November 7, 2019

SPECIFICATION SHEET: CMV_C1C2 Platform

Description: Category 1 and 2 Commercial Marine Vessel (cmv_c1c2) emissions, for simulating 2016 and future year U.S. air quality

1. Executive Summary

Commercial Marine Vessel (CMV) emissions for ships with Category 1 and Category 2 engines are modeled in the cmv_c1c2 sector as hourly point sources. Category 2 (C2) and Category 1 (C1) engines are defined as having displacement below 30 liters per cylinder and greater than or equal to 7 liters per cylinder and below 7 liters per cylinder, respectively. The cmv_c1c2 modeling sector includes emissions in U.S. state and federal waters and in surrounding areas of Canada, Mexico, and international waters. CMV C1C2 emissions were developed for the 2017 National Emission Inventory (NEI) based on Automated Identification System (AIS), a tracking system used by vessels to enhance navigation and avoid collision with other AIS transmitting vessels. The data were retrieved at 5-minute intervals, spatially allocated into gridded datasets, and summed into hourly point source emissions files for modeling. The year 2016 cmv_c1c2 sector emissions were backcast from the 2017 NEI CMV emissions based on national U.S. Army Corps of Engineers Entrance and Clearance data. The 2017 NEI CMV emissions were also projected to 2023 and 2028 based on factors derived from the Locomotive and Marine rule

Regulatory Impact Assessment (RIA)[1]. Base and future year inventories were processed for air quality modeling with the Sparse Matrix Operating Kernel Emissions (SMOKE) modeling system version 4.7. National and state-level emission summaries for key pollutants are provided.

2. INTRODUCTION

This document details the approach and data sources used for developing 2016, 2023, and 2028 emissions for the Commercial Marine Vessel, Category 1 and Category 2 sectors (cmv_c1c2) inventory sector. The 2016 v1 platform cmv_c1c2 inventory was backcast from the U.S EPA 2017 National Emission Inventory (NEI) data to represent the year 2016, although the emissions for the modeling platform are gridded and hourly.

The cmv_c1c2 inventory sector contains small to medium-size engine CMV emissions. Category 1 (C1) and Category 2 (C2) marine diesel engines typically range in size from about 700 to 11,000 hp. These engines are used to provide propulsion power on many kinds of vessels including tugboats, towboats, supply vessels, fishing vessels, and other commercial vessels in and around ports. They are also used as stand-alone generators for auxiliary electrical power on many types of vessels. C1 represents engines up to 7 liters per cylinder displacement. C2 includes engines from 7 to 30 liters per cylinder.[2]

The cmv_c1c2 inventory sector contains sources that traverse state and federal waters that are in the 2017NEI along with emissions from surrounding areas of Canada, Mexico, and international waters. The cmv_c1c2 sources are modeled as point sources but using plume rise parameters that cause the emissions to be released in the ground layer of the air quality model.

The cmv_c1c2 sources within state waters are identified in the inventory with the Federal Information Processing Standard (FIPS) county code for the state and county in which the vessel is registered. The cmv_c1c2 sources that operate outside of state waters but within the Emissions Control Area (ECA) are encoded with a state FIPS code of 85. The ECA areas include parts of the Gulf of Mexico, and parts of the Atlantic and Pacific coasts. The cmv_c1c2 sources in the 2016v1 inventory are categorized as operating either in-port or underway and as main and auxiliary engines are encoded using the two source classification codes (SCCs) listed in Table 1.

[1] https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-control-emissions-air-pollution-locomotive
[2] https://www.epa.gov/sites/production/files/2015-10/documents/fy12-marine-rule-flowchart.pdf

Table 1. 2016v1 platform SCCs for cmv_c1c2 sector

SCC	Tier 1 Description	Tier 2 Description	Tier 3 Description	Tier 4 Description
2280002101	C1/C2	Diesel	Port	Main
2280002102	C1/C2	Diesel	Port	Auxiliary
2280002201	C1/C2	Diesel	Underway	Main
2280002202	C1/C2	Diesel	Underway	Auxiliary

3. INVENTORY DEVELOPMENT METHODS

Core Inventory Development

Category 1 and 2 CMV emissions were developed for the 2017 NEI[3]. The 2017 NEI emissions were developed based signals from Automated Identification System (AIS) transmitters. AIS is a tracking system used by vessels to enhance navigation and avoid collision with other AIS transmitting vessels. The USEPA Office of Transportation and Air Quality received AIS data from the U.S. Coast Guard (USCG) in order to quantify all ship activity which occurred between January 1 and December 31, 2017. The provided AIS data extends beyond 200 nautical miles from the U.S. coast (Figure 1). 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 are captured as well.

