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LAKE MICHIGAN AIR DIRECTORS CONSORTIUM (LADCO)

Emission Inventory Assistance for Commercial Marine Vessels on the Great Lakes and Major Midwest Rivers

FINAL REPORT

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1 INTRODUCTION

1 INTRODUCTION

1.1 Introduction

Shipping is an important mode of transportation, however, unlike a few decades ago, ships now carry goods rather than people. The movement of vessel traffic has generally increased on the Great Lakes and generally decreased on the major Midwest rivers. Ships are an important source of air pollutants such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter (PM). Ships are also a source of emission of pollutants such as black carbon (BC), organic acids such as formic acid and elements such as iron (Fe), nickel (Ni), vanadium (V) and zinc (Zn).

The primary source of emissions from Marine Vessels are the diesel engines. Diesel engines in marine vessels such as container ships, tankers, bulk carriers, and cruise ships utilize two types of engines — (1) main propulsion engines and (2) auxiliary engines. Auxiliary engines are operated during hotelling, while main engines are operated during cruising and maneuvering modes.

The primary goal of this project was to estimate the emissions of Marine Vessels on the Great Lakes and major Midwest rivers for base year 2014 and project emissions for years 2020 and 2030. Data for the major Midwest rivers primarily included the gross tonnages on the National Waterway Networks (NWN) provided by US Army Corps of Engineers (USACE). The emissions due to vessel movements on the Great Lakes were estimated using vessel positional data and vessel characteristics obtained from `www.MarineTraffic.Com` (MarineTraffic).

Emissions from Marine Vessel traffic can be estimated using a combination of the vessel's gross tonnage, engine rating, fuel consumption and pollutant specific emission factors.

Marine vessels primarily operate in three modes: cruising/underway, hotelling and maneuvering. During maneuvering, ships move into or out of the port zone, and hotelling covers the operational activities of the vessel during the period it is docked at a port. Cruising operations occur outside of the port zone and are typically associated with an engine load of 80%.

In this work, emissions from Marine Vessels in the Great Lakes region and Major Midwest rivers are estimated for the following modes and categories:

- Underway/Cruising Emissions
- Hotelling (operations while stationary) at Ports/Docks
- Emissions during Maneuvering at Ports
- Itemized Emissions by Ship/Vessel Category

This report is organized into four sections, Section 1 covers the Introduction (this section),

Section 2 covers the details of the calculation methods, Section 3 summarizes the results and provides brief discussions on the results derived in this work and finally Section 4 provides the conclusions and recommendations for future work.

2 CALCULATION METHODS

2 CALCULATION METHODS

Emissions in this project were estimated using data from two distinct sources. Therefore, the calculation methodologies have been discussed separately for the major Midwest Rivers (Rivers Data) and for the Great Lakes region (Great Lakes Data).

2.1 Emissions Calculations for Vessels in the Major Midwest Rivers

The U.S. Waterway Data is a collection of data related to the navigable waters in the United States including the inland waterways, off-shore waters, the Great Lakes, and the Saint Lawrence Seaway[1]. As of September 24, 2015, the most current year link level data available from USACE was for the year 2013[2]. Therefore, for the Rivers Data, the 2013 data was assumed to be the same for the year 2014 (base year for this work). The Rivers Data, published by USACE, was compiled from several agencies, including the U.S. Army Corps of Engineers Navigation Data Center, the U.S. Bureau of the Census, the U.S. Coast Guard, Oak Ridge National Laboratory and Vanderbilt University by USACE.

2.1.1 National Waterway Network Link Commodity Data

The National Waterway Network (NWN) link commodity data consists of link databases with the total gross tonnage of all vessels in each link. Links are linear paths created from a beginning and an end point that approximate vessel's track in each section of the waterway. The key task was to assign each of these links to the National Emission Inventory (NEI) Shape files and the Counties that are adjacent to the links in the waterway networks. This was accomplished by intersecting the USACE NWN shape files with counties and the NEI shipping lanes shape files using ArcGIS version 10.3.1. In equation 1 below, 'i' refers to the county or NEI Shape ID and 'pol' refers to the pollutant for which the emissions are being calculated. In this work, for the Rivers Data emissions calcualtions, 'FuelEff' is the fuel efficiency value for vessels in the major Midwest rivers and inland waterways. This parameter was set at 514 ton-miles per gallon. In the above equation, 'D' refers to the link distance, 'M' is the gross tonnage of the vessel (in tons), 'EF' is the pollutant emission factor. The calculated emissions, $M_{pol,i}$, is the emissions of pollutant in ShapeID 'i' in Metric Tons (MT).

$$
\begin{aligned}
M_{pol,i}\,(\mathrm{MT}) = \frac{D_i}{\sum\limits_{i=1}^{n} D_i} \cdot \sum_{i=1}^{n} D_i\,(\mathrm{miles}) \cdot M_i\,(\mathrm{tons}) \cdot \frac{1}{FuelEff}\left(\frac{\mathrm{gallon}}{\mathrm{ton\text{-}miles}}\right) \\
\cdot EF_{pol}\left(\frac{\mathrm{g}}{\mathrm{gallon}}\right) \cdot 10^{-6}\left(\frac{\mathrm{MT}}{\mathrm{g}}\right)
\end{aligned} \tag{1}
$$

[1]`http://www.navigationdatacenter.us/data/data1.htm`
[2]`http://www.navigationdatacenter.us/gis/gis1.htm`

2.1.2 Emission Distribution Between Counties

In order to distribute emissions to the counties bordering the network, a buffer distance of 1000 meters (m) was created using the Proximity Analysis Tool in ArcGIS. The NWN movement links were intersected with the resulting buffered county shape. The concept of buffer distance is being illustrated by Figure 2.1. In this figure, the distance between the NWN segment (highlighted) and the Livingston-Pope County boundary is greater than 1000 meters. Therefore, emissions from that segment are allocated completely to Livingston county. Conversely, the segment in McCracken county (highlighted) is less than 1000 meters to the nearest McCracken-Massac county boundary. Therefore, emissions in that segment are equally distributed between Massac county and McCracken county. The calculation of emissions distribution is based on the distance of a network link and the number of counties surrounding the link and weighted according to the first term in Equation 1.

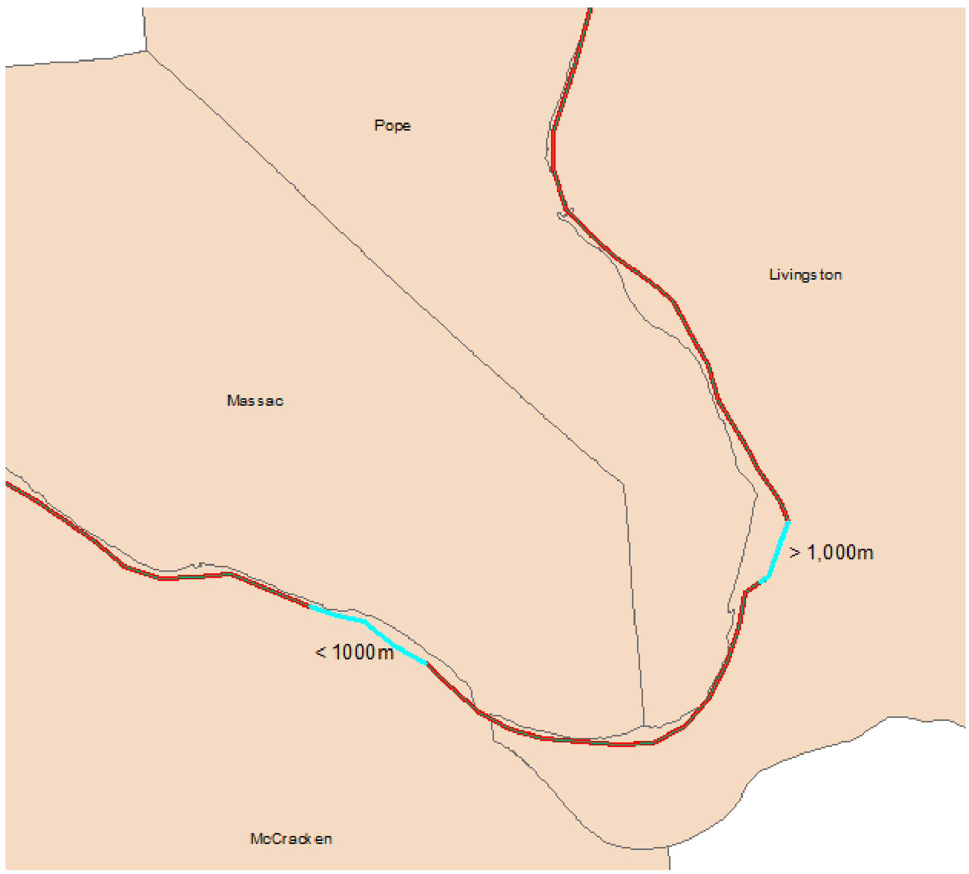

Figure 2.1: Distribution of Marine Vessel Emissions Between Counties in the Major Midwest Rivers.

2.1.3 Emission Distribution in NEI Shipping Lane Shape Files

NEI Shipping Lanes shape files (obtained from EPA[3]) was first intersected with the NWN links and with the County Boundaries. This, as a result, provided shape files that linked

[3]`http://www.epa.gov/ttn/chief/eis/2011nei/shippinglanes_072914.zip`

the ShapeIDs in the NEI shape file and the County Federal Information Processing Standard (FIPS) ID codes. The emissions, thus calculated and allocated to the counties, were referenced with the ShapeIDs in the NEI shipping lane shape files.

2.2 Emissions Calculations for Vessels in the Great Lakes Region

Vessel position data for the Great Lakes Region was obtained from MarineTraffic. MarineTraffic project is a community based effort dedicated in collecting and presenting data used in marine vessel traffic research, among other applications in the marine traffic related work. Data from MarineTraffic is primarily collected using an Automatic Identification System (AIS) transponder that provides the Global Positioning System (GPS) coordinates of the vessel including a latitude and a longitude. As of December 2004, the International Maritime Organization (IMO) requires all vessels over 299 GT (Gross Tonnage) to carry an AIS transponder on board, which transmits their position, speed and course, among other static information, such as vessel name, dimensions and voyage details. Therefore, this data from MarineTraffic has wide coverage of marine vessel traffic in the Great Lakes region to provide a very comprehensive air emissions inventory. In addition to the vessel position, data on vessel characteristics was also obtained from MarineTraffic.

2.2.1 Cruising Emissions from Vessels in the Great Lakes Region

Vessel position data from MarineTraffic was first imported into ArcGIS as Points shape file. Data points that fell on land were first removed by intersecting the water bodies shape files obtained from the National Hydrography Dataset (NHD)[4] in Minnesota, Iowa, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania and New York. Additionally, data points on land in Canada were removed by analyzing shape fieles from Statistics Canada - 2011 Census Boundary Files [5].

