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Final Report Link-based Modeling Emissions Inventory of Marine Vessels (Ocean Going Vessels) in Transit and at Anchor in the Gulf of Mexico

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GLOSSARY OF TERMS

Adjustment factors: Used to adjust emission factors or engine load factors or other situations for non-standard conditions.

Anchorage: Vessels anchored off-shore waiting for berth or next assignment.

Assist mode: Period when a tugboat is engaged in assisting a ship to/from its berth or maneuvering in the harbor.

Automatic Identification System (AIS): AIS is an automatic tracking system used on ships and by vessel traffic services (VTS) for identifying and locating vessels by electronically exchanging data with other nearby ships, AIS base stations, and satellites.

Auxiliary engine: Used to drive on-board electrical generators to provide electric power or to operate equipment on board the vessel.

Auxiliary power: Typically electric power generated via the auxiliary engine.

Berth: A location alongside a pier to moor vessels.

Bulk: Vessels designed to transport dry bulk (e.g. grain, potash, sand and gravel, etc.).

Cargo: Vessels designed to transport break bulk too big to fit into containers (e.g. machinery, parts, etc.)

Container: Vessels designed to carry freight containers.

Cruise mode: The vessel mode while traveling in the open ocean or in an area without speed restrictions.

Gross tonnage (GT): The internal volume of tween-decks and deck space used for cargo and is a measurement of volume of all enclosed spaces on a ship with 100 cubic feet = to one ton.

Diesel-electric: Ship propulsion designs where sets of diesel engines generate electric power to drive propellers and primarily used on most cruise ships.

Emission Control Areas (ECAs): These areas must comply with international regulations on fuel sulfur and engine NOx emission standards, and applies to most U.S. and Canadian waters.

Emission factor: The average emission rate of a given pollutant for a given source, relative to a unit of activity. Typical examples are grams per kilowatt of actual power or grams per hour of engine operation.

Emissions inventory: A listing of all the pollutant emissions included in the study.

Gas turbines: An alternative engine type to internal combustion diesel engines used on some cruise ships.

Gross Tonnage (GT): Defined by the volume of space within the hull and enclosed space above the deck of a merchant ship which are available for cargo, stores, fuel, passengers and crew with units of 100 cubic feet of capacity equivalent to one gross ton.

g/kW-hr: This is the unit for reporting emission or fuel consumption factors, and means the grams per kilowatt-hour of work performed. Work and energy are used synonymously in this context.

Harbor Craft: The smaller vessels conducting business in the bay, including excursion vessels, pilot boats, assist tugs, and towing tugs.

Hotelling: On-board activities while a ship is in port and at its berth or at anchor.

IHS Fairplay: Database of vessel characteristics including speed, engine power, and other information and is cross referenced with IMO or MMSI number.

Installed power: The engine power available on the vessel. The term most often refers only to the propulsion power available on the vessel, but could incorporate auxiliary engine power as well.

IMO ship identification number: The International Maritime Organization (IMO) number is made of the three letters "IMO" followed by the seven-digit number assigned to all ships by IHS Fairplay (formerly known as Lloyd's Register-Fairplay) when constructed.

Knot: A nautical unit of speed meaning one nautical mile per hour and is equal to about 1.15 statute miles per hour.

Link: A defined portion of a vessel's travel. For example a link was established extending from Ports out to the ocean. A series of links defines all of the movements within a defined area or a trip.

LNG: Liquefied natural gas

Load: The actual power output of the vessel's engines or generator. The load is typically the rated maximum power of the engine multiplied by the load factor if not measured directly.

Load factor: Average engine load expressed as a fraction or percentage of rated power.

LPG: Liquid petroleum gas, or primarily propane.

Maneuvering: Very slow transiting to position the ship.

Maritime Mobile Service Identity (MMSI): is a series of nine digits which are sent in digital form over a radio frequency channel in order to uniquely identify ship stations, ship earth stations, coast stations, coast earth stations, and group calls.

Maximum power: A power rating usually provided by the engine manufacturer that states the maximum continuous power available for an engine.

Medium speed engine: A 4-stroke engine used for auxiliary power and rarely, for propulsion. Medium speed engines typically have rated speeds of greater than 130 revolutions per minute.

Mode: Defines a specific set of activities, for example, a tug's transit mode includes travel time to/from a port berth while escorting a vessel.

NOx: nitrogen oxides and includes all nitrogen oxide compounds.

Ocean-going vessels (OGV): Vessels equipped for travel across the open oceans. These do not include the vessels used exclusively in the harbor, which are covered in this report under commercial harbor craft. In this report, OGV are restricted to the deep draft vessels.

Operation mode: the current mode of operation for a ship – for example, cruising, maneuvering, or hotelling.

PM_{10}: Particulate matter emissions less than 10 micrometers in diameter.

$PM_{2.5}$: Particulate matter emissions less than 2.5 micrometers in diameter

Port of Call: A specified port where a ship docks.

Propulsion engine: Shipboard engine used to propel the ship.

Propulsion power demand: Power used to drive the propeller and the ship.

Rated power: A guideline set by the manufacturer as a maximum power that the engine can produce continuously.

Reduce Speed Zone (RSZ): Mode where ship transit at slower speeds due to traffic or speed limits.

ROG: Reactive organic gas; all hydrocarbon compounds that can assist in producing ozone (smog). Includes hydrocarbons (HC) plus aldehyde and alcohol compounds minus methane, often used interchangeably with HC although they are not quite the same.

RoRo: Roll on/Roll off vessel usually designed to carry new vehicles but could include other rolling freight

SOx: Oxides of sulfur. Interchangeable term with sulfur dioxide but include some other minor forms of sulfur oxides.

Spatial allocation: Areas on a map allocating a specific set of activities.

Spatial scope: A specified area on a map that defines the area covered in study.

Slow speed engine: Typically a 2-stroke engine or an engine that runs below 130 rpm.

Steam boiler: Boiler used to create steam or hot water using external combustion.

Time in mode: The amount of time a vessel remains in a specified mode, for example the amount of time a ship spends in the reduced speed zone.

Tons: Represents short tons (2,000 lbs) unless otherwise noted.

Tonnes: Metric tons (1,000 kg)

Two-stroke engine: Engine designed so that it completes the four processes of internal combustion (intake, compression, power, exhaust) in only two strokes of the piston.

1.0 INTRODUCTION

Nitrogen oxides (NOx) and sulfur dioxide (SO_2) emissions associated with shipping remain a significant component of the total NOx and SO_2 inventories. The current open ocean Emissions Inventory (EI) for ocean going vessels (OGV) within the near-Texas modeling domain is based on 2002 ship movements and is devoid of ship type information. The transponder data available today (as part of the Automatic Identification System, AIS) allows for improved EI development based on recorded shipping activity. This study used 2014 AIS data to estimate OGV emissions at off-shore locations which were not previously assessed.

The existing Environmental Protection Agency (EPA, 2003) transit OGV emission estimates were prepared using traffic data from 2002. Likewise, the emissions in Federal waters in the Gulf of Mexico from smaller vessels used for off-shore support, survey, pipe laying, tug and barge, and other activity has been included in periodic emission inventories (BOEM, 2014[1]).

In Texas, many ports (PHA[2], Farooqui et al. 2013, Corpus Christi Air Quality Committee[3]) have conducted studies to detail activity within the port area defined uniquely for each port. These port inventories provide a detailed understanding of the in-port activity and emissions. The near and in-port emissions have been estimated for many ports using port call data from individual ports, marine exchange, and harbor pilots that provide detailed at dock or at anchor times. However, the port emission inventories have had a spatial scope limited to near and in-harbor activity. While AIS data may not be the best information for in-port activity, such as to determine at-berth time when main engines are shut off, AIS provides a more complete account of Gulf ship activity when operating away from ports. This work allows the port inventories to be incorporated by defining the domain of the AIS data to be separate of those defined for port inventories.

This study used AIS data to estimate OGV emissions at off-shore locations which were not previously assessed. In addition to transiting ships emissions, a significant number of vessels also anchor and some tankers lighter (off-load liquid freight to another ship) outside of Ports' study areas such that estimated emissions from those vessels are not included in EPA's, the Galveston Bay ports', or other port inventories used by TCEQ.

Since the original EPA (2003) emission estimates were made, all ships now signal their position along with speed and direction at regular and short intervals through the AIS using a unique ship identification number, either the International Maritime Organization (IMO) or Maritime Mobile Service Identity (MMSI) number. In addition, the ships can be cross-referenced to ship type, model year, size, design speed, engine characteristics, and other inputs to estimate the engine loads and emission rates using the IHS Fairplay data. Other researchers (Goldsworthy

[1] BOEM 2014. "Year 2011 Gulfwide Emission Inventory Study," U.S. Department of the Interior Bureau of Ocean Energy Management, Gulf of Mexico OCS Region, BOEM 2014-666, November 2014.
[2] PHA. 2007. "2007 Goods Movement Air Emissions Inventory at the Port of Houston," Prepared by Starcrest Consulting Group, January 2009.
[3] Attachment D:http://www.epa.gov/ozoneadvance/pdfs/corpustxpath.pdf

2015) have developed emission inventories using AIS activity data and similar methods to better estimate off-shore emissions.

The domain for this study is shown in Figure 1. The vessel transiting was assessed from 3 nautical miles offshore to the boundary domain. The domain for this study was chosen to reduce conflicts with port inventories, and to encompass the TCEQ near-Texas air quality modeling domain.

Figure 1. Domain for the Emission Inventory

In this region, major shipping lanes associated with all ports in the Gulf of Mexico are described from the U. S. Department of the Interior Bureau of Ocean Energy Management (BOEM) as shown in Figure 2. BOEM and other federal agencies have defined shipping fairways, traffic lanes, and zones to delineate activities and regulations for marine vessel traffic. Traffic lanes define specific traffic flow, while traffic separation zones assist opposing streams of marine traffic; anchorage and lightering zones define areas used by vessels for anchoring, transferring cargo, reducing the draft of a vessel, and other maritime operations.

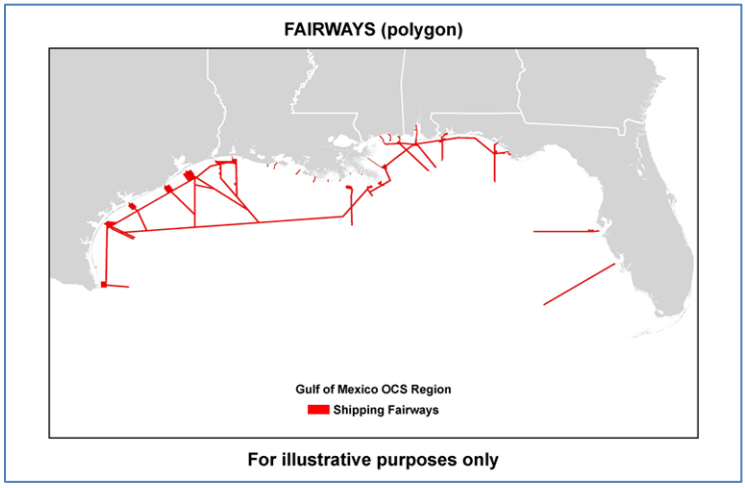

Figure 2. Shipping Fairways[4]

Outside of the fairways, there are three main transit routes: 1) Mexican ports, 2) Central American ports and Panama Canal, and 3) South American ports. The routes outside of the fairway, but still within the domain for this inventory, are not spatially distinct because there are no formal routes, fairways, or shipping channels.

Fairway links in Figure 2 show domestic coastal routes and the domestic route from the Mississippi delta to Corpus Christi with opportunity to access other Texas ports. As discussed later, some transiting and anchorage occur off the fairways near the coast.

1.1 Purpose

This study was designed to develop improved ocean going vessel (OGV) emissions using AIS data to produce modeling input files and inventories for a TCEQ-defined Gulf of Mexico domain offshore of Texas. Ramboll Environ assessed OGV emissions, which are larger freight and cruise passenger ships and do not include off-shore support vessels, tugs, and other smaller vessels. Ramboll Environ also developed activity growth and emission control factors backcast to 2012 and forecast to 2023, including planned port expansion.

[4] https://catalog.data.gov/dataset/shipping-fairways-in-the-gulf-of-mexico-from-boem

2.0 METHODOLOGY

Ramboll Environ purchased AIS ship position data from Oceaneering with vessel identification with IMO and MMSI numbers, speed, and vessel heading in 3 minute increments. These data were used to assess the activity of vessels outside of 3 nautical miles from the Texas shoreline and constrained on the outer perimeter by the TCEQ modeling domain. The vast amount of data was processed using the Python programming language. The data were reduced to contain only movement within the domain and assessed for contiguous voyages by individual vessels. The development of emissions additionally required vessel characteristics such as vessel type, propulsion engine power, engine stroke type, gross tonnage (GT), engine speed, cruise speed, and build date. These characteristics were obtained by cross referencing the AIS data's MMSI and IMO numbers with Fairplay registry data. Together, these data provided the ability to estimate emissions within the domain for 2014.

The analysis of the data included preprocessing, voyage determinations, inbound/outbound determinations, activity calculations, and emission calculations. The processes and details associated with each of these steps are provided in the following subsections.

2.1 Data Preprocessing

The data received from Oceaneering included 127.3 million records of vessel movements during 2014 within the requested domain (shown in Figure 3). Initially, these data were cross-referenced with the Fairplay registry data to obtain additional vessel characteristics. Once cross-referenced, the data were reduced by eliminating vessels having gross tonnage (GT) less the 495, effectively removing off-shore support vessels, tugs, and other small vessels.

This phase did not involve reducing data to the "Water-side Domain" shown in Figure 3. While reducing the data in this way would make the data set much more manageable, the data outside of the domain was kept to aid in determining individual vessel transects, or voyages, across the domain.

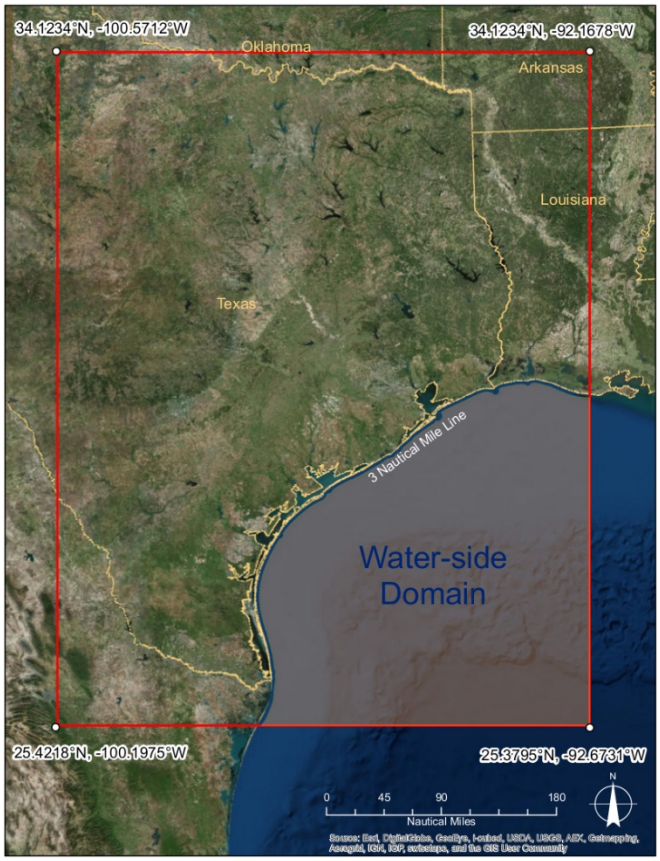

Figure 3. AIS Data Extent

2.2 Voyage Determination

Individual vessel voyages across the domain were established to enable the ability to calculate time-in-mode speed profiles. Here, a voyage is defined as an individual vessel's contiguous set of points traversing the domain (i.e., a voyage will not exit and reenter the domain). This definition of a voyage allows for the classification of distinct inbound and outbound movements.

Initially, the data were sorted so each of the vessels movements was ordered by date and time. The criteria for determining a voyage were:

1. If a sample is outside of the domain it is not part of a voyage
2. If a sample is within the domain and has a different vessel identification number than the previous sample, or if the sample is within the domain and the previous sample is outside of the domain, it is a new voyage.

With the voyages established, the remaining AIS data records outside of the "water-side domain" were removed. Additionally, any voyage which was comprised of 10 records or fewer (usually less than an hour of time in the domain) was dropped and assumed incomplete.

2.3 Inbound/Outbound Calculation

The voyages were used to determine whether a vessel was inbound or outbound within the domain. Speed profiles of different vessel types were expected to differ between inbound and outbound voyages. By distinguishing inbound and outbound these speed profiles could be assessed.

The voyages were designated as inbound or outbound based on the bearing between the first and last locations of the individual voyages. As ships travelled in many directions during a voyage, using the initial and final points provided a more consistent method of identifying the direction of the vessel and prevented miscategorization of voyages due to individual data points' instantaneous headings. Once bearing was established, inbound voyages were assumed to have a bearing between 200 to 360 and 0 to 20 degrees (measured from north, so vessels heading north and west). Conversely, outbound voyages were assumed to have a bearing between 20 and 200 degrees.

2.4 Activity Analysis

The activity, in kilowatt-hours, was determined between each data record of a voyage for use with the emission factors. The point to point vessel transiting time duration was calculated using the difference in time stamps between sequential records for a voyage. Engine energy was calculated for the propulsion engines, auxiliary engines, and boilers using load (in kW) multiplied by the time for each sequence. Details of how energy was calculated are provided in the following subsections.

2.4.1 Propulsion Engines

The propulsion engine activity considered the total main engine power and load factor. The main engine power was reported for nearly all of the vessels by the Fairplay registry data. Where gaps in the engine power existed (for 0.3% of the cases), the EPA's Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories (EPA CMEI, 2009) provided estimates by vessel type, shown in Table 1.

Table 1. EPA Default Propulsion and Auxiliary Engine Power

Ship Type	Average Propulsion Engine (kW)	Average Auxiliary Engines			Engine Speed	Auxiliary to Propulsion Ratio
		Number	Power Each (kW)	Total Power (kW)		
Auto Carrier	10,700	2.9	983	2,850	Medium	0.266
Bulk Carrier	8,000	2.9	612	1,776	Medium	0.222
Container Ship	30,900	3.6	1,889	6,800	Medium	0.220
Cruise Ship	39,600	4.7	2,340	11,000	Medium	0.278
General Cargo	9,300	2.9	612	1,776	Medium	0.191
RORO	11,000	2.9	983	2,850	Medium	0.259
Reefer	9,600	4	975	3,900	Medium	0.406
Tanker	9,400	2.7	735	1,985	Medium	0.211

The load factor associated with these engines was calculated using the Propeller Law:

$$Load\ Factor = \left(\frac{Actual\ Speed}{Maximum\ Speed}\right)^3$$

The actual speed was provided within the AIS data. Cruise, or service, speed is reported in the Fairplay registry data and is taken as 94% of maximum speed. (EPA CMEI, 2009) Back calculation of the maximum speed allowed the load factor to be determined for each record. Multiplying the propulsion power by the load factor provided an initial estimate of activity. Additional adjustments due to engine inefficiency at low loads are taken into account on a per pollutant basis as discussed in section 2.5.

