Automatic Identification Systems(AIS) Data Use in Marine Vessel Emission Estimation

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ABSTRACT

Eastern Research Group, Inc. (ERG) used Automatic Identification Systems (AIS) data to create a state-of-the-art inventory of 2007 commercial marine vessel emissions in Texas State waters. AIS is a unique program that provides a means for ships to electronically broadcast ship data at regular intervals including: vessel identification, position, course, and speed. These and other data are transmitted continuously, providing a comprehensive and detailed data set for individual vessels which can be used to estimate and allocate emissions based on improve traffic pattern data.

ERG used a Geographic Information System (GIS) to map and analyze both individual vessel movements and general traffic patterns on inland waterways and within 9 miles of the Texas coastline. ERG then linked the vessel tracking data to individual vessel characteristics from Lloyd's Register of Ships, American Bureau of Shipping, and Bureau Veritas to match vessels to fuel and engine data, which were then applied to the latest emission factors to quantify criteria and hazardous air pollutant emissions from these vessels. The use of AIS data provides the opportunity for highly refined vessel movement and improved emissions estimation, however, such a novel and detailed data set also provides singular challenges in data management, analysis, and gap filling, which are examined in depth in this paper along with potential methods for addressing limitations.

INTRODUCTION

With over 600 miles of tidewater coastline, Texas requires a clear picture of commercial marine vessel emissions to develop accurate State Implementation Plan (SIP) emission inventories, risk assessments, dispersion modeling, and proactive planning. Activity and emissions within state waters are of particular importance given potential air quality and human health impacts. However, unlike activity in other mobile source categories such as on-road and rail traffic, the category of marine vessel emissions poses particular challenges as the location of these activities remain relatively uncertain.

The Texas Commission on Environmental Quality (TCEQ) contracted with ERG to develop the 2007 inventory of commercial marine vessel (CMV) emissions for counties not included in the Houston/Galveston/Brazoria nonattainment area[1]. The intent of this project was to compile activity, vessel traffic pattern and vessel characteristics data, emission factors, and information about operating load required to estimate emissions of criteria and hazardous air pollutants.

ERG opted to use state-of-the-art AIS data as the source for most of the activity data for this inventory. The AIS program uses individual vessel tracking data to quantify traffic patterns in Texas State waters. ERG linked the vessel tracking data to individual vessels characteristics, thereby matching vessels to fuel and engine data. These data were applied to the latest emission factors to quantify emissions from these vessels. While the AIS data provided very detailed and useful data in some areas, additional data processing steps were required to fill in data gaps and overcome limitations of the dataset.

BODY

Automated Identification System

Among the numerous security regulations that came into effect after September 11, 2001 was the requirement for most commercial marine vessels to be fitted with Automatic Identification Systems (AIS). AIS provides a means for ships to electronically send data including vessel identification, position, speed, and course with Vessel Traffic Services (VTS) stations as well as with other ships. AIS uses Global Positioning Systems (GPS) in conjunction with shipboard sensors and digital VHF radio communication equipment to automatically exchange navigation information electronically. Vessel identifiers such as the vessel name and VHF call sign are programmed in during initial equipment installation and are included in the transmittal along with location information originating from the ship's global navigation satellite system receiver and gyrocompass. AIS is used by marine vessels in coordination with VTS to monitor vessel location and movement primarily for traffic management, collision avoidance, and other safety applications.

AIS transmitters send data every 2 to 10 seconds depending on a vessel's speed while underway, and every 3 minutes while vessels are at anchor. These data include:

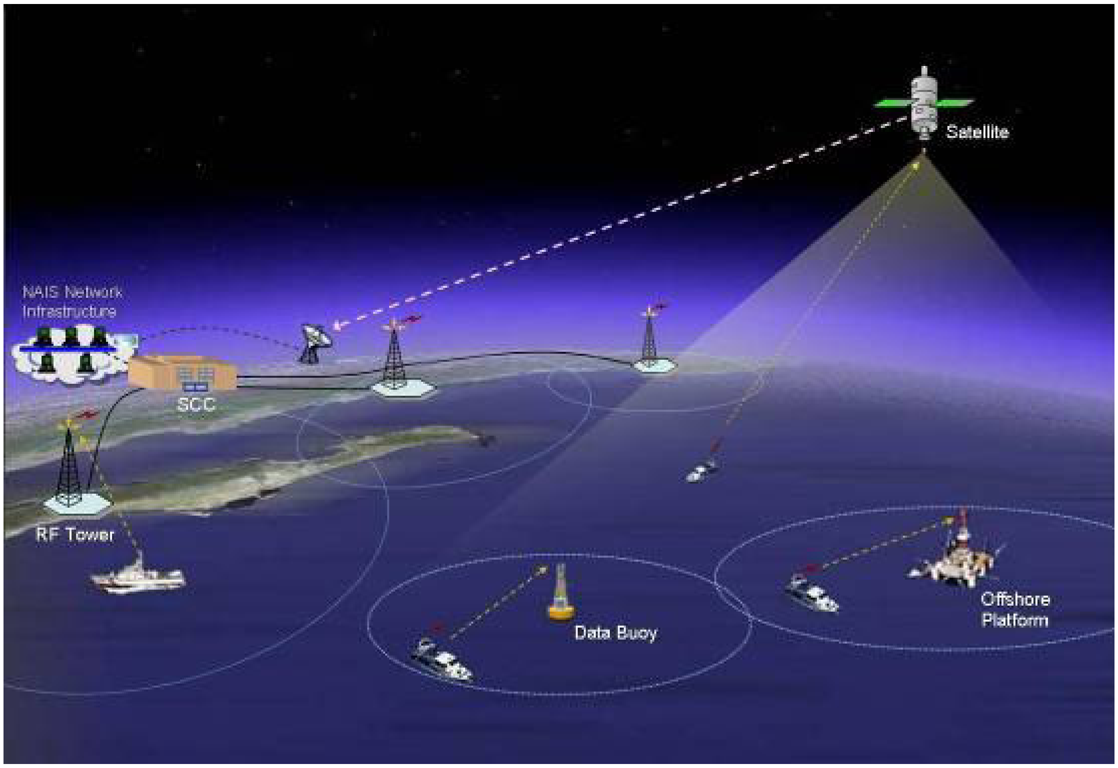
- The vessel's Maritime Mobile Service Identity (MMSI) – a unique, nine-digit identification number;
- Navigation status – "at anchor", "under way using engine(s)", or "not under command"
- Rate of turn – right or left, 0 to 720 degrees per minute;
- Speed over ground – 0 to 102 knots with 0.1 knot resolution;
- Position accuracy;
- Longitude and Latitude – to 1/10,000 minute;
- Course over ground – relative to true north to 0.1 degree;
- True Heading – 0 to 359 degrees from gyro compass; and
- Time stamp – Coordinated Universal Time (UTC) time accurate to nearest second when this data was generated.