The data points were then converted to vessel tracks using Tracking Analyst Toolbox[6] in ArcGIS. Vessel tracks are created by joining two points to form a straight line. During this process, the vessel track speed and track distance is computed using the Date/Time Stamp of the two GPS coordinates in ArcGIS. These tracks included three vessel operation modes, (1) ships traveling at relatively constant speed - termed as Cruising Mode, (2) ships maneuvering at ports - termed as Maneuvering Mode, and (3) ships docked at the ports - termed as Hotelling Mode.

2.2.2 Validation of Vessel GPS Coordinates and Vessel Tracks

The vessel tracks, thus generated, linked bad GPS coordinates and missing data points that were present in the "validated" GPS coordinates that were exclusively present on a water surface. "bad" or "missing" GPS coordinates exist because of the following reasons:

[4] `ftp://nhdftp.usgs.gov/DataSets/Staged/States/FileGDB/HighResolution/`

[5] `https://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/bound-limit-2011-eng.cfm`

[6] `http://help.arcgis.com/en/arcgisdesktop/10.0/pdf/tracking-analyst-tutorial.pdf`

- Bad GPS Coordinates - coordinates that placed points farther away spatially but were closer or sequential temporally
- Missing GPS Coordinates - coordinates that are not relayed at their normal frequency (generally one GPS coordinate every 2 or 3 minutes)
- Vessels travelling on narrow waterways relay GPS coordinates typically every 3 minutes, sometimes longer, but not fast enough to create vessel tracks such that they fall completely on narrow waterway surface.

Due to the foregoing reasons, vessel tracks thus created, generated a number of tracks that partially traversed land surfaces. Therefore, in order to remove these "bad" vessel tracks, a simple query was run in ArcGIS to identify vessel tracks that were above 200 miles in distance and above 50 knots in speed. This query helped remove bad GPS coordinates that placed coordinates farther away spatially while being closer temporally. In addition to this, this query also removed GPS coordinates from Helicopters and Non-Marine vessels, traveling at high speeds, that carried an AIS transponder. Based on this query and identification, these vessel tracks were removed from further processing. A summary table of the vessel GPS data points and tracks processed is provided in the table below. This data validation and processing still produced vessel tracks on land surface.

Data Description	**Data Magnitude**
Total Number of GPS Points	12,317,103
Total Number of Wet Points	10,485,280
Total Number of Dry Points	1,831,823
Perecentage of Wet Points	85.1%
Query on Track Speed and Distance	Knots $<$ 50 AND Miles $<$ 200
Number of Tracks after Above Query	10,480,752
Total Number of Tracks Before Query	10,483,843
Number of Tracks Removed	3,091

Table 2.1: Summary Statistics of Vessel Data GPS Coordinates and Vessel Tracks Processing.

The remaining vessel tracks (about 10,480,752 vessel tracks), thus obtained and processed, were were intersected with the Natioinal Emissions Inventory (NEI) Shipping Lane shapefiles[7] (modified to include the Canadian portion of the Great Lakes) and NEI Port Shapefiles[8] in ArcGIS. Intersection of vessel tracks with Shipping Lanes and Port shapefiles (that are water surfaces) removed vessel tracks that traversed land surfaces. These losses (because of tracks on land surface) were small but were quantified. However, they were not corrected because such an operation may place a positive bias on the calculated emissions when the travel routes for each vessel are not known.

[7] `http://www.epa.gov/ttn/chief/eis/2011nei/shippinglanes_072914.zip`
[8] `http://www.epa.gov/ttn/chief/eis/2011nei/ports_20140729.zip`

Twenty-one Marine Vessels in the Great Lakes region did not complete the "Intersection" operation with the NEI shapefiles in ArcGIS discussed above. This was primarily due to multiple overlapping lines in a small geographic area mostly seen in recreational/tour vessels. Therefore, these vessels were subjected to a "Spatial Join" in ArcGIS. The only difference in the "Spatial Join" process as opposed a the "Intersection" process is that the vessel tracks are not split if they traverse multiple polygons in a "Spatial Join" function. Therefore, if a vessel track traversed more than one polygon, emissions for that track were equally distributed between the intersected polygons. Based on the results of the Spatial Join analysis, less than 5% of the vessel tracks (for these 21 Marine Vessels) traversed more than one polygon (i.e., ShapeID).

2.2.3 Loss of Vessel Tracks Traversing Land Surfaces

The intersection of vessel tracks with NEI Shipping Lane shapefiles and Port shapefiles (both a polygon feature) splits the tracks (a polyline feature) into a number of pieces of tracks (or lines) depending on the number of ShapeIDs (polygons) a single vessel track travels through. In the same manner, if the vessel track traverses a land surface they are removed from further processing because NEI Shipping lane shapefiles only include water surfaces and land surfaces are treated by ArcGIS as being outside the processing domain. This loss was computed using geometry calculations in ArcGIS. The total distance of all tracks prior to intersection with Shipping Lanes was 5,356,482 miles. The total distance retrieved after the intersection with NEI Shipping Lanes was 5,017,650 miles. This difference in the distances that were accounted for and those that were lost was approximately 6.3%. However, this loss ratio does not include distances that were included in the intersection with the port shape files. The distance of vessel tracks that were inside the Ports was computed to be 13,125 miles. Including the distances of vessel tracks inside the Port shapefiles, the net loss ratio was computed to be approximately 6.1%.

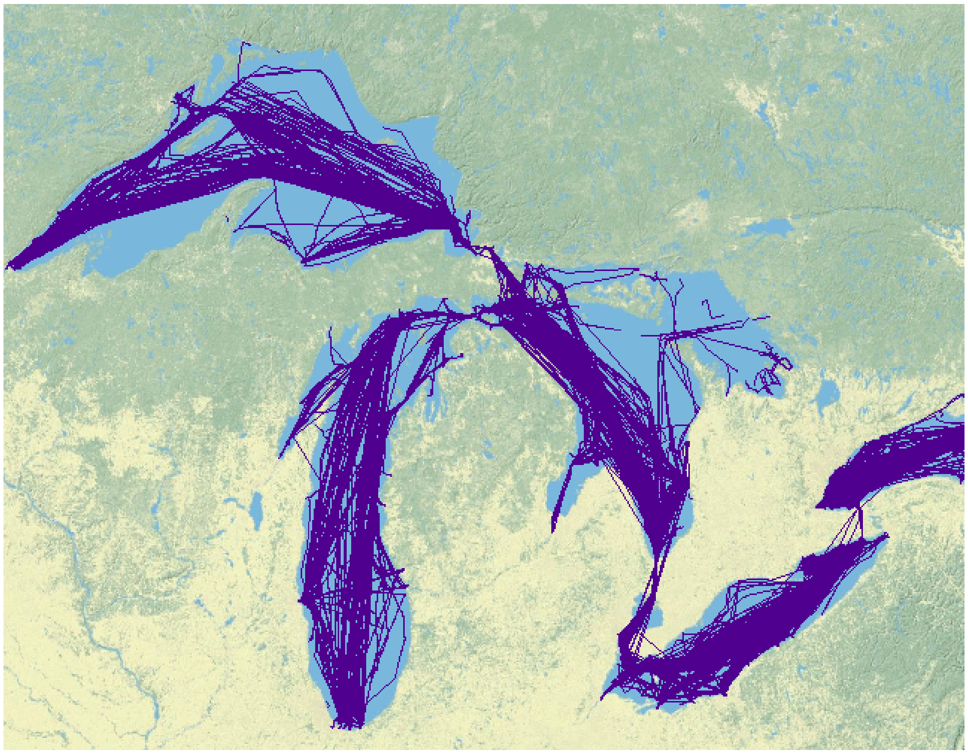

Figure 2.2: Vessel Tracks in the Great Lakes.

2.2.4 Maneuvering and Hotelling Emissions from Vessels in the Great Lakes Region

In the maneuvering mode, ships spend time approaching, docking and departing the harbor, while hotelling takes place when ships are berthed along piers. The vessel tracks created as discussed in the previous section (Section 2.2.1) was intersected with the ports shape files (obtained from USEPA). This intersection operation provided a set of tracks that were present inside the ports. These tracks include a multitude of tracks that had slower speeds to speeds that were closer to zero. Therefore, speeds greater than 0.1 knots were considered as maneuvering in the tracks inside the port boundaries, while speeds lesser than 0.1 knots were considered as hotelling.

2.2.5 Emissions Calculation for Great Lakes Data

Emissions for vessels in the Great Lakes region was computed using Equation 2 & 4. In Equation 2, $\text{Track}_{Time,i,j,k}$ refers to a vessel track in vessel type grouping 'k', in a county or a NEI ShapeID reference 'i', moving in a vessel operation mode 'j' for a total duration (Time) given in units of days. Equation 3 was used when emissions factors are available in units of grams/kilowatt-hour (g/kw-hr).

Fuel consumption rate is calculated in units of MT-Fuel/day for each vessel type - 'k'. Emission along each track is then summed up by each time-step 'Time', on a vessel-by-vessel basis within each vessel group 'k' that are present inside a geographical County/NEI ShapeID 'i' and operating in mode 'j', to provide emissions on an hourly, monthly or quarterly basis.

$$\begin{aligned} M^{T}_{pol,i,j,k}\,(\mathrm{MT}) = Track_{Time,i,j,k}\,(\mathrm{days}) \cdot FuelUse_k \left(\frac{\text{MT-Fuel}}{\text{day}}\right) \cdot ModeFrac_j \\ \cdot EF_{pol,j,k}\left(\frac{\text{MT}}{\text{MT-fuel}}\right) \end{aligned} \tag{2}$$

$$\begin{aligned} M^{T}_{pol,i,j,k}\,(\mathrm{MT}) = Track_{Time,i,j,k}\,(\mathrm{days}) \cdot FuelUse_k \left(\frac{\text{MT-Fuel}}{\text{day}}\right) \cdot ModeFrac_j \\ \cdot EF_{pol,j,k}\left(\frac{\text{MT}}{\text{kw-hr}}\right) \cdot E_{fuel}\left(\frac{\text{kW-hr}}{\text{MT-Fuel}}\right) \end{aligned} \tag{3}$$

$$M^{Annual}_{pol,i,j,k}\,(\mathrm{MT}) = \sum_{T=1}^{n} M^{T}_{pol,i,j,k} \tag{4}$$

2.3 Emission Factors and Fuel Consumption

2.3.1 Emission Factors for Rivers Data

Table 2.4 provides the emission factors used in the present work for Rivers Data and is compared with the emission factors used in the previous, 2010 base year emission inventory work. These emission factors were used to calculate emissions for Rivers Data. Table 2.4 also provides the sources of emission factors used in this work. A comprehensive search for emission factors was conducted in this work and the data from this search was compiled in an Excel file. Based on this data search, emission factors used in this work primarily came from work in the United States. Although, emission for PM and HC came from [5] because data in this work was more recent data than other available sources. CO_2 emissions although obtained from [1], this value is similar to several other sources available from work in the United States.