2.4.2 Auxiliary Engines and Boilers

The auxiliary and boiler power reported within Fairplay registry data is often incomplete and, in some cases, erroneous. In an effort to obtain complete power data for the AIS records, the auxiliary and boiler power was taken, by vessel type, from the EPA CMEI shown in Table 2 and Table 3. Similarly, the auxiliary engine load factors were taken from EPA CMEI defaults and were delineated by speed bin. This study binned speeds as cruise (>= 12 knots), reduced speed zone (>= 9 knots and < 12 knots), or maneuvering (> 1 knots and < 9 knots) and associated them with the respective loads provided in the EPA CMEI. The default boiler energy consumption rate reported within the EPA CMEI was derived from fuel use data, thus the load was determined without the use of a load factor. Activity from boilers was only calculated for vessels in maneuvering and hoteling modes because boilers are not expected to be used when the propulsion engines are generating sufficient heat (i.e., during cruising and reduced speed zone movements). The boiler loads are identical for hoteling and maneuvering modes except for tankers where only the maneuvering load was used, because higher hoteling boiler loads for tankers are used to supply the steam pump demand only when tankers are off-loading product, such as during lightering operations. Lightering operations were not included in the emission estimates developed for this work.

Table 2. Auxiliary Engines Load Factors

Ship Type	Cruise	RSZ	Maneuver	Hotel
Auto Carrier	0.15	0.30	0.45	0.26
Bulk Carrier	0.17	0.27	0.45	0.10
Container Ship	0.13	0.25	0.48	0.19
Cruise Ship	0.80	0.80	0.80	0.64
General Cargo	0.17	0.27	0.45	0.22
Miscellaneous	0.17	0.27	0.45	0.22
OG Tug	0.17	0.27	0.45	0.22
RORO	0.15	0.30	0.45	0.26
Reefer	0.20	0.34	0.67	0.32
Tanker	0.24	0.28	0.33	0.26

Table 3. Boiler Load (kW)

Ship Type	Cruise	RSZ	Maneuver	Hotel
Auto Carrier	0	0	371	371
Bulk Carrier	0	0	109	109
Container Ship	0	0	506	506
Cruise Ship	0	0	1,000	1,000
General Cargo	0	0	106	106
Miscellaneous	0	0	371	371
OG Tug	0	0	0	0
RORO	0	0	109	109
Reefer	0	0	464	464
Tanker	0	0	371	3,000
Tanker – other	0	0	346	346

2.5 Emissions

Emissions associated with the span between sequential records of a voyage were determined using the activity calculated in the previous section in conjunction with emission factors with units of grams per kilowatt-hour. The appropriate emission factors were selected based on the engine speed, fuel, fuel sulfur content (1.0% in 2014), and propulsion engine load. The precontrolled engine emission factors are presented in Table 4.

Table 4. Precontrolled Engine Emission Rates (g/kW-hr)

Engine Type	Fuel Type	Fuel Sulfur	NOx	PM_{10}	$PM_{2.5}$	HC	CO	SOx	CO_2	BSFC
Slow Speed Diesel	RO	2.70%	18.1	1.42	1.31	0.6	1.4	10.29	620.62	195
	MDO	1.00%	17.0	0.45	0.42	0.6	1.4	3.62	588.79	185
	MGO	0.50%	17.0	0.31	0.28	0.6	1.4	1.81	588.79	185
	MGO	0.10%	17.0	0.19	0.17	0.6	1.4	0.36	588.79	185
Medium Speed Diesel	RO	2.70%	14.0	1.43	1.32	0.5	1.1	11.24	677.91	213
	MDO	1.00%	13.2	0.47	0.43	0.5	1.1	3.97	646.08	203
	MGO	0.50%	13.2	0.31	0.29	0.5	1.1	1.98	646.08	203
	MGO	0.10%	13.2	0.19	0.17	0.5	1.1	0.4	646.08	203
Gas Turbine	RO	2.70%	6.1	1.47	1.35	0.1	0.2	16.1	970.71	305
	MDO	1.00%	5.7	0.58	0.53	0.1	0.2	5.67	922.97	290
	MGO	0.50%	5.7	0.35	0.32	0.1	0.2	2.83	922.97	290
	MGO	0.10%	5.7	0.17	0.15	0.1	0.2	0.57	922.97	290
Steam Turbine, & Auxiliary Boiler	RO	2.70%	2.1	1.47	1.35	0.1	0.2	16.1	970.71	305
	MDO	1.00%	2.0	0.58	0.53	0.1	0.2	5.67	922.97	290
	MGO	0.50%	2.0	0.35	0.32	0.1	0.2	2.83	922.97	290
	MGO	0.10%	2.0	0.17	0.15	0.1	0.2	0.57	922.97	290
Auxiliary	RO	2.70%	14.7	1.44	1.32	0.4	1.1	11.98	722.54	227
	MDO	1.00%	13.9	0.49	0.45	0.4	1.1	4.24	690.71	217
	MGO	0.50%	13.9	0.32	0.29	0.4	1.1	2.12	690.71	217
	MGO	0.10%	13.9	0.18	0.17	0.4	1.1	0.42	690.71	217

The engine speed, in revolutions per minute, was largely provided by the Fairplay registry data. Records were defined as slow (<130 RPM), medium (130 - 1,400 RPM), or high (>1,400 RPM) based on the reported engine speed. Gaps in the Fairplay registry were filled by checking the engine stroke type. For Fairplay data reporting 2-stroke engines, slow speed was assumed and if reporting 4-stroke, medium speed was assumed. While 4-stroke engines could be medium or high, medium was selected since it is much more prevalent in OGVs' propulsion engines. For the remaining records lacking either engine speed or stroke type within the Fairplay registry, the engine speeds were filled using the most frequent engine speed within the populated records (counted by engine speed by voyage, not by record).

When a load factor is calculated to be below 20%, OGV engine efficiency worsens and emission rates are adjusted upwards. To account for this worsening efficiency, low load multiplicative adjustment factors were applied to records with such loads. These factors are shown in Table 5.

Table 5. Low-Load Emission Factor Adjustments (EPA CMEI, 2009)

Load	NOx	HC	CO	PM	SO_2	CO_2
1%	11.47	59.28	19.32	19.17	5.99	5.82
2%	4.63	21.18	9.68	7.29	3.36	3.28
3%	2.92	11.68	6.46	4.33	2.49	2.44
4%	2.21	7.71	4.86	3.09	2.05	2.01
5%	1.83	5.61	3.89	2.44	1.79	1.76
6%	1.60	4.35	3.25	2.04	1.61	1.59
7%	1.45	3.52	2.79	1.79	1.49	1.47
8%	1.35	2.95	2.45	1.61	1.39	1.38
9%	1.27	2.52	2.18	1.48	1.32	1.31
10%	1.22	2.20	1.96	1.38	1.26	1.25
11%	1.17	1.96	1.79	1.30	1.21	1.21
12%	1.14	1.76	1.64	1.24	1.18	1.17
13%	1.11	1.60	1.52	1.19	1.14	1.14
14%	1.08	1.47	1.41	1.15	1.11	1.11
15%	1.06	1.36	1.32	1.11	1.09	1.08
16%	1.05	1.26	1.24	1.08	1.07	1.06
17%	1.03	1.18	1.17	1.06	1.05	1.04
18%	1.02	1.11	1.11	1.04	1.03	1.03
19%	1.01	1.05	1.05	1.02	1.01	1.01
20%	1	1	1	1	1	1

The emissions spanning from one point to the next within a voyage were estimated by multiplying the record-specific activity data and emission factor. The resulting emissions segments for each voyage, by vessel type, were aggregated into a 4 kilometer grid overlaying the TCEQ domain to get total emissions by grid cell.

3.0 RESULTS

3.1 Vessel Activity

The AIS data was initially analyzed to assess each vessel's movement activity within the domain. By classifying a voyage based on the criteria discussed in section 2.3, inbound and outbound movements were distinguished and instances where the same vessel visited the domain more than once were isolated. Diagrams of the voyages, by vessel-type, are provided in Appendix A.

Using the distinct inbound and outbound voyages, time-in-mode speed profiles were developed. These profiles provided an initial, qualitative check on the efficacy of the voyage splitting methodology. The maximum speed bin of each speed profile agreed with the typical design speed of each vessel type and, generally, demonstrated that outbound speeds exceed inbound speeds. However, overall speeds, and therefore engines loads, are lower than one would estimate using the vessel cruise speed from the Fairways database of vessel characteristics. The average speed-profile plots, by vessel type, are provided in Appendix B and show that ships spend significant time transiting below the designed cruise speed.

3.2 Vessel Emissions

Following the methodology described in the section 2.4 and 2.5, emissions were calculated between each vessel's sequential records within the study domain. The domain-wide emission totals are provided in Table 6. Emissions were formatted for use with the photochemical modeling system used by the TCEQ. The TCEQ conducts ozone modeling using the Comprehensive Air Quality Model with extensions (CAMx[5]) and prepares emission inventories for CAMx using the Emissions Processor System v3 (EPS3[6]).

EPS3 has a data input module for shipping emissions (PRESHP) that allows emissions to be located in shipping lanes (i.e., a link connecting two points that has non-zero width) or as gridded points. Formatting emissions in PRESHP provides flexibility because emissions can be gridded to any CAMx domain, plume rise (i.e., model layer distributions) and temporal distribution factors can be applied.

[5] http://www.camx.com/
[6] ftp://amdaftp.tceq.texas.gov/pub/HGB8H2/ei/EPS3_manual/EPS3UG_UserGuide_200908.pdf

Table 6. 2014 Domain-wide OGV Emissions

Vessel Type	Domain-wide 2014 Emissions (tons/day)						
	NO_x	HC	CO	PM_{10}	$PM_{2.5}$	SO_2	CO_2
Bulk	7.8	0.3	0.7	0.3	0.3	2.3	373
Cargo	3.4	0.1	0.3	0.1	0.1	1.1	183
Container	8.2	0.4	0.8	0.3	0.3	2.2	358
Container/Cargo	0.3	0.01	0.03	0.01	0.01	0.1	14
Cruise	4.6	0.2	0.4	0.2	0.2	1.6	259
RoRo	1.6	0.1	0.2	0.1	0.05	0.4	69
Tanker	27.6	1.1	2.6	1.2	1.1	10.0	1,624
Tanker Crude	25.0	1.0	2.4	1.0	1.0	8.9	1,441
Tanker LNG/LPG	4.5	0.2	0.4	0.2	0.2	1.5	244
Total	**83.1**	**3.4**	**8.0**	**3.3**	**3.1**	**28.1**	**4,564**

The emissions from the AIS activity were distinguished between transiting and anchorage. Anchorage was defined as any movement at or below 1 knot and most frequently occurred near shore. As expected, the percentage of emissions due to anchorage away from shore was elevated for tanker vessel types. In part, this may be due to the process of lightering large tankers, but, regardless of the reason, these ships lie at anchor more than other types of ships. The contribution of anchorage emissions as a percent of the domain-wide total emissions is provided in Table 7.

Table 7. Anchorage Contribution to Domain-Wide Emissions

Vessel Type	2014 Anchorage Emissions (% of Total)						
	NO_x	HC	CO	PM_{10}	$PM_{2.5}$	SO_2	CO_2
Bulk	12.0%	10.2%	11.6%	21.2%	21.0%	23.4%	23.4%
Cargo	16.9%	14.0%	16.2%	24.3%	24.2%	26.0%	26.1%
Container	3.6%	2.6%	3.2%	5.8%	5.7%	6.5%	6.6%
Container/Cargo	1.1%	0.9%	1.1%	2.7%	2.6%	3.0%	3.1%
Cruise	1.0%	0.8%	1.0%	1.1%	1.1%	1.1%	1.1%
RoRo	5.2%	4.1%	4.9%	7.3%	7.2%	8.0%	8.0%
Tanker	26.3%	22.9%	25.4%	43.1%	42.7%	46.3%	46.3%
Tanker Crude	35.1%	28.9%	33.4%	48.6%	48.3%	51.9%	52.0%
Tanker LNG/LPG	19.8%	17.2%	19.2%	34.3%	34.0%	37.2%	37.2%

The individual link-level emissions were allocated to a grid with a 4 kilometer resolution. Examples of the gridded emissions is provided in Figure 4 and vessel-type plots are provided in Appendices C and D. The emissions derived from this work were produced in EPS-ready format as a part of the deliverable to TCEQ.

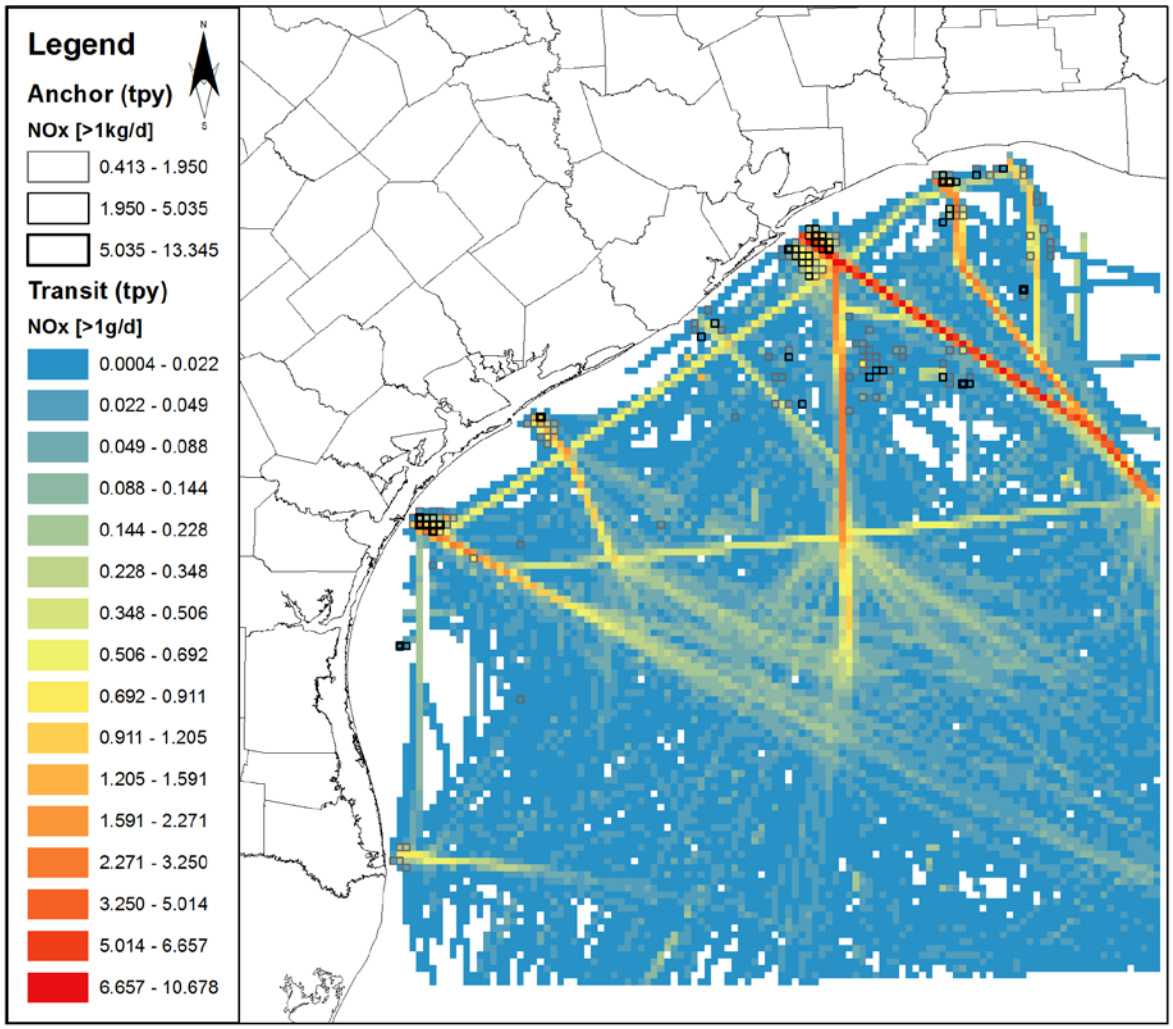

Figure 4. Gridded Transit and Anchorage NOx Emissions (tpy)

4.0 FORECASTS

Marine emission forecasts are often based on the predicted change in vessel activity and expected emission reductions due to scheduled changes in policy. Vessel activity can be approximated using broad economic growth estimates (e.g., gross state product) and can be refined to ship-type detail by assessing the trends of the associated commodities which the ship types serve. Here, we assessed how the tonnage of cargo moved by ship-type varied from 2008 to 2012 in an effort to understand how each commodity was trending. These trends were contrasted against the gross state product (GSP) and were used to inform future year activity estimates. Additionally, policy implications on emission rates were assessed for engine NOx controls and fuel sulfur limits. The resulting activity forecast and emission rates for 2012 and 2023 were compiled as scaling values for use with the AIS-derived 2014 gridded emissions.

The broad economic growth trends and, importantly, forecasts were taken from the Texas GSP estimates, shown in Table 8. Additionally, Table 8 provides the GSP relative to both 2008 and 2014. The GSP relative to 2008 provides a means for comparing the broad economic trends to the ship-type data provided in Table 9. The GSP relative to 2014 provides a mechanism for forecasting from the AIS-derived 2014 emissions to future years.

Table 8. Gross State Product (Billion 2009$)[7]

Estimate	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
GSP	1,338.6	1,386.5	1,439.3	1,477.2	1,532.9	1,590.2	1,634.8	1,683.4	1,740.5	1,792.4	1,846.8	1,902.8
Rel. to 2014	0.93	0.96	1.00	1.03	1.07	1.10	1.14	1.17	1.21	1.25	1.28	1.32
Rel. to 2008	1.14	1.18	1.23									

To assess type-specific trends in vessel activity, tonnage data[8] for the Texas ports were used to compare yearly shipments from 2008 through 2012, as shown in Table 9. Bulk and crude tanker transfers were volatile during the five year period and ultimately decreased from 2008 to 2012. Crude tanker shipments were relatively flat because increased domestic shipments offset decreased imports due to domestic oil production. Cargo tonnage and vehicle roll-on/roll-off (RoRo) ship activity reduced from 2008 to 2009, but recovered from 2010 to 2012. Tankers Other (which carry products such as distillate fuel and chemicals) and LNG/Other Gases tankers showed consistent increases.

