it was assumed that the vessel was Tier 0, such that actual emissions may be less than those estimated in this inventory. Without more specific data, the magnitude of this emissions difference cannot be estimated.

Table 5. C1C2 Propulsive and Auxiliary Emission Factors

Tier	NO_x (g/kWhr)	PM_{10} (g/kWhr)	$PM_{2.5}$ (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)	SO_2 (g/kWhr)	VOC (g/kWhr)
Tier 0	10.28152	0.258902	0.251135	1.612632	679.47	0.006246	0.295615
Tier 1	9.624039	0.258902	0.251135	1.61	679.47	0.006246	0.295615
Tier 2	5.642273	0.148049	0.143608	0.918732	679.47	0.006246	0.295615
Tier 3	4.749214	0.082975	0.080486	0.918732	679.47	0.006246	0.124798
Tier 4	1.3	0.03	0.0291	0.918732	679.47	0.006246	0.124798

Table 6 reports the boiler engine emissions factors.

Table 6. C1C2 Auxiliary Boiler Emission Factors

NO_x (g/kWhr)	VOC (g/kWhr)	CO (g/kWhr)	SO_2 (g/kWhr)	CO_2 (g/kWhr)	PM_{10} (g/kWhr)	$PM_{2.5}$ (g/kWhr)
2	0.11	0.2	0.59	961.8	0.2	0.19

7.1 Low Load Adjustment Factor

Propulsive emissions from low-load operations were adjusted to account for elevated emission rates associated with activities outside the engines' optimal operating range. Table 7 below shows the emission factor adjustments by load and pollutant, based on the data compiled for the Port Everglades 2015 Emission Inventory (USEPA, 2018). Adjustment to the criteria emissions were made using the following equation:

$$EF\_LLAF_{iy} = EF_{iy} \times LLAF_y \quad (2)$$

Where:

EF_LLAF_{iy}	=	Emission Factor adjusted for low load operation for vessel i and pollutant y (g/kWh)
EF_{iy}	=	Emission Factor of pollutant y for vessel i (g/kWh)
$LLAF_y$	=	Adjustment factor for a given AIS observation for pollutant y dependent on the load factor of vessel i during a given AIS activity interval (unitless)

Table 7. Low Load Adjustment Factors

Load	PM_{10}	NO_X	SO_2	VOC	CO_2	$PM_{2.5}$	CO
0.01	7.29	4.63	1	21.18	1	7.29	1
0.02	7.29	4.63	1	21.18	1	7.29	1
0.03	4.33	2.92	1	11.68	1	4.33	1
0.04	3.09	2.21	1	7.71	1	3.09	1
0.05	2.44	1.83	1	5.61	1	2.44	1
0.06	2.04	1.6	1	4.35	1	2.04	1
0.07	1.79	1.45	1	3.52	1	1.79	1
0.08	1.61	1.35	1	2.95	1	1.61	1
0.09	1.48	1.27	1	2.52	1	1.48	1
0.1	1.38	1.22	1	2.18	1	1.38	1
0.11	1.3	1.17	1	1.96	1	1.3	1
0.12	1.24	1.14	1	1.76	1	1.24	1
0.13	1.19	1.11	1	1.6	1	1.19	1
0.14	1.15	1.08	1	1.47	1	1.15	1
0.15	1.11	1.06	1	1.36	1	1.11	1
0.16	1.08	1.05	1	1.26	1	1.08	1
0.17	1.06	1.03	1	1.18	1	1.06	1
0.18	1.04	1.02	1	1.11	1	1.04	1
0.19	1.02	1.01	1	1.05	1	1.02	1
0.2	1	1	1	1	1	1	1

7.2 HAP Specific Profiles

The EPA developed hazardous air pollutant (HAP) speciation profiles in order to calculate HAPs as speciation of criteria pollutants estimated by the above-described methodology. The fractions reported in Table 8 were multiplied by the emissions of their assigned basis pollutant to complete this calculation.

Table 8. 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]	7664417	$PM_{2.5}$	0.019247

Pollutant	Pollutant Code	Basis	Fraction
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)Fluoranthene[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
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	0.031304
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 2018.

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

8.0 Summary

Table 9 presents the total 2020 emissions from C1C2 vessels in the NEI area.

Table 9. Total C1C2 2020 Emissions for NEI area (tons)

VOC	CO_2	CO	NO_X	$PM_{2.5}$	SO_2	PM_{10}	kWhrs
5,032.01	10,578,770	21,717.06	142,009.8	3,682.24	641.86	3,799.98	1.37E+10

Table 10 presents the total 2020 emissions from C1C2 by vessel group and Figure 8 shows the relative distribution of NO_x emissions by vessel group.

Table 10. C1C2 NEI Emissions by Vessel Group (tons)

Vessel Group	VOC	CO_2	CO	NO_X	$PM_{2.5}$	SO_2	PM_{10}	kWhrs
Bulk Carrier	60.07	132,724.45	281.49	1,847.89	48.12	10.16	49.68	1.71E+08
Commercial Fishing	195.52	412,939.29	973.25	6,283.90	155.31	3.80	160.11	5.51E+08
Container Ship	3.44	15,497.23	15.35	79.54	3.14	5.03	3.27	1.75E+07
Ferry Excursion	196.42	395,295.02	872.33	5,513.03	138.68	3.63	142.97	5.28E+08
General Cargo	843.91	2,376,825.67	3,938.66	26,077.51	759.28	496.37	786.13	2.87E+09
Government	626.48	1,386,101.58	3,269.43	20,969.60	514.66	12.74	530.58	1.85E+09
Miscellaneous	97.07	214,488.02	379.78	2,297.62	56.80	1.97	58.55	2.86E+08
Offshore support	861.36	1,850,168.28	3,848.25	24,588.16	604.51	17.01	623.21	2.47E+09
Pilot	4.97	7,773.00	16.78	116.81	2.99	0.07	3.08	1.04E+07
Reefer	0.69	4,123.17	4.31	23.55	0.59	0.73	0.61	5.06E+06
Ro Ro	143.29	351,990.85	627.75	4,016.80	107.69	39.99	111.28	4.46E+08
Tanker	40.36	110,481.33	179.76	1,158.52	33.44	19.84	34.61	1.35E+08
Tug	1,808.58	3,012,286.66	6,638.74	44,768.52	1,148.67	27.69	1,184.20	4.02E+09
Work Boat	149.86	308,076.22	671.19	4,268.31	108.35	2.83	111.70	4.11E+08

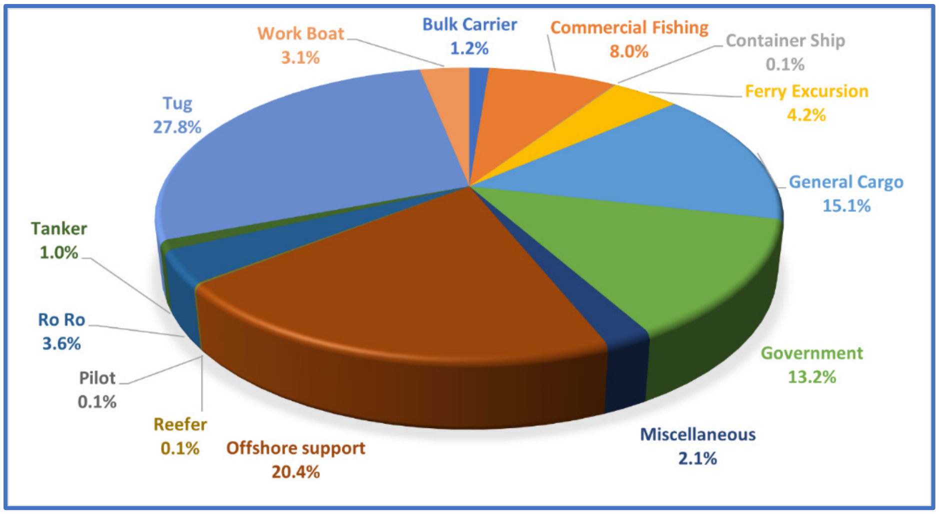


Figure 7. Relative Distribution of C1C2 NO_X Emissions by Vessel Type

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 or surrogate installed power ratings and load based on service speed. kWhrs were summed by ship type as well as by SCC. Each ship type's total kWhrs were analyzed and presented as percentages for each SCC category (Figure 8).