2.3.2 Emission Factors for Great Lakes Data

Emission factors used in this work for the Great Lakes Data is provided in Appendix A. The emission factors for each pollutant varies by engine load, vessel type, and operational mode. The operational modes include cruising (80% engine load), maneuvering (40% engine load), and hotelling (20% engine load). The emission factors which varied by engine load were not available at the specific operational mode values. The emission factor for the engine load closest to the value of the operational mode was used without interpolation. The fuel consumption fractions for each operational mode were analogous to percent engine load.

2.3.3 Fuel Consumption Fractions

Fuel consumption during each of the three modes, cruising maneuvering and hotelling are different. In this work data on fuel consumption fraction during these three modes was obtained from Rashidi and Koto, (2014)[1]. This fuel consumption fractions by vessel operation mode was specifically applied to Great Lakes data obtained from MarineTraffic.

Mode	Fraction
Cruising	0.8
Maneuvering	0.4
Hotelling - Default	0.2
Hotelling - Passenger	0.32
Hotelling - Liquid Bulk	0.2
Hotelling - Other	0.12
Tug - Moderate Activity	0.5

Table 2.2: Fuel Consumption Fraction in Different Modes of Operation.

Pollutant	Emission Factor (grams/gallon of fuel)	
	Current Work	Previous Work
BC	1.25[3]	0.32
CO	35.44[2]	35.3
CO2	10,078[1]	10,505
Fe	0.06[4]	-
HC	8.08[5]	4.14
HCOOH	0.07[6]	-
Ni	0.19[4]	-
NOx	213.07[2]	-
PM	7.17[5]	4.6
SO2	19.84[2]	16.70
V	0.85[4]	-
Zn	0.002[4]	-

[1] - Data obtained from Rashidi and Koto, (2014)
[2] - Data obtained from Williams et al., (2009)
[3] - Data obtained from Buffaloe et al., (2014)
[4] - Data obtained from Agrawal et al., (2008)
[5] - Data obtained from Kristensen, (2012)
[6] - Data obtained from Crisp et al., (2014)

Table 2.4: Comparison of Emission Factors Used in the Present Work and Previous Work.[9]

2.3.4 Fuel Consumption Rates

Maximum fuel consumption rates for each vessel type was calculated using the equations below in Table 2.3 and was obtained from Rashidi and Koto, (2014)[1]. These fuel consumption equations were specifically applied to the MarineTraffic data available for the Great Lakes region. For vessels with missing Gross Tonnages (GT), a class specific average gross tonnage was used.

[9] `http://www.ladco.org/reports/technical_support_document/references/commercial_marine_emissions_LADCO_final_report.pdf`

Fuel consumption computed using the gross tonnages in the NWN data from USACE (referenced in Section 2.1.1) for the Great Lakes was estimated to be 234,643,345 gallons. Fuel consumption computed using the MarineTraffic data for vessels in the Great Lakes was estimated to be 204,112,052 gallons. Based on this, we expect the fuel consumption rates using data in Table 2.3 to provide similar consumption rates from data in other sources such as USACE.

Ship Type	**Consumption (MT/day**
Solid Bulk	20.1860+0.00049 x GT
Liquid Bulk (Tanker)	14.6850+0.00079 x GT
General Cargo	9.8197+0.00143 x GT
Container	8.0552 + 0.00235 x GT
Ro-Ro Cargo	12.8340 + 0.00156 x GT
Passenger	16.9040 + 0.00198 x GT
High Speed Ferry	39.4830 + 0.00972 x GT
Inland Cargo	9.8197 + 0.00143 x GT
Sail Ship	0.4268 + 0.00100 x GT
Tugs	5.6511 + 0.01048 x GT
Fishing	1.9387+0.00448 x GT
Other Ships	9.7126+0.00091 x GT

Table 2.3: Average Fuel Consumption at Full Power as Function of Gross Tonnage.

3 RESULTS AND DISCUSSIONS

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3.1 Emissions in the Major Midwest Rivers

A summary of the 2014 emissions for the major Midwest rivers by each river system is provided in 3.1. From Figure 3.1, we note that the activity in the Mississippi is much higher than in the rivers located in the upper Mid-West. Among the rivers in the upper Midwest, Ohio river has the highest emissions, followed by Illinois river and then by the Chicago river.

Pollutant	**Ohio River**	**Mississippi River**	**Illinois River**	**Chicago River**
BC	175	544	22	1
CO	4,944	15,358	616	30
CO_2	1,405,735	4,366,595	175,133	8,484
Fe	8	24	1	0
HC	1,126	3,499	140	7
HCOOH	10	31	1	0
Ni	26	81	3	0
NO_x	29,722	92,323	3,703	179
PM	1,000	3,107	125	6
SO_2	2,768	8,597	345	17
V	118	368	15	1
Zn	0	1	0	0

Table 3.1: Summary of 2014 Emissions in the Major Midwest Rivers. Emissions reported in Metric Tons (MT).

Since the Rivers Data was simply based on the link level tonnages data provided by USACE, additional data analysis are not presented for this data.

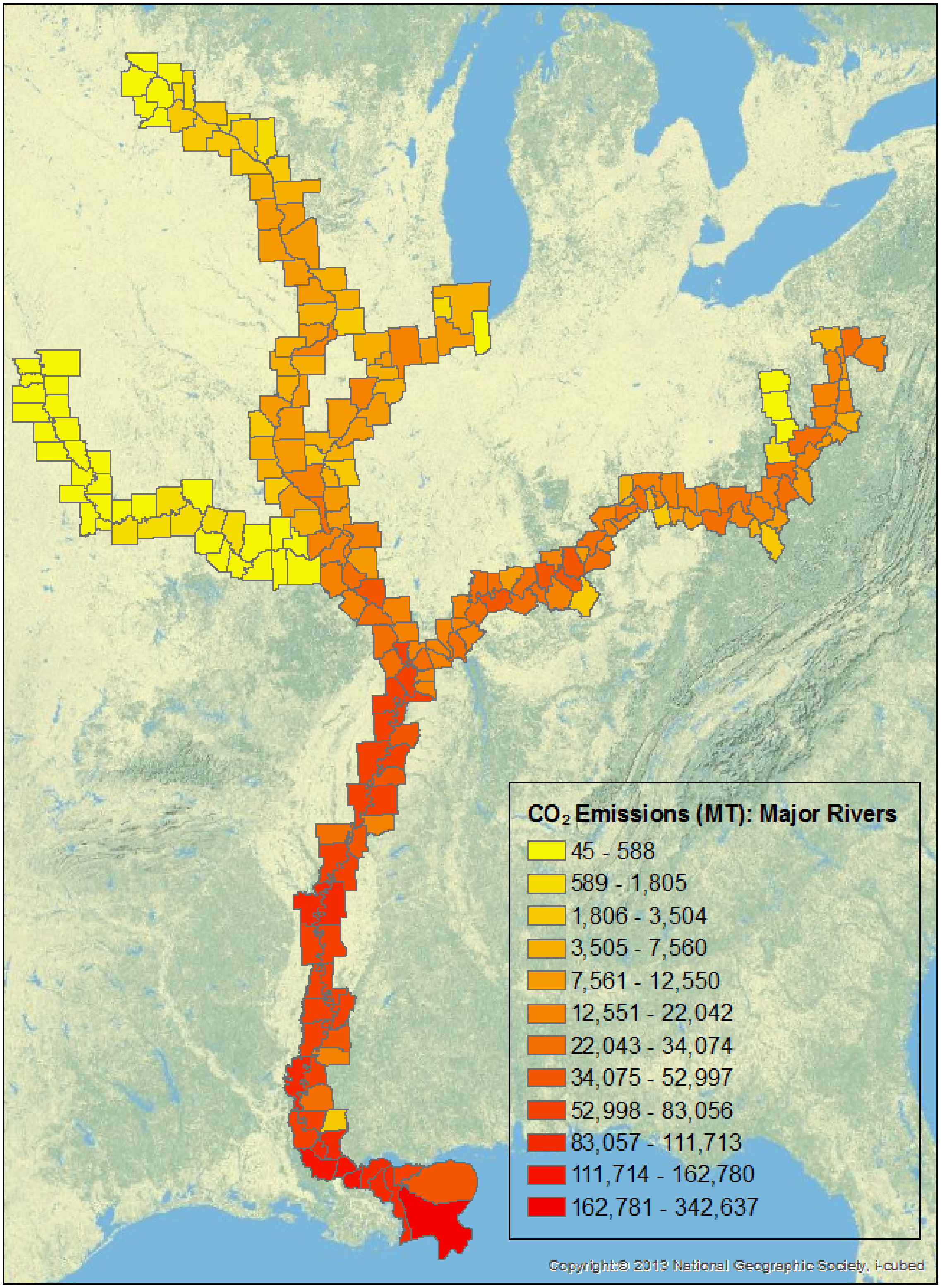

Figure 3.1: Estimated CO_2 Emissions from Marine Vessels in Major Rivers of the United States for the Base Year 2014 (Referenced to Counties).

3.2 Emissions in the Great Lakes

In this work, emissions from Marine Vessels were computed for Great Lakes in both the United States (US) and Canada. Figure 3.2 shows the CO_2 emissions per square mile in the Great Lakes for all types of vessels. From this plot, we note that the emissions per square mile of Marine Vessels in the Canadian side is higher than the vessels on American side of the Great Lakes. However, the net emissions are higher on the US side of the Great Lakes in comparison to the emissions computed in the Canadian side of the Great Lakes.