[7] http://www.texastransparency.org/State_Finance/Budget_Finance/Reports/Forecasts/2014-15/
[8] http://www.navigationdatacenter.us/wcsc/wcsc.htm

Table 9. All Texas Ports Tonnage Relative to 2008[4]

Ship Type	2008	2009	2010	2011	2012	Compared to State Economy
Bulk	1	0.77	0.92	0.97	0.84	Lower
Cargo (and includes Container and Break Bulk)	1	0.56	0.69	0.79	0.92	Lower/ Recovering
RoRo (Vehicles)	1	0.87	1.09	1.16	1.35	Higher
Tankers Other	1	1.04	1.12	1.21	1.17	Similar
Tankers Crude	1	0.98	1.02	0.91	0.95	Lower
Tankers LNG/Other Gases	1	1.14	1.49	1.57	1.93	Higher
			2012	**2013**	**2014**	
Container Houston (TEU)			1,922,529	1,950,071	1,951,088	Lower
Cruise Houston/Galveston (Passengers)				1,235,706	1,396,527	Higher (One year)

Bulk, crude oil tankers, and cargo tonnage decreased during from 2008 to 2012 and, despite some variability in the intervening years, an assumption of no growth from 2012 was selected for these vessel types given that the decrease over that 4 year period was small. In contrast, RoRo and compressed LNG/LPG tankers both showed increased activity, and so a higher growth trend from 2012 to future years was selected for those ships. General cargo, including container ships, showed a decrease from 2008 to 2009, but total freight moved increased yearly beginning in 2009, so the overall economic growth trend was selected as a reasonable estimate of cargo movements in the future. Lastly, tankers that carry petroleum products and chemicals (majority of Texas ports freight across all ship types) closely mimicked the state economic growth from 2008 to 2012 and the future vessel activity is expected to continue trending with the forecast GSP. The ship backcast and forecast activity estimates are summarized in Table 10.

Table 10. Ship Activity by Type Relative to 2014

Ship Type	2012	2014	2023
Bulk	1.00	1	1.00
Cargo (and includes Container and Break Bulk)	0.93	1	1.32
RoRo (Vehicles)	0.87	1	1.64
Tankers Other	0.93	1	1.32
Tankers Crude	1.00	1	1.00
Tankers LNG/Other Gases	0.87	1	1.64

4.1.1 Emissions Forecasting

Emissions from ship engines and boilers have been regulated by the International Maritime Organization (IMO)[9], which has limited fuel sulfur levels and new ship engine NOx emission rates as well as other air emissions from ships including those from incineration, tanker venting, and ozone depleting substances. IMO regulations set worldwide maximum fuel sulfur levels

[9] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx

and NOx emission rates, and more stringent emission standards when ships operate within emission control areas (ECAs).

For the US waters, an ECA was declared and began implementation, with the first level of fuel sulfur limits that began in August 2012 with further control beginning in 2015:

- Late 2012 <10,000 ppm (1.0%) sulfur
- 2015 <1,000 ppm

NOx emission standards for Tier I and II apply worldwide and Tier III engine NOx emission rates limits apply when operating within an ECA. The Tier emissions standards are outlined in Table 11. Applying these emission levels for current and especially future years requires estimates of the ship fleet age distributions.

Table 11. International NOx Emission Limits for Ship Engines

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	January 1, 2000	17.0	$45 \times n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	January 1, 2011	14.4	$44 \times n^{(-0.23)}$ e.g., 720 rpm – 9.7	7.7
III	January 1, 2016 when operating in an ECA	3.4	$9 \times n^{(-0.2)}$ e.g., 720 rpm – 2.4	2.0

The emission factors used for the 2014 emission inventory estimates assumed 1.0% sulfur content fuel and the EPA estimated emission reduction from unregulated NOx emission rates. The application or determination of the fleet age distribution is not straightforward because each ship transit was used in this work and has a unique activity profile as well as a ship or engine model year. Therefore, we applied average NOx levels forecasted by EPA (2009) when evaluating the impact of the international emission regulations and ECA designation.

The emission control scenarios used for this work are based on EPA (2009) forecasted emission factor adjustments shown in Table 12. The ECA includes nearly the entire region modeled, and therefore all activity was assumed to be governed by the ECA. The ECA was declared in EPA rulemaking with international approval in 2009, and emissions and fuel controls within the ECA began in August 2012 with a fuel sulfur limit of 1.0%. Additional fuel sulfur limits to 0.1% sulfur began in 2015 and require NOx controls for new ships built in 2016 or later. Ship NOx emissions were adjusted by the emission reductions shown in Table 12. Interpolation of the NOx reduction estimates were used to estimate emission control factors for 2012, 2014, and 2023.

EPA had assumed 1.0% sulfur would be used in 2010, but the implementation of the ECA did not begin until fall of 2012. We incorporated the effect of using 1% sulfur fuel in the 2014 emission inventory, equivalent to the PM reductions shown for 2010 in Table 12. For 2012, we assumed no further fuel sulfur limits for the entire year even though fuel sulfur should have been lower for the latter part of the year. The final implementation schedule required 1,000

ppm (0.1%) fuel sulfur or equivalent engine particulate matter (PM) control beginning in 2015, benefits of which are included in forecasted 2023 emissions.

Table 12. PM and NOx Scaling Factors for Pre-controlled, 1% Sulfur Emission Factors (EPA 2009)

Main	2010 PM EF ECA	2010 NOx EF ECA	2015 PM EF ECA	2015 NOx EF ECA	2020 PM EF ECA	2020 NOx EF Baseline	2020 NOx EF ECA	2030 NOx EF ECA
SSD (slow speed diesel)	0.3169	0.8750	0.1352	0.8020	0.1352	0.9037	0.5967	0.3138
MSD (medium speed diesel)	0.3287	0.8750	0.1328	0.8020	0.1328	0.8987	0.5515	0.2559
ST (steam boiler)	0.3946	1	0.1108	1	0.1108	1	0.9524	0.9524
GT (gas turbine)	0.3946	1	0.1108	1	0.1108	1	0.9344	0.9344
Auxiliary								
Pass (passenger)	0.3287	0.8767	0.1328	0.8059	0.1328	0.9025	0.5869	0.3003
Other (all except passenger)	0.3287	0.8767	0.1550	0.8059	0.1550	0.9025	0.5940	0.3039

*Average estimated as 80% slow speed propulsion, 10% medium speed propulsion, and 10% auxiliary 10,000 ppm required in 2010

Therefore the PM emission factors were determined in a stepwise fashion following the fuel sulfur requirements and implementation years, and NOx emission factors were estimated by interpolation attributed to continuous fleet turnover.

Starting with emission factors for pre-controlled engines using 1.0% (10,000 ppm) sulfur fuel for the fleet operating in 2014, we adjusted the emission factors for other calendar years following the adjustments shown in Table 13. PM adjustment factors reflect uncontrolled fuel sulfur levels for 2012, 1.0% sulfur in 2014, and 0.1% sulfur in 2015 and later. The 2012 emission factors incorporated the use of high sulfur (nominally 2.7% sulfur) fuel, but also account for fleet turnover for Tier I and II engines in the NOx emission factor adjustment for 2012. The 2014 NOx emission factors included fleet average NOx emissions, but there was no adjustment of the PM emission factor because 1.0% fuel sulfur was already considered. The 2023 emission factors include reducing fuel sulfur to 1,000 ppm (0.1%) and continuing fleet turnover to newer engines.

Table 13. Emission Factor Adjustment of NOx and PM Emission Rates with 1.0% Fuel Sulfur Relative to 2014

Emissions	Engine Type	2012	2014	2023
NOx	SSD (slow speed diesel)	1.103	1	0.627
	MSD (medium speed diesel)	1.099	1	0.567
	ST (steam boiler)	1.070	1	0.952
	GT (gas turbine)	1.050	1	0.934
	Auxiliary	**2012**	**2014**	**2023**
	Other (all except passenger)	1.094	1	0.618
	Engine Type	**2012**	**2014**	**2023**
PM	SSD (slow speed diesel)	3.156	1	0.422
	MSD (medium speed diesel)	3.042	1	0.404
	ST (steam boiler)	2.534	1	0.293
	GT (gas turbine)	2.534	1	0.293
	Auxiliary	**2012**	**2014**	**2023**
	Other (all except passenger)	3.042	1	0.367

The results from these forecasts were developed as growth and control tables for use with EPS, providing a method to readily change modeling year scenarios in CAMx. To accomplish the control cross reference, we applied the emission factor adjustments in Table 12 to the 2014 emissions and activity across main and auxiliary engines and boilers to develop relative emissions by ship type and mode (either transiting or at anchor). The relative emissions factors by ship type and mode are shown in Table 14 and can be used as a control factor table, and Table 10 provides an activity growth table.

Table 14. 2012 and 2023 Emission Factors Relative to 2014

Calendar Year[1]	Ship Type	NOx Scaling Factor		PM Scaling Factor[2]	
		Anchorage	Transit	Anchorage	Transit
2012	Bulk	1.086	1.102	2.208	3.132
	Cargo	1.088	1.100	2.386	3.085
	Container	1.089	1.102	2.428	3.128
	Container/Cargo	1.080	1.102	1.921	3.141
	Cruise	1.093	1.097	2.865	3.041
	RoRo	1.092	1.102	2.764	3.131
	Tanker	1.083	1.102	2.062	3.101
	Tanker Crude	1.088	1.101	2.333	3.089
	Tanker LNG/LPG	1.084	1.102	2.087	3.118
2023	Bulk	0.652	0.626	0.626	0.419
	Cargo	0.642	0.604	0.571	0.412
	Container	0.640	0.625	0.558	0.417
	Container/Cargo	0.674	0.627	0.715	0.421
	Cruise	0.623	0.584	0.422	0.392
	RoRo	0.626	0.625	0.454	0.416
	Tanker	0.662	0.624	0.671	0.425
	Tanker Crude	0.645	0.627	0.587	0.427
	Tanker LNG/LPG	0.660	0.624	0.663	0.421

[1] Calendar year scaling values are relative to emission rates calculated for the 2014 emissions developed from the AIS data
[2] PM scaling values are applicable to both PM_{10} and $PM_{2.5}$

5.0 CONCLUSIONS & RECOMMENDATIONS

The AIS analysis allowed for a detailed, spatial inspection of vessel movements and highlighted the benefits and drawbacks of using these data. Data provided by Oceaneering was collected using land-based transponders. These transponders have limited range and a noticeable falloff in AIS data records was observed approximately beyond 100 nautical miles. This resulted in a small low bias in the emission calculated as part of this project. However, AIS data is also collected via satellite. The ability to use satellite data for an annual emission inventory is problematic because satellite retrievals can occur in swaths and may have missing time periods and spatial extents within their data sets. Using both land-based transponders and satellite retrievals together may produce a fuller and more comprehensive depiction of vessel movement than either data set alone.

The transit emission estimates were developed without determining the fraction of cruise ships which are equipped with diesel-electric or gas turbine-electric propulsion. By identifying these engine types, low-load adjustment factors could be removed, thereby decreasing emissions estimates. Also, gas turbines have different emission characteristics compared with diesel engines, though ships equipped with gas turbines also use diesel engines for some or all of the power.

Additionally, the extent of tanker emissions occurring at anchorage could be significant. As mentioned earlier, this may be due to lightering of large tanker vessels by smaller tankers. The lightering process involves transferring liquids which displace the gases within the tankers and may produce significant VOC emissions, thereby contributing to the formation of ozone. The AIS data readily captured the tanker anchorage activity and could be used to derive displacement VOC emissions associated with lightering and increased NOx and PM emissions from increased boiler loads to run steam pumps.

Lastly, the AIS data purchased for 2014 has smaller vessel movements, but perhaps not all such vessels operating off-shore. The ocean-going tug category should be complete and includes articulated and integrated tug and barge as well as standard towboats. The ocean-going tugs move much the same freight as larger ships and over ocean routes, but smaller tugs may be used due to draft depth, Jones Act that requires US flagged vessels to move cargo between US ports, limited dock facilities, or other reasons.

6.0 REFERENCES

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EPA 2009. "Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories," Prepared for U.S. Environmental Protection Agency, Prepared by: ICF International, Final Report, April 2009.

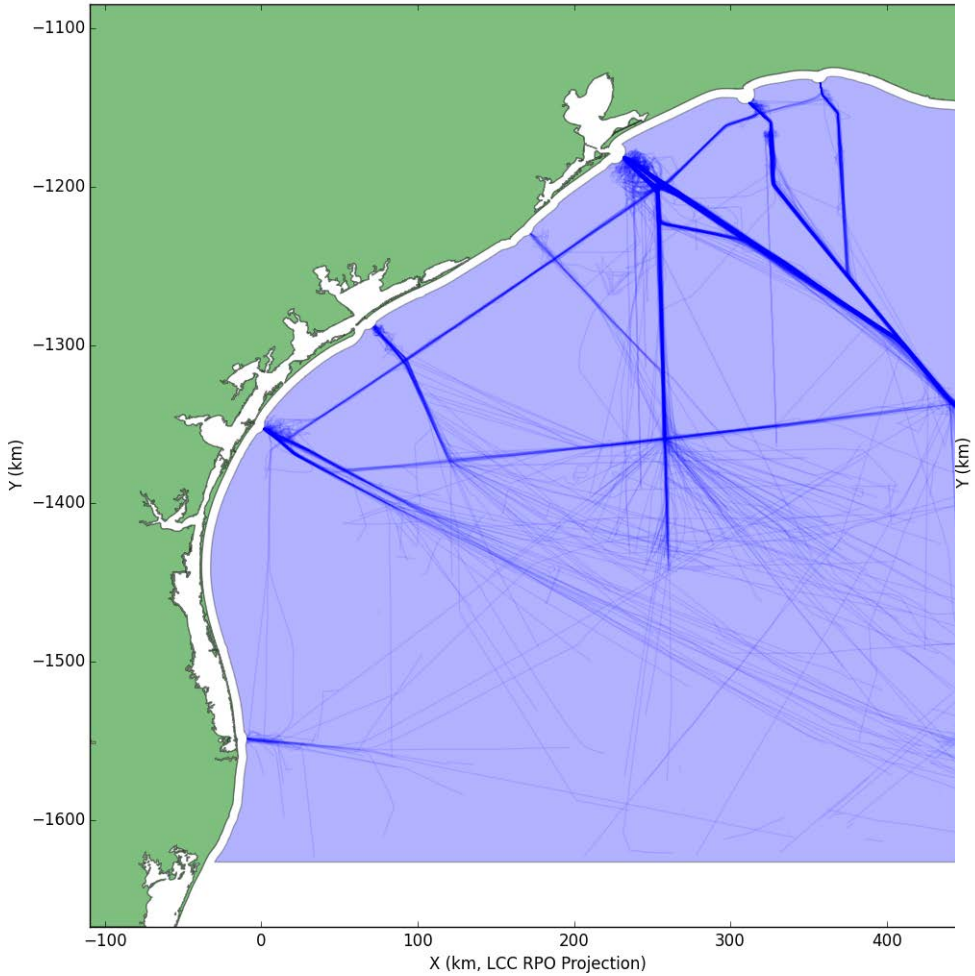
Farooqui, Z.M., John, K., and Sule, N., "Evaluation of Anthropogenic Air Emissions from Marine Engines in a Coastal Urban Airshed of Texas," Journal of Environmental Protection, 2013, 4, 722-731.

Goldsworthy, L. and Goldsworthy, B. 2015, "Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data - An Australian case study," Environmental Modelling & Software 63 (2015).