In addition, the following data are broadcast every 6 minutes whether underway or at anchor:

- International Maritime Organization's (IMO) ship identification number – a seven digit number that remains unchanged upon transfer of the ship's registration to another country;
- International radio call sign, up to seven characters, assigned to the vessel by its country of registry;
- Vessel Name – 20 characters to represent the name of the vessel;
- Type of ship/cargo;
- Dimensions of ship – to nearest meter;
- Type of positioning system – such as GPS, Differential Global Positioning Systems (DGPS) or Long Range Navigation (LORAN) -C;
- Location of positioning system's antenna onboard the vessel;
- Draught of ship – 0.1 meter to 25.5 meters;
- Destination – max 20 characters; and
- Estimated time of arrival (ETA) at destination – UTC date hour: minute.[2]

Figure 1 illustrates how the signals are transmitted and received by other AIS transponders in a variety of locations, including the following: other vessels, radio frequency towers, National Oceanic and Atmospheric Administration (NOAA) weather buoys, offshore oil platforms, and geostationary satellites. The received information can then be plotted by the vessel or at a land-based VTS facility, showing the vessel's positions in much the same manner as a radar display.

Figure 1. AIS conceptual operation view.



The IMO's *International Convention for the Safety of Life at Sea* (SOLAS) requires AIS to be fitted aboard international voyaging ships with gross tonnage (GT) of 300 or more tons, and all passenger ships regardless of size[3]. In 2005, the U.S. Coast Guard mandated that all commercial marine vessels must continuously transmit AIS signals while transiting U.S. inland waterways and ports in order to improve vessel safety and navigation. It is estimated that more than 40,000 ships worldwide currently carry AIS equipment.

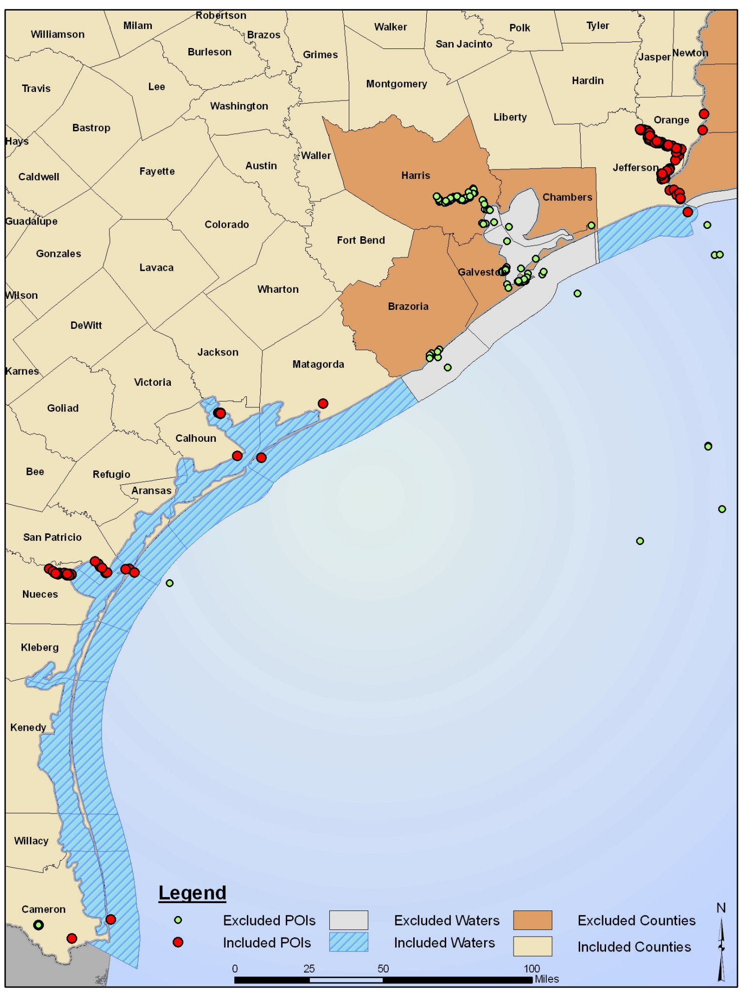
Previous marine vessel emissions estimates have depended upon activity provided by the U.S. Army Corps of Engineers (U.S. ACE) entrance and clearance data. These data are well-suited for use in inventory applications as they are readily available, comprehensive, and frequently updated. When used in coordination with the U.S. ACE waterway network, it is possible to create segment-level activity and emissions estimates compatible with inventory databases, modeling inputs, etc. However, these datasets require assumptions to be made regarding all vessel movements and activity between each trip's origin and destination. The consistency and wealth of AIS data provide a unique opportunity for superior movement and traffic data, leading to significantly more refined activity data and emissions estimates.

AIS Data Query Customization

To obtain AIS data for use in quantifying CMV activity, ERG worked with AIRSIS, Inc., a maritime technology company with particular experience in Texas state waters. AIRSIS developed the PortVision data, which leverage the existing AIS technology and process each unique signal – more than one million records a day along the Sabine-Neches ship channel, providing real-time information about the location and status of vessels on the waterway. In 2000, AIRSIS used satellite-based technology in the Houston ship channel to optimize the movements of tankers within the Houston/Galveston Area (HGA). By 2003, waterway users relied on this technology to optimize scheduling and communications for over 60% of tanker activities in the region.[4] The points of interest (POI) noted in Figure 2 are the locations where AIRSIS maintains vessel monitoring stations, such that the data files report vessel activity as they approach and pass the POIs. Each POI has a coverage radius of approximately 40 miles, though depending on the receiver's location and elevation and current atmospheric conditions, reliable coverage can reach 60 miles or more.

AIRSIS's PortVision data are primarily provided via a web-based service focusing on real-time and historical transit data. As a result, ERG worked directly with AIRSIS to create a customized dataset to meet the needs of TCEQ. ERG delineated the area of interest (AOI) to include all Texas state waters, which extend 9 nautical miles from the coastline, excluding the Houston-Galveston (HGA) nonattainment area as it had been evaluated in other inventory projects implemented by the port authority. A polygon shapefile delineating the area of exclusion around the HGA nonattainment area was provided to AIRSIS to ensure accuracy and consistency in POI selection. All POIs within nine miles of the Texas coastline were selected for retention, and those within the Houston-Galveston nonattainment area were specifically excluded from this inventory effort. At the time of the data pull (March 2008), AIRSIS had 132 POIs in the area of interest, listed in Appendix A. Figure 2 illustrates the distribution of the selected POIs with respect to coastal county boundaries, state waters, and excluded HGA nonattainment area.

Figure 2. Points of interest (POI) for Texas state waters



All departures, arrivals, and passings where at least one of the POIs was in the target area during the 2007 calendar year were included in the dataset. This included data points outside of the area of interest but within the coverage area of the POI, as seen in Figure 3. Data points as late as March 9, 2008 were included if they were part of a transit that originated in 2007 in order to provide a complete trip record. While each data record was given a unique Event ID, the origin, waypoints, and destination points within one trip were identified by a single Transit ID. The transits in this dataset had anywhere from 1 to 594 events. Trips that had origins or destinations outside of the AOI were marked as "AT SEA" in order to simplify the dataset.

Of PortVision's 64 available data elements, ERG's retained data elements include vessel IMO, vessel type, latitude/longitude, and date/time as shown in Table 1. The final dataset was provided as three comma-delimited text files:

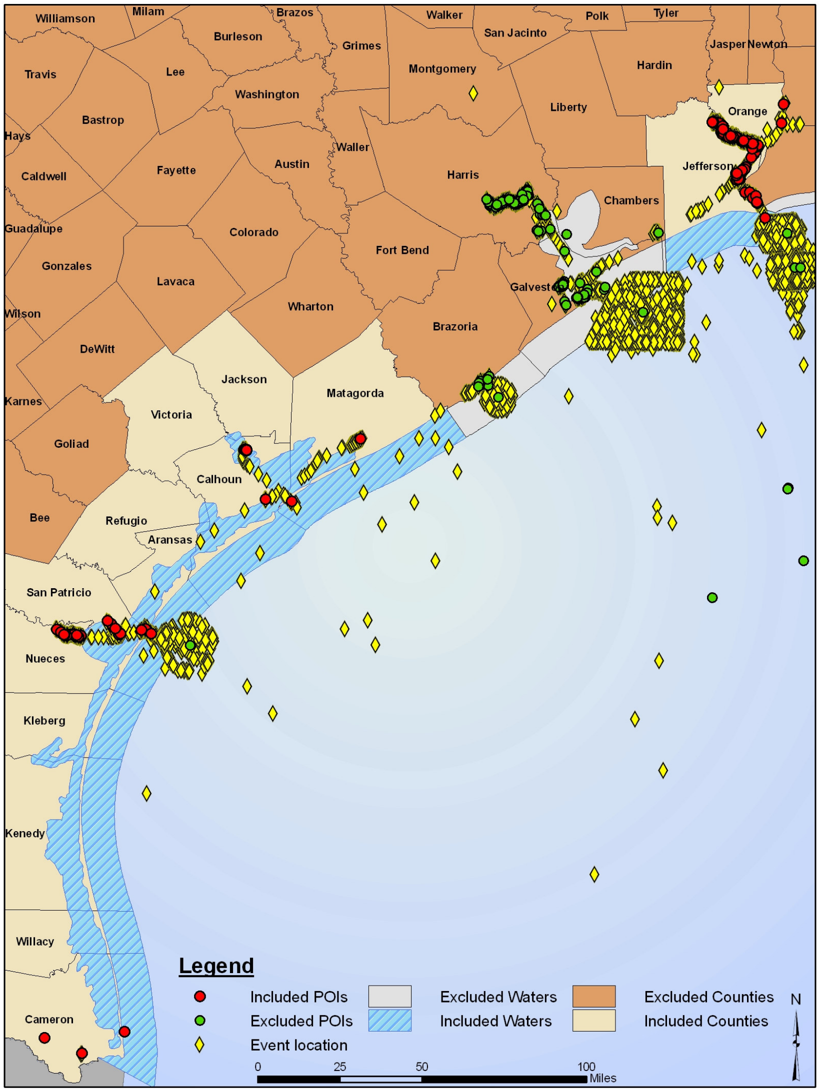
- Transit table – includes general transit data without individual events
- Transit detail – includes every event ID for each transit recorded by the selected POIs
- Dwellings – vessel dwelling/stopping captured at POI

Table 1. Data elements received from AIRSIS's PortVision data set for each event record.

Attribute	Description
Transit ID	Unique trip ID
Event ID	Unique record ID
Vessel Name	Ship name
Vessel MMSI	The vessel's Maritime Mobile Service Identity (MMSI)
Vessel IMO Number	International Maritime Organization's (IMO) ship identification number
Vessel Type	Bulker, Tanker, Reefer, Tug, Passenger, Research, Supply, Vehicle, etc.
Vessel Latitude	Vessel Y location in decimal degrees
Vessel Longitude	Vessel X location in decimal degrees
Event Type	Arrival, Departure, or Passing
Event UTC Date	Date in Coordinated Universal Time
Event Local Date	Date in CST or CDT
Event Time Zone	Central Standard Time (CST) or Central Daylight Time (CDT)
Seconds in Transit	Seconds in transit, calculated from UTC
POI ID	Point of Interest unique identification number
POI Name	Point of Interest name
Port Name	Port name, where applicable
In Target Area	Flag noting if the event occurred within this study's area of interest

The final tables included 2,919 unique vessels; 82,355 individual transits; 545,141 events; and 110,475 dwellings. The Events located within the study area are shown in Figure 3.

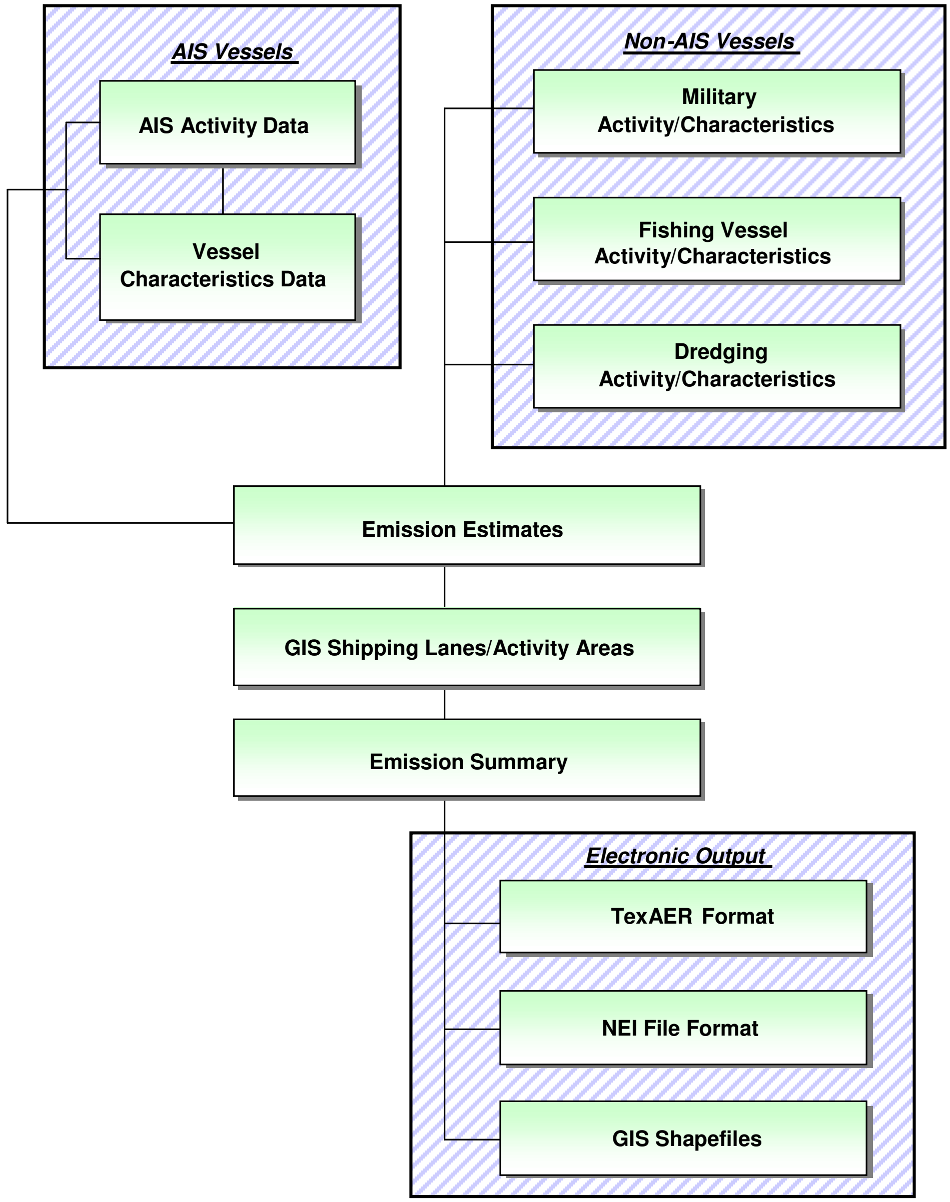
Figure 3. Plotted event locations within study area.



Data Processing

Since AIS data quantified individual vessel activities, significant processing was required to summarize and prepare the data for use in developing a comprehensive emission inventory. The AIS data were matched to vessel characteristics data obtained from vessel classification associations such as Lloyds or the American Bureau of Shipping. The vessel characteristics data include information about the horsepower rating of individual vessels and information concerning auxiliary engines. By evaluating the AIS time stamp data and applying the hours of operation to the vessels horsepower rating, it was possible to quantify the horsepower-hours of operation for individual vessels and to assign them to shipping lanes and port areas where they operate. The horsepower-hours were applied to emission factors from the Swedish EPA to provide emission estimates for criteria and hazardous air pollutants. Ultimately, the emission estimates were applied to specific shipping lane segments where they occurred using GIS shapefiles and data analysis tools, and the data were summarized both at the shipping lane segment and county level. This process is illustrated in Figure 4 below.

Figure 4. General approach to developing Texas state waters CMV emission inventory.



Spatial Analysis within GIS

All individual event records were plotted in a GIS using ArcInfo 9.3. Events within each transit were plotted sequentially and connected by a line indicating an individual vessel trip. However, as seen in Figure 5, data gaps resulted in clearly erroneous routes that avoided federal waters and transited large land masses. Additionally, some vessels would appear moving out of a port and several hours later would enter a nearby port without any intermediate data transmittals. As a result, the transit data were summarized to identify unique origin and destination pairs, which were then individually routed along U.S. ACE shipping lanes between the POIs. The resulting shipping lanes are illustrated in Figure 6.

Figure 5. Data gaps in transit event detail resulted in erroneous vessel routes.

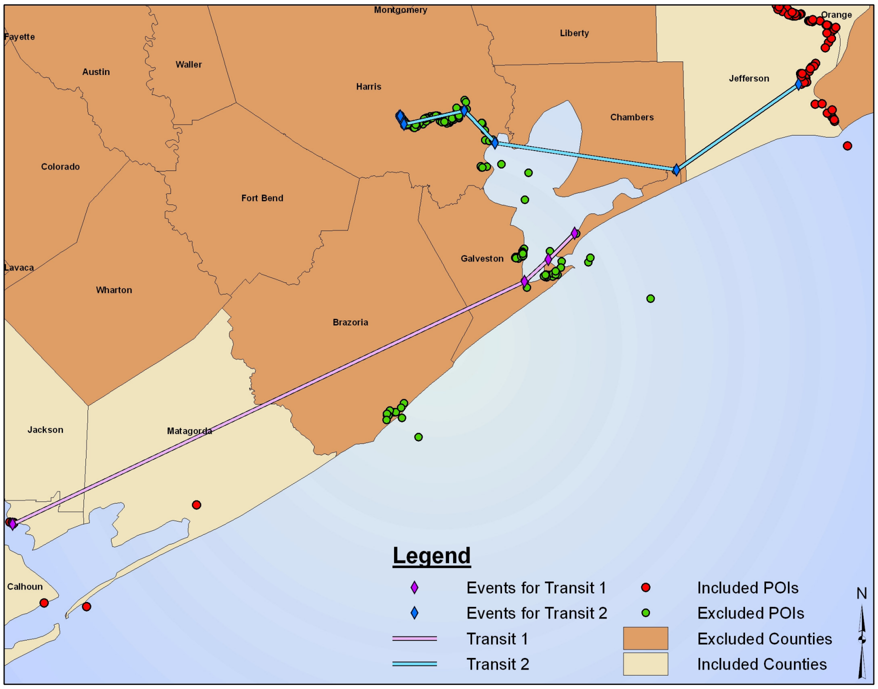
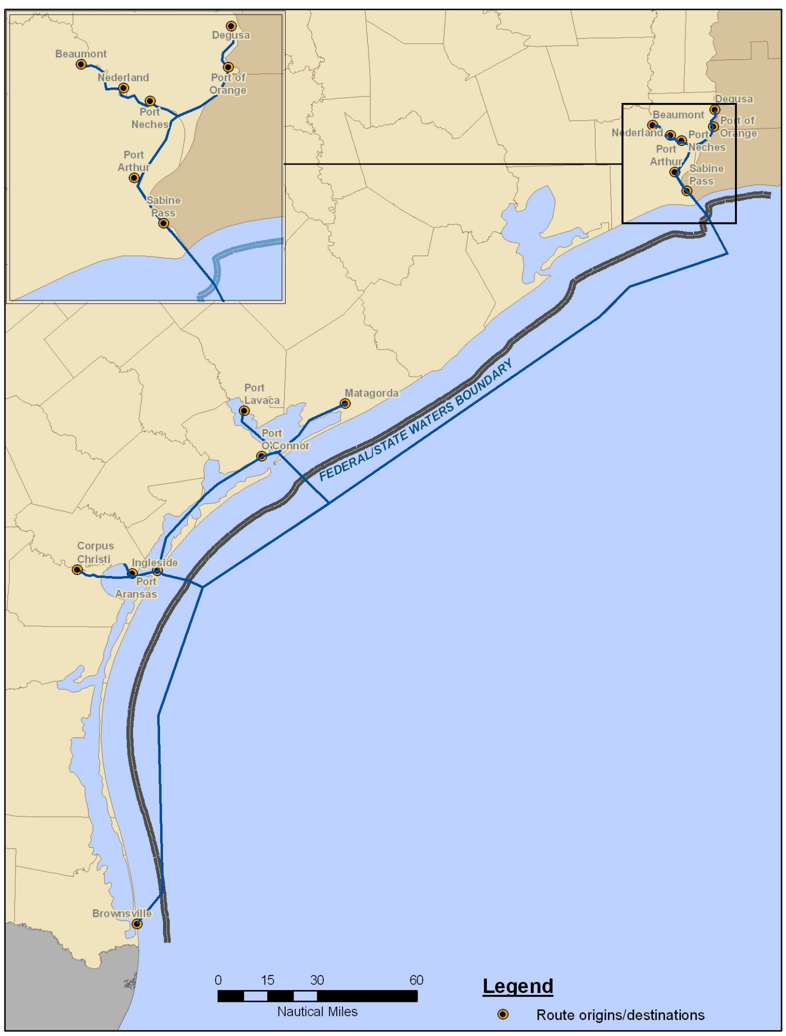


Figure 6. Final mapped shipping lanes using departure and arrival data.



Vessel activities were then assigned to each route based on the transit records provided by AIRSIS. Transits that began or ended "At sea" were mapped from the known POI out of state waters using the most direct shipping lane path available. Transits that both began and ended "At sea" did not have sufficient information to map them to individual shipping lanes; however, their activity was mapped to the event ID location and included in county-level activity estimates. Because of the location of the POIs, it was not possible to differentiate between traffic that transits into federal waters, stays along the Texas coast, or travels on the intracoastal waterways. Also of note is that some monitoring locations came online partway through the year, so that a route may be listed with a destination "at sea" earlier in the year, but may have a true POI destination later in the year. Given the location of the POIs and shipping lanes, this potential source of error was assumed to be relatively small.

Vessel Characteristics

Vessels identified in the AIS dataset were matched to vessel characteristic data compiled in vessel classification data sets. Classification associations included the following:

- Lloyd's Register of Ships[5]. This data set contains over 70,000 vessels operating around the world. Lloyd's is a marine research company as well as a vessel classification and insurance company, similar to the next two entries.
- American Bureau of Shipping[6]. Similar to the Lloyds Register of Ships, but includes smaller U.S. vessels such as offshore support vessels, fishing boats, tugs and towboats.
- Bureau Veritas[7]. This database includes vessels involved in international travel to and from Europe.

The vessel characteristics data obtained from the classification associations are listed in Table 2.

Table 2. Vessel characteristics available from classification associations.

Ship name	Draft	Revolutions per minute (RPM)
Owner	Length	Engine speed
Flag	Engine type	Bore
Date built	Propulsion type	Stroke
Ship type	Number of main engines	Auxiliary index
Call sign	Engine make	Number of auxiliary engines
Vessel speed	Engine model	Auxiliary kW
Dead weight tonnage	Engine kilowatt (kW) rating	Total power
Gross registered tonnage	Cylinders	Fuel bunker 1
Net registered tonnage	Cylinder displacement	Fuel bunker 2

Note, not all data fields included in the classification association data sets are fully populated. For this project procedures were developed to gap fill missing data that were needed to estimate emissions. Typically the reported data were averaged by vessel type and used to fill identified data gaps.

Vessel Matching Procedures

The individual vessels included in the AIRSIS data query were compiled and the vessels were matched with their vessel-specific characteristics as discussed above. The AIRSIS data included 3,398 vessels. Out of 2,657 vessels with IMO identification codes included in the AIRSIS data, ERG matched 1,913 vessels (72 percent) with vessel characteristics. Unfortunately, many of the remaining vessels did not have valid IMO numbers. Where IMO numbers were incorrect or not available, the MMSI identification codes were used. If the vessels had neither IMO nor MMSI numbers, the vessels were tentatively matched to vessel characteristic data based on the vessel name and the vessel type.

Because this is an imprecise method for vessel matching, certain checks were made to identify and correct possibly incorrect matches. If more than one possible match was identified based on vessel name, the vessel was deemed unmatchable. If the vessel name matched, but the vessel types did not match, the vessel was deemed unmatchable. However, if no vessel type was given, but the vessel name matched, the vessel was considered matched. In addition to invalid or missing IMO or MMSI numbers, there were also a number of records where the vessel name and other identifying data were entered into the wrong fields. These records were not cleaned up to ensure that the record could be linked back to the original activity data. However, horsepower data were linked to these records manually to allow for accurate emission calculations. An additional 1,006 vessels were matched based on vessel name or vessel MMSI number, bringing the total number of matched vessels up to 2,919 (86 percent of total vessels). In addition, a small number of vessels were identified with identical IMO or MMSI numbers. These duplicates were flagged and retained in the project database.

Vessel Activity

The original intent was to gather actual hours of operation from the time stamps included in the AIS data. However, due to the data gaps inherent in the data set, the activity calculated based on the UTC date and time stamps were artificially high and did not accurately reflect true hours of operation. Furthermore, hours of activity could not be calculated at all for route segments that passed into federal waters. To compensate for this data limitation, once the vessels were matched to their characteristics, they were mapped to their associated route, which was comprised of individual shipping lane segments. The length of the shipping lane segment (nautical miles) was divided by the vessel's speed (nautical miles per hour) to quantify hours of operation along each shipping lane segment. These hours of operation were applied to the vessel's engine data to estimate horsepower hours using the following equation:

Equation (1) $$\text{Hp-Hrs} = \text{Hp} \times \text{En} \times (\text{St}_2 - \text{St}_1)$$

where

Hp-Hrs = Horsepower hours

Hp = Horsepower rating of the vessel's propulsion engines

En = Number of propulsion engines the vessel is equipped with

St_1 = Time when the vessel enters a specific waterway segment

St_2 = Time when the vessel leaves a specific waterway segment

Approximately 12 percent of ship movements included in the AIS data documented that the origination and destination of the vessel movement were the same port. For vessels that are generally associated with port activities such as assist tugs, pilot boats, and police patrol boats, it was assumed that all vessel transit times occur within state waters. For larger vessels with transit times less than or equal to 12 hours, it was assumed that these vessels were involved in intra-port shifts between terminals and, therefore, all transit times were assumed to also occur within state waters. For vessels with longer transit times, it was assumed that these vessels left the port temporarily until space at a terminal was available. For these vessels, transit times were estimated to move the ship from the port to the federal/state water boundary (as many of these anchorage locations are outside state waters) and back. It was assumed that all of these vessels were operating under maneuvering loads and speeds.

Other Vessel Types

Some vessels are not required to participate in the AIS program due to their size, weight, or special function. The emission estimates for these vessels were developed separately, and the AIS data were reviewed to ensure that there were no cases of double counting. These vessels include:

- Military vessels;
- Dredging activities; and
- Fishing boats.

To ensure that the emission estimates developed for these other vessel types were comparable with the AIS-derived emission estimates, the same emission factors were used and comparable spatial allocation files were developed for each vessel type.

Emission Estimation Procedures

Emission estimates for 2007 were developed for nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), sulfur dioxide (SO_2), ammonia (NH_3), particulate matter less than or equal to 10 µm (PM_{10}), particulate matter less than or equal to 2.5 µm ($PM_{2.5}$), and several significant hazardous air pollutants using the following equation:

Equation (2): $$AE = AH \times CF_1 \times LF \times EF \times CF_2$$

where

AE = Annual Emissions (tons per year)
AH = Annual activity (Hp-Hr)
CF_1 = Conversion factor (0.741 kW/Hp)
LF = Engine load factor
EF = Emissions factor (g/kW-Hr)
CF_2 = Conversion factor (1.10231 E-6 ton/g)

Load factors for propulsion engines were assumed to be 80 percent for cruising and maneuvering modes and 10 percent for hotelling base on EPA guidance[8]. Load factors for auxiliary engines were assumed to be 16 percent while cruising and 50 percent for maneuvering and hotelling.

The emission factors used in estimating the emissions are from the Swedish Methodology for Environmental Data's (SMED) *Methodology for Calculating Emission from Ships: 1. Update of Emission Factors*[9]. The 2002 base factors were chosen because these emission factors do not take into account various control methods. The 2002 data were also chosen over the other years, because the factors are presented according to the modes of operation. Because marine vessels are designed to operate efficiently using a variety of grades of marine fuel and vessels currently do not report what grade of fuel they combust while in state waters, it was necessary to use global fuel usage data as reported by the IMO in order to weight the SMED emission factors to provide the most appropriate emission factors. In 2007, larger vessels that have a gross tonnage greater than 400 tons, used 339 million metric tons of marine fuels of which 286 million metric tons (84 percent) were residual fuels and 53 million metric tons (16 percent) were marine distillates. The IMO assumed that vessels with gross tonnage below 400 tons only used marine distillates.

Results

Total state annual and ozone season daily emission estimates excluding the HGA nonattainment area are presented in Table 3 for all criteria and hazardous air pollutants included in this study. For the ozone season daily estimates, it was assumed that activity was uniform throughout the year. Although this assumption may not be accurate for fishing vessels which are more seasonal in nature, the absence of information quantifying variance in fishing vessel activity throughout the year made it impossible to account for fishing activity seasonality in this inventory.

Table 3. Emissions from marine vessels in Texas state waters excluding the HGA nonattainment area.

Pollutant	Annual (tons)	OSD (tons)
Criteria		
Carbon Monoxide	13,391.10	36.69
Volatile Organic Compounds	3,114.15	8.53
Nitrogen Oxides	162,621.94	445.54
Sulfur Oxides	92,425.76	253.22
Primary PM_{10} (Includes Filterables + Condensables)	7,874.50	21.57
Primary $PM_{2.5}$ (Includes Filterables + Condensables)	7,874.50	21.57
HAP		
Arsenic & Compounds (Inorganic Including Arsine)	1.78	4.87E-03
Benzo[a]Pyrene	0.011	3.13E-05
Benzo[b]Fluoranthene	0.023	6.27E-05
Benzo[k]Fluoranthene	0.011	3.13E-05
Cadmium & Compounds	0.028	7.57E-05
Chromium	2.46	6.74E-03
Copper	4.76	1.30E-02
Dioxins	0.00001	3.13E-08
Hexachlorobenzene	0.00009	2.51E-07
Mercury & Compounds	0.006	1.55E-05
Indeno[1,2,3-c,d]Pyrene	0.023	6.27E-05
Ammonia	34.30	9.40E-02
Nickel & Compounds	65.39	1.79E-01
Polycyclic Organic Matter	0.07	1.88E-04
Lead & Compounds	0.36	9.95E-04
Polychlorinated Biphenyls	0.0011	3.13E-06
Selenium & Compounds	0.038	1.05E-04
Zinc	3.17	8.68E-03

Emissions results were also provided by source classification codes (SCC) and are presented in Table 4 for each vessel type considered in this study. The vessel types with the highest emissions (including port and underway emissions) are: 1) Other Vessels (28 percent of NO_x); 2) Offshore Support Vessels (18 percent of NO_x), and Dry Cargo (16 percent of NO_x). Together, these three categories account for approximately 60 percent of the NO_x emissions. It should be noted that it is believed that tug and towboats may be included in the unclassified vessels in the "Other Vessel" category.

Details of the emissions by source category for non-AIS data are available in TCEQ's *Diesel Inventory of Marine Vessels Phase II* Report.[1]

Table 4. Emission summary by vessel type (tons per year)

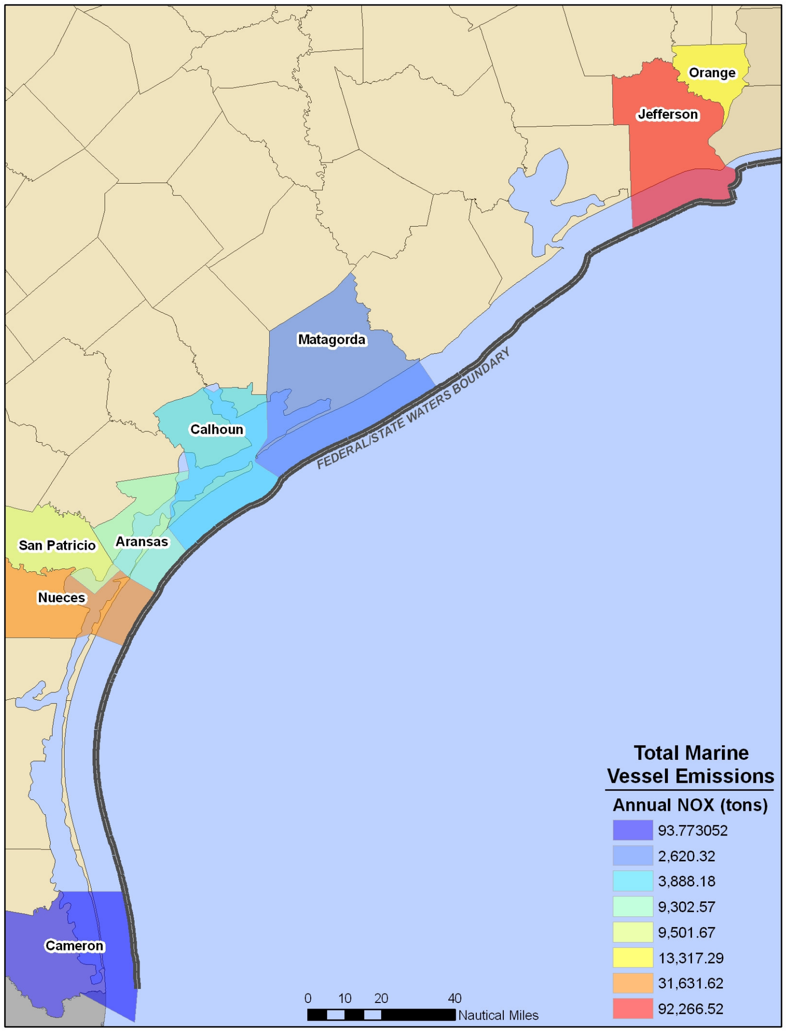
SCC Description (Proposed)	CO	NO_X	PM_{10}	PM_{25}	SO_X	VOC
Port emissions: Cruise	344	2,377	149	149	1,699	67
Port emissions: Dry Cargo	1,377	9,508	597	597	6,798	268
Port emissions: Ferry	344	2,377	149	149	1,699	67
Port emissions: Fishing	17.3	83.5	3.1	3.1	14.2	3.1
Port emissions: Offshore/Support	1,033	7,131	448	448	5,098	201
Port emissions: Pilot boat	344	2,377	149	149	1,699	67
Port emissions: Tanker	688	4,754	299	299	3,399	134
Port emissions: Tug, Assist	688	4,754	299	299	3,399	134
Port emissions: Tug, Line	344	2,377	149	149	1,699	67
Port emissions: Other	1,377	9,508	597	597	6,798	268
Underway emissions: Container Ship	229	4,076	174	174	2,082	63
Underway emissions: Cruise	229	4,076	174	174	2,082	63
Underway emissions: Dredging	54	587	10	10	78	10
Underway emissions: Dry Cargo	916	16,305	696	696	8,330	251
Underway emissions: Ferry	458	8,152	348	348	4,165	125
Underway emissions: Fishing	0.9	11.1	0.2	0.2	1.3	0.2
Underway emissions: Military	25	268	4	4	36	4
Underway emissions: Offshore/Support	1,489	22,758	1,019	1,019	12,112	381
Underway emissions: Pilot boat	229	4,076	174	174	2,082	63
Underway emissions: Tanker	458	8,152	348	348	4,165	125
Underway emissions: Tug, Assist	458	8,152	348	348	4,165	125
Underway emissions: Tug, Line	229	4,076	174	174	2,082	63
Underway emissions: Other	2,061	36,686	1,566	1,566	18,742	564
Total	**13,391**	**162,622**	**7,875**	**7,875**	**92,426**	**3,114**

Emissions were spatially allocated to counties outside the HGA nonattainment area using GIS shapefiles and are summarized in Table 5 and Figure 5. Jefferson (57 percent of NO_x) and Nueces (19 percent of NO_x) counties were the counties with the largest amount of marine vessel emissions. Together these two counties account for approximately 75 percent of NO_x emissions.

Table 5. Annual criteria emissions (tons) from marine vessels in Texas state waters by FIPS

FIPS	County	CO	NO_X	PM_{10}-PRI	PM_{25}-PRI	SO_2	VOC
48007	Aransas County	474.33	9,302.57	423.55	423.55	4588.81	145.39
48057	Calhoun County	263.56	3888.18	181.58	181.58	2,065.43	67.81
48061	Cameron County	10.44	93.77	1.96	1.96	14.79	1.9
48245	Jefferson County	7,673.5	92,266.52	4,374.94	4,374.94	5,2703.06	1,750.54
48321	Matagorda County	171.74	2620.32	101.31	101.31	1385.39	40.38
48355	Nueces County	3,111.95	31,631.62	1,738.24	1,738.24	19,085.22	702.29
48361	Orange County	987.39	13,317.29	583.03	583.03	7,430.52	229.78
48409	San Patricio County	698.19	9,501.67	469.9	469.9	5,152.54	176.06

Figure 7. Total annual vessel NO_x emissions by county for military, dredging, fishing, and commercial marine vessels

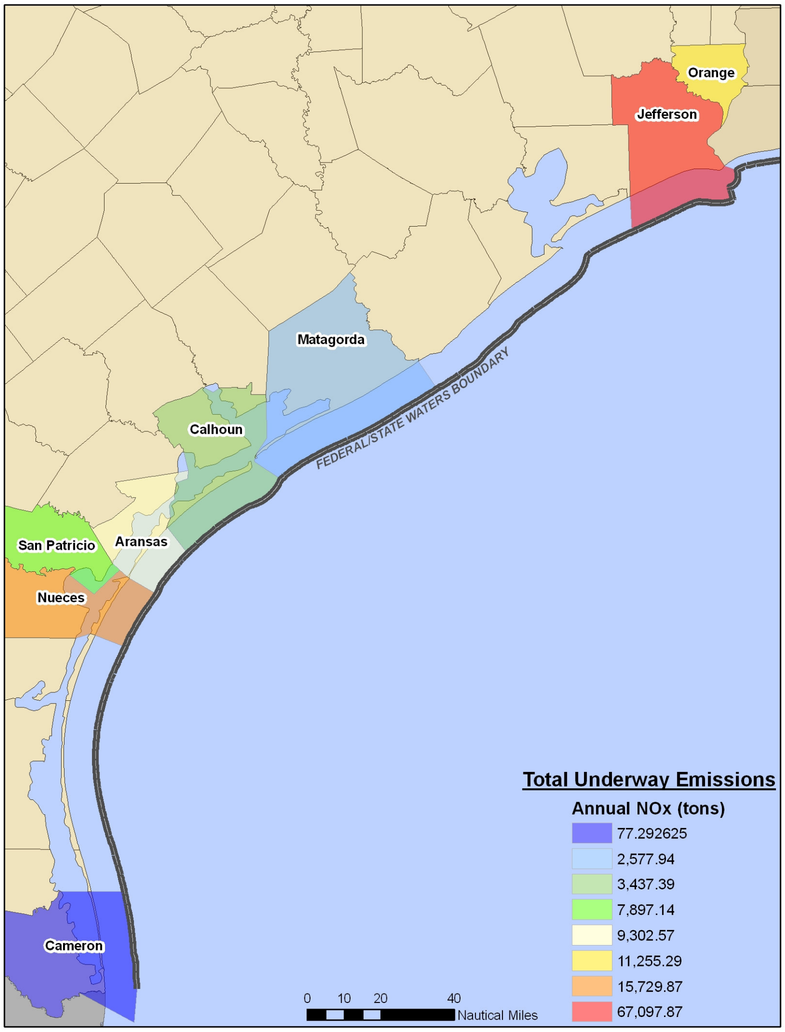


Discussion

The use of AIS data in this inventory effort highlights some of the promising aspects of AIS data as well as some of the data's major limitations. Some of the potential benefits of using AIS data in inventory applications include improved hours of operation and greater spatial accuracy particularly for in-port activities. The automatic and electronic nature of these data improves reporting consistency both spatially and temporally while minimizing data entry errors, particularly over other datasets that rely on voluntary reporting by vessel operators. Clear SOLAS requirements also ensure data are received from the largest vessels and include both foreign and domestic traffic.

However, processing massive amounts of data for use in applications such as emission inventories is a challenging endeavor. New techniques are needed to address some of the problems encountered in implementing this inventory in order to maximize the potential benefits of these data. One of the most striking limitations is the number and total coverage of the POIs. As Figure 5 indicates, there are several coastal counties that show no marine vessel emissions even though vessel traffic occurs along the entire coast of Texas and the Gulf Intracoastal Waterway. The lack of emissions for these counties is due to the placement of the POIs, in particular, monitoring buoys that could only document vessel traffic out-to-sea, thereby underestimating traffic that occurs closer to shore or along the Gulf Intracoastal Waterway. Additionally, the POIs are concentrated near large ports with heavier traffic; in fact, Kleberg, Kenedy, and Willacy counties had no POIs at all, as seen previously in Figure 2. Because the AIS data did not accurately represent activity levels along the coast and in the Gulf Intracoastal Waterway, emissions are underestimated for counties without port activities, as noted in Figure 8.

Figure 8. Annual AIS vessel underway NOx emissions (tons)



In reviewing the AIS data for this project, it was discovered that not all of the data fields were fully or correctly populated; for example, the vessel type field was often not reported or incorrectly reported. These data elements were programmed into the unit upon installation and were gap-filled by linking to other vessel characteristics data sources when possible. Notwithstanding, this is likely one source for the relatively high emissions in the "Other Vessel" category.

Another concern regarding use of the AIS data was whether the tug and tow boat traffic would be accurately and completely represented. Some tug and tow boat operations may not be included due to the fact that smaller tugs do not meet the reporting requirements (i.e., > 300 gross tons). For example, the AIS data accounts for 360 vessels identified as tugs, though there may have been more in the dataset where the vessel type data were not provided or were classified in generic terms. This is in contrast with the 1,056 tugs identified in the Houston Routine Vessel Study.[10] On the other hand, the 360 AIS tugs accounted for a sizable portion (26 percent) of the total AIS traffic. To evaluate this issue, the data were summarized and provided to an independent external reviewer. The reviewer received the "Tugs Trip Count Data" that quantified the number of trips for each shipping route included in the study. Also provided was the "Tugs Count by Port Data" that quantified the number of times a vessel travels to or from a specific port. The count data included both vessels specifically identified as tugs and those for which the vessel type was unknown or blank in the AIS data. The reviewer compared these data with the latest (2006) Waterborne Commerce of the United States (WCUS) data.[11] It should be noted that the WCUS data are provided voluntarily by vessel operators and owners and probably underestimate actual activity levels.

The Sabine-Neches area that encompasses Beaumont, Port Arthur, and Orange had about 33,000 towboat movements in 2006 according to the WCUS. If a sizable portion of the "unknown" vessels included in the AIS data are tug traffic activities, then tug activity in both data sets are roughly similar, though it should be recognized that this is a very complicated port system and may require further consideration. The Corpus Christi area had about 6,000 vessel movements according to the WCUS, which is significantly less than the 12,809 tug movements reported in the AIS data set. In this case, it appears that the AIS data may be overestimating tug traffic in this port as Corpus Christi does not typically have a lot of tug traffic. Further evaluation of tug activities in the Corpus area may be needed, but it should be appreciated that the additional 6,809 vessel movements represents only 7 percent of the total trip movements documented in the AIS data.

The WCUS reported that the Brownsville area had about 1,100 vessel movements. As the AIS data did not extend to Brownville, a small amount of vessel activity was estimated based on vessels' reported destinations; still, the AIS data underreported activity in Brownsville. For Victoria, which is in the Matagorda area, the WCUS reported 2,400 trips compared with 1,677 for Matagorda and Port Lavaca as reported by AIS. The decrease in activity reported in 2007 AIS data may be indicative of the decline in economic activity in Victoria as the Alcoa and Dow facilities had recently closed.

In general it appears that the AIS data may accurately represent activity in the biggest port area, Sabine-Neches, but may be overestimating activity in Corpus Christi and underestimating activity in Brownsville, where there are fewer POIs.

CONCLUSIONS

There have been several detailed and comprehensive emission inventories of the Houston/Galveston/Bazoria port area; but considerably less for other coastal counties that include some very active ports and shipping lanes. The AIS data used to develop this emission inventory provided reasonably accurate information about vessel traffic patterns outside of the Houston/Galveston nonattainment area. These AIS data included over 80,000 ship transits for nearly every vessel type.

However, further enhancements are required to more accurately identify and spatially allocate coastal and intracoastal waterway trips. Until additional POIs are added to statewaters, such allocations could be improved by using U.S. Army Corps of Engineers domestic traffic data. These data are not disaggregated by individual vessels but rather estimate total traffic movements. Such information could be used in conjunction with the tