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Automation of Commercial Marine Vessel Emissions Inventory Development

Final Report

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1.0 INTRODUCTION

1.1 Background

The Texas Commission on Environmental Quality (TCEQ) needs commercial marine vessel (CMV) emission inventories of the highest possible quality as inputs for air quality modeling to support State Implementation Plan (SIP) development. Since 2009, the U.S. Coast Guard has collected Automatic Identification System (AIS) data in real time to track the location and characteristics of large vessels operating in both U.S. and international waters. AIS data sets are available from the Coast Guard throughout the U.S. and surrounding oceanic waters. The level of detail included in AIS data sets has expanded over time. Starting in 2015, the Maritime Mobile Service Identity (MMSI) code for each vessel became readily available in the AIS data sets. Starting in March 2016, all commercially active vessels were required to install AIS transponders, including many smaller vessels that operate primarily within harbors and near-shore waters. This high-resolution tracking system for all operational vessels is an excellent activity data set for use in CMV emissions inventory development.

The Sea-web Ships database is one of the most comprehensive registries available for identifying characteristics of specific vessels such as ownership, size, age, type of cargo transported, etc. Sea-web is commercially available from IHS Markit. AIS tracking data and Sea-web vessel characteristics are the two essential components for developing high-resolution CMV emission inventories. Both the AIS and Sea-web data sets are comprehensive, but they are not readily available in a "plug-in" format for automating emissions inventory calculations. A processing tool is needed to combine, process, and quality assure the AIS and Sea-web data sets so that CMV emissions inventories can be developed for use by TCEQ staff.

The TCEQ uses version 3 of the Emissions Processor System (EPS3) to prepare emission inventories for air quality modeling using the Comprehensive Air Quality Model with Extensions (CAMx). A primary function of the tool developed under this work order will be to develop CMV emission input files in a format suitable for input to the EPS3 PRESHP (PREprocessor for SHiPPing) module by including the geographic area of operation, a source classification code (SCC) to identify the type of vessel, time periods of operation, location of activity, and emissions of each pollutant.

1.2 Purpose and Objectives

This project develops a set of automated scripts that TCEQ staff can use to develop CMV emission inventories for their regional chemical transport modeling. The tool automates the conversion of AIS data into CMV emissions estimates in a format that is compatible with the EPS3 system. The tool allows for the extraction of CMV activity data by year, month, day type, and hour for specific vessel types operating within a defined geographic area. This feature enables development of temporal allocation profiles specific to areas of interest such as Texas ports and the Gulf of Mexico and allows the TCEQ to characterize CMV activity trends over time (several years) which may be useful for developing future year activity projection factors that vary by SCC. Lastly, the U.S. Environmental Protection Agency (EPA) currently has 71 SCC options for identifying CMVs by use and fuel type. The TCEQ sometimes uses custom SCCs for CMVs to obtain greater resolution of emission inventories for air quality modeling applications. An important feature of this tool is the option of assigning custom SCCs using a combination of 10 numeric codes and/or alpha characters.

2.0 METHODOLOGY

Ramboll developed the Marine Emissions Resolver (MARINER) Python tool that automates the estimation of commercial marine vessel (CMV) emission inventories and the generation of air quality modeling inputs. Broadly, the tool is designed to process vessel movement records to estimate vessel activity, merge the results with characteristics of the unique vessels where possible, and generate estimates of vessel emissions. MARINER has been designed to follow the 2020 EPA draft guidance (EPA, 2020) on estimating vessel emissions, but it is structured such that future updates or guidance from other entities can be incorporated without great difficulty.

2.1 Data Sources

2.1.1 Vessel emission sources

Vessel operations produce emissions from main engines, auxiliary engines, and, in the case of ocean-going vessels, boilers. Emissions produced by these sources occur depending on the vessel's mode of operation. When transiting, emissions are produced by the main and auxiliary engines, but the boiler is not used under typical loads because heat is recovered from main engines. In maneuvering, all three sources are typically used because at these low loads inadequate heat is generated by the main engines. When at-anchor or at-berth, the vessels operate without the main propulsion engines and emissions are only produced by the auxiliary engines and, if applicable, the boiler.

2.1.2 AIS Records

Since 2009, the U.S. Coast Guard has collected Automatic Identification System (AIS) data in real time to track the location and characteristics of large vessels operating in both U.S. and international waters. AIS data sets are available from the Coast Guard throughout the U.S. and surrounding oceanic waters. The level of detail included in AIS data sets has expanded over time. Starting in 2015, the Maritime Mobile Service Identity (MMSI) and International Maritime Organization (IMO) identification codes for each vessel became readily available in the AIS data sets. Starting in March 2016, all commercially active vessels were required to install AIS transponders, including many smaller vessels that operate primarily within harbors and near-shore waters. This high-resolution tracking system provides the activity data set that serves as input to MARINER for estimating emissions.

The AIS records provide a variety of attributes associated with vessel movements, including position, date and time, speed over ground, course over ground, instantaneous draft, vessel identification codes, and vessel type. These attributes feed into emission calculations in a variety of ways:

- spatial and temporal allocations can be produced through use of position and timestamps;
- ocean-going vessel propulsion engine load can be estimated using the Admiralty formula which relies on speed over ground and draft;
- vessel specifications can be determined by relating MMSI and/or IMO codes to a vessel characteristics database;
- operating mode can be approximated from speed over ground; and
- where vessel specifications are unavailable, vessel type from the AIS records can serve to relate a vessel to EPA default vessel characteristics.

The AIS data are available from the Marine Cadastre website and the IHS Sea-web vessel database. The AIS data are also available via Freedom of Information Act requests, but the data provided by the Marine Cadastre site has been quality assured via the Authoritative Vessel Identification System which corrects vessel identification codes and vessel type indicators.

2.1.3 Vessel engine characteristics

Vessel characteristics can be acquired through a variety of suppliers that maintain detailed databases of vessel characteristics. These databases provide a large expanse of data, but the fields which are pertinent to the development of emission estimates are limited to those which provide insights to engine attributes (e.g., bore, stroke, total installed power), design characteristics (e.g., service speed, maximum draft, keel laid date), and vessel use info (e.g., ship type detail). Additional fields can also be of use depending on the end-use of the emissions results. Such fields may include vessel owner, country flag, vessel capacities, or other design features (e.g., number of reefer plugs, shore power capability flag).

2.1.4 Guidance documentation for estimating emissions

The data processing in MARINER generally follows the approach outlined in the draft guidance from the EPA (EPA, 2020). This document provides guidance on how to process AIS records to develop emission estimates and is a significant step forward since the prior EPA guidance (EPA, 2009).

2.2 Tool Functionalities

The data processing follows the methodologies used for prior AIS-derived emissions for TCEQ modeling (Ramboll 2018; Ramboll Environ 2017, Ramboll Environ 2015) and the latest draft guidance from the EPA (EPA, 2020). The general process is depicted in Figure 2-1. There are five primary functions for these scripts:

- Combining AIS and IHS Sea-web Data Sets
- Allocation of Processed Data to Shapefiles (e.g., by county, by grid)
- Assignment of 10-Character SCCs
- Summarizing Processed Data by Temporal Extents

Emissions Calculations by Geographic Area, SCC, and Time Period

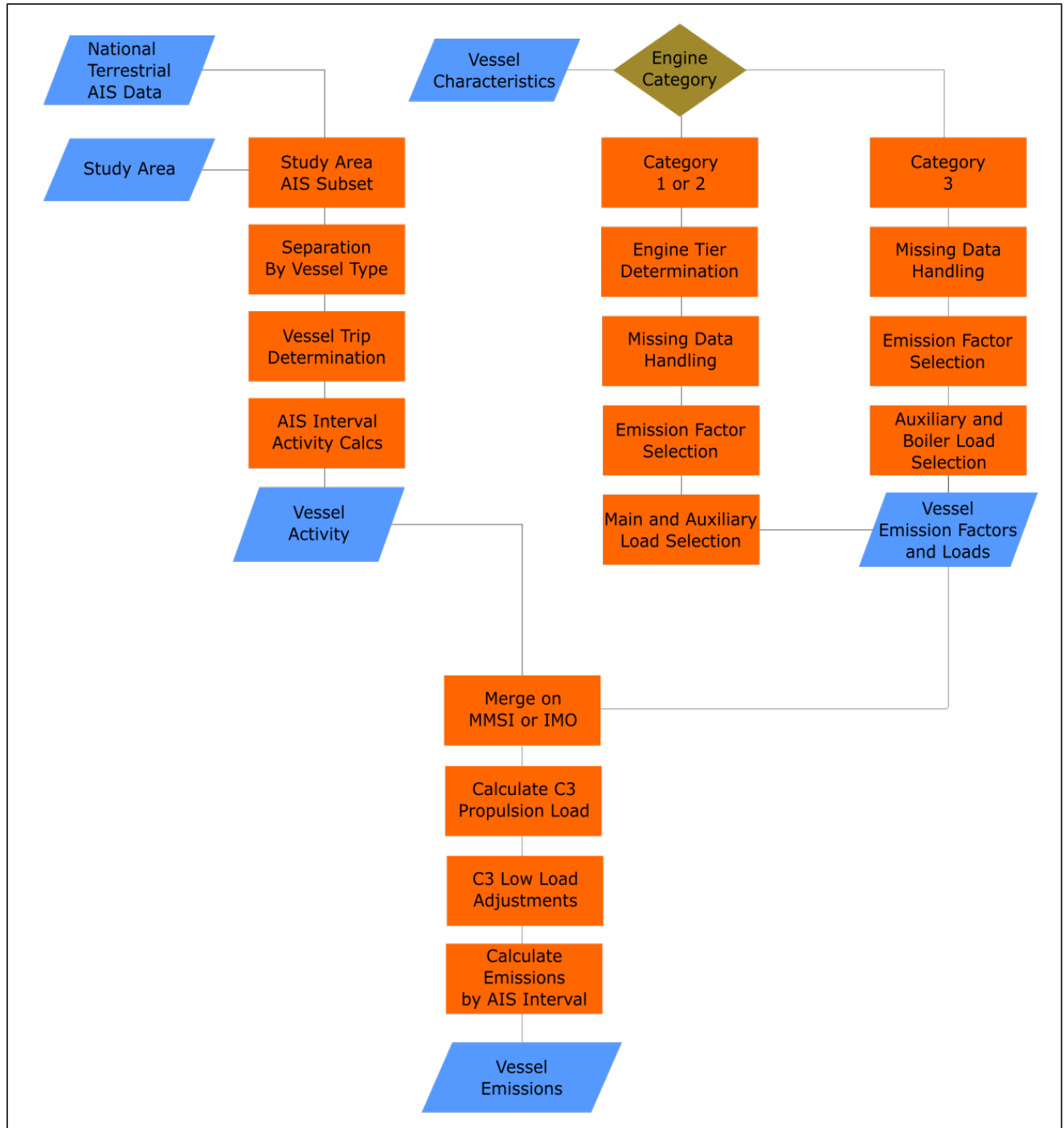


Figure 2-1. Overview of Emission Estimation Process

2.2.1 Combining AIS and IHS Sea-web Data Sets

The scripts provide the user with the ability to combine AIS activity data from multiple months and within specific longitude and latitude bounds with IHS Sea-web registration data by individual vessel. This combination is done by matching the vessel with the IMO identification code or the MMSI number. In some instances, it is expected that data for more than two UTM zones will first need to be combined

before this step can occur. For example, of the 18 AIS data sets by month and UTM zone available for North America in 2017, Texas is split between zones 14 and 15. The scripts will allow AIS data for zones 14 and 15 to first be combined into one larger data set before the matching step is done with the IHS Sea-web data. Since the AIS data sets for an individual month or year can be very large for one of these zones, the TCEQ anticipates working with smaller groups of data at once rather than one large North American AIS data set covering all 18 zones. The spatial extent of the data selection will control the size of the data acquisition and, if too large, may exceed TCEQ hardware capabilities. In the event that AIS and/or IHS Sea-web records have missing fields that are needed for subsequent calculations, the scripts populate these fields by identifying the appropriate vessel type information and using EPA-generated vessel type defaults. Starting with 2018, each AIS file includes data spanning all UTM zones for each calendar day. The MARINER tool has the capability of processing AIS data files by month and UTM zone (e.g., for 2017) or calendar day and all UTM zones (e.g., 2018).

2.2.2 Allocation of Processed Data to Shapefiles (e.g., by county, by grid):

The scripts allow for the latitude and longitude data from the AIS data sets to be intersected with a geographic information systems (GIS) shapefile or set of multiple shapefiles. For each geographic area with a shapefile identified by the user, the scripts add a unique five-character code to the output record. These unique codes are needed for performing source apportionment modeling and other air quality analyses. Table 2-1 presents examples of these unique codes for Texas counties and non-Texas areas.

Processing emission estimates into a modeling grid followed the approach used in prior work for the Texas Commission on Environmental Quality (Ramboll, 2018; Ramboll Environ, 2017; Ramboll Environ 2015).

Table 2-1. Examples of Customized Area Codes

Area	Five-Character Code	Note
Brazoria County	48039	FIPS Code
Calhoun County	48057	FIPS Code
Non-Texas Continental U.S.	CONUS	Customized
Alaska	02000	State Code
Mexico	MEXIC	Country Code
U.S. Territorial Waters - Gulf of Mexico	GLFUS	Customized

2.2.3 Assignment of 10-Character SCCs

The scripts assign SCCs to specific vessel types, engine types, and/or fuel types. The U.S. EPA currently has 71 SCC options for CMV emissions beginning with the three-digit 228 prefix. In order to have the highest possible resolution in its modeling inventories, the TCEQ often adds custom SCCs with a combination of alpha and numeric characters. The scripts include the ability to assign custom SCCs by vessel type and activity. For example, bulk carriers and container ships may be classified by EPA under the aggregate code of 2280002010 for diesel ocean-going vessels (OGVs). The TCEQ can further code these vessel types separately, such as 228000BLKA for bulk carriers at anchor, 228000BLKT for bulk carriers in transit, 228000CONA for container ships at anchor, and 228000CONT for container ships in transit.

Marine vessels are also categorized as Category 1 (C1), Category 2 (C2), or Category 3 (C3). The primary sources of emissions on these vessels come from propulsion (P) engines, auxiliary (X) engines, and boilers (B). The scripts allow for the option of adding three characters to the SCC to identify the vessel category and engine type. For this type of customization, the codes of C1, C2, and C3 would be used along with P for propulsion, X for auxiliary, and B for boiler. For example, the three zeros in 228000BLKT could be replaced with C3P to obtain 228C3PBLKT to identify emissions from the propulsion engine on a bulk carrier in transit. The scripts assign any vessel type that cannot be readily classified to a miscellaneous or "other" category. Sample custom SCCs are presented in Table 2-2 for currently known vessel types.

Table 2-2. Examples of Customized SCC Codes

Custom SCC	Description
228000ATCA	Auto Carrier at Anchor
228000ATCT	Auto Carrier in Transit
228000ATGA	Assist Tug at Anchor
228000ATGT	Assist Tug in Transit
228000BLKA	Bulk Carrier at Anchor
228000BLKT	Bulk Carrier in Transit
228000BRGA	Barge at Anchor
228000BRGT	Barge in Transit
228000CONA	Container Ship at Anchor
228000CONT	Container Ship in Transit
228000CRGA	Cargo Vessel at Anchor
228000CRGT	Cargo Vessel in Transit
228000CRSA	Cruise Ship at Anchor
228000CRST	Cruise Ship in Transit
228000CRTA	Crude Oil Tanker at Anchor
228000CRTT	Crude Oil Tanker in Transit
228000CRWA	Crew Boat at Anchor
228000CRWT	Crew Boat in Transit
228000DRGA	Dredge Tender at Anchor
228000DRGT	Dredge Tender in Transit
228000DRLA	Drilling Vessel at Anchor
228000DRLT	Drilling Vessel in Transit
228000FRYA	Ferry Boat at Anchor
228000FRYT	Ferry Boat in Transit
228000FSHA	Fishing Vessel at Anchor
228000FSHT	Fishing Vessel in Transit
228000LNGA	Liquefied Natural Gas (LNG) Tanker at Anchor
228000LNGT	LNG Tanker in Transit
228000MILA	Military Vessel at Anchor
228000MILT	Military Vessel in Transit
228000MSCA	Miscellaneous (Other) Vessel at Anchor
228000MSCT	Miscellaneous (Other) Vessel in Transit

Custom SCC	Description
228000OTGA	Ocean Tug at Anchor
228000OTGT	Ocean Tug in Transit
228000RECA	Recreational Boat at Anchor
228000RECT	Recreational Boat in Transit
228000REFA	Refrigerated (REEFER) Cargo Vessel at Anchor
228000REFT	REEFER Cargo Vessel in Transit
228000RORA	Roll-On/Roll-Off (RORO) Vessel at Anchor
228000RORT	RORO Vessel in Transit
228000TGBA	Tugboat at Anchor
228000TGBT	Tugboat in Transit
228000TNKA	Tanker at Anchor
228000TNKE	Tanker Exhaust while Lightering
228000TNKL	Tanker Evaporation while Lightering
228000TNKT	Tanker in Transit
228000TUGA	Ocean-Going Tug at Anchor
228000TUGT	Ocean-Going Tug in Transit
228000WBTA	Work Boat at Anchor
228000WBTT	Work Boat in Transit

2.2.4 Summarizing Processed Data by Temporal Extents:

The AIS data sets typically provide marine vessel location information on a five-minute basis. The scripts include the ability to aggregate this activity to the hourly level for subsequent emissions inventory development and processing. The scripts allow a user the option of developing an emissions inventory for all 8,760 hours that occur in a 365-day calendar year.

Based on an historical year of AIS data, the scripts allow the user to develop summaries of temporal activity by year, month, day type, and hour for a single SCC or group of SCCs. The temporal output is numerically coded as 1-12 for months of the year, 1-7 for days of the week, and 1-24 for hours of the day. These temporal summaries are organized in a manner that allows TCEQ to readily develop temporal profiles by geographic area and SCC for efficient allocation of CMV emissions. The scripts readily work with AIS data sets for 2017-and-later calendar years since 2017 was the first full year that included AIS data on all commercial vessels.

The TCEQ plans to create summaries of activity on an annual basis to identify changes over time in the use of specific vessel types and use these trends to develop future year CMV emission inventories. The specific units of CMV activity for these temporal profiles may vary. The scripts include the ability to develop profiles based on different activity parameters that can be reasonably obtained from the AIS/Sea-web data sets such as kilowatt-hours of engine operation, hours at anchor, hours in transit, nautical miles traveled, etc.

2.2.5 Emissions Calculations by Geographic Area, SCC, and Time Period

The scripts perform all calculations to estimate CMV emissions for the geographic area(s), time period(s), and SCC(s) specified by the user. The user can easily modify and configure these scripts in

the event that updates become available. For example, more stringent fuel sulfur limits may apply in the future and need to be modified in the scripts for emissions estimation.

The scripts have the option of reporting the estimated quantity of fuel consumed for a specified geographic area, period of time, and SCC or groups of SCCs. The scripts allow the user to output the CMV emissions estimates in the format required by the EPS3 PRESHP module. The scripts allow the user to choose between developing a single PRESHP input file for all SCCs within a geographic area, or for developing multiple PRESHP input files for groups of SCCs within a geographic area to allow for more focused quality assurance.

The modeling domain currently employed by the TCEQ relies on a Lambert Conformal Conic (LCC) map projection. The scripts convert all AIS activity data from latitude/longitude into the appropriate LCC projection that is summarized in Table 2-3. Table 2-4. lists the emission compounds and appropriate five-digit pollutant codes currently used by the TCEQ for EPS3 processing.

Table 2-3. TCEQ’s modeling domain projection

LCC Parameter	Value
First True Latitude (Alpha)	33 degrees North
Second True Latitude (Beta)	45 degrees North
Central Longitude (Gamma)	97 degrees West
Projection Origin	97 degrees West and 40 degrees North
Spheroid	Perfect Sphere with Radius of 6,370 km

Table 2-4. Pollutant Codes

Alpha Code	Numeric Code	Compound Description
NO _x	42603	Oxides of Nitrogen
VOC	43104	Volatile Organic Compounds
CO	42101	Carbon Monoxide
CO ₂	42102	Carbon Dioxide
SO ₂	42401	Sulfur Dioxide
NH ₃	42604	Ammonia
PM _{2.5}	81104	Particulate Matter at or Below 2.5 Microns
PM ₁₀	81102	Particulate Matter at or Below 10 Microns

2.3 Output Products

The MARINER tool produces several different files as part of its processing. These files include intermediate files as MARINER steps through the various stages, a raw emissions file, a gridded geospatial emissions file, and an EPS3 PRESHP emissions input file for use in regional chemical transport modeling applications.

- Intermediate files are produced in the Apache Feather file format. This format allows for rapid read and write access to the data which improves the performance of the MARINER program.
- Raw emissions data include the emissions for each AIS interval of all voyages identified in the AIS records. This data is also output in the Feather format due to its size.

- A gridded emission file is developed as an intersection of the raw emissions with an analysis grid and the emissions are summed across each grid. The result is emissions per grid, presented as tons per year or tons per day. The output file is provided as a shapefile to allow for easy interaction through most geographic information system software packages.

The EPS3 PRESHP input file is ASCII formatted and can be accessed using simple text editors.

3.0 APPLICATION FOR TEXAS COAST AND GULF OF MEXICO

Ramboll demonstrated operation of the script functions through an application that uses the AIS and IHS data sets for all months in 2017 for the TCEQ modeling domain with UTM zones 14 and 15. We tested all functions including combining the AIS and IHS data sets, geographic allocation by area, assignment of SCCs, summarizing of temporal activity, and building example emission files for the EPS3 PRESHP module.

Ramboll worked with TCEQ to ensure that TCEQ could satisfactorily load in the appropriate python modules and could execute MARINER functions on a subset of a calendar year of AIS records. The processing of the full 2017 AIS records resulted in the emissions shown in Table 5.

Table 5. MARINER Emission Estimates for 2017 within the TCEQ Modeling Domain

Vessel Category	Row Labels	NOx	HC	CO	PM10	PM2.5	SO2
Ocean-Going Vessels	Bulk Carrier	5,175	226	532	83	76	184
	Chemical Tanker	17,889	767	1,850	296	273	660
	Container Ship	6,565	364	755	99	91	237
	Cruise	3,162	129	303	52	48	114
	General Cargo	2,951	127	306	49	45	110
	Liquified Gas Tanker	10,323	472	1,131	294	271	746
	Miscellaneous (C3)	23	0.9	2	0.4	0.3	0.8
	Offshore Support/Drillship	235	12	26	4	4	10
	Oil Tanker	20,155	920	2,129	558	514	1,432
	Other Tanker	1,532	67	151	30	27	71
	Reefer	145	6	14	2	2	4
RORO	1,392	64	145	21	19	46	
Harbor Craft	Crew and Supply	2,853	59	519	53	51	2
	Pilot	25	0.4	4	0.5	0.5	0.01
	Towboat/Pushboat	105	2	19	2	2	0.03
	Tug Boat	14,347	157	2,699	232	225	7
	Work Boat	621	16	135	16	16	4
Total		87,498	3,389	10,721	1,793	1,665	3,627

The results were compared against a variety of sources to assess the appropriateness of the emission totals. To provide perspective, the NOx emissions associated with activity located within the waters of the State of Texas were compared against both the near-shore emissions assessment produced by Ramboll in 2018 (29,379 tons of NOx) and the 2017 NEI vessel emission estimates for Texas (39,910 tons). This study resulted in total NOx emissions within the state boundary of 31,830 tons of NOx. The prior Ramboll study had resulted in 29,379 tons of NOx – a discrepancy that can be attributed to the use of updated EPA guidance and modified processing of the AIS records (e.g., voyage determination thresholds). Differences in the NOx emissions between the NEI and this study can likely be attributed to different assumptions made in the processing procedures and the use of different vessel characteristics databases, which can lead to either more or less data in-fill depending on the database used.

A comparison was also made between the TCEQ’s OGV offshore emission estimates for 2014 and this study. The prior TCEQ study estimated 30,331 tons of NO_x outside of the Texas State boundary, but within the TCEQ’s modeling domain. Within the same domain this study estimates 51,951 tons of NO_x. The differences in these estimates can be attributed to the different emission calculation methodologies, the different activity and fleets in each of the years, the use of U.S. Coast Guard data without data corrections, the updated processing approach, and, potentially, the change in AIS regulations since 2014. Regardless, the comparisons, both near-shore and off-shore, demonstrate that MARINER is producing reasonable results. Notably, the results from any model, including MARINER, should always be interpreted carefully and compared to known activities as a method of additional validation.

An example of the processed level of detail from MARINERs raw emissions file is provided in Figure 3-1. The image on the left depicts the NO_x emissions summed by grid cell (4-kilometer resolution offshore and 1-kilometer resolution within State waters) for the 2017 activity of tankers found classified as vessel type 70 in the AIS records.

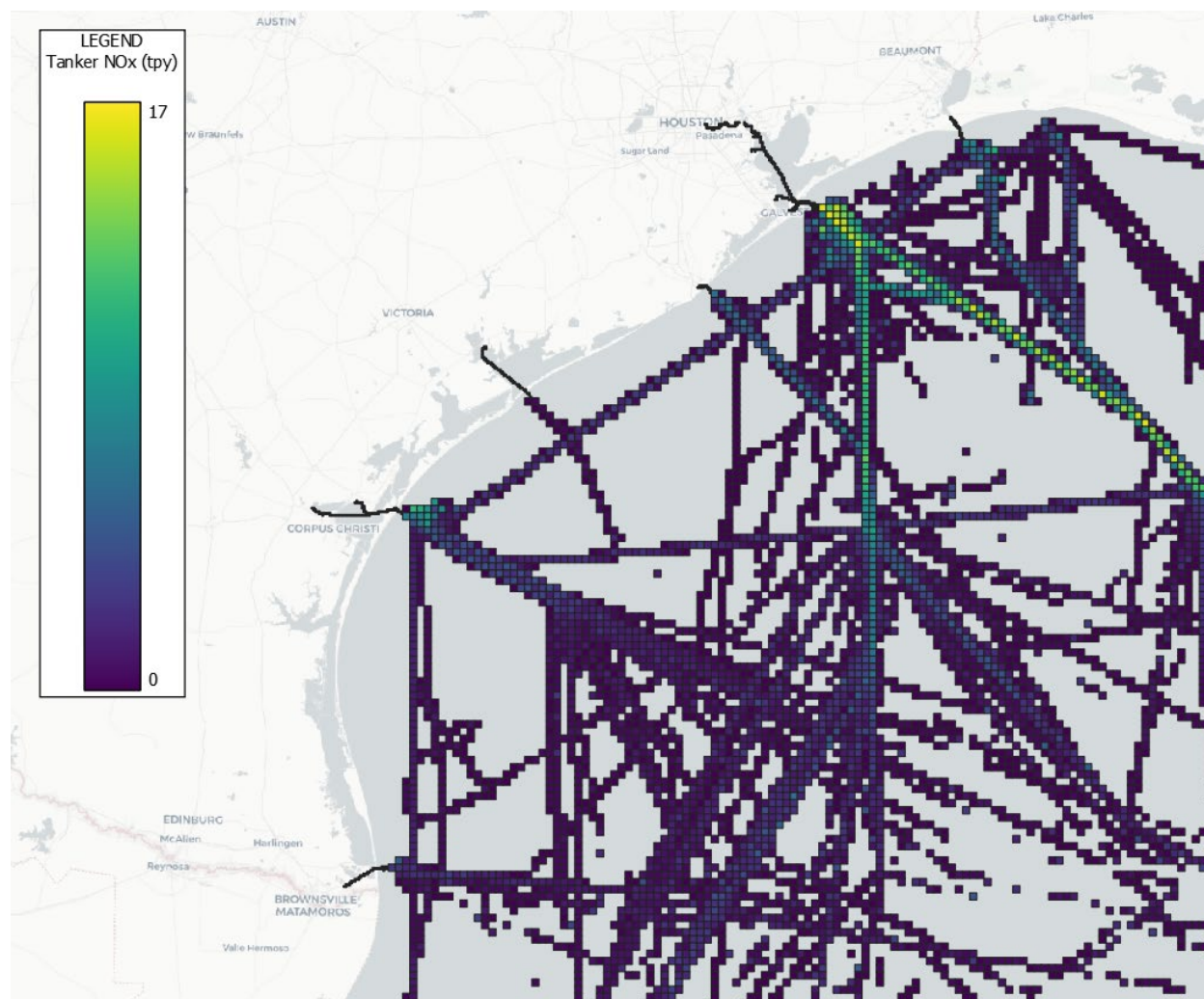


Figure 3-1. Tanker (vessel type 70) spatial distribution of NO_x emissions.

4.0 SUMMARY AND RECOMMENDATION

Ramboll developed the Marine Emissions Resolver (MARINER) Python tool that automates the estimation of CMV emission inventories and the generation of air quality modeling inputs. The methodology in MARINER follows the approach outlined in the latest draft guidance from the EPA (EPA, 2020). The tool was successfully tested through an application for the Texas Coast and Gulf of Mexico using the 2017 AIS data sets. The MARINER output is in a format that is compatible with the EPS3 system which the TCEQ uses to prepare emission inventories for air quality modeling.

4.1 Deliverables

- MARINER source codes
- User Guide that provides specific details about setting up and running MARINER

4.2 Recommendation for future work

The MARINER tool has been developed using the draft 2020 EPA guidance for developing port-related emission inventories. A final version of the guidance, along with associated updates, are expected to be published by the end of the 2020 calendar year. The updates to the guidance are recommended and may provide additional functionality to the tool (e.g., a streamlined approach when specific vessel characteristics are unavailable). As an example, the tool is currently designed to use the most conservative auxiliary engine and boiler loads, instead of selecting by vessel-specific capacity. Matching on vessel specific capacities and falling back to, yet to be seen, streamlined defaults when a match is not available from a vessel characteristics database could improve the resulting emissions. The current results also reflect the assumption that harbor craft with speeds less than or equal to 1 knot are presumed inactive, akin to the approach used for the 2017 NEI commercial marine vessel emissions.

The tool was developed using a vessel characteristics database from IHS that did not include specifications for fishing vessels. Without these characteristics the vessel emissions were not well characterized and not included in this analysis. An updated characteristics dataset will allow for characterization of these vessels in the future. Additionally, emissions from dredging operations are not included because the nuance of such operations requires additional review and verification.

The tool could be enhanced to use the California Air Resources Board's emission factors and defaults to provide the ability to generate emissions that are consistent with other emissions estimates within California. The MARINER tool may also benefit from increased flexibility of the in-use fuel sulfur content. Functionality could be added to allow the tool to provide more localized fuel sulfur analyses, especially for international locations where the regulatory environment is less structured than it is in the United States.

Outside of any guidance-based updates, various inspection tools could be developed for isolating and analyzing specific geographic and temporal aspects of the raw emissions output. Such tools could allow a user to understand various trends in the data (e.g., diurnal emission profiles, speed profiles) and assess specific voyages of interest or regions of concern. Geospatial analyses could also be enhanced to allow for assessing emissions at the county level and producing XML output that could be submission-ready for various government entity reporting requirements.

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