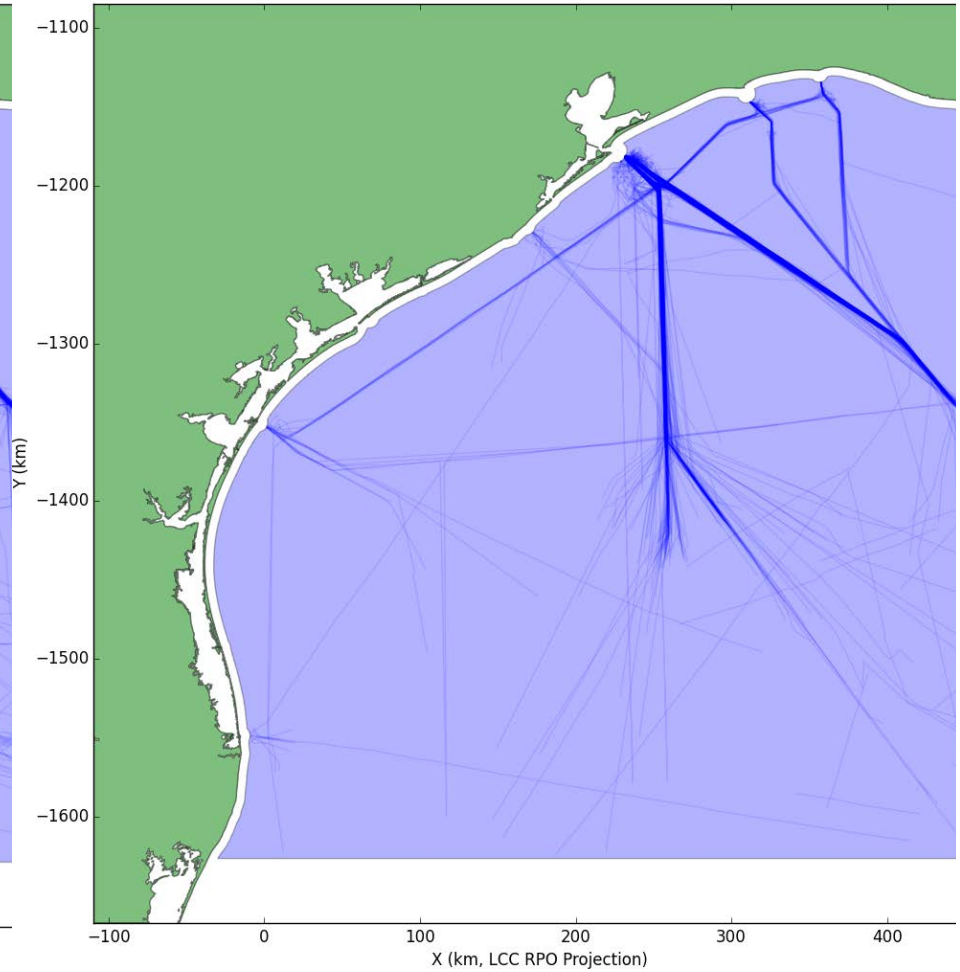
APPENDIX A

AIS Voyage Lines by Vessel Type

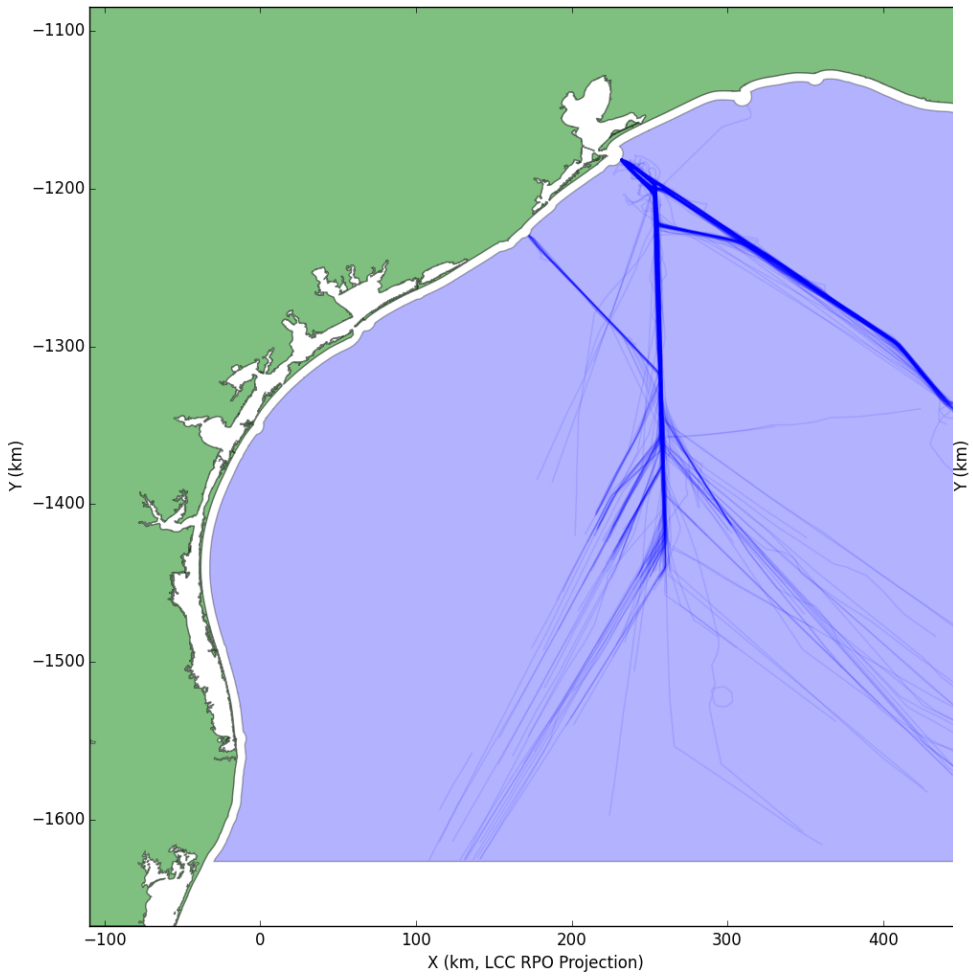
Bulk Vessel Voyage Lines



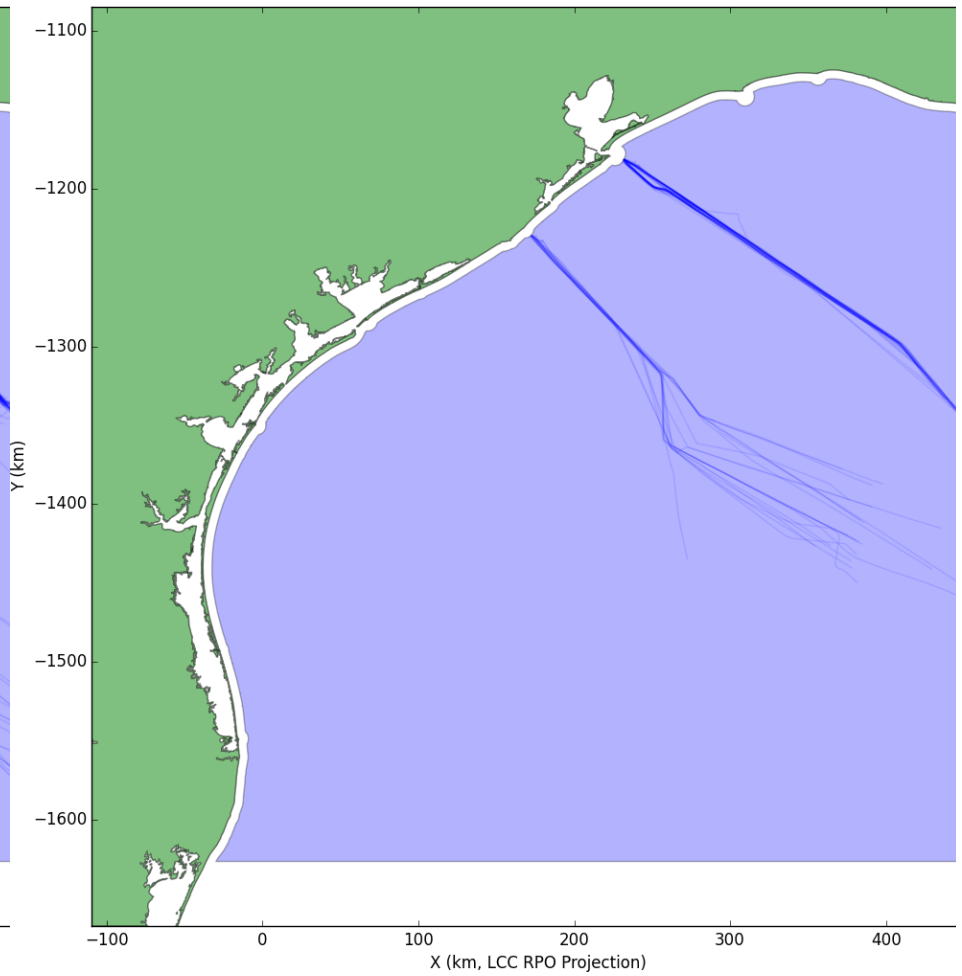
Cargo Vessel Voyage Lines

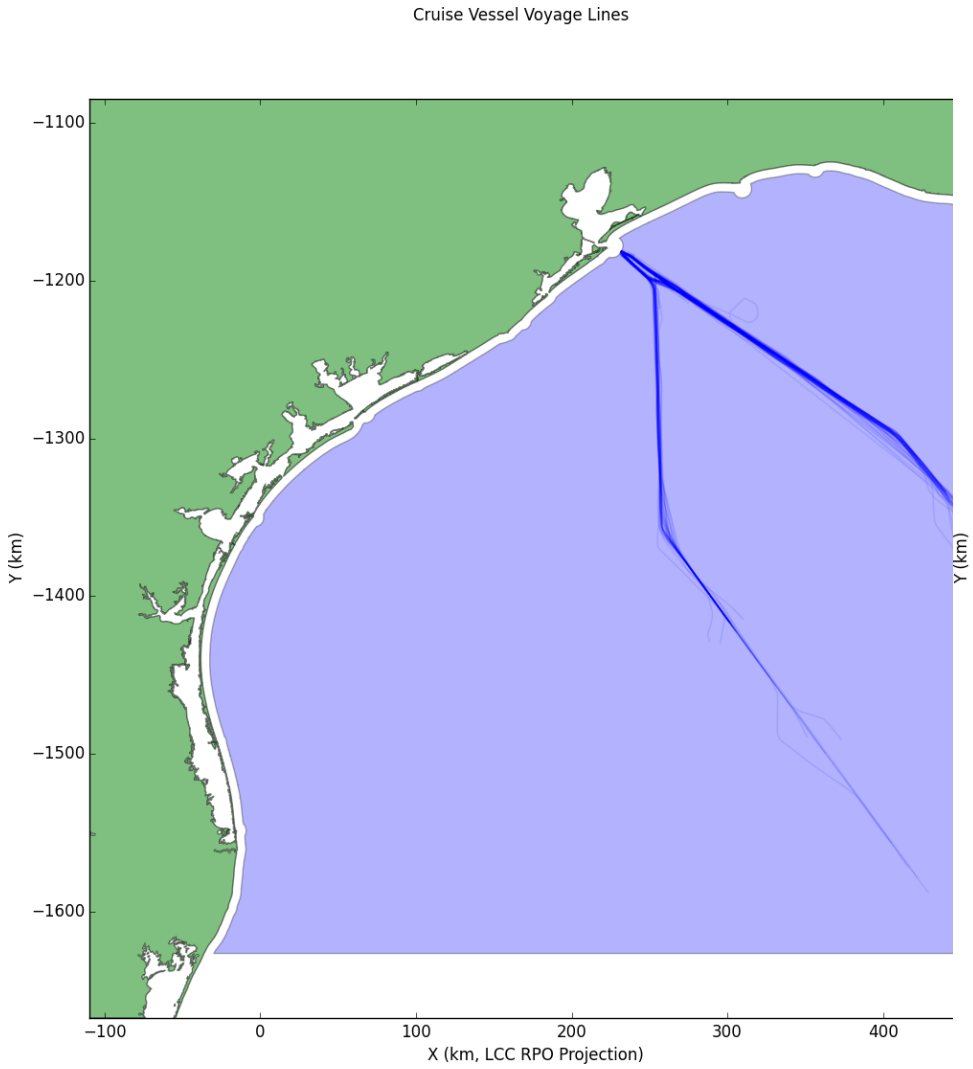


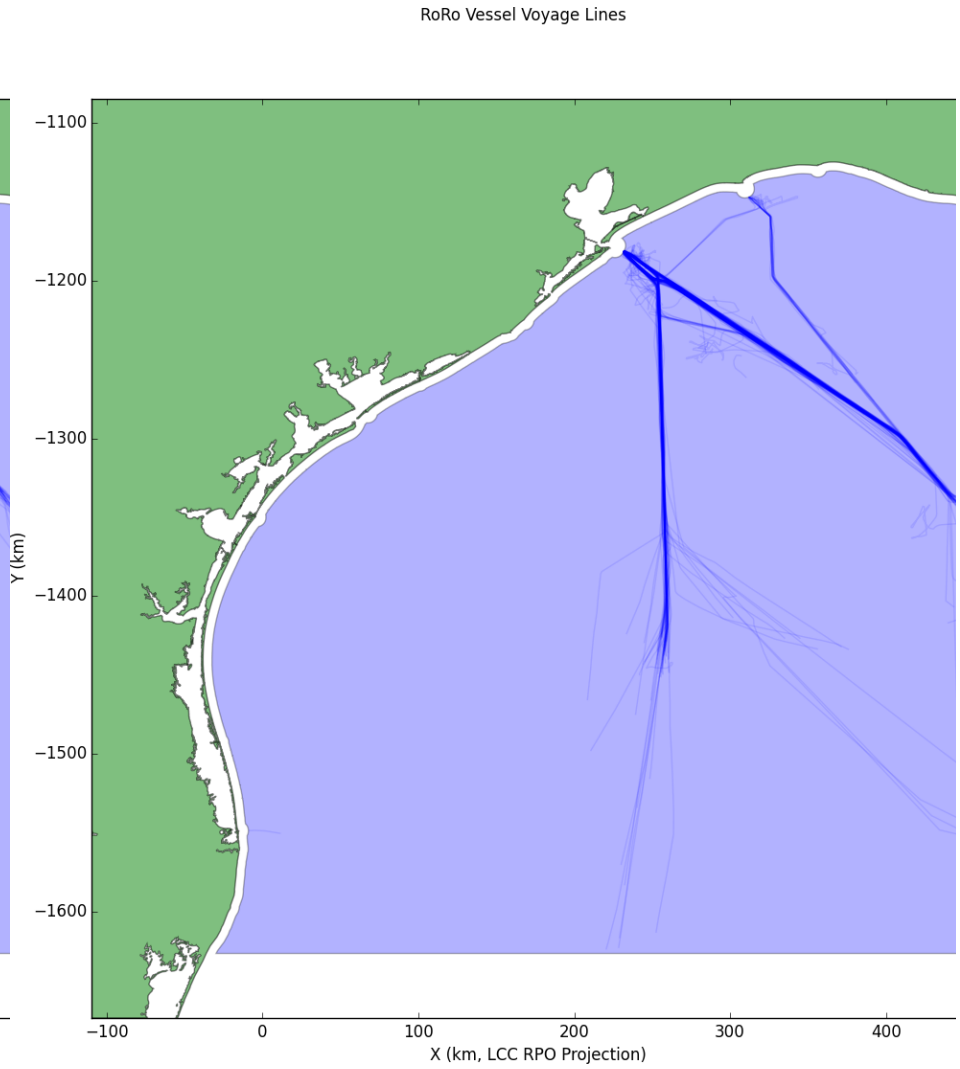
Container Vessel Voyage Lines



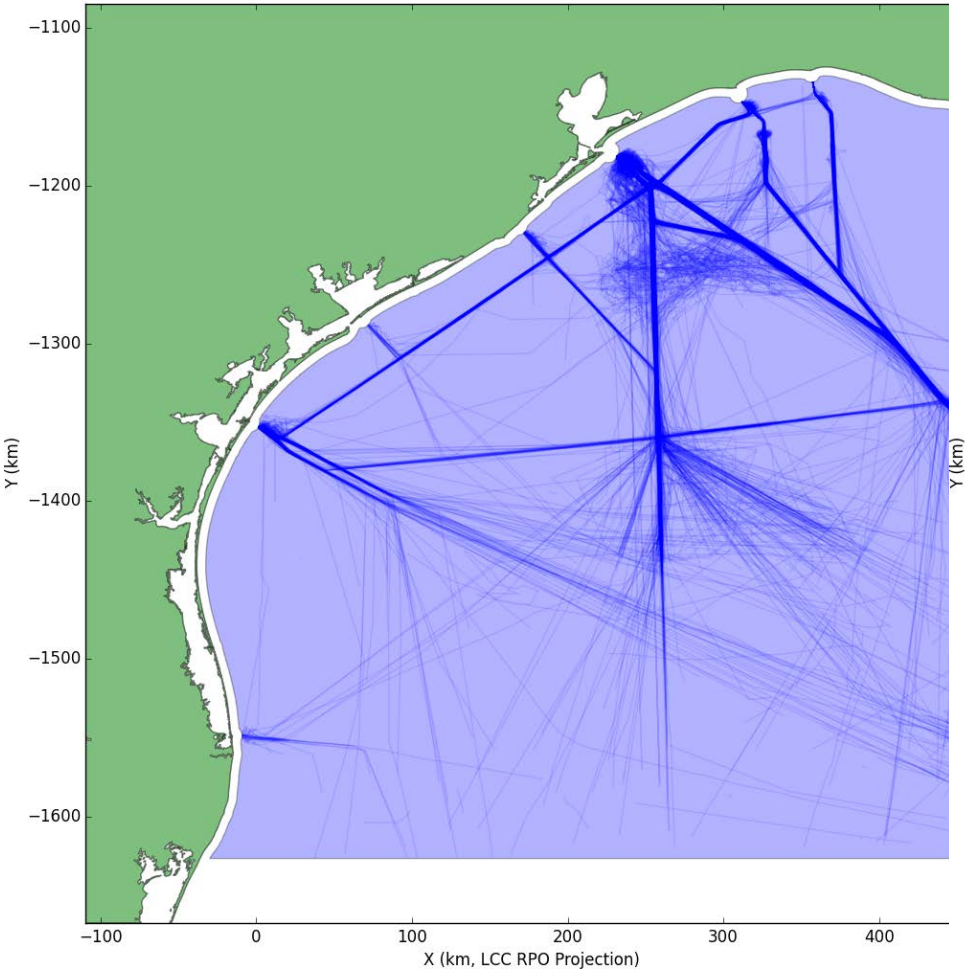
Container/Cargo Vessel Voyage Lines



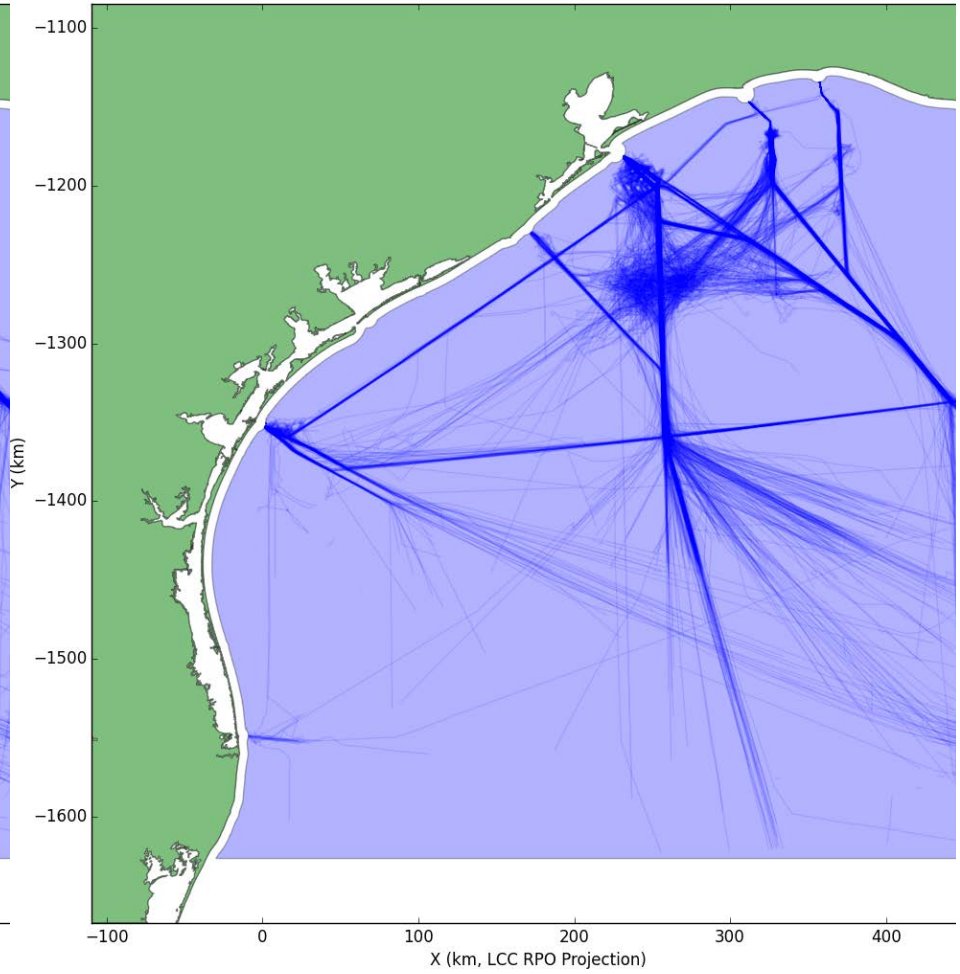

Cruise Vessel Voyage Lines
−1100
−1200
−1300
−1400
−1500
−1600
Y (km)
−100
0
100
200
300
400
X (km, LCC RPO Projection)