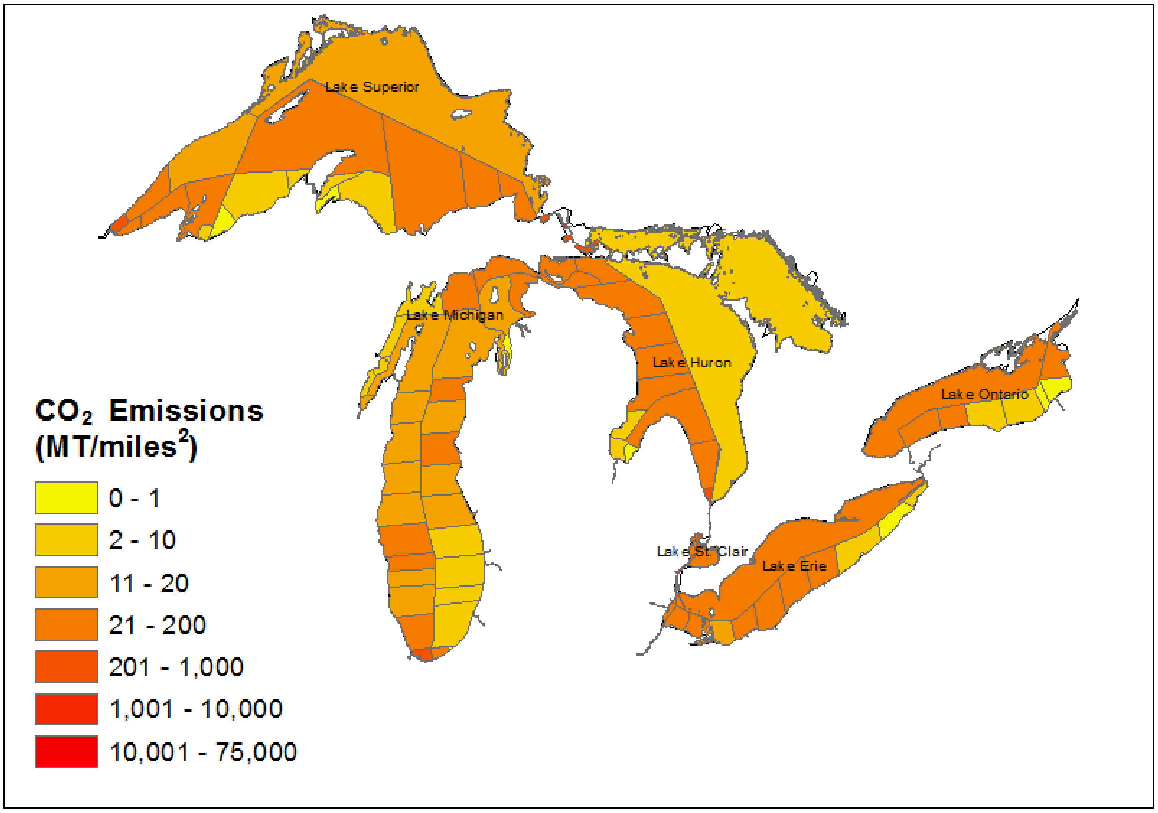

Figure 3.2: Estimated CO_2 Emissions per Square Mile from Marine Vessels in the Great Lakes for the Base Year 2014 (Referenced to NEI Shipping Lanes ShapeID).

3.3 Marine Vessel Emissions in the Great Lakes by Vessel Type

Tables 3.2 and 3.3 show the emissions by vessel type on the US and Canadian Great Lakes, respectively. The pollutants shown in this table include carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_x), particulate matter (PM) and sulfur dioxide (SO_2). From these two tables, we note that vessel categorized as “Cargo” had the highest emissions in comparison to other types of vessel. $3/4^{th}$ of the total Marine Vessel emissions on the Great Lakes were estimated to be from the US side of the Great Lakes (2,063,413 MT of CO_2), while the emissions on the Canadian side accounted for $1/4^{th}$ of the total emissions on the Great Lakes (683,931 MT of CO_2). Table 3.4 shows the emissions by registered Country of Origin. Note that these emissions are only emissions on the U.S. side of the Great Lakes. As expected the largest category is for US vessels, followed by Canadian vessels. Figure 3.3 shows the emissions from both the Major Rivers and the Great Lakes with emissions referenced to the counties. This plot is referenced to the counties because the polygons in shipping lanes (particularly along the Major Rivers) are very narrow and are difficult to visualize.

Vessel Type	CO_2	CO	HC	NO_X	PM	SO_2
Cargo	1,859,542	5,530	617	33,260	549	16,880
Fishing	1,073	4	1	25	0	2
High Speed Craft	7	0	0	0	0	0
Other	3,558	13	3	76	3	8
Passenger	53,388	211	43	953	38	111
Pleasure Craft	13,086	52	11	232	9	28
Sailing Vessel	447	2	0	11	0	1
Special Craft	4,447	16	3	95	3	10
Tanker	21,828	48	17	567	15	139
Tug	72,717	268	80	1,424	71	134
Unspecified	33,321	113	24	763	22	291
Total	**2,063,413**	**6,256**	**800**	**37,404**	**712**	**17,605**

Table 3.2: Emissions by Marine Vessel Type During Cruising in the Great Lakes. Emissions shown in Metric Tons (MT).

Vessel Type	CO_2	CO	HC	NO_X	PM	SO_2
Cargo	529,182	1,585	334	9,306	297	4,593
Fishing	261	1	0	6	0	1
High Speed Craft	9	0	0	0	0	0
Other	284	1	0	6	0	1
Passenger	18,956	75	6	332	5	39
Pleasure Craft	20,454	82	18	369	16	43
Sailing Vessel	495	2	1	14	1	1
Search and Rescue	0	0	0	0	0	0
Special Craft	17,197	59	17	352	15	37
Tanker	56,788	124	38	1,409	34	359
Tug	15,768	57	31	304	28	29
Unspecified	24,534	83	21	537	19	213
Hovercraft	5	0	0	0	0	0
Total	**683,931**	**2,070**	**467**	**12,636**	**415**	**5,316**

Table 3.3: Emissions by Marine Vessel Type During Cruising in the Canadian Great Lakes. Emissions shown in Metric Tons (MT).

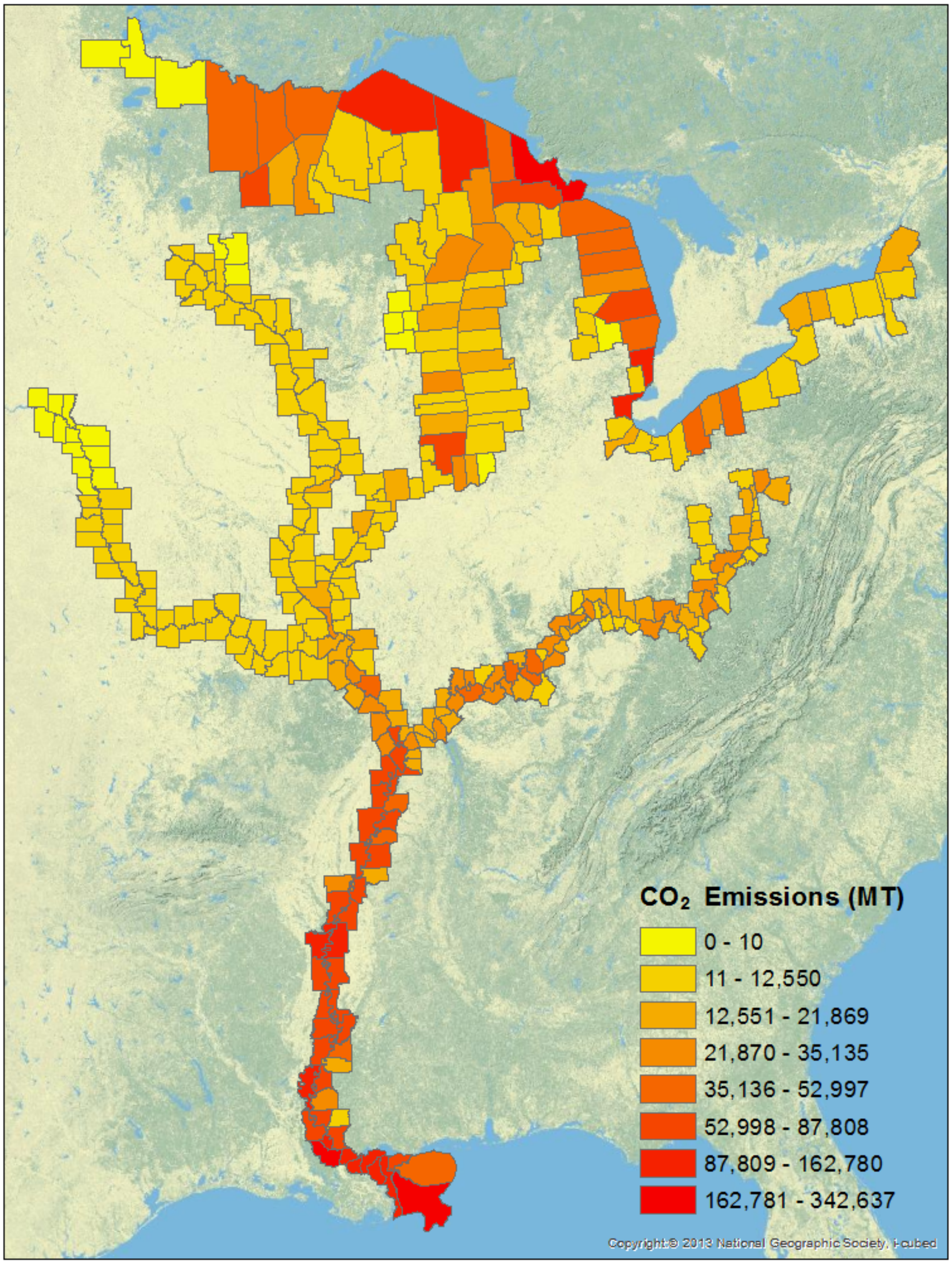

Figure 3.3: Estimated CO_2 Emissions from Marine Vessels in the Great Lakes and Major Rivers (Referenced to Counties).

Flag State	CO_2	CO	HC	NO_X	PM	SO_2
Not Specified	18,444	63	17	424	15	160
Antigua Barbuda	22,819	68	20	392	18	182
Bahamas	23,336	71	19	411	17	187
Barbados	11,423	34	8	207	7	98
Canada	592,017	1,770	432	10,895	385	5,239
Cayman Is	1,926	8	0	35	0	4
Cyprus	37,052	110	20	650	17	317
Denmark	263	1	0	7	0	2
Germany	37	0	0	1	0	0
Gibraltar	1,526	4	1	29	1	13
Greece	4,886	15	3	82	3	35
Italy	43	0	0	1	0	0
Lithuania	1,658	5	1	28	1	14
Malta	14,856	44	13	257	12	119
Netherlands	30,398	92	23	511	21	283
Norway	45	0	0	1	0	0
Portugal	1,121	2	0	28	0	7
Spain	2	0	0	0	0	0
Switzerland	2,595	6	2	65	2	17
Turkey	117	0	0	3	0	1
United Kingdom	1,155	3	0	25	0	8
USA	1,297,693	3,958	240	23,354	213	10,918
Total	**2,063,413**	**6,256**	**800**	**37,404**	**712**	**17,605**

Table 3.4: Marine Vessel Emissions by Country of Origin During Cruising in the U.S. Great Lakes. Emissions shown in Metric Tons (MT).