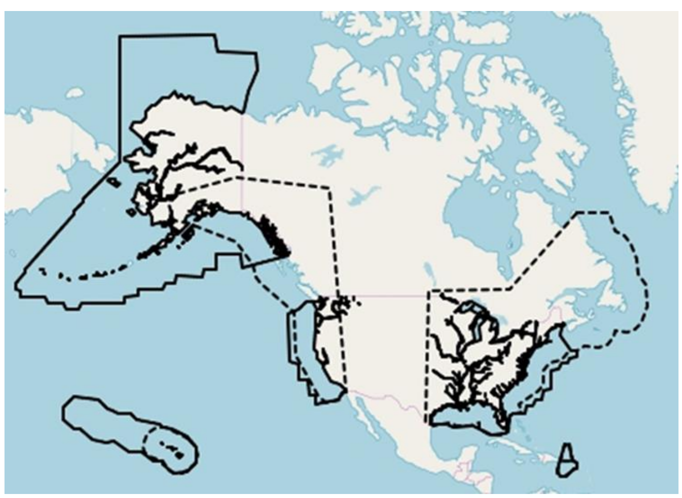

Figure 1. Geographic boundary of 2017 CMV C1C2 AIS data

The AIS 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

[3] Category 1 and 2 Commercial Marine Vessel 2017 Emissions Inventory (ERG, 2019)

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 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, 2018).

USEPA used the engine bore and stroke data to calculate cylinder volume. Any vessel that had a calculated cylinder volume greater than 30 liters was incorporated into the USEPA's new Category 3 Commercial Marine Vessel (C3CMV) model. The remaining records were assumed to represent Category 1 and 2 (C1C2) or non-ship activity. The C1C2 AIS data were quality assured including the removal of duplicate messages, signals from pleasure craft, and signals that were not from CMV vessels (e.g., buoys, helicopters, and vessels that are not self-propelled). Following this, there were 422 million records remaining.

The emissions were 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 were 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.

Next, vessels were identified in order determine their vessel type, and thus their vessel group, power rating, and engine tier information which are required for the emissions calculations. See the 2017 NEI documentation for more details on this process. Following the identification, 108 different vessel types were match to the C1 C2 vessels. Vessel attribute data was not available for all these vessel types, so the vessel types were aggregated into 16 different vessel groups for which surrogate data were available as shown in Table 2. 14,687 vessels were directly identified by their ship and cargo number. The remaining group of miscellaneous ships represent 14 percent of the AIS vessels (excluding recreational vessels) for which a specific vessel type could not be assigned.

Table 2. Vessel groups in the cmv_c1c2 sector

Vessel Group	NEI Area Ship Count
Bulk Carrier	37
Commercial Fishing	1,147
Container Ship	7
Ferry Excursion	441
General Cargo	1,498
Government	1,338
Miscellaneous	1,475
Offshore support	1,149
Reefer	13
Ro Ro	26
Tanker	100
Tug	3,994
Work Boat	77
Total in Inventory:	11,302

As shown in Equation (1), power is an important component of the emissions computation. Vessel-specific installed propulsive power ratings and service speeds were pulled from Clarkson's ship registry and adopted from the Global Fishing Watch (GFW) dataset when available. However, there is limited vessel specific attribute data for most of the C1C2 fleet. This necessitated the use of surrogate engine power and load factors, which were computed for each vessel group shown in Table 2. In addition to the power required by propulsive engines, power needs for auxiliary engines were also computed for each vessel group. Emissions from main and auxiliary engines are inventoried with different SCCs as shown in Table 1.

The final components of the emissions computation equation are the emission factors and the low load adjustment factor. The emission factors used in this inventory take into consideration the EPA's marine vessel fuel regulations as well as exhaust standards that are based on the year that the vessel was manufactured to determine the appropriate regulatory tier. Emission factors in g/kWhr by tier for NO_x, PM_{10}, $PM_{2.5}$, CO, CO_2, SO_2 and VOC were developed using Tables 3-7 through 3-10 in USEPA's (2008) Regulatory Impact Analysis on engines less than 30 liters per cylinder. To compile these emissions factors, population-weighted average emission factor were calculated per 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.

Propulsive emissions from low-load operations were adjusted to account for elevated emission rates associated with activities outside the engines' optimal operating range. The emission factor adjustments were applied by load and pollutant, based on the data compiled for the Port Everglades 2015 Emission Inventory[4]. Hazardous air pollutants and ammonia were added to the inventory according to multiplicative factors applied either to VOC or $PM_{2.5}$.

For more information on the emission computations for 2017, see the supporting documentation for the 2017 NEI C1C2 CMV emissions. The emissions from the 2017 NEI were adjusted to represent 2016 in the cmv_c1c2 sector using factors derived from U.S. Army Corps of Engineers national vessel Entrance and Clearance data[5] by applying a factor of 0.98 to all pollutants. For consistency, the same methods were used for California, Canadian, and other non-U.S. emissions.

4. ANCILLARY DATA

Spatial Allocation

For the 2017NEI, emissions data were computed at 5-minute intervals. They were then adjusted to 2016 levels by multiplying by 0.98, gridded, and converted into a pseudo-point inventory where each point is the center of a grid cell. Emissions in that cell are the sum of the emissions in the area covered by the grid cell. The stack parameters used for cmv_c1c2 are a stack height of 1 ft, stack diameter of 1 ft, stack temperature of 70°F, and a stack velocity of 0.1 ft/s. These parameters force emissions into layer 1. The data were processed on the various grids as shown in Figures 1 through 5 at the end of this document, including grids around Alaska, Hawaii, Puerto Rico, and the Virgin Islands.

Temporal Allocation

The 2017NEI C1C2 CMV data were aggregated up to hourly data from 5-minute interval data to hourly levels, therefore no temporal profiles were applied. A corresponding annual data file was also developed as required by SMOKE for processing hourly point emissions. Because the AIS data were for 2017 and not 2016, analyses were performed to determine whether it would be appropriate to preserve the appropriate days-of-week with respect to 2016. The analyses

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[4] USEPA. EPA and Port Everglades Partnership: Emission Inventories and Reduction Strategies. US Environmental Protection Agency, Office of Transportation and Air Quality, June 2018. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100UKV8.pdf.

[5] U.S. Army Corps of Engineers (USACE). Foreign Waterborne Transportation: Foreign Cargo Inbound and Outbound Vessel Entrances and Clearances. US Army Corps of Engineers, 2018.

revealed that there were not strong weekday-weekend signals in the data, therefore days of week were not preserved in the 2016 inventory. However, emissions for February 28, 2017 were duplicated to represent February 29, 2016.

Chemical Speciation

The cmv_c1c2 sector includes emissions for particulate matter < 2.5 μm ($PM_{2.5}$), oxides of nitrogen (NOx), and VOC, among other criteria pollutants. These three inventory pollutants must be converted to air quality modeling species through an emissions processing step referred to as "chemical speciation". The U.S. EPA SPECIATE[6] database was used to develop factors to map the inventory species to the chemical species required for air quality modeling. All of the emissions in the cmv_c1c2 sector were assigned the $PM_{2.5}$ speciation profile 91106 (HDDV Diesel) and the NONHAPTOG speciation profile 2480 (Industrial Cluster, Ship Channel, Downwind Sample). The components of these profiles are shown in Table 3 and Table 4. Note that because the entire cmv_c1c2 sector is integrated, the NONHAPTOG profile is used instead of the VOC profile. The VOC-to-TOG conversion factor for profiles 2480 is 1.033. In the profile, SOAALK is an extra tracer, so the factors sum to 1.0 if SOAALK is excluded from the sum. The cmv_c1c2 NOx emissions were speciated using a 90:9.2:0.8 split for NO:NO2:HONO. In addition, NH_3 was added to the inventory through a multiplicative factor of 0.019247*$PM_{2.5}$.

Table 3. PM2.5 Speciation Profile 91106

Species	Factor
PCA	0.000583
PCL	0.000205
PEC	0.7712
PFE	0.000262
PK	0.000038
PMOTHR	0.004091
PNCOM	0.0439
PNO3	0.001141
POC	0.1756
PSO4	0.00295
PTI	0.000004

Table 4. NONHAPTOG Speciation Profile 2480

Species	Factor	Molecular weight
ETH	0.0149	28.0532
ETHA	0.0321	30.069
ETHY	0.0218	26.0373

[6] https://www.epa.gov/air-emissions-modeling/speciate-version-45-through-40

Species	Factor	Molecular weight
IOLE	0.0119	56.2694
ISOP	0.00957	68.117
OLE	0.0308	29.0229
PAR	0.5584	15.0347
PRPA	0.0363	44.0956
SOAALK	0.2244	81.5503
TOL	0.1114	96.4914
UNR	0.0571	16.3928
XYLMN	0.1157	110.2229

5. EMISSIONS PROJECTION METHODS

The cmv_c1c2 emissions outside of California were projected from 2016 to 2023 and 2028 using factors derived from the Regulatory Impact Analysis (RIA) Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters per Cylinder1. Table 5 lists the pollutant-specific projection factors to 2023, and 2028 that were used for cmv_c1c2 sources outside of California. California sources were projected to 2023 and 2028 using the factors in Table 6, which are based on data provided by CARB.

Table 5. National projection factors for cmv_c1c2

Pollutant	2016-to-2023	2016-to-2028
CO	-2.67%	-1.11%
NOX	-34.6%	-48.7%
PM10	-36.2%	-49.6%
PM2.5	-36.2%	-49.6%
SO2	-86.2%	-86.5%
VOC	-37.0%	-51.4%

Table 6. California projection factors for cmv_c1c2

Pollutant	2016-to-2023	2016-to-2028
CO	20.1%	25.3%
NOX	-29.3%	-17.7%
PM10	-29.9%	-33.5%
PM2.5	-29.9%	-33.5%
SO2	24.1%	48.7%
VOC	1.5%	1.9%

6. Emissions Processing Requirements

CMV_c1c2 emissions were processed for air quality modeling as hourly point source emissions using the Sparse Matrix Operator Kernel Emissions (SMOKE[7]) modeling system. Because data are hourly, every day was processed. The cmv_c1c2 sector was processed through SMOKE as pseudo point sources. This is a point sector with all sources treated as elevated sources.

7. Emissions Summaries

Table 7 compares annual, national total cmv_c1c2 emissions for the 2016 v1 platform to cmv_c1c2 emissions from previous modeling platforms. Table 8 provides a national comparison by SCC for state and federal waters. Table 9 and Table 10 show comparisons for state total cmv_c1c2 NOx and VOC emissions, respectively. Figures 2 through 5 are gridded emissions plots of annual total NOx on various grids. Additional cmv_c1c2 plots and maps are available online through the LADCO website[8] and the Intermountain West Data Warehouse[9].