RoRo Vessel Voyage Lines
−1100
−1200
−1300
−1400
−1500
−1600
Y (km)
−100
0
100
200
300
400
X (km, LCC RPO Projection)

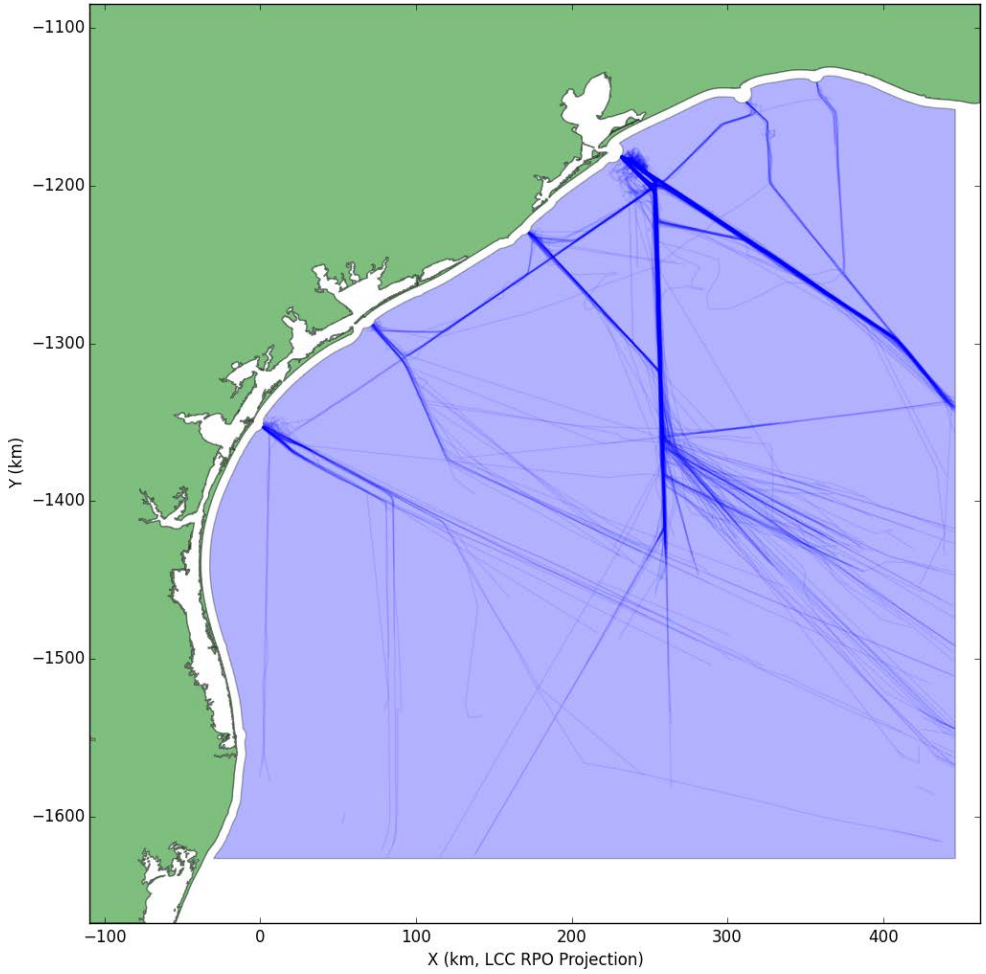
Tanker Vessel Voyage Lines



Tanker Crude Vessel Voyage Lines

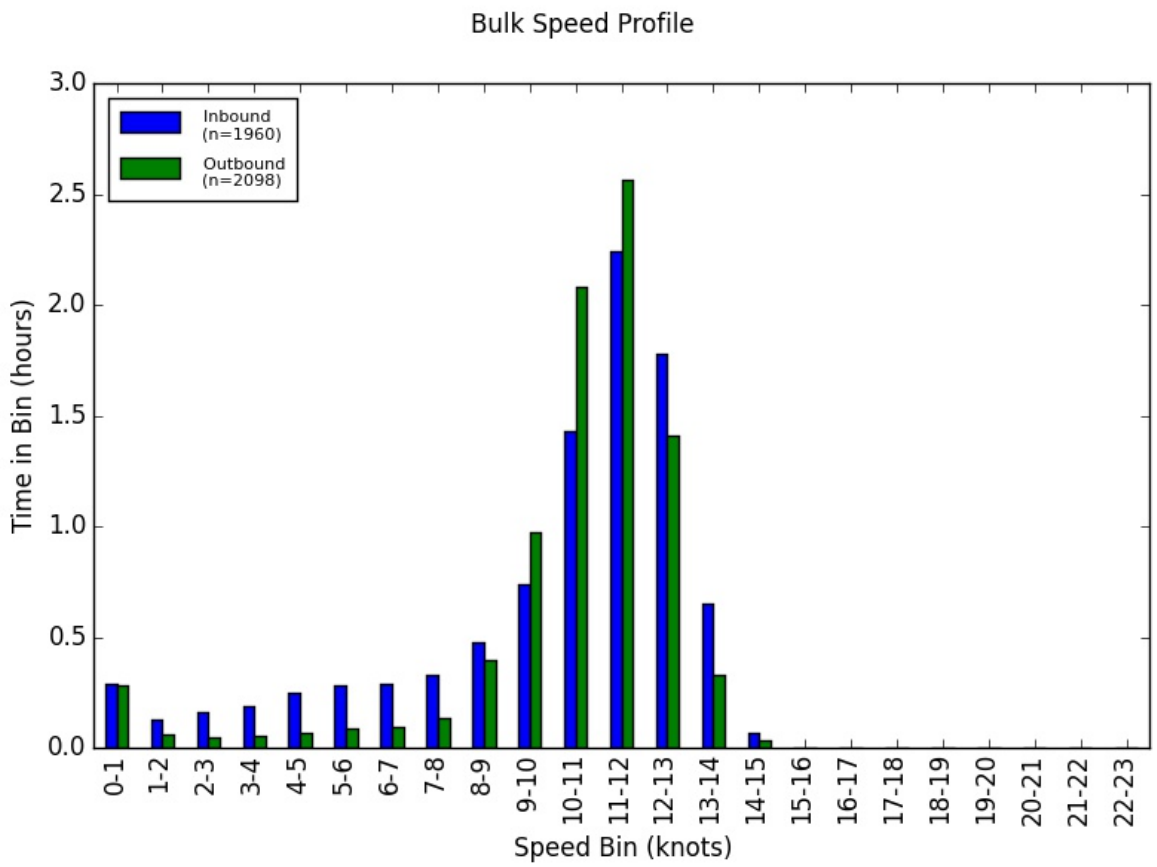


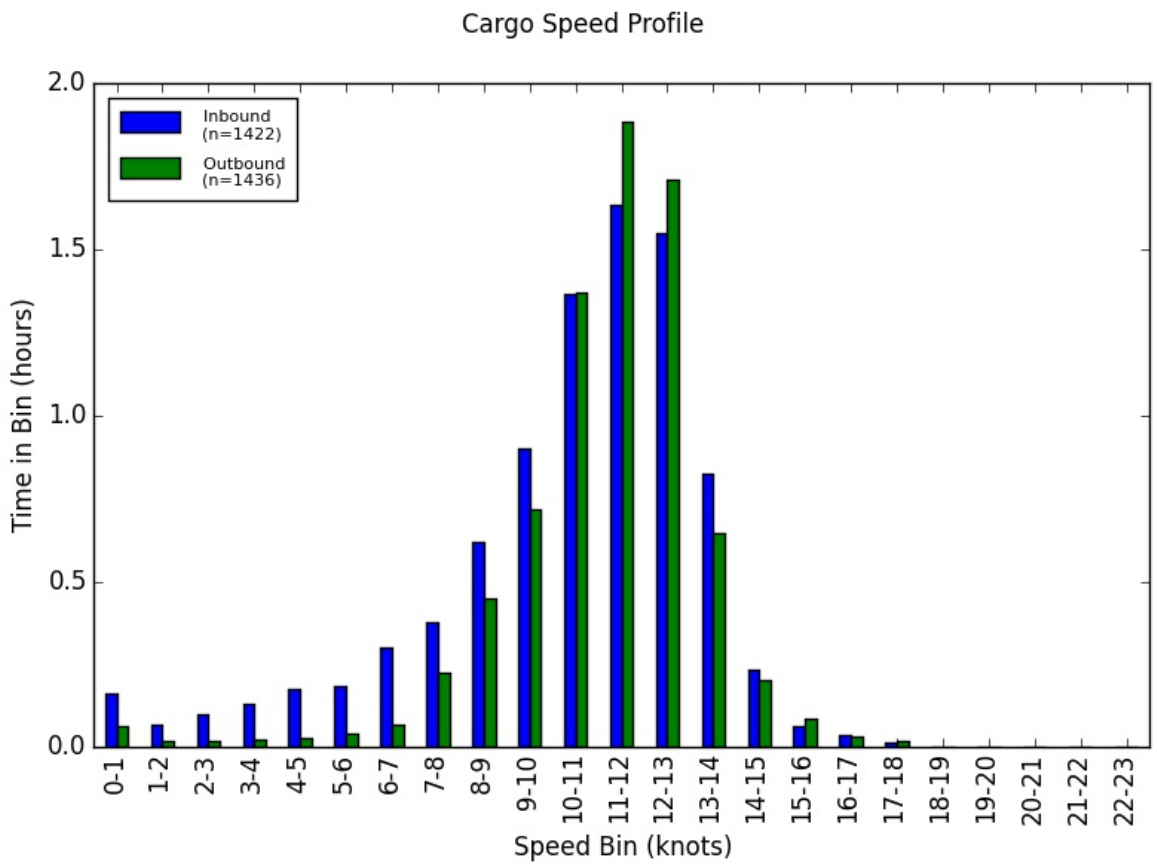
Tanker LNG/LPG Vessel Voyage Lines

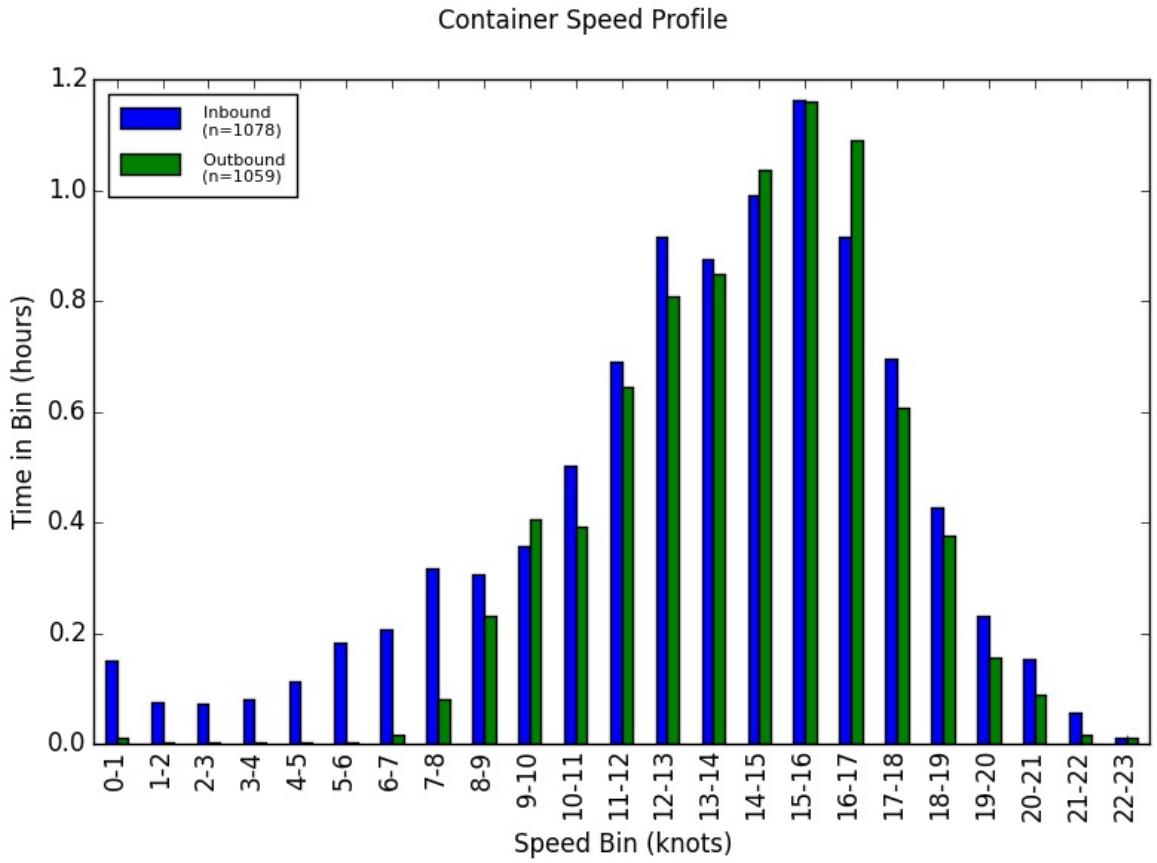


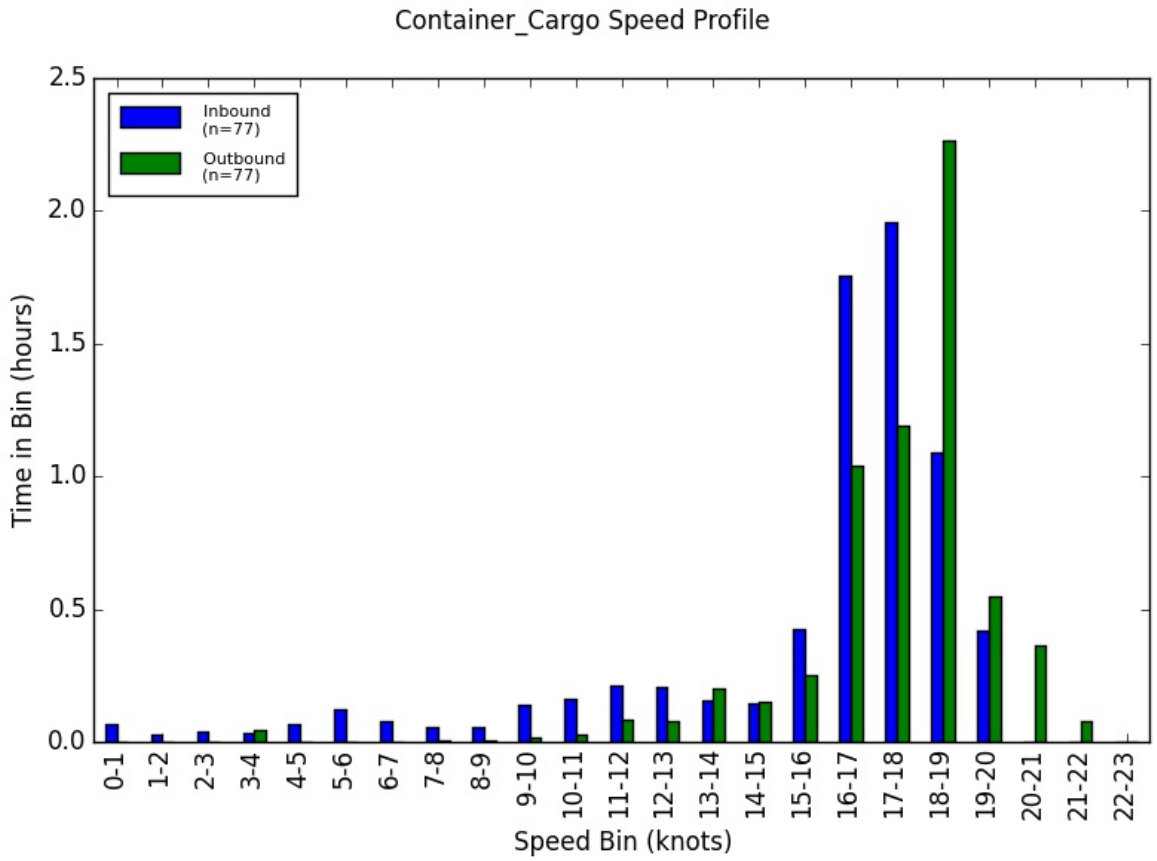
APPENDIX B

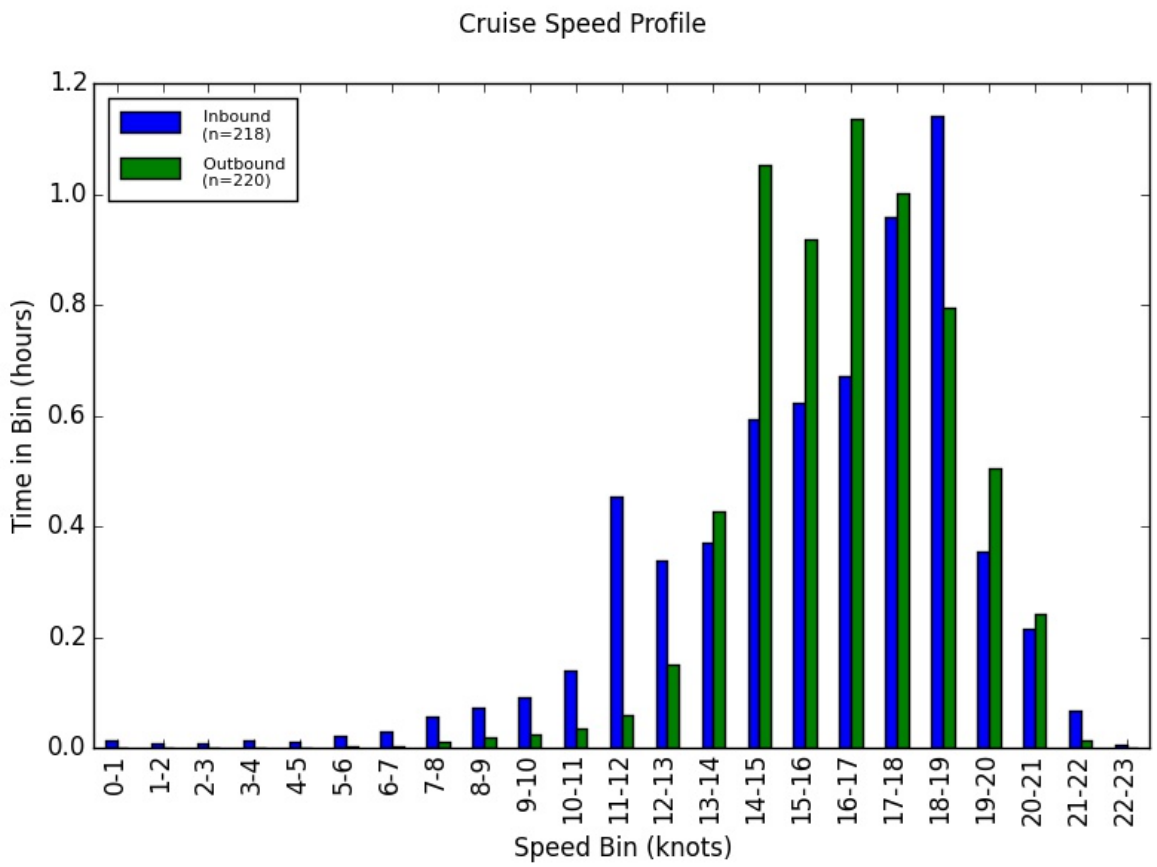
Average Transit Speed Profiles By Vessel Type