3.4 Marine Vessel Emissions During Hotelling and Maneuvering in Ports

Table 3.5 shows the emissions estimated during hotelling at the ports in the Great Lakes. Table 3.6 shows the emissions estimated during maneuvering at the ports in the Great Lakes. Both these tables are arranged alphabetically by the Port Name. From this table, we note that emissions were highest in Duluth-Superior during both maneuvering and hotelling. Table 3.7 shows the emissions estimated by vessel type for hotelling at the ports and Table 3.8 shows the emissions estimated by vessel type for maneuvering at the ports. From these two tables (Table 3.7 & Table 3.8), Cargo vessels and Tug Boats contributed the highest emissions during maneuvering and hotelling at ports.

Port Name	CO_2	CO	HC	NO_X	PM	SO_2
Alpena	0.17	0	0	0	0	0
Ashland	114.2	0.46	0.1	2.06	0.09	0.24
Ashtabula	1,460.5	2.39	2.9	19.94	2.57	12.33
Buffalo	146.7	0.24	0.06	2.03	0.05	1.22
Burns Harbor	651.3	1.2	0.84	10.16	0.74	4.82
Calcite	35.43	0.06	0.01	0.47	0.01	0.3
Cheboygan	204.23	0.64	0.24	3.44	0.21	1.23
Chicago	4,044.01	9.4	3.68	79.34	3.27	21.09
Cleveland	1,294.85	2.07	0.5	17.71	0.45	10.87
Conneaut	18.31	0.03	0.01	0.25	0.01	0.15
Copper Harbor	0.09	0	0	0	0	0
Detroit	1,775.16	3.3	0.8	28.13	0.71	12.85
Drummond Island, MI	13.05	0.02	0.01	0.17	0.01	0.11
Duluth-Superior	8,839.83	14.76	8.01	125.77	7.11	71.55
Erie	0.63	0	0	0.01	0	0.01
Escanaba	5.15	0.01	0	0.12	0	0.02
Fairport Harbor	0.4	0	0	0.01	0	0
Gary	251.14	0.39	0.44	3.36	0.39	2.15
Grand Haven, MI	5.51	0.01	0.01	0.07	0.01	0.05
Grand Marais	0.12	0	0	0	0	0
Huron, OH	3.38	0.01	0	0.08	0	0.01
Indiana Harbor	178.6	0.32	0.08	2.67	0.07	1.39
Lorain	0.11	0	0	0	0	0
Ludington	36.68	0.14	0.03	0.67	0.03	0.08
Mackinaw City	0.81	0	0	0.02	0	0
Manitowoc	62.18	0.18	0.03	1.34	0.02	0.25
Milwaukee	4,551.58	8.06	4.19	66.78	3.72	35.33
Oswego	0.22	0	0	0	0	0
Port Dolomite	12.72	0.02	0.02	0.19	0.02	0.1
Sandusky	0.01	0	0	0	0	0
Toledo	526.42	1.18	0.4	8.74	0.36	3.3
Two Harbors	745.69	1.16	0.24	9.97	0.22	6.39
Total	**24,979.17**	**46.07**	**22.61**	**383.50**	**20.07**	**185.84**

Table 3.5: Emissions from Marine Vessels During Hotelling at Ports in the Great Lakes. Emissions shown in Metric Tons (MT).

Port Name	CO_2	CO	HC	NO_X	PM	SO_2
Alpena	0.12	0	0	0	0	0
Ashland	0.32	0	0	0.01	0	0
Ashtabula	43.73	0.14	0.04	0.82	0.04	0.39
Bettendorf	0.07	0	0	0	0	0
Buffalo	27.57	0.09	0.01	0.52	0.01	0.21
Burns Harbor	250.77	0.8	0.16	4.74	0.14	1.7
Calcite	8.59	0.03	0	0.16	0	0.08
Cape Vincent	0.09	0	0	0	0	0
Carrollton	1.02	0	0	0.02	0	0.01
Charlevoix, MI	0.38	0	0	0.01	0	0
Cheboygan	8.32	0.03	0.01	0.18	0.01	0.04
Chicago	1,760.01	6.13	1.49	33.62	1.32	4.2
Cleveland	898.93	2.8	0.24	16.79	0.21	7.66
Conneaut	3.64	0.01	0	0.07	0	0.03
Copper Harbor	0.29	0	0	0.01	0	0
Detroit	181.43	0.58	0.1	3.42	0.09	1.37
Drummond Island, MI	170.57	0.53	0.11	3.18	0.1	1.5
Duluth-Superior	3,042.36	9.5	1.64	56.9	1.46	25.47
Erie	2	0.01	0	0.04	0	0.02
Escanaba	1.41	0	0	0.03	0	0.01
Fairport Harbor	15.03	0.05	0.01	0.29	0.01	0.04
Gary	157.68	0.48	0.04	2.94	0.03	1.47
Grand Haven, MI	17.95	0.06	0.01	0.34	0.01	0.16
Grand Marais	0.03	0	0	0	0	0
Green Bay, WI	0.11	0	0	0	0	0
Huron, OH	2.04	0.01	0	0.04	0	0
Iale Royale	0.03	0	0	0	0	0
Indiana Harbor	109.6	0.38	0.09	2.08	0.08	0.36
Kelleys Island, OH	0.42	0	0	0.01	0	0
Lorain	4.43	0.02	0	0.1	0	0.03
Ludington	4.07	0.02	0	0.07	0	0.01
Mackinaw City	0.23	0	0	0	0	0
Manistee	0.09	0	0	0	0	0
Manitowoc	30.01	0.11	0.02	0.61	0.02	0.06
Marblehead	0.01	0	0	0	0	0
Marine City, MI	0.73	0	0	0.01	0	0
Milwaukee	99.52	0.35	0.21	1.88	0.18	0.53
Muskegon	0.95	0	0	0.02	0	0.01
Oswego	0.07	0	0	0	0	0

Table 3.6: Estimated Vessel Emissions During Maneuvering at Ports in the Great Lakes. Emissions shown in Metric Tons (MT).

Port Name	CO_2	CO	HC	NO_X	PM	SO_2
Port Dolomite	0.86	0	0	0.02	0	0.01
Port Inland	3.16	0.01	0	0.06	0	0.03
Sandusky	3.33	0.01	0	0.06	0	0.02
St. Clair	0.12	0	0	0	0	0
Stoneport	0.3	0	0	0.01	0	0
Sturgeon Bay	0.73	0	0	0.01	0	0.01
Toledo	68.21	0.22	0.05	1.32	0.05	0.55
Turkey River	0.17	0	0	0	0	0
Two Harbors	198.5	0.61	0.04	3.7	0.03	1.88
Total	**7,120**	**22.96**	**4.28**	**134.09**	**3.8**	**47.86**

Table 3.6 (cont.): Estimated Vessel Emissions During Maneuvering at Ports in the Great Lakes. Emissions shown in Metric Tons (MT).

Vessel Type	CO_2	CO	HC	NO_X	PM	SO_2
Cargo	19,407.3	30.23	18.5	259.37	16.43	166.26
Fishing	99.11	0.35	0.09	2.09	0.08	0.21
Other	12.75	0.04	0.01	0.27	0.01	0.03
Passenger	109.15	0.44	0.57	1.97	0.51	0.23
Pleasure Craft	166.91	0.67	0.26	3.01	0.23	0.35
Sailing Vessel	0.59	0	0	0.01	0	0
Search and Rescue	0	0	0	0	0	0
Special Craft	172.41	0.6	0.13	3.63	0.12	0.36
Tanker	17.06	0.04	0.02	0.29	0.02	0.13
Tug	4,796.86	13.15	2.79	110.43	2.48	16.29
Unspecified	197.05	0.55	0.23	2.42	0.21	1.98
Total	**24,979.17**	**46.07**	**22.61**	**383.5**	**20.07**	**185.84**

Table 3.7: Emissions by Marine Vessel Type During Hotelling in the Great Lakes Ports. Emissions shown in Metric Tons (MT).

Vessel Type	**CO_2**	**CO**	**HC**	**NO_X**	**PM**	**SO_2**
Cargo	4,547.63	13.88	1.93	84.72	1.72	43.07
Fishing	3.76	0.01	0	0.08	0	0.01
NULL	0.06	0	0	0	0	0
Other	54.41	0.19	0.05	1.15	0.04	0.11
Passenger	46.95	0.19	0.15	0.85	0.13	0.1
Pleasure Craft	13.87	0.06	0.01	0.25	0.01	0.03
Sailing Vessel	0.16	0	0	0	0	0
Search and Rescue	0	0	0	0	0	0
Special Craft	24.23	0.08	0.03	0.51	0.03	0.05
Tanker	6.85	0.01	0.01	0.19	0.01	0.04
Tug	2,391.53	8.42	2.08	45.6	1.85	4.17
Unspecified	30.55	0.11	0.02	0.75	0.02	0.27
Total	**7,120**	**22.96**	**4.28**	**134.09**	**3.8**	**47.86**

Table 3.8: Emissions by Marine Vessel Type During Maneuvering in the Great Lakes Ports. Emissions shown in Metric Tons (MT).

3.5 Monthly Variations in Marine Vessel Emissions

Since data on the Great Lakes were available on a very fine time resolution, it is possible to calculate emissions even on a daily basis. In order to understand the variations in vessel activity and emissions on a monthly basis, data from Access was queried to sum up emission for the three modes (cruising, hotelling and maneuvering). The total emissions from all vessels on the Great Lakes (both US and Canadian Great Lakes) are plotted in Figure 3.4. Based on this 2014 data, in general, we can expect the vessel activity to peak after March and recede during January, February and March in a given year.

Figure 3.5, shows a Box and Whisker plots of all Cruising, Maneuvering and Hotelling mode data points on a monthly basis, where each data point is a sum of all vessel tracks in each NEI shipping lane with a unique ShapeID. In this plot, for Cruising mode, we note that the majority of emissions (as shown by the inter-quartile range) are more or less similar for each of the months after March. However, the variations on a monthly basis appear to be driven more by the outliers that are on specific shipping lanes. This is because, as noted earlier, each data point (in Figure 3.5) is a sum of CO_2 emissions for a specific shipping lane (ShapeID) in a given month. However, for Hotelling and Maneuvering, data shows increased activity (in terms of CO_2 emissions) during the months of March, October, November and December in 2014. Although, this increase is slightly subdued in Maneuvering.

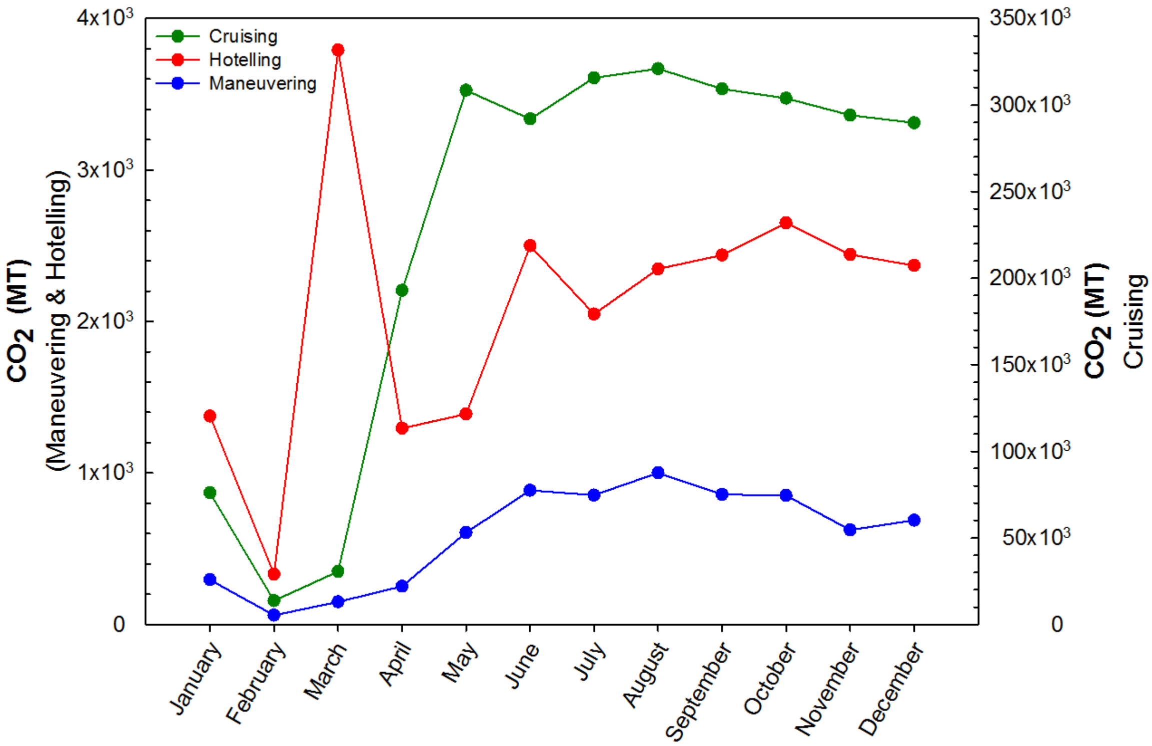

Figure 3.4: Monthly Variations in Estimated CO_2 Emissions of Marine Vessels in the Great Lakes (both in the US and Canada).

3.6 Growth Rates for Future Years

Growth rates for future years were estimated by reviewing the Marine Vessel link-level tonnages data on the Major Rivers and the Great Lakes obtained from USACE[10]. The data obtained from USACE included the link level tonnages from 2001 to 2012 (as of September 24, 2014). Year over year, compounded annual growth rate (CAGR) was computed using Equation 5.

$$CAGR = \left[\frac{EndingTonnage}{BeginningTonnage}\right]^{\frac{1}{n}} - 1 \tag{5}$$

Figure 3.6 shows the CAGR for the Major Rivers and the Great Lakes. From this plot, we note that the variability in the growth rates decrease from 2001 upto 2009 and then increase after 2009 for Ohio River, Mississippi River and the Great Lakes. Tonnage data for Illinois River and Chicago River show steady decrease from 2001 and the continue to decrease after year 2009. Due to this variability in the data between 2001 and 2009, an average CAGR was computed from 2009 to 2012. This average value was used as projected growth rates future years. Future year projected values are listed in Table 3.9.

[10] `http://www.navigationdatacenter.us/data/datalink.htm`

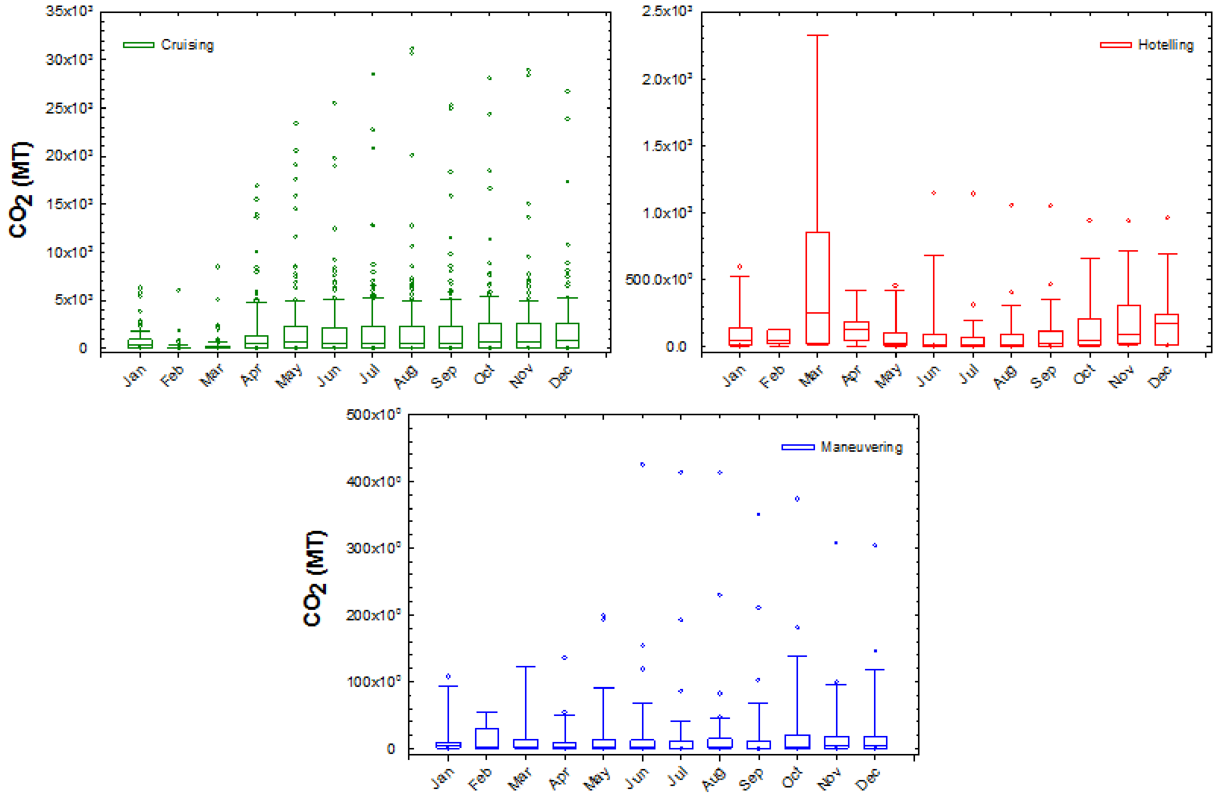

Figure 3.5: Monthly Variations in Estimated CO_2 Emissions of Marine Vessels in the Great Lakes (both in the US and Canada) during Cruising, Maneuvering and Hotelling.

Waterbody Name	**Projected Growth**
Ohio River	-1.2%
Mississippi	-2.5%
Illinois River	-10.5%
Chicago River	-16.3%
Great Lakes	+2.2%

Table 3.9: Projected Growth Rates for Major Rivers and the Great Lakes.

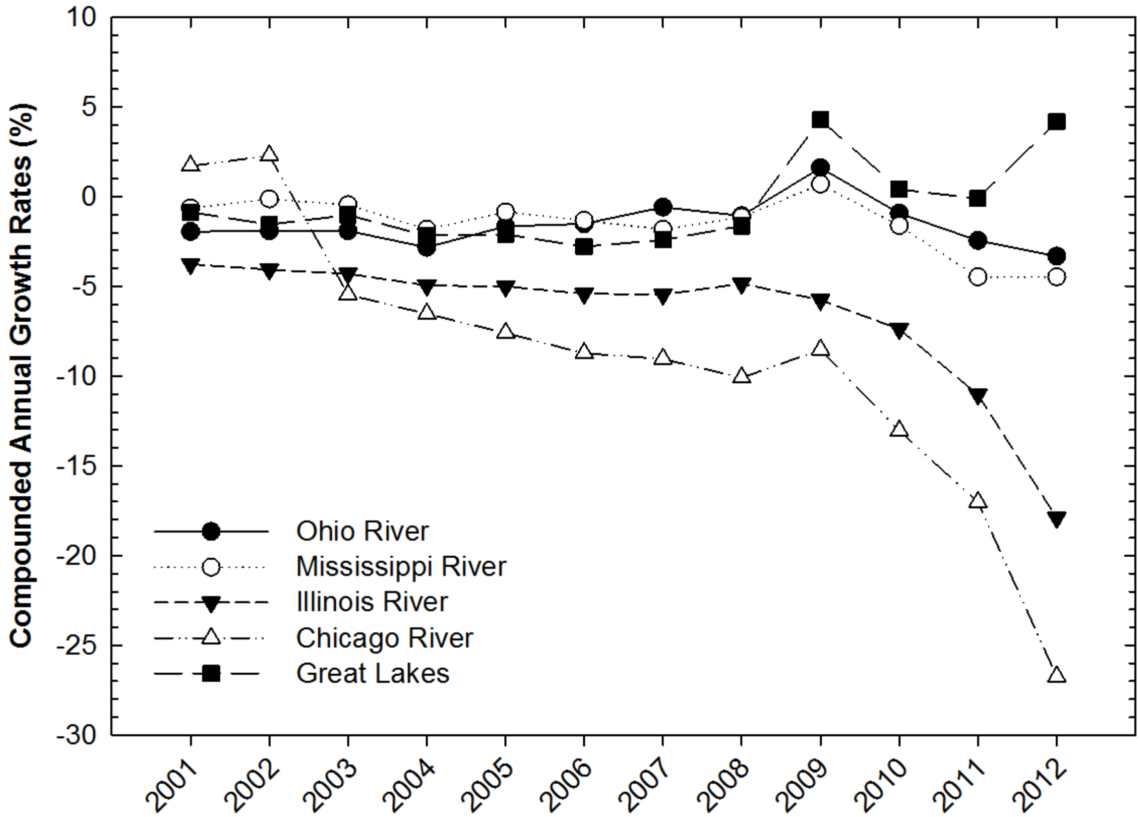

Figure 3.6: Compounded Annual Growth Rates in Marine Vessel Link-Level Tonnages from 2001 through 2012 in Major Midwest Rivers and the Great Lakes. Data obtained from USACE.

4 CONCLUSIONS AND RECOMMENDATIONS

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This project utilized data from two distinct sources, (1) link tonnages on the National Waterway Networks provided by USACE, and (2) Vessel Traffic data including data from AIS transponder provided by MarineTraffic. Emissions were estimated using the most current emission factors available from peer-reviewed journal articles and other publications referenced in Section 5. Emission results show substantial vessel traffic that result in air emissions on the Ohio River and Mississippi River in comparison to the emissions on the Great Lakes. Within Great Lakes, emissions on the Canadian side of the Great Lakes appear to account for approximately 25% of the total emissions on the Great Lakes.

4.2 Recommendations for Future Work

The following are suggested avenues for future development on this work and potential issues that may be important, if AIS Transponder data is used to estimate emissions on the rivers and inland waterways.

4.2.1 AIS Transponder Collection Frequency and Track Resolution

During the course of this work there were minor losses of vessel tracks caused by generated tracks leaving the water surface due to both the interval between AIS reported coordinate points and the intricacy of the waterways connecting between the Great Lakes. These losses were not significant for analyzing the emissions in the Great Lakes region since the majority of the activity occurs within larger water-bodies where inaccuracy between the actual vessel path and the straight-line path was of less importance. However, if the methods described in this work were to be used in an environment requiring higher precision, such as a network of inland rivers, this source of inaccuracy would need to be further addressed. Moreover, the loss of vessel tracks on the rivers may be much higher than the loss of vessel tracks calculated in this work for the Great Lakes due to the reasons noted above.

This issue may be resolved through a combination of two adjustments. First, using an AIS dataset that consists of time intervals between each GPS coordinate in the 2-3 minute range. This, as a result, would improve time resolution and reduce the potential error inherent in approximating the vessel path as a straight line between the two coordinates. Second, a process could be developed that automated the iterative addition of an intermediate point between each set of points until the vessel paths lay completely within a water surface boundary.

For reference, 84.6% of the MarineTraffic data used in this work had an interval of 4 minutes or lower between each GPS coordinate. There were two spikes in the data that accounted for 3.0% and 1.7% of the entire data, with average GPS coordinate data intervals of 21 and 24 minutes, respectively.

Again, some of the larger time intervals are not an issue for use in the Great Lakes, but generally it is expected that a domain containing more intricate pathways would require additional manipulation of the dataset as discussed above or needing finer time-resolution AIS transponder GPS data. To put this in perspective, even one-tenth of one percent of the Marine Traffic database corresponds to thousands of track segments that would potentially need further evaluation and manual injection of GPS coordinates to address intricate vessel pathways in narrow waterways.

4.2.2 Refinement of the Intersection Grid

The purpose of this work was to develop an Emission Inventory that was compatible with the format of the EPA's National Emissions Inventory (NEI). To this end, the vessel tracks in the Great Lakes region were intersected with the Shipping Lane polygons present in the NEI. However, since the track data remains segregated by vessel, time and location, the intersection mesh could be redrawn as smaller divisions and the intersection process could be done for the new finer mesh. This would allow for greater spatial resolution and more accurate modeling for situation such as coastal interactions during ozone months and other Photochemical Modeling applications. Since the numerical uncertainty in the reported GPS coordinates is on the order of tenths of a feet, the potential resolution of the intersection grid could be increased to a much greater resolution than the NEI shape file resolution which generally aggregates, in the Great Lakes region, on or near the county level. However, the intersection process could take several days and require powerful computational hardware.

4.2.3 Consideration of Additional Pollutants and Other Sources for Emission Factors

Although a comprehensive search for emission factors was conducted in this work, the emission factors were only obtained for limited pollutants. The calculation may be extended for more pollutants, particularly Hazardous Air Pollutants (HAPs) when new information becomes available. In addition to this, the emission factors used in this work were based on the best data available at the time of this work. Therefore, if better data is available, the Access Database and Excel Spreadsheets may be updated with newer emission factors.

5 REFERENCES

5 REFERENCES

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A - APPENDIX: GREAT LAKES DATA INPUTS

BC_EF

ID	Type	EF	Unit
1	Passenger	0.27	g/kg-fuel
2	Pleasure	0.12	g/kg-fuel
3	Cargo	0.39	g/kg-fuel
4	Tanker	0.22	g/kg-fuel
5	Fishing	0.29	g/kg-fuel
6	Tug	0.59	g/kg-fuel
7	Tow	0.47	g/kg-fuel
8	All	0.44	g/kg-fuel

CO2_EF

ID	Type	EF	Unit
1	All	3.21	ton/ton-fuel

Fe_EF

ID	Type	EF	Unit
1	8%	2.84E-03	g/kw-hr
2	27%	2.58E-03	g/kw-hr
3	52%	2.15E-03	g/kw-hr
4	63%	3.48E-03	g/kw-hr
5	70%	3.89E-03	g/kw-hr

NOx_EF

ID	Type	EF	Unit
1	BulkFreight	87.00	g/kg-fuel
2	BulkFreight_0	54.10	g/kg-fuel
3	Container	59.80	g/kg-fuel
4	Container_0	42.90	g/kg-fuel
5	CrudeTanker	79.20	g/kg-fuel
6	CrudeTanker_0	27.70	g/kg-fuel
7	LPGTanker	78.70	g/kg-fuel
8	LPGTanker_0	39.50	g/kg-fuel
9	Passenger	57.90	g/kg-fuel
10	Tug	61.20	g/kg-fuel
11	Tug_0	73.90	g/kg-fuel
12	General	67.66	g/kg-fuel

CO_EF

ID	Type	EF	Unit
3	BulkFreight	7.00	g/kg-fuel
4	BulkFreight_0	7.50	g/kg-fuel
5	Container	9.80	g/kg-fuel
6	Container_0	5.00	g/kg-fuel
7	CrudeTanker	16.70	g/kg-fuel
8	CrudeTanker_0	3.60	g/kg-fuel
9	LPGTanker	11.10	g/kg-fuel
10	LPGTanker_0	8.90	g/kg-fuel
11	Passenger	12.80	g/kg-fuel
13	Tug	11.30	g/kg-fuel
14	Tug_0	8.80	g/kg-fuel
15	General	11.26	g/kg-fuel

HC_EF

ID	Type	EF	Unit
1	2Stroke	0.50	g/kw-hr
2	4Stroke	0.50	g/kw-hr

HCOOH_EF

ID	Type	EF	Unit
1	Passenger	4.56	mg/kg-fuel
2	Cargo	18.65	mg/kg-fuel
3	Tanker	27.15	mg/kg-fuel
4	All	20.35	mg/kg-fuel

Ni_EF

ID	Type	EF	Unit
1	8%	1.20E-02	g/kw-hr
2	27%	9.65E-03	g/kw-hr
3	52%	1.04E-02	g/kw-hr
4	63%	1.16E-02	g/kw-hr
5	70%	1.27E-02	g/kw-hr

EF-Emission Factor   % Values in Emission Factors Indicate Engine Load
'Type_0' indicates that the Factor is for Hotelling
Fuel 'Constant' is the mathematical intercept and 'Scalar' is the coefficient of the Gross Tonnage (GT)

SO2_EF			
ID	Type	EF	Unit
1	BulkFreight	20.40	g/kg-fuel
2	BulkFreight_0	24.70	g/kg-fuel
3	Container	30.40	g/kg-fuel
4	Container_0	27.50	g/kg-fuel
5	CrudeTanker	27.30	g/kg-fuel
6	CrudeTanker_0	48.10	g/kg-fuel
7	LPGTanker	28.80	g/kg-fuel
8	LPGTanker_0	32.30	g/kg-fuel
9	Passenger	6.70	g/kg-fuel
10	Tug	5.60	g/kg-fuel
11	Tug_0	10.90	g/kg-fuel
12	General	6.70	g/kg-fuel

PM_EF				
ID	Type	EF	Unit	Comment
1	All_Content	0.44	g/kw-hr	0.26+0.081*%S+0.103*(%S^2)

V_EF			
ID	Type	EF	Unit
1	8%	5.36E-02	g/kw-hr
2	27%	4.41E-02	g/kw-hr
3	52%	4.65E-02	g/kw-hr
4	63%	5.26E-02	g/kw-hr
5	70%	5.60E-02	g/kw-hr

FuelConsumption					
ID	ShipType	Constant	Scalar	Unit	Comments
1	SolidBulk	20.186	0.00049	ton-fuel/day	Scaled by GT
2	Tug	5.6511	0.01048	ton-fuel/day	
3	LiquidBulk	14.685	0.00079	ton-fuel/day	
4	GenCargo	9.8197	0.00143	ton-fuel/day	
5	Container	8.552	0.00235	ton-fuel/day	
6	RoRoCargo	12.834	0.00156	ton-fuel/day	
7	Passenger	16.904	0.00198	ton-fuel/day	
8	HighSpeedFerries	39.483	0.00972	ton-fuel/day	
9	InlandCargo	9.8197	0.00143	ton-fuel/day	
10	SailShips	0.4268	0.001	ton-fuel/day	
11	Fishing	1.9387	0.00448	ton-fuel/day	
12	Other	9.7126	0.00091	ton-fuel/day	

Zn_EF			
ID	Type	EF	Unit
1	8%	1.29E-04	g/kw-hr
2	27%	1.02E-04	g/kw-hr
3	52%	9.23E-05	g/kw-hr
4	63%	9.85E-05	g/kw-hr
5	70%	1.43E-04	g/kw-hr

Power-Fuel_Conversion			
ID	Type	Conversion	Unit
1	Slow Speed	175	g-fuel/kw-hr
2	Medium Speed	195	g-fuel/kw-hr
3	High Speed	210	g-fuel/kw-hr

EF-Emission Factor % Values in Emission Factors Indicate Engine Load
'Type_0' indicates that the Factor is for Hotelling
Fuel 'Constant' is the mathematical intercept and 'Scalar' is the coefficient of the Gross Tonnage (GT)

B - APPENDIX: Outline of Data Processing Steps

B.0.4 Rivers Data - Processing Steps

1. Import NWN shapefile from USACE and the Scope County Data file into ArcGIS. The working coordinate system for all ArcGIS work was as follows: (1) Projected Coordinate System was "North America Equidistant Conic", and (2)Geographic Coordinate System was "North American 1983".

2. Create a buffered county boundary shape file using the following steps

   - Click on ArcToolbox
   - Open Analysis Tools
   - Open Proximity
   - Click on Buffer
   - Input feature is the County Boundary Shape File
   - Save the output to a folder of interest
   - Distance Value set as 150m, 300m and 1000m. This would be changed based on how close the apportionment to bounding counties needs to be. For this project, a 1000m buffer distance was finalized.
   - Click OK

3. Create Intersect Lines using the Buffered County Boundary file and the NWN file provided by USACE.

   - Open "Geoprocessing"
   - Select "intersect"
   - Select nwn shape file and the buffered County Boundary file
   - Select output file name
   - Join ALL attributes - select from dropdown menu
   - Leave XY Tolerance empty
   - Output type "Line"
   - Click OK

4. The intersection of USACE NWN Shape File with NEI Shape File splits the network by county. This split network length must be computed using a projected coordinate system. In the present work, it was computed using "North America Equidistant Conic" Projected Coordinate System. The Geographic Coordinate System was "North American 1983". In the Intersect file created in above:

   - Open Attribute Table
   - Add Field
   - Select Name "MilesLength" and number with float precision

- Select top row of the "MilesLength" column and right click
- Select "Calculate Geometry", Property "Length" and units of "miles"
- Click OK

5. Export file as text file for further calculations
6. Similar intersection process (described in item #3 was applied to the NEI Shipping Lane Shapefiles.

B.0.5 Great Lakes AIS Data - Processing Steps

Processing Steps to Remove GPS Coordinates on Land Surface:

1. List of Shapefiles used to remove GPS Coordinates reported by the AIS Transponder that fell on land surfaces

   - Use VesselPosition.shp (a file where GPS coordinates were converted to Point Shapefile) — This is a Point shapefile showing GPS navigation points. Note when importing a text file with data, use the "Schema.ini" file to specify the data formats. This would save a lot of headache.
   - NHDWaterbody.shp — Polygon file showing the water areas for selected states (MN, IA, WI, IL, IN, MI, OH, PA and NY). USGS National Hydrography Dataset obtained from `ftp://nhdftp.usgs.gov/DataSets/Staged/States/FileGDB/`
   - ghy_000c11a_e.shp — Polygon file showing the water areas for Canada. Statistics Canada, 2011 Census — Boundary files. `https://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/bound-limit-2011-eng.cfm`
   - The first step was to make sure that the shapefiles were in the same projection (GCS_North_American_1983).

2. With all the associated shapefiles opened in ArcMap, use the "Select By Location" tool. This tool will select features from the shapefile "VesselPosition.shp" that would intersect the source layer feature "NHD Waterbody.shp" (this shapefile includes US States Waterbody) and "ghy_000c11a_e.shp" (Canadian Waterbody). An added search distance of 1 feet from the waterbody to allow for error.

   - Selection — Select by Location
   - Select Features from "VesselPosition"
   - Source — NHDArea
   - Intersect the Source Later feature
   - Apply Search Distance of 1 feet
   - Open Attribute Table after search is complete
   - Select only the selection (smaller box) — "show selected records"
   - Right click and enter "Wet_Dry" Column Name
   - Field Calculator — Enter "Wet"
   - Click OK

3. In the "VesselPosition.shp" shapefile, a column was added into the attribute table called Wet_Dry. After selecting the points that would intersect the waterbodies, The attribute column Wet_Dry was populated with the word "Wet". Repeat this process until all the states and Canada Waterbodies are compared with the point file. The Blank attributes in the Wet column were then labeled "Dry".

Processing Steps to Convert "Validated" GPS Coordinates to Vessel Tracks:

1. Add the "VesselPosition.shp" point feature shapefile into ArcGIS
2. Open Arc Toolbox and navigate to "Tracking Analyst Tools" and select "Track Intervals to Line"
   - In the "Track Intervals to Line", select the "VesselPosition.shp" file
   - Enter a shapefile name for the output feature class. It saves a lot of computational time if the shapefiles are saved in a geodatabase file format.
   - TimeField format needs to be in MM/DD/YYYY HH:MM:SS with leading zeroes for MM, DD, HH, MM and SS. That is when month and dates have single digits from 1 through 9, they need to have leading zeroes in the date format.
   - Select the units, in this work Time was chosen in minutes, Distance in miles and speed in Knots.
   - Click OK
3. Once Tracking Analyst completes the process, the GPS points would have been converted to polyline feature that connects two GPS coorindates into on vessel track. However, the number of vessel tracks are approximately the same number of GPS coordinates. This is because each GPS coordinate connected sequentially with increasing time.
4. Vessel tracks thus obtained from Tracking Analyst Tool, was split by each unique Vessel ID (in this case by the Vessel's MMSI) using USGS Split By Attribute Tool available from `http://www.umesc.usgs.gov/management/dss/split_by_attribute_tool.html`

Intersection of Vessel Tracks with NEI Shipping Lanes and Port Shapefiles

- Split vessel tracks needs to be intersected with NEI Shipping Lanes and Port Shapefiles so that the emissions can be referenced with NEI ShapeID and County ID. Vessel tracks are intersected with Port Shapefiles so that emissions can be computed for Hotelling and Maneuvering, intersection with Shipping Lanes shapefiles provide Cruising mode emissions.

  Vessel tracks intersected with Shipping Lanes Shapefiles and Port Shapefiles, in ArcGIS software, contains the following fields as shown in the Table B.1.

Field Names in Tracking Analyst Results	**Description**
OBJECTID	ReferenceID for each Polyline Feature
From_ID	Starting ID for Vessel Track (obtained from GPS Coordinate) Shapefile
To_ID	Ending ID for Vessel Track (obtained from GPS Coordinate) Shapefile
Start_Time	Starting time for Vessel Track
End_Time	Ending time for Vessel Track
Track_ID	Vessel MMSI ID
Miles	Distance of this Vessel Track
Minutes	Duration of travel by this Vessel Track
Knots	Speed of this Vessel Track
Degrees	Direction of this Vessel Track
FID_Canada_Lanes_NoGap	Reference ID from Shipping Lane file(intersected file)
Shape_Length	Shipping Lane Shape Length
Area_sqmi	Area of Shipping Lane Polygon
ShapeID	ShapeID of Shipping Lane Polygon
FIPS2014	County ID of Shipping Lane Polygon
Shape_Length	Unused Carryover Data
Miles_Segment	Calculated Vessel Track in the Projected Coordinate System of this work

Table B.1: Header Field Names/Description in Vessel Track Intersection Results.

Processing Steps to Calculate Air Emissions from Vessel Tracks in Microsoft Access Software:

1. Import exported files from ArcGIS into the appropriate tables in the Access Database "LakeEmissions_Calculations". Tracks intersected with the NEI ShippingLanes shapefile should be imported into the Tracks_p1 though Tracks_p4 or Tracks_remnant tables. Tracks intersected with the NEI Ports shapefile should be imported into the Ports table. If the imported data is replacing previous data delete all of the rows from the existing table before importing, leaving only the header row.

2. If it is necessary to change the emission factors; variables in the fuel consumption equation; or conversion factor between engine power and fuel use, this can be done in the tables labeled <Pollutant>_EF, FuelConsumption, and Power-Fuel_Conversion respectively.

3. The emission are calculated for each pollutant according to the equations written in each of the Modules for each pollutant. Assignment of the relationship between the EF table categories and the vessel types are done using IF statements in the Modules.

4. Various selections and combinations on the data are done in the queries. The purpose of each query and the dataset used are included in the query name, ex. AddVessChar_p1 adds the Vessel Characteristics (engine power, vessel type, Gross Tonnage) to the intersected paths in Tracks_p1.

5. Emissions_p1, Emissions_p2, Emissions_p3, Emissions_p4, Emissions_remnant, and Emissions_ports are the final queries that calculate emissions for each vessel path segment. To transfer these emissions to the database "EmissionResults":

   (a) Delete all of the data, that is being updated, contained in the Tables Emissions_Cruising and PortEmissions.

   (b) Either:

      - Export Emissions_p1-p4,Emissions_remnant to text files and import into Emissions_Cruising. Export Emissions_ports to a text file and import into PortEmissions.
        Or;
      - Run the queries Port_Append and Underway_Append. The filepath for the EmissionResults database may need to be changed to reflect where the file was placed on the user's machine.

Guide to Queries on Calculated Emissions

1. Open the "EmissionResults" Access Database.
2. There are several queries, named according to their function, that perform selections and table combinations on the input data tables The only one of these that may need alteration are the queries including '_Commercial'. This query currently excludes vessels categorized as Pleasure Craft, Sailing Vessels, or Wing in Ground to prevent double-counting of emissions between this emission inventory and the NMIM/MOVES dataset. To alter the vessel categories excluded open the query in design mode and change the NOT statements in the WHERE SQL statement.
3. The UserInputs table is where the bounds of the returned data is entered by the User. This includes the beginning and ending date-times for emission summation and the FIPS regions to include. For example, the user could enter 1/1/2014, 2/1/2014, 17000, and 17999 to have the queries return only the emissions that occurred between January and February 2014 in Shapes associated with the state of Illinois.
4. For exporting the data into Smoke Flat-file format run the SmokeExport_Ports and SmokeExport_Underway queries and replace the data in the "NEI_Shapes" Excel file. The data tables to replace in this spreadsheet are in tabs ShapeEmissions_Lakes_Underway and ShapeEmissions_Lakes_Ports. Repeat running the SmokeExport queries for each month January-December to update the monthly fields in the Smoke FF format.
5. To export the data in the EIS format run the query "StagingTable_Annual_AllSources". The results of this query include emissions from major Midwest River vessel traffic, Great Lake cruising emissions, and Great Lake port maneuvering/hotelling emissions.
   - Note that this query is for the entirety of the year and can not be altered by the User date-time inputs, because the River Emissions are not calculated from AIS points and do not have a temporal distribution. The results can still be restricted based on a user-specified range of FIPS codes.
   - Depending on the desired ordering of lines (ex. identical ShapeIDs together) the resulting table can be sorted by clicking the drop-down arrows next to each column header.
   - The table generated by this query can be exported to a '.xml' format either through the ExternalData ribbon tab or by right-clicking the query and choosing 'Export'.

Generating the Smoke FlatFile Format:

1. As discussed in the above section run the SmokeExport queries in the database and overwrite the data already present in the referenced Excel sheets.

2. The imported data is pulled into the "Smoke _FF _Linked" sheet. SCC codes, growth factors, and FIPS codes are tied to each data row by the value arrays in the "Lookups" sheet. If the number of pollutants are changed from the current value of '8' then the River, GL_Cruising, and GL_Port sections will need to be copied downward and the StartingRow values will need to be updated.

3. To generate a future year inventory estimate change the value for 'FutureYear' in the "Lookups" sheet. The future year inventory is generated in the "SMOKE_FF_FutureYear" sheet and the data is also reflected in the "FutureInventory_Pivot" table sheet. Note that the value for FutureYear can also be a past year and the equations will still work as intended.

4. The header information can be changed to include any metadata desired by the user.