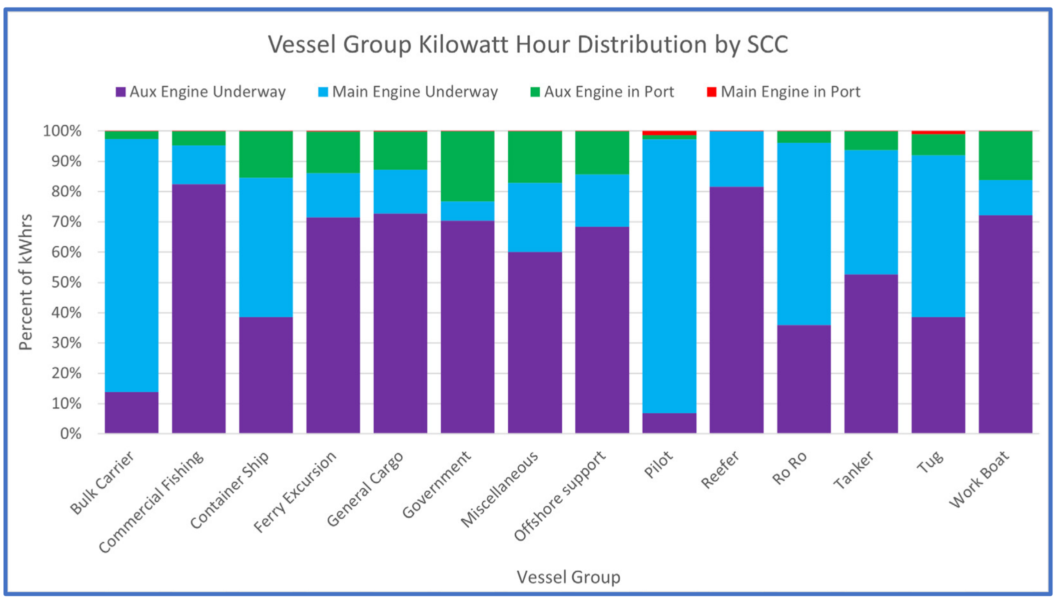


Figure 8. Ship Type Kilowatt Hour Distribution by SCC

Table 11. NEI Emissions by SCC (tons)

SCC	Fuel Type	Port/ Underway	Engine	VOC	CO_2	CO	NO_X	$PM_{2.5}$	SO_2	PM_{10}	kWhrs
2280002201	MGO/MDO	Underway	Main	2,591.73	3,595,343.83	7,604.03	53,603.15	1,415.16	33.05	1,458.93	4.80E+09
2280002202	MGO/MDO	Underway	Aux	3,190.58	8,238,631.94	16,547.54	104,543.85	2,675.24	605.26	2,761.74	1.07E+10
2280002101	MGO/MDO	Port	Main	80.36	42,346.12	88.74	904.84	28.31	0.39	29.19	5.65E+07
2280002102	MGO/MDO	Port	Aux	622.88	1,601,525.72	3,225.73	20,251.68	513.36	100.14	529.84	2.08E+09

9.0 Limitations

Use of AIS data to develop emission inventories is a significant improvement over early methods that required assumptions about vessel power, operating load, and level of activity. Assumptions made in these earlier inventories are replaced with actual vessel specific power data and other attributes provided by classification societies, calculated load factors based on the vessel's actual speed relative it is service speed, and other details related to vessel location and time stamp included in the AIS data stream.

These data are more complete and readily available for larger C3 vessels, but when it comes to smaller C1C2 vessels, many of the earlier assumptions about power and operating load are still required as is the question about whether the dataset represent a complete inventory of these smaller vessels.

The AIS system continues to evolve and expand coverage, but there are still areas where the VHF signals are missing and there are vessels that do not have transponders or turn off their transponders. In processing the AIS data for 2020, record counts could vary significantly from day to day indicating possible gaps suggesting that the AIS data may underestimate actual activities.

Review of the processed AIS data also indicated that there are distinct periods of satellite outage. This has an impact for sections of shipping lanes that are beyond the range of VHF towers (25-30 miles), particularly for vessels traveling in federal and international waters.

Earlier AIS approaches estimated duration relative to the last known observation. By creating a buffer that extended into international waters, it was possible to identify and address vessels that leave federal waters and return later generating very unreasonably large duration times. But for some vessels, not near the federal/international boundary, there may be long periods of time between observations. It is impossible to tell if these vessels are not operating or if there is a problem with the AIS transponder or receiver. In this version, any last known observation greater than 24 hours is considered suspect, and periods without a signal greater than 24 hours are filtered. Further study is needed to better understand these events.

Though AIS has been instrumental in improving the overall quality of propulsion engine emission estimates, similar improvements are needed for auxiliary engines, specifically better methods to estimate auxiliary engine operating loads.

Further study of dockside operations are needed to better understand when vessel shut off their engines when dockside to reduce fuel consumption and emissions.

As use of shore power expands it would be helpful to have ports provide information about utilization rates for all vessels categories to adjust dockside emissions to account for these initiatives and avoid double counting with landside Electricity Generating Units (EGUs).

Recently, states have provided vessel specific information about strategic engine and vessel replacements targeted to improve local air quality. This information can be linked directly to the vessels' AIS data to account for emission reductions associated with the use of higher tiered engines. We encourage provision of such information.

Unlike Category 3 vessels, there is limited vessel characteristics data for most Category 1 and 2 vessels; often there is not vessel specific data for main and auxiliary power, engine specifications, design max speed and vessels dimensions. It should be noted that these data gaps are filled by averaging data from a relatively small vessels for which data are available in a suitable format, such that there is considerable uncertainty associated with these default values. Further study is needed to expand Category 1 and 2 vessel attributes which will allow for better matching vessels to appropriate characteristics. It would also be helpful to develop a better understanding of the variance within the key surrogate data elements to help quantify uncertainty.

10.0 References

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APPENDIX A

Vessel Type and Ship Group Bridge

Table A-1. Bridge Between Vessel Type and Ship Group

Vessel Type	Ship Group
Accommodation Barge	Offshore support
Accommodation Unit - Semi Sub.	Offshore support
Accommodation Vessel	Offshore support
Aggregates Carrier	Bulk Carrier
Amphibious Assault Ship LHA	Government
Anchor Handling Tug	Offshore support
Anchor Handling Tug/Supply	Offshore support
Anti-Pollution Vessel	Offshore support
Asphalt & Bitumen Carrier	Tanker
Backhoe/Dipper/Grab Dredger	Offshore support
Bulk	Bulk Carrier
Bulk Carrier	Bulk Carrier
Bulk Carrier, Self-discharging	Miscellaneous
Buoy/Lighthouse Tender	Government
Cable Layer (Fibre Optic)	Offshore support
Cable Layer, Naval Auxiliary	Government
Cable, Umbilicals & FP/Flowline Lay	Offshore support
cargo	General Cargo
Cargo	General Cargo
Cargo and Passenger	General Cargo
Cement Carrier	Bulk Carrier
Chemical & Oil Carrier	Tanker
Chemical Tanker (Inland)	Tanker
Chemical/Products Tanker (Inland)	Tanker
Coast Guard	Government
Container Barge, Propelled	Container Ship
Container Ship (Inland)	Container Ship
Covered Bulk Cargo Barge	Barge
Crane Barge	Barge
Crane Pontoon	Barge
Crew Boat	Offshore support
Crew Boat, Naval Auxiliary	Government
Crew Tender	Offshore support
Crew/Fast Supply Vessel	Offshore support
Crewboat / Supply / Utility Vessel	Offshore support
Cruise	Ferry Excursion
Cruise (Inland)	Ferry Excursion

Vessel Type	Ship Group
Cruise Ship	Ferry Excursion
Cutter Suction/Bucket Wheel Dredger	Offshore support
Deck Cargo Carrier	General Cargo
Diving Support	Offshore support
Diving Support Vessel	Miscellaneous
Diving Vessel, Naval Auxiliary	Government
Dredge	Offshore support
dredge_fishing	Commercial Fishing
Dredger (Unspecified)	Offshore support
Dredgers (Stone Dumping, Fallpipe)	Offshore support
Dredging Pontoon	Barge
drifting_longlines	Commercial Fishing
Drilling	Offshore support
Drillship	Offshore support
Electricity Generating Vessel	Miscellaneous
ERRV	Government
Extended Well Test Vessel	Offshore support
Factory Stern Trawler	Commercial Fishing
Ferry	Ferry Excursion
Fire	Government
Fire-fighting Tug	Tug
Fish Factory Ship	Commercial Fishing
Fishery Patrol Vessel	Government
Fishery Research Vessel	Miscellaneous
Fishery Support Vessel	Commercial Fishing
Fishing	Commercial Fishing
fishing	Commercial Fishing
Fishing Vessel	Commercial Fishing
fixed_gear	Commercial Fishing
Floating Production Unit	Offshore support
FPSO	Offshore support
Frigate	Government
Fruit Juice Carrier	Reefer
FSO	Offshore support
FSRU	Offshore support
Fully Cellular Container	Container Ship
gear	Commercial Fishing
General Cargo	General Cargo
General Cargo (Inland)	General Cargo

Vessel Type	Ship Group
Geophysical Survey	Offshore support
Government	Government
Gravel/Stone Discharge	Offshore support
Heavy Lift/Crane Ship	Offshore support
Heavy Load Carrier	General Cargo
High Speed	Ferry Excursion
Hopper Barge	Barge
Hydrographic Survey	Offshore support
Icebreaker	Government
Icebreaker AGB	Government
Jack-up Drilling Rig	Offshore support
Jack-up Production Unit	Offshore support
Landing Craft	Government
Landing Ship (Dock Type)	Miscellaneous
Live Fish Carrier (Well Boat)	Commercial Fishing
Livestock Carrier	Miscellaneous
LNG Carrier	Tanker
Logistics Vessel (Naval Ro Ro Cargo)	Government
LPG Carrier	Tanker
Maintenance	Miscellaneous
Marine Research	Miscellaneous
Merchant	General Cargo
Merchant, Passenger Ship	Miscellaneous
Merchant, Pilot Tender	Pilot
Merchant, Supply Vessel	Miscellaneous
Merchant, Tug	Tug
Military	Government
Miscellaneous	unknown
Miscellaneous Cargo	General Cargo
Miscellaneous Offshore Service	Offshore support
Motor Yacht	Pleasure Craft
motor_passenger	Pleasure Craft
Multi-Purpose	Miscellaneous
Multi-Purpose Support	Miscellaneous
NA; Tug Tow	Tug
Not Available; Tug Tow	Tug
Ocean-going Salvage Tug	Tug
Ocean-going Tug	Tug
Oceanographic Survey	Offshore support

Vessel Type	Ship Group
Official Service Shp	Offshore support
Official Service Shp, Auxiliary Ship	Miscellaneous
Official Service Shp, Cargo and Passenger	Miscellaneous
Official Service Shp, Supply Vessel	Miscellaneous
Offshore Construction Vessel, jack up	Miscellaneous
Offshore Launch Barge/Pontoon	Barge
Offshore Oil and Gas Support	Offshore support
Oil and Gas	Offshore support
Oil Bunkering Tanker	Tanker
Oil Tanker (Inland)	Tanker
Oilfield Pollution Control	Offshore support
Ore Carrier	Bulk Carrier
Other Activities (Inland)	Miscellaneous
Other Dredger	Offshore support
other_fishing	Commercial Fishing
other_purse_seines	Commercial Fishing
other_seines	Commercial Fishing
Palletised Cargo Carrier	Bulk Carrier
Pass./Car Catamaran Vessel	Ferry Excursion
Pass./Car Ferry	Ro Ro
Passenger	Ferry Excursion
Passenger (Inland)	Ferry Excursion
Passenger Catamaran Vessel	Ferry Excursion
Passenger Vessel	Ferry Excursion
Passenger/Cargo Vessel	General Cargo
Passenger/Ro-Ro (Inland)	Ro Ro
Patrol Vessel	Government
Patrol Vessel, Naval	Government
Pilot	Pilot
pilot	Pilot
Pilot Vessel	Pilot
Pipe Layer	Offshore support
Pipe Laying Barge	Barge
Platform Rig	Offshore support
Platform Supply	Offshore support
Platform Supply Ship	Offshore support
pleasure craft	Pleasure Craft
Pleasure Craft/Sailing	Pleasure Craft
Pleasure Craft/Sailing; Tug Tow	Pleasure Craft

Vessel Type	Ship Group
pole_and_line	Commercial Fishing
Pontoon (Function Unknown)	Barge
pots_and_traps	Commercial Fishing
Product Carrier	General Cargo
Products Tank Barge	Barge
purse_seines	Commercial Fishing
Pushboat	Miscellaneous
Reefer	Reefer
Reefer Fish Carrier	Reefer
Reefer/Pallets Carrier	Reefer
Rescue	Government
Research or Survey Ship	Miscellaneous
Research Survey Vessel	Miscellaneous
Research Vessel	Miscellaneous
Research Vessel, Naval Auxiliary	Government
RORO	Ro Ro
Ro-Ro	Ro Ro
Ro-Ro Freight/Passenger	Ro Ro
Ro-Ro/Lo-Lo	Ro Ro
ROV/Submersible Support	Offshore support
sailing ship	Pleasure Craft
Sailing Vessel	Pleasure Craft
Salvage Vessel	Offshore support
Salvage Vessel, Naval Auxiliary	Government
SAR	Government
Search & Rescue	Government
seiners	Commercial Fishing
Seismic Support	Offshore support
Seismic Survey	Offshore support
seismic_vessel	Offshore support
Self Elevating Install. Barge	Barge
Semi-Submersible Drilling Rig	Offshore support
Semi-Submersible Heavy Lift	Offshore support
Semi-Submersible Production Unit	Offshore support
Service	Offshore support
set_gillnets	Commercial Fishing
set_longlines	Commercial Fishing
Ship	Miscellaneous
Small Commercial	General Cargo

Vessel Type	Ship Group
Split Hopper Barge	Barge
squid_jigger	Commercial Fishing
Standby Safety/Guard	Offshore support
Stern Trawler	Commercial Fishing
Submarine Salvage Vessel	Offshore support
Suction Dredger	Offshore support
Suction Hopper Dredger	Offshore support
Supply	Offshore support
Supply Tender	Offshore support
Support Vessel	Offshore support
Survey	Offshore support
Tank Landing Craft	Government
Tanker	Tanker
tanker	Tanker
Tender	Offshore support
Torpedo Recovery Vessel	Government
Towing/Pushing (Inland)	Tug
Trailing Suction Hopper Dredger	Offshore support
Training Ship	Government
Training Ship, Naval Auxiliary	Government
Transport (Heavy Lift)	General Cargo
Trawler	Commercial Fishing
trawlers	Commercial Fishing
trollers	Commercial Fishing
Tug	Tug
tug	Tug
Tug Tow	Tug
Tug Tow; NA	Tug
Tug Tow; Pleasure Craft/Sailing	Tug
Tug, Anchor Hoy	Offshore support
Tug, Naval Auxiliary	Government
tuna_purse_seines	Commercial Fishing
Unknown	unknown
USCG	Government
Utility/Workboat	Work Boat
Waste Disposal Carrier	Miscellaneous
Well Stimulation	Offshore support
Wind Turbine Installation	Offshore support
Windfarm Crew/Supply Tender	Offshore support

Vessel Type	Ship Group
Work/Repair Vessel	Work Boat
Yacht (Sailing)	Pleasure Craft
Yacht Support Vessel	Miscellaneous
Yacht/Recreational	Pleasure Craft