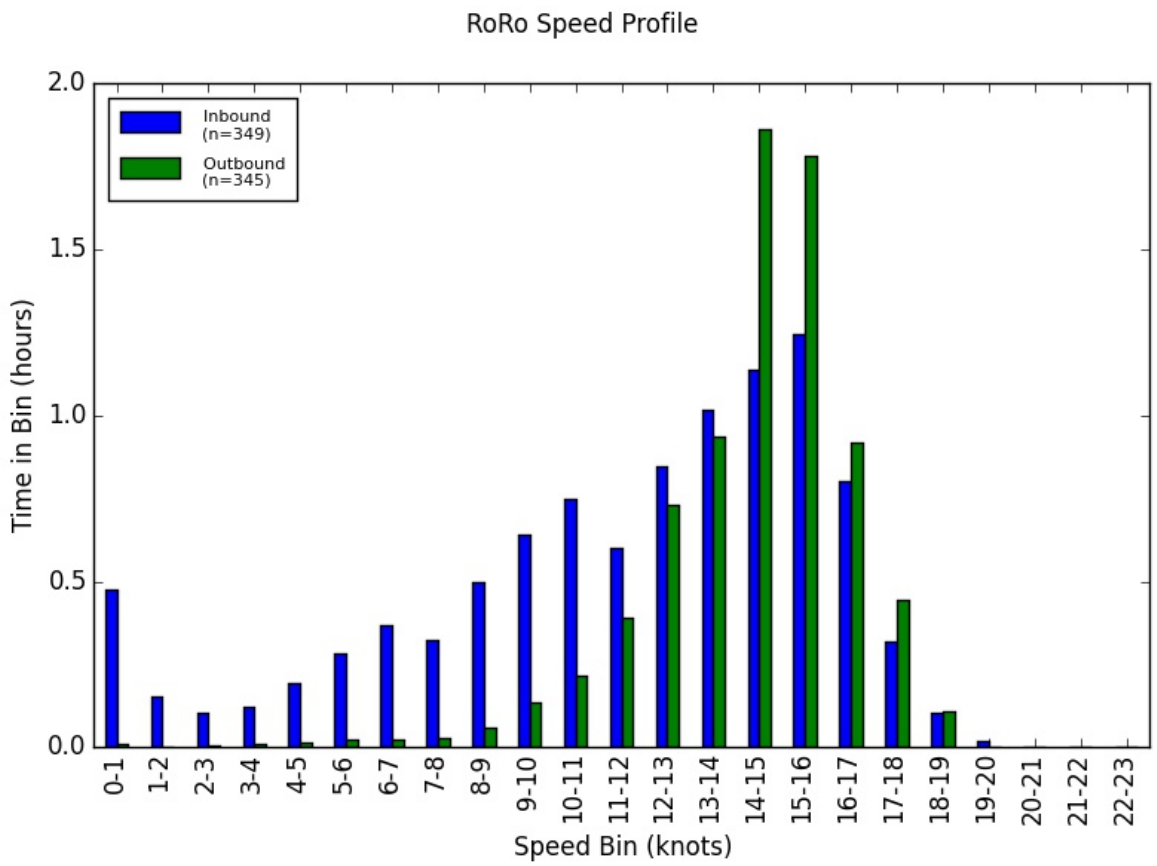

Bulk Speed Profile
Inbound (n=1960)
Outbound (n=2098)
Time in Bin (hours)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23
Speed Bin (knots)

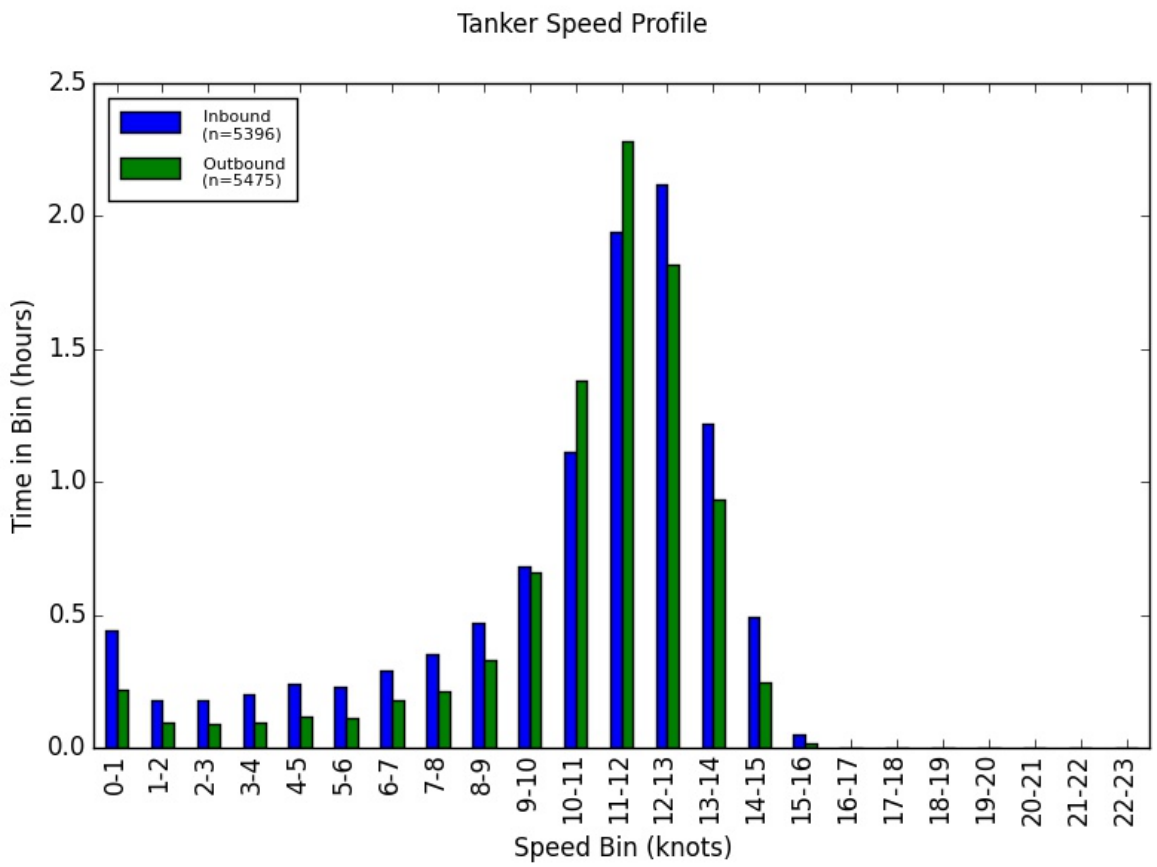

Cargo Speed Profile
Inbound (n=1422)
Outbound (n=1436)
Time in Bin (hours)
2.0
1.5
1.0
0.5
0.0
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23
Speed Bin (knots)

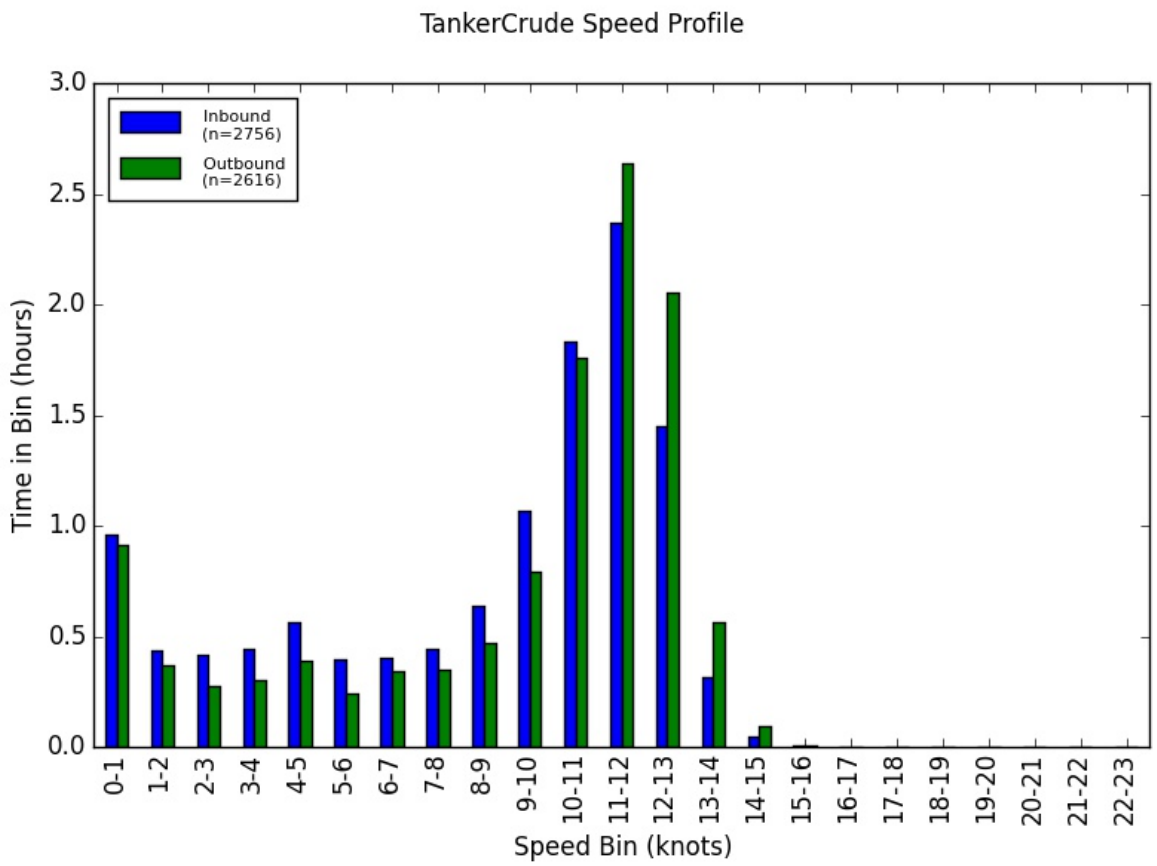

Container Speed Profile
Inbound (n=1078)
Outbound (n=1059)
Time in Bin (hours)
Speed Bin (knots)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23

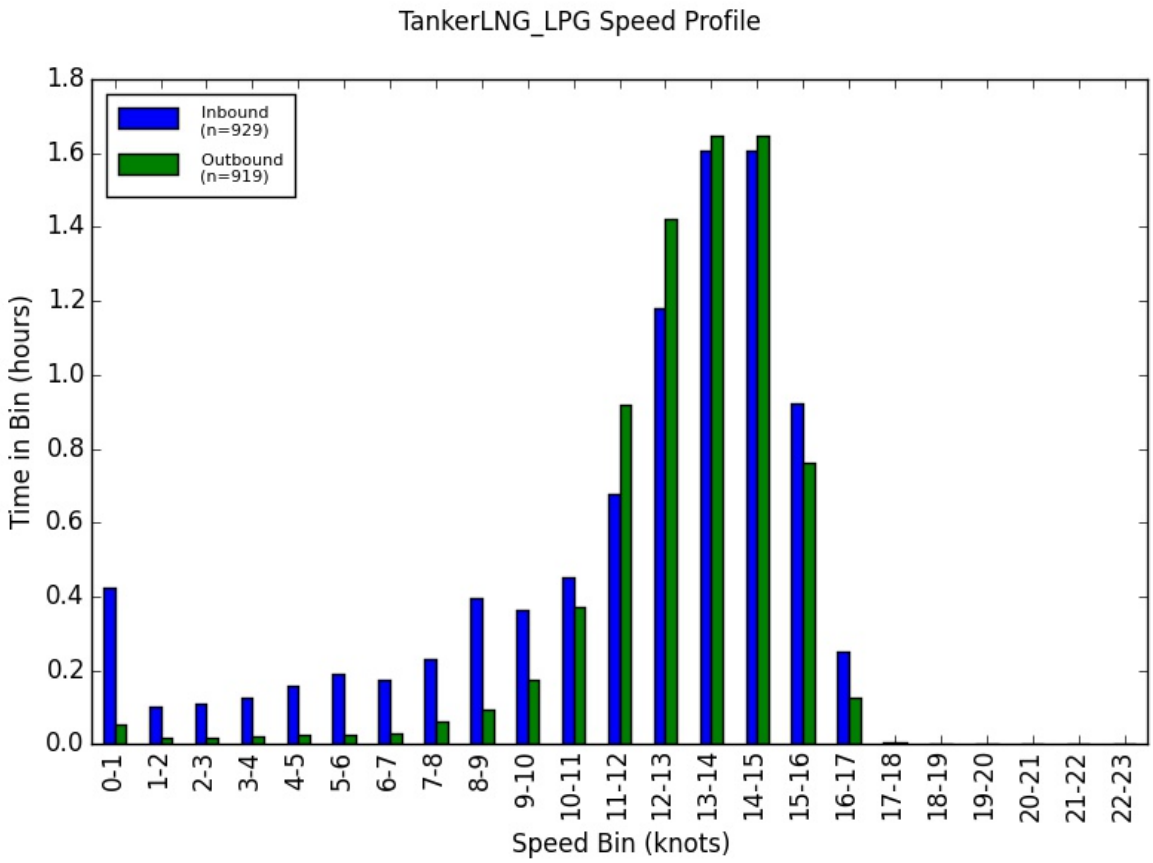

Container_Cargo Speed Profile
Inbound (n=77)
Outbound (n=77)
Time in Bin (hours)
Speed Bin (knots)
0.0
0.5
1.0
1.5
2.0
2.5
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23


Cruise Speed Profile
Inbound (n=218)
Outbound (n=220)
Time in Bin (hours)
Speed Bin (knots)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23


RoRo Speed Profile
Inbound (n=349)
Outbound (n=345)
Time in Bin (hours)
Speed Bin (knots)
0.0
0.5
1.0
1.5
2.0
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23


Tanker Speed Profile
Inbound (n=5396)
Outbound (n=5475)
Time in Bin (hours)
Speed Bin (knots)
0.0
0.5
1.0
1.5
2.0
2.5
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23

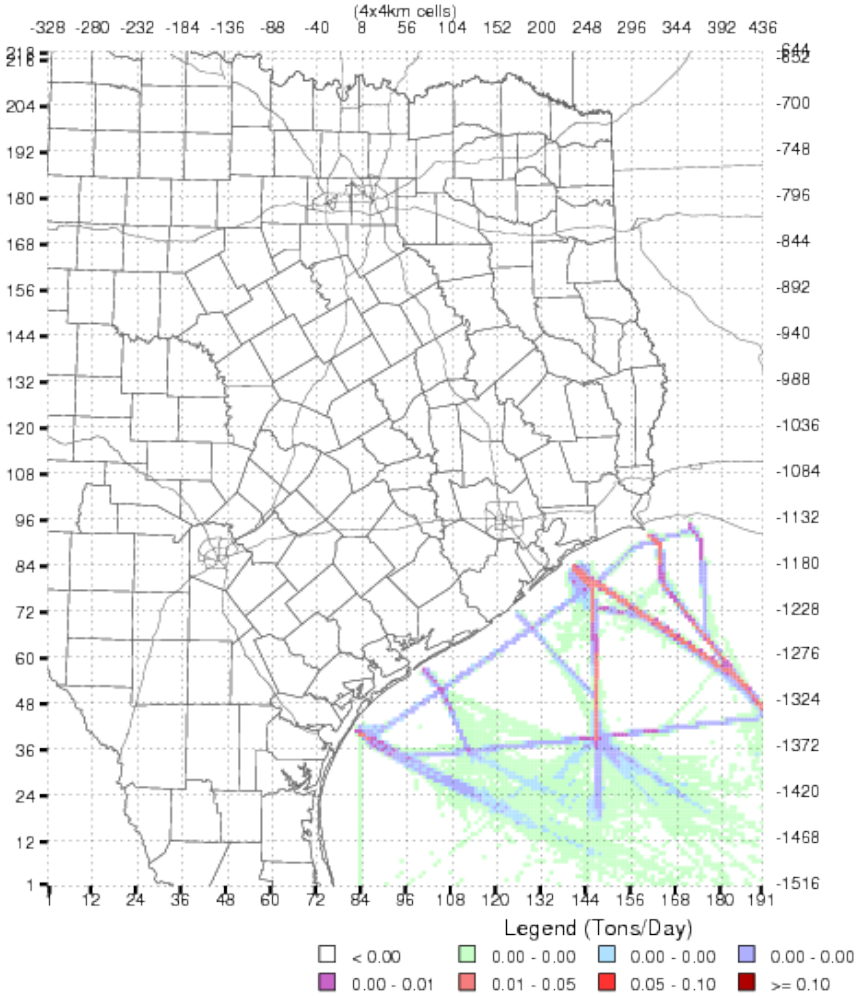

TankerCrude Speed Profile
Inbound (n=2756)
Outbound (n=2616)
Time in Bin (hours)
Speed Bin (knots)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23


TankerLNG_LPG Speed Profile
Inbound (n=929)
Outbound (n=919)
Time in Bin (hours)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23
Speed Bin (knots)

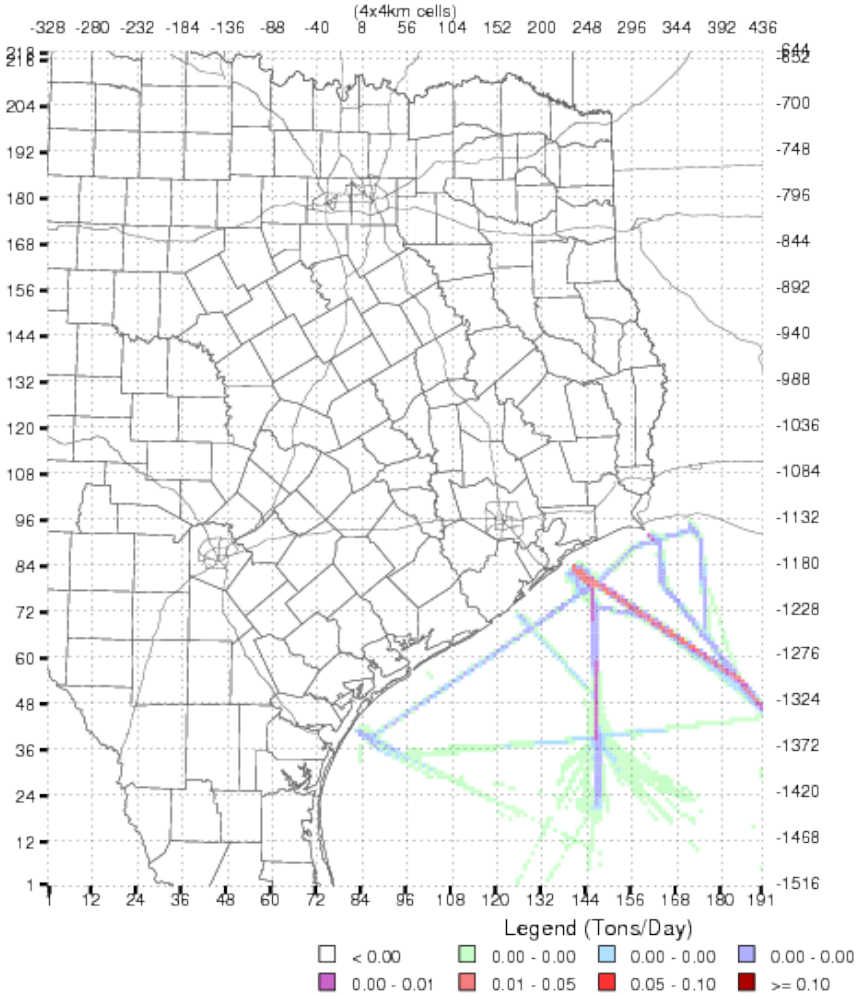
APPENDIX C

Gridded NOx Transit Emissions

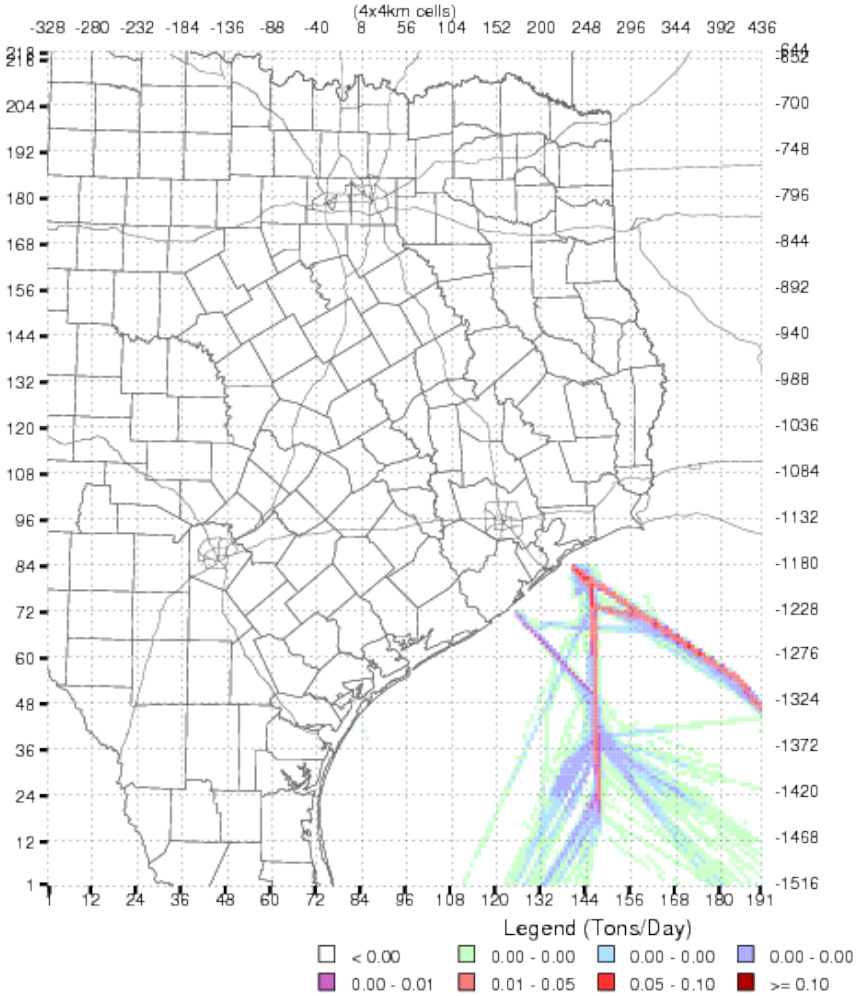
2014 Bulk Transiting NOx Emissions
(Total Emissions: 5.6 tons/day)



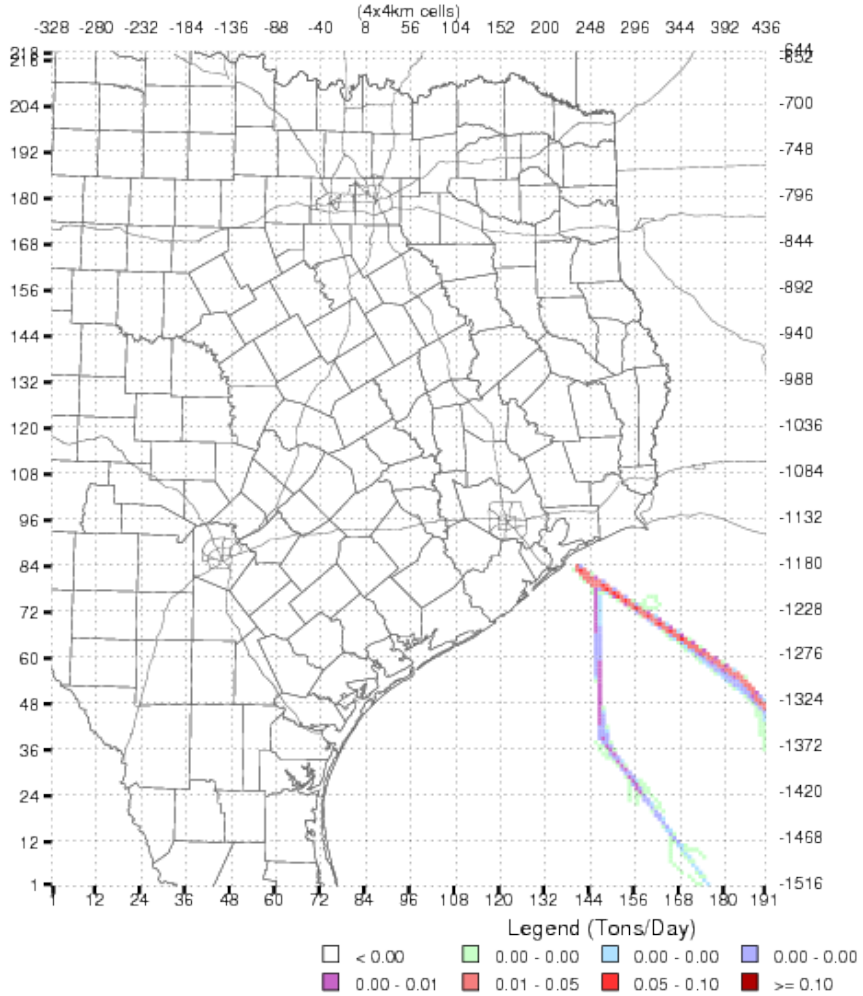
2014 Cargo Transiting NOx Emissions
(Total Emissions: 2.3 tons/day)



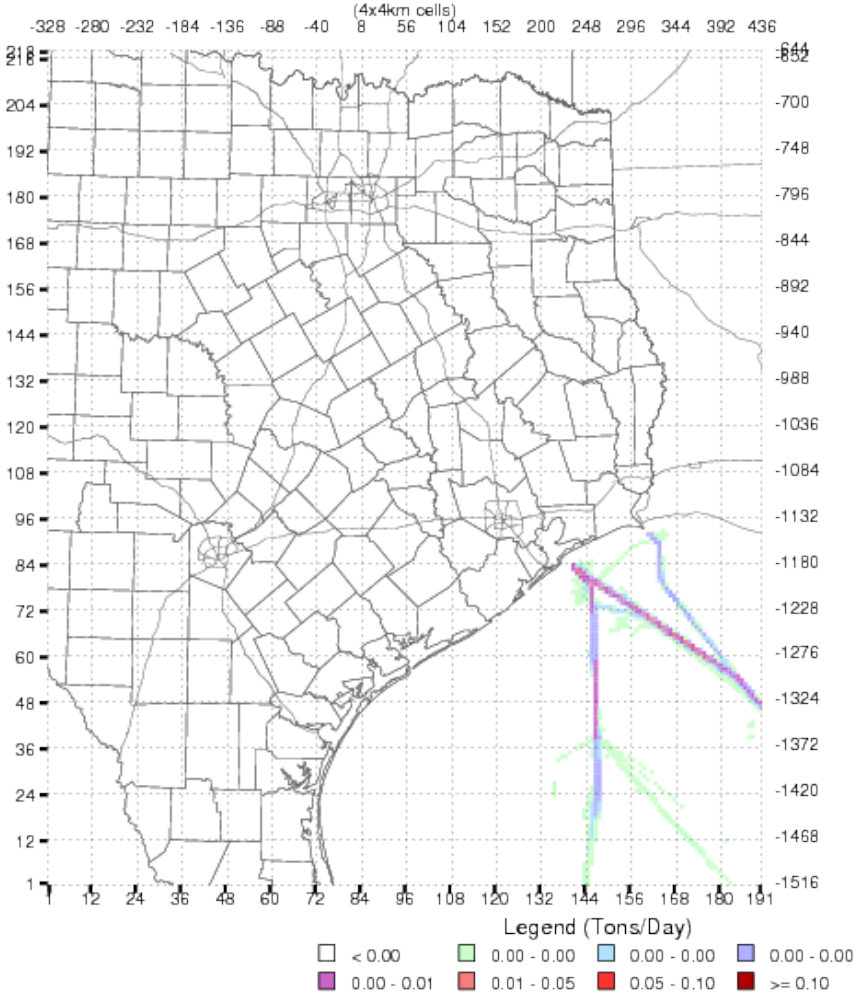
2014 Container Transiting NOx Emissions
(Total Emissions: 6.9 tons/day)



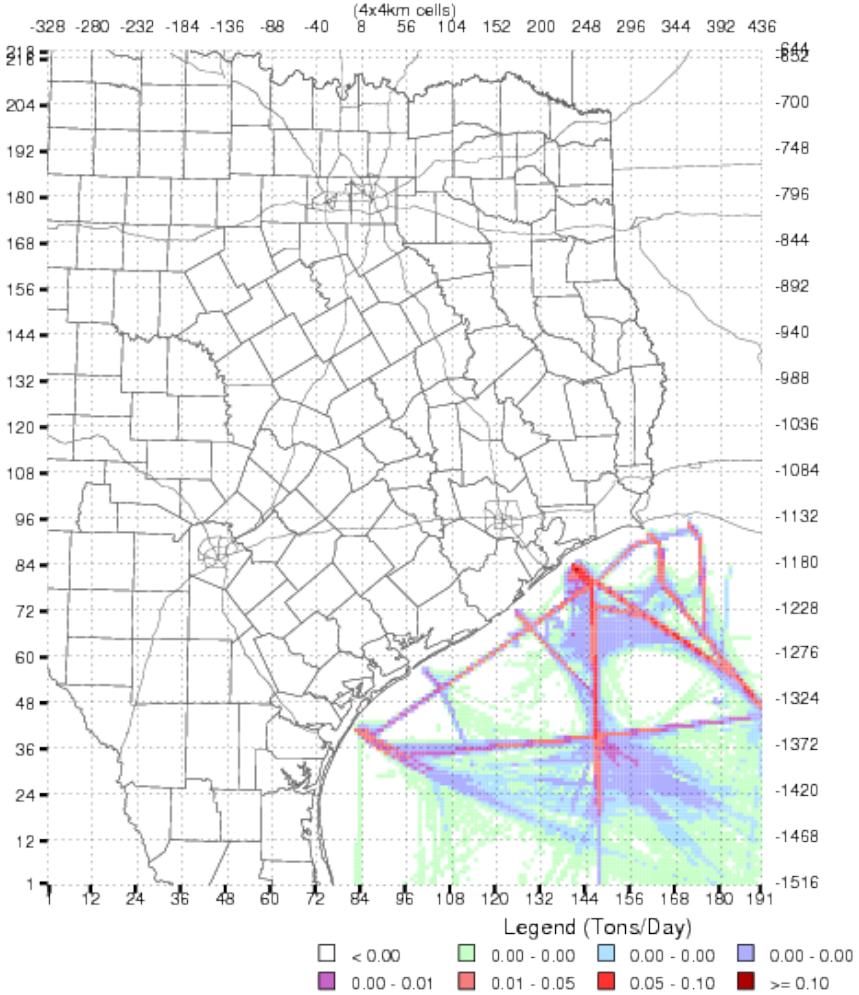
2014 Cruise Transiting NOx Emissions
(Total Emissions: 3.8 tons/day)



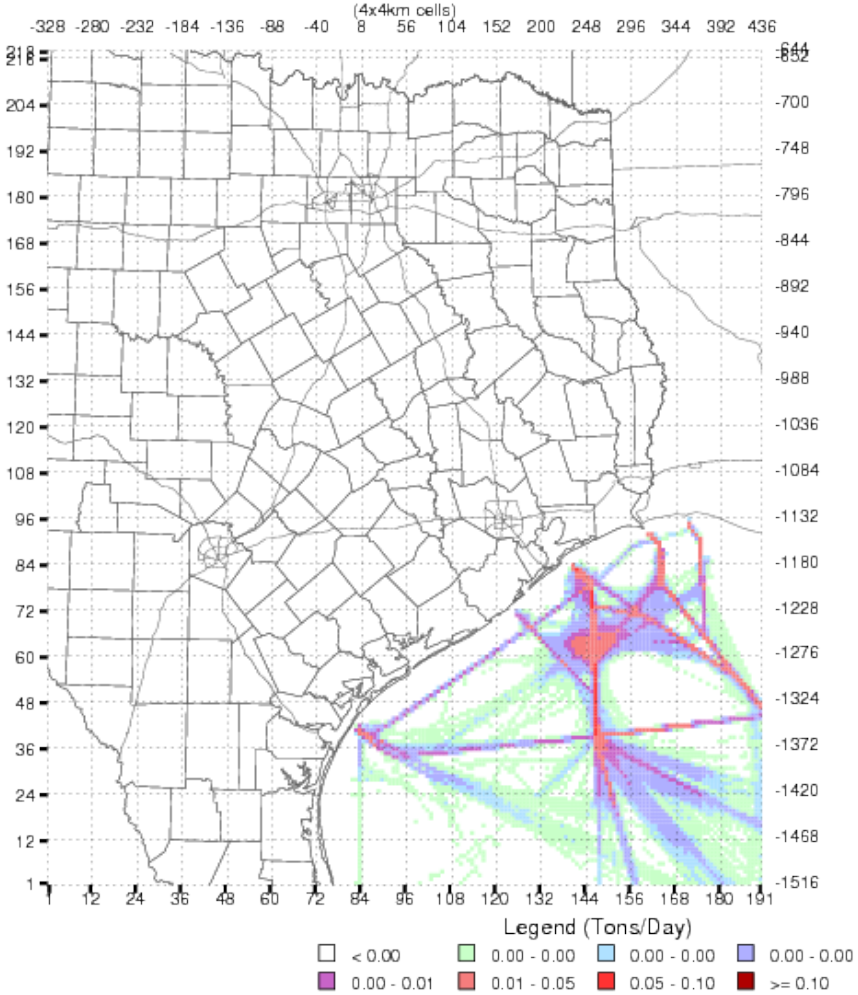
2014 RoRo Transiting NOx Emissions
(Total Emissions: 1.2 tons/day)



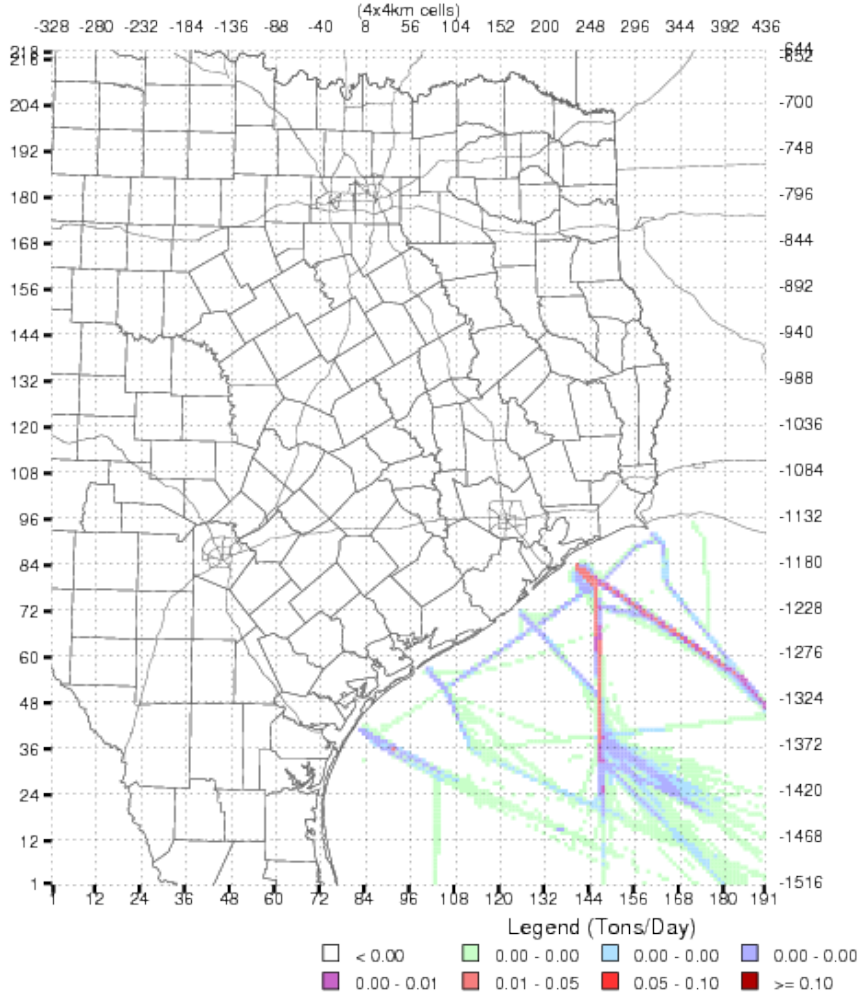
2014 Tanker Transiting NOx Emissions
(Total Emissions: 17.1 tons/day)



2014 Crude Tanker Transiting NOx Emissions
(Total Emissions: 13.5 tons/day)



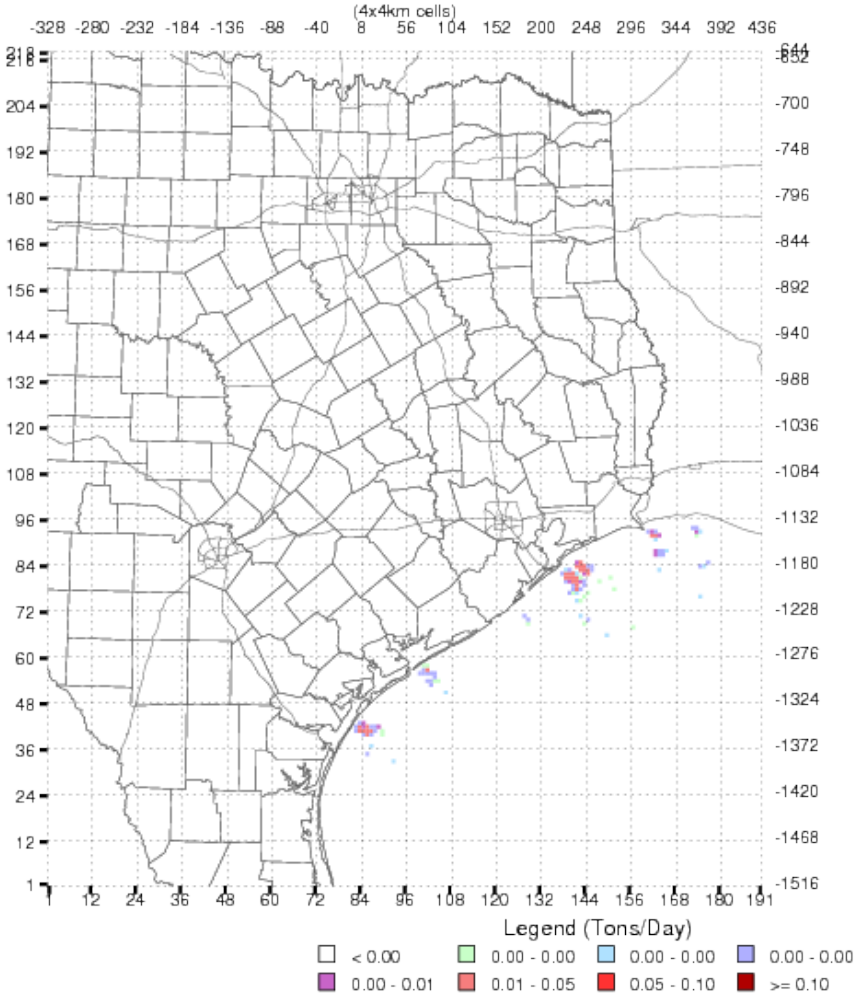
2014 LNG/LPG Tanker Transiting NOx Emissions
(Total Emissions: 3.0 tons/day)



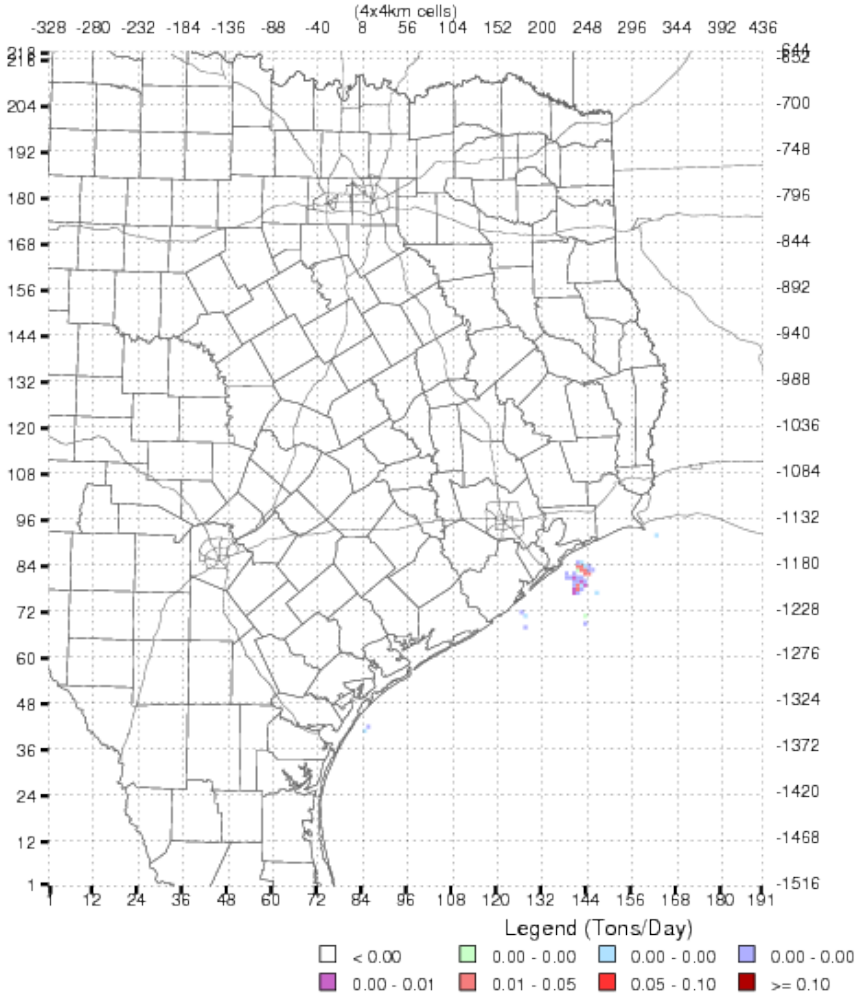
APPENDIX D

Gridded NOx Anchorage Emissions

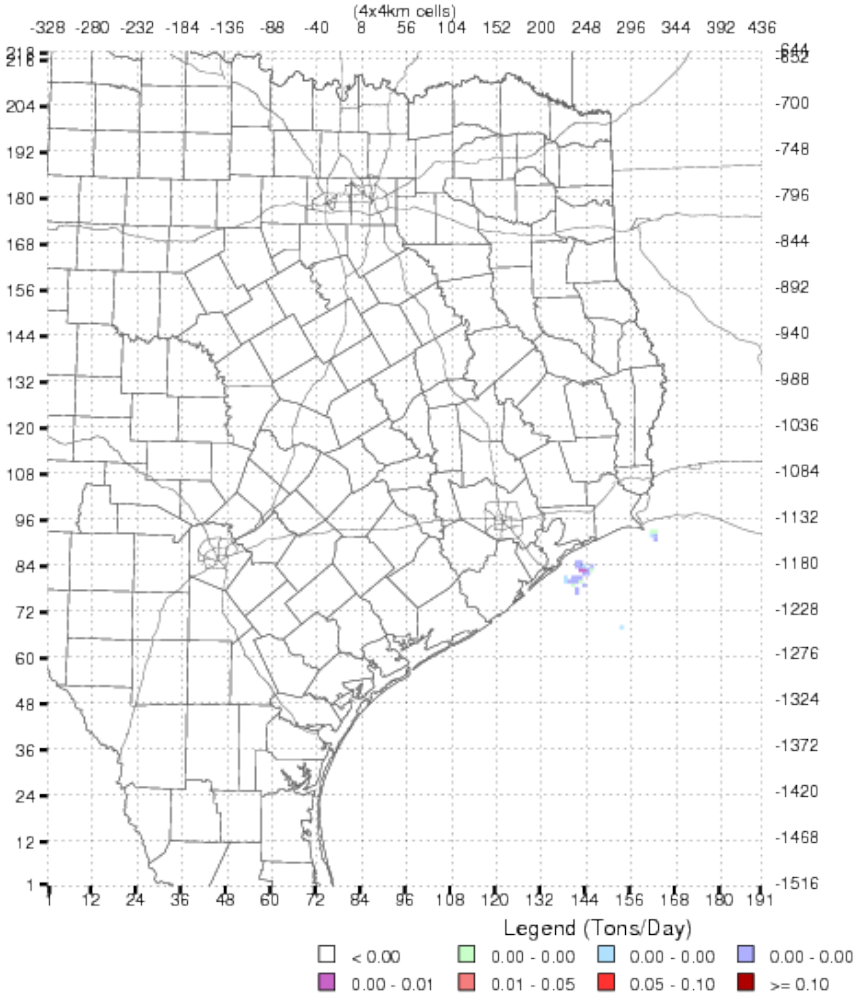
2014 Bulk Anchoring NOx Emissions
(Total Emissions: 0.8 tons/day)



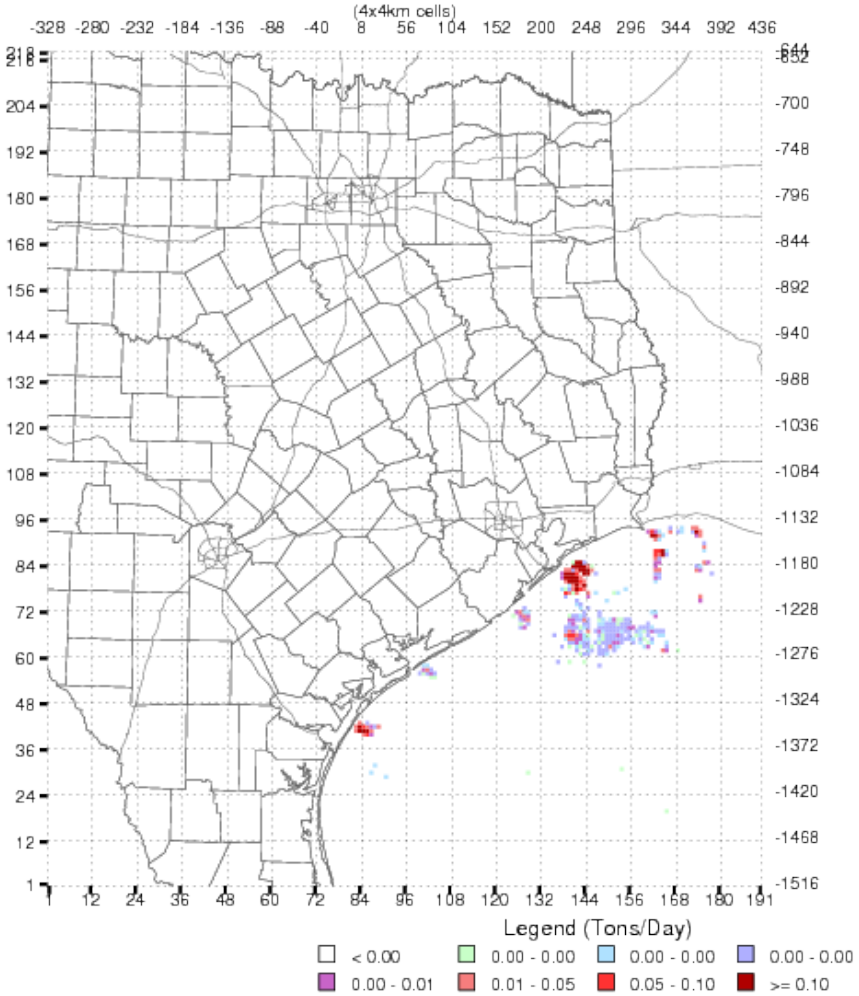
2014 Container Anchoring NOx Emissions
(Total Emissions: 0.2 tons/day)



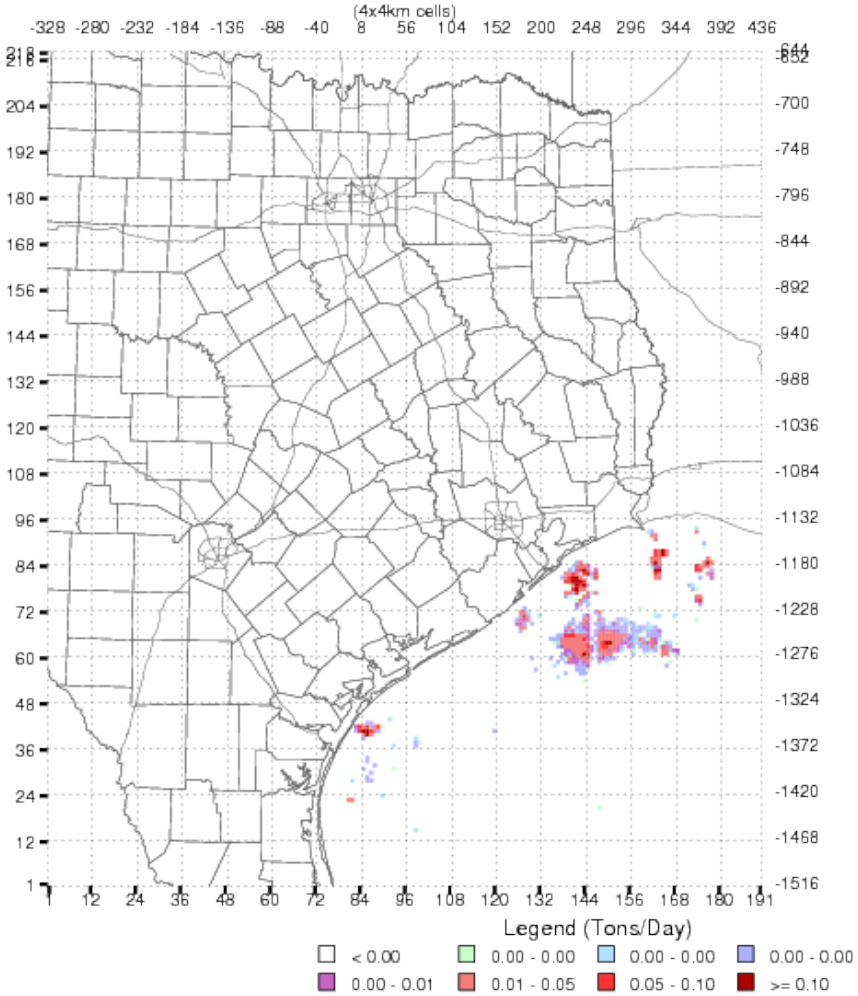
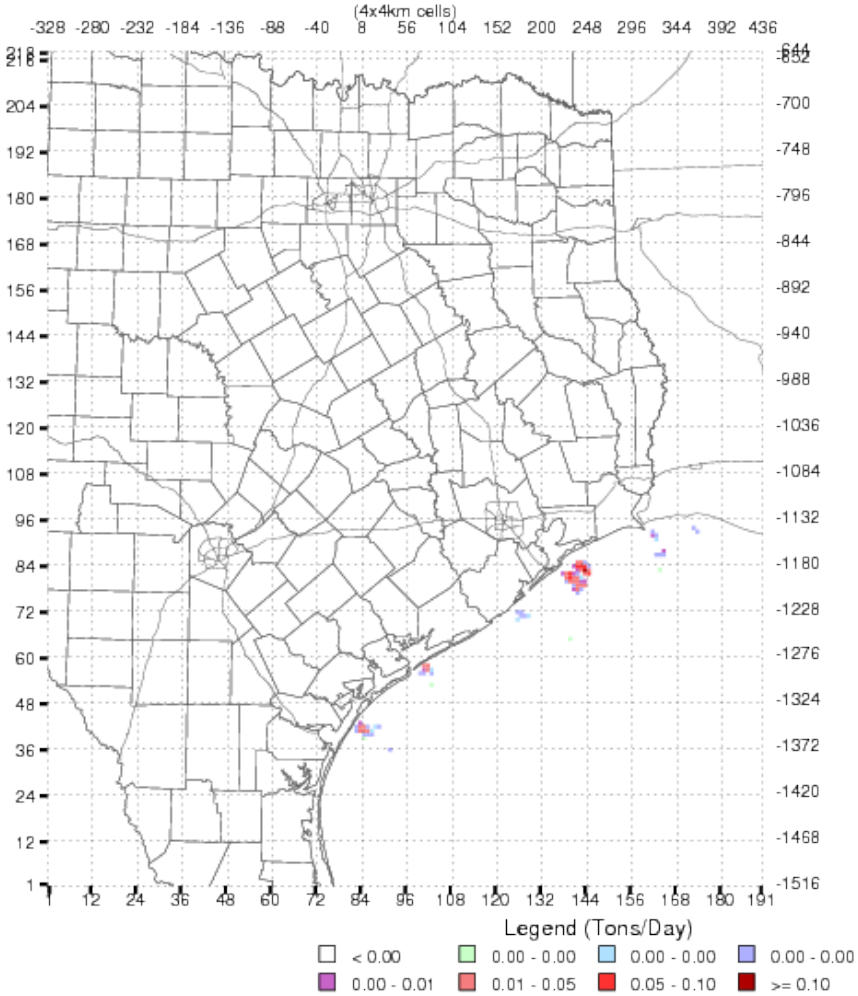
2014 RoRo Anchoring NOx Emissions
(Total Emissions: 0.1 tons/day)



2014 Tanker Anchoring NOx Emissions
(Total Emissions: 10.5 tons/day)



2014 Crude Tanker Anchoring NOx Emissions
(Total Emissions: 10.6 tons/day)



2014 LNG/LPG Tanker Anchoring NOx Emissions
(Total Emissions: 1.3 tons/day)