For summary purposes all CONUS and near-CONUS federal values come from the 12US1 domain. It is noted that the 12US1 domain slightly cuts off the southern Pacific federal waters on the western boundary, so there may be discrepancies versus the NEI.

All Hawaiian CMV emissions, including FIPS 85006, come from the 3HI1 inventory. There may be discrepancies versus the NEI because the extent of the 3HI1 inventory does not match the totality of the area of the federal waters.

Alaska state water emissions come from the 9AK1 domain inventories except for FIPS 02016, which comes from the 27AK1. All of the AK federal waters, FIPS 85005, comes from the 27AK1 inventory. Both FIPS 02016 and 85005 should be removed from any 9AK1 summaries.

The entirety of the PR/VI emissions comes from the 3PR1 inventory.

The 36US3 domain overlaps with both AK domains and the PR/VI domain. FIPS 02*, 72*, 78*, 85005, and 85007 should be removed from 36US3 summaries when used for comparison purposes.

Descriptions of the emissions platform cases shown in the tables and plots below are as follows:

2014fd = 2014NEIv2 and 2014 NATA

2016fe = 2016 alpha platform (grown from 2014NEIv2)

[7] http://www.smoke-model.org/index.cfm

[8] https://www.ladco.org/technical/modeling-results/2016-inventory-collaborative/

[9] http://views.cira.colostate.edu/iwdw/eibrowser2016

2016ff, 2023ff, and 2028ff = 2016, 2023, and 2028 cases from the 2016 beta platform

2016fh, 2023fh, and 2028fh = 2016, 2023, and 2028 cases from the 2016 v1 platform

Table 7. Comparison of national total annual CAPs cmv_c1c2 emissions (tons/yr)

Pollutant	2014fd	2016fe	2016ff	2016fh	2023ff	2023fh	2028ff	2028fh
CO	116,080	116,080	114,782	30,563	114,431	30,492	116,593	31,036
NH3	334	334	335	105	336	76	337	60
NOX	609,605	609,605	564,394	208,692	399,745	148,996	315,434	118,344
PM10	17,321	17,321	15,445	5,673	11,113	4,063	8,932	3,237
PM2.5	16,670	16,670	14,864	5,499	10,695	3,938	8,592	3,138
SO2	5,788	579	3,159	721	2,208	272	2,392	274
VOC	10,814	10,814	10,080	8,158	7,406	5,706	6,183	4,482

Table 8. Comparison of national total annual CAPS cmv_c1c2 emissions by SCC (tons/yr)

Region	Pollutant	SCC	SCC Description	2016fh	2023fh	2028fh
US State Waters	CO	2280002101	Port Emissions - Main	179	183	187
US State Waters	CO	2280002102	Port Emissions - Aux	3,416	3,447	3,515
US State Waters	CO	2280002201	Underway Emissions - Main	7,713	7,683	7,818
US State Waters	CO	2280002202	Underway Emissions - Aux	13,374	13,375	13,619
US Federal Waters	CO	2280002101	Port Emissions - Main	0	0	0
US Federal Waters	CO	2280002102	Port Emissions - Aux	18	18	18
US Federal Waters	CO	2280002201	Underway Emissions - Main	3,347	3,304	3,357
US Federal Waters	CO	2280002202	Underway Emissions - Aux	2,514	2,482	2,522
US State Waters	NH3	2280002101	Port Emissions - Main	0	0	0
US State Waters	NH3	2280002102	Port Emissions - Aux	0	0	0
US State Waters	NH3	2280002201	Underway Emissions - Main	0	0	0
US State Waters	NH3	2280002202	Underway Emissions - Aux	0	0	0
US Federal Waters	NH3	2280002101	Port Emissions - Main	0	0	0
US Federal Waters	NH3	2280002102	Port Emissions - Aux	0	0	0
US Federal Waters	NH3	2280002201	Underway Emissions - Main	0	0	0
US Federal Waters	NH3	2280002202	Underway Emissions - Aux	0	0	0
US State Waters	NOX	2280002101	Port Emissions - Main	2,137	1,554	1,265
US State Waters	NOX	2280002102	Port Emissions - Aux	21,705	15,667	12,629
US State Waters	NOX	2280002201	Underway Emissions - Main	60,543	43,144	34,181
US State Waters	NOX	2280002202	Underway Emissions - Aux	85,660	61,307	48,858
US Federal Waters	NOX	2280002101	Port Emissions - Main	3	2	2
US Federal Waters	NOX	2280002102	Port Emissions - Aux	114	81	63
US Federal Waters	NOX	2280002201	Underway Emissions - Main	22,645	16,010	12,545
US Federal Waters	NOX	2280002202	Underway Emissions - Aux	15,885	11,231	8,800
US State Waters	PM10	2280002101	Port Emissions - Main	72	52	42
US State Waters	PM10	2280002102	Port Emissions - Aux	571	409	329
US State Waters	PM10	2280002201	Underway Emissions - Main	1,740	1,246	991

Region	Pollutant	SCC	SCC Description	2016fh	2023fh	2028fh
US State Waters	PM10	2280002202	Underway Emissions - Aux	2,272	1,627	1,299
US Federal Waters	PM10	2280002101	Port Emissions - Main	0	0	0
US Federal Waters	PM10	2280002102	Port Emissions - Aux	3	2	2
US Federal Waters	PM10	2280002201	Underway Emissions - Main	602	431	341
US Federal Waters	PM10	2280002202	Underway Emissions - Aux	413	296	234
US State Waters	PM2.5	2280002101	Port Emissions - Main	70	50	41
US State Waters	PM2.5	2280002102	Port Emissions - Aux	554	396	319
US State Waters	PM2.5	2280002201	Underway Emissions - Main	1,688	1,209	961
US State Waters	PM2.5	2280002202	Underway Emissions - Aux	2,201	1,576	1,259
US Federal Waters	PM2.5	2280002101	Port Emissions - Main	0	0	0
US Federal Waters	PM2.5	2280002102	Port Emissions - Aux	3	2	2
US Federal Waters	PM2.5	2280002201	Underway Emissions - Main	584	418	330
US Federal Waters	PM2.5	2280002202	Underway Emissions - Aux	400	287	226
US State Waters	SO2	2280002101	Port Emissions - Main	1	0	0
US State Waters	SO2	2280002102	Port Emissions - Aux	112	47	48
US State Waters	SO2	2280002201	Underway Emissions - Main	31	12	12
US State Waters	SO2	2280002202	Underway Emissions - Aux	504	187	188
US Federal Waters	SO2	2280002101	Port Emissions - Main	0	0	0
US Federal Waters	SO2	2280002102	Port Emissions - Aux	0	0	0
US Federal Waters	SO2	2280002201	Underway Emissions - Main	15	5	5
US Federal Waters	SO2	2280002202	Underway Emissions - Aux	59	20	20
US State Waters	VOC	2280002101	Port Emissions - Main	200	145	117
US State Waters	VOC	2280002102	Port Emissions - Aux	665	477	384
US State Waters	VOC	2280002201	Underway Emissions - Main	3,307	2,303	1,802
US State Waters	VOC	2280002202	Underway Emissions - Aux	2,526	1,781	1,408
US Federal Waters	VOC	2280002101	Port Emissions - Main	0	0	0
US Federal Waters	VOC	2280002102	Port Emissions - Aux	3	2	2
US Federal Waters	VOC	2280002201	Underway Emissions - Main	958	657	506
US Federal Waters	VOC	2280002202	Underway Emissions - Aux	498	341	263

Table 9. Comparison of state total annual NOx cmv_c1c2 emissions (tons/yr)

State	2014fd	2016fe	2016ff	2016fh	2023ff	2023fh	2028ff	2028fh
Alabama	9,228	9,228	8,542	3,470	6,039	2,453	4,731	1,922
Alaska	29,294	29,294	27,116	3,964	19,172	2,803	15,020	2,196
Arkansas	1,727	1,727	1,598	2,267	1,130	1,602	885	1,256
California	20,182	20,182	18,808	10,142	13,999	8,621	13,227	8,347
Connecticut	1,096	1,096	1,015	1,723	717	1,218	562	955
Delaware	860	860	796	1,091	563	771	441	604
D.C.	0	0	0	161	0	114	0	89
Florida	16,786	16,786	15,537	8,390	10,985	5,932	8,606	4,648
Georgia	1,468	1,468	1,359	1,084	961	766	753	600
Hawaii	372	372	344	1,612	244	1,139	191	893

State	2014fd	2016fe	2016ff	2016fh	2023ff	2023fh	2028ff	2028fh
Idaho								
Illinois	16,515	16,515	15,287	5,455	10,808	3,856	8,468	3,022
Indiana	5,655	5,655	5,235	1,513	3,701	1,069	2,900	838
Iowa	2,770	2,770	2,564	418	1,813	295	1,420	232
Kansas	16	16	15	0	10	0	8	0
Kentucky	13,567	13,567	12,558	4,694	8,879	3,318	6,956	2,600
Louisiana	30,672	30,672	28,391	33,349	20,073	23,578	15,726	18,476
Maine	2,204	2,204	2,040	2,528	1,443	1,788	1,130	1,401
Maryland	598	598	554	3,859	391	2,728	307	2,138
Massachusetts	13,046	13,046	12,075	4,101	8,538	2,899	6,689	2,272
Michigan	28,218	28,218	26,119	4,028	18,467	2,848	14,468	2,232
Minnesota	2,868	2,868	2,655	729	1,877	516	1,471	404
Mississippi	7,110	7,110	6,581	3,498	4,653	2,473	3,645	1,938
Missouri	12,912	12,912	11,952	2,577	8,450	1,822	6,620	1,428
Montana	0	0	0		0		0	
Nebraska	1	1	1		1		0	
New Hampshire	37	37	34	208	24	147	19	115
New Jersey	7,644	7,644	7,076	9,035	5,003	6,387	3,919	5,005
New York	8,995	8,995	8,326	4,787	5,887	3,384	4,612	2,652
North Carolina	2,718	2,718	2,516	3,684	1,779	2,604	1,394	2,041
Ohio	8,055	8,055	7,456	2,218	5,272	1,568	4,130	1,229
Oklahoma	347	347	322	346	227	245	178	192
Oregon	1,435	1,435	1,329	2,430	939	1,718	736	1,346
Pennsylvania	846	846	783	1,644	554	1,162	434	911
Rhode Island	3,473	3,473	3,215	1,328	2,273	939	1,781	736
South Carolina	1,604	1,604	1,485	1,464	1,050	1,035	822	811
Tennessee	3,912	3,912	3,621	2,709	2,560	1,915	2,006	1,501
Texas	15,465	15,465	14,315	17,950	10,121	12,691	7,929	9,944
Utah	1	1	1		0		0	
Vermont	15	15	14	2	10	1	8	1
Virginia	2,116	2,116	1,959	5,951	1,385	4,207	1,085	3,297
Washington	7,038	7,038	6,515	10,028	4,606	7,090	3,609	5,556
West Virginia	3,511	3,511	3,250	1,701	2,298	1,203	1,800	943
Wisconsin	5,625	5,625	5,206	1,472	3,681	1,041	2,884	816
Puerto Rico	956	956	885	1,200	626	848	490	665
Virgin Islands	200	200	186	1,236	131	874	103	685
Offshore to EEZ	318,444	318,444	294,761	38,647	208,405	27,324	163,272	21,411

Table 10. Comparison of state total annual SO2 cmv_c1c2 emissions (tons/yr)

State	2014fd	2016fe	2016ff	2016fh	2023ff	2023fh	2028ff	2028fh
Alabama	10	1	4	16	1	5	1	5
Alaska	16	2	7	8	2	3	2	3
Arkansas	1	0	0	9	0	3	0	3
California	1,329	133	1,387	24	1,593	30	1,788	36

State	2014fd	2016fe	2016ff	2016fh	2023ff	2023fh	2028ff	2028fh
Connecticut	1	0	0	2	0	1	0	1
Delaware	84	8	34	3	12	1	11	1
D.C.	0	0	0	0	0	0	0	0
Florida	85	9	34	21	12	7	12	7
Georgia	2	0	1	3	0	1	0	1
Hawaii	5	0	2	2	1	1	1	1
Idaho								
Illinois	1,591	159	632	20	219	7	215	7
Indiana	0	0	0	9	0	3	0	3
Iowa	1	0	0	1	0	0	0	0
Kansas	0	0	0	0	0	0	0	0
Kentucky	6	1	3	19	1	7	1	7
Louisiana	52	5	20	178	7	62	7	61
Maine	6	1	2	4	1	1	1	1
Maryland	1	0	1	4	0	2	0	2
Massachusetts	8	1	3	8	1	3	1	3
Michigan	15	2	6	10	2	4	2	4
Minnesota	1	0	0	4	0	1	0	1
Mississippi	4	0	2	13	1	5	1	5
Missouri	1	0	0	6	0	2	0	2
Montana	0	0	0		0		0	
Nebraska	0	0	0		0		0	
New Hampshire	2	0	1	0	0	0	0	0
New Jersey	68	7	27	21	9	7	9	7
New York	12	1	5	18	2	6	2	6
North Carolina	2	0	1	7	0	2	0	2
Ohio	10	1	4	9	1	3	1	3
Oklahoma	0	0	0	2	0	1	0	1
Oregon	3	0	1	5	0	2	0	2
Pennsylvania	1	0	0	8	0	3	0	3
Rhode Island	2	0	1	3	0	1	0	1
South Carolina	1	0	1	3	0	1	0	1
Tennessee	2	0	1	9	0	3	0	3
Texas	92	9	37	155	13	54	13	53
Utah	0	0	0		0		0	
Vermont	0	0	0	0	0	0	0	0
Virginia	3	0	1	10	0	3	0	3
Washington	51	5	20	17	7	6	7	6
West Virginia	2	0	1	9	0	3	0	3
Wisconsin	2	0	1	3	0	1	0	1
Puerto Rico	38	4	15	2	5	1	5	1
Virgin Islands	24	2	9	3	3	1	3	1
Offshore to EEZ	2,252	225	894	74	310	26	305	25

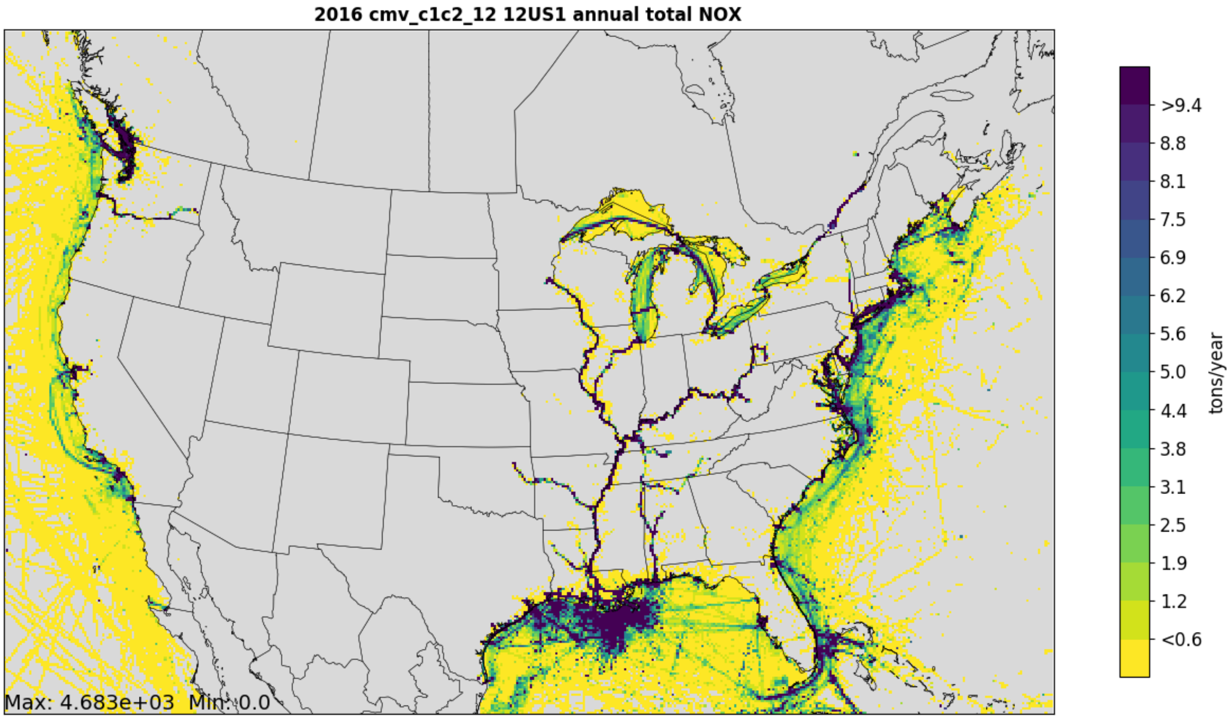

Figure 2. 12-km Gridded Annual CONUS cmv_c1c2 NOx Emissions

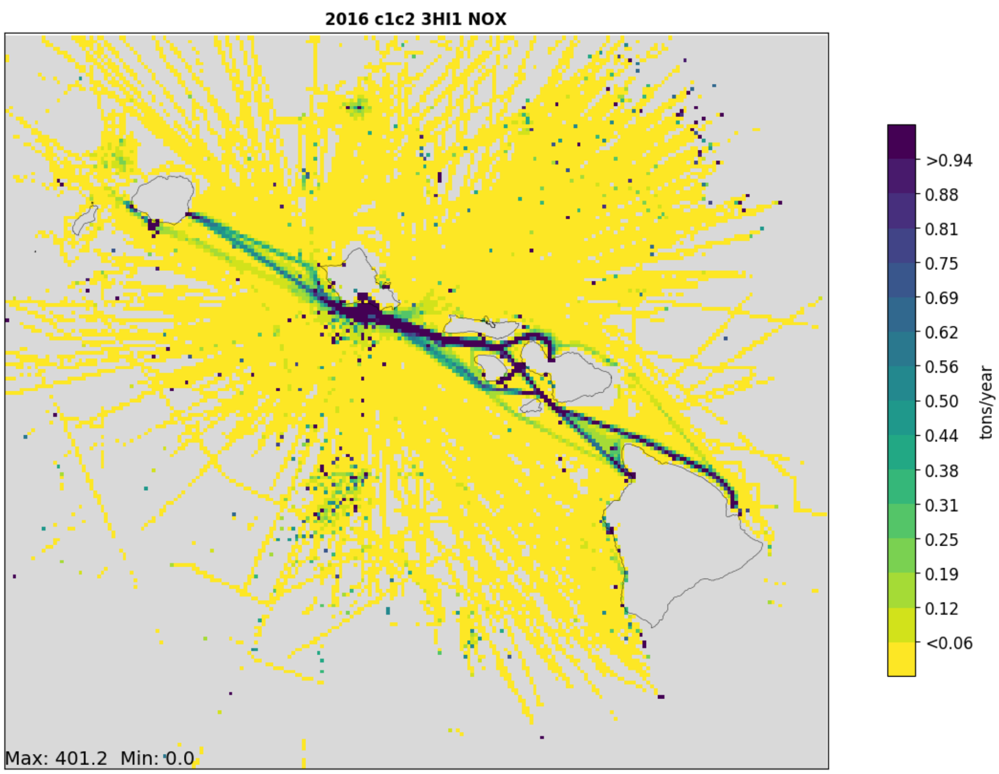

Figure 3. 3-km Gridded Annual Hawaii cmv_c1c2 NOx Emissions

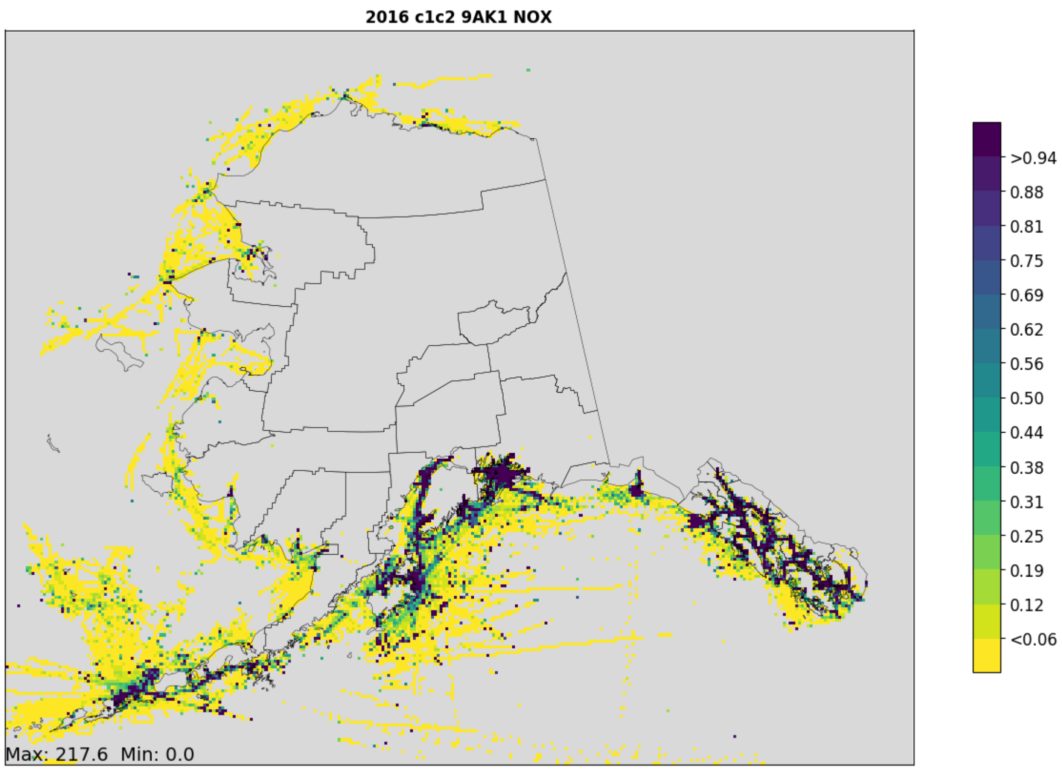

Figure 4. 9-km Gridded Annual Alaska cmv_c1c2 NOx Emissions

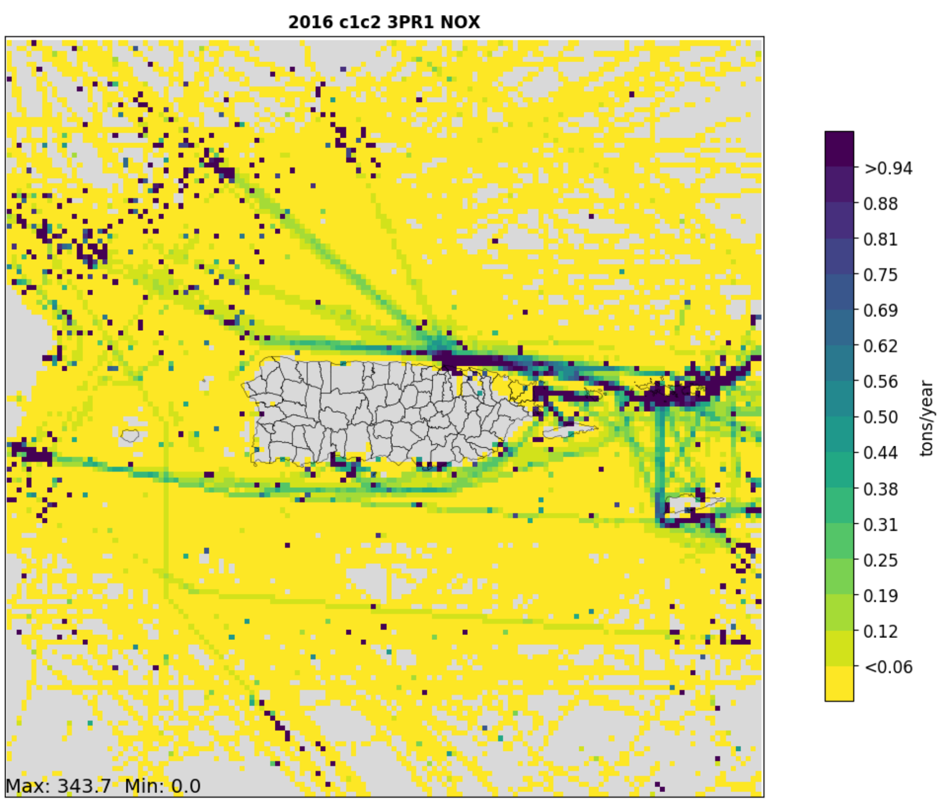

Figure 5. 3-km Gridded Annual Puerto Rico / Virgin Islands cmv_c1c2 NOx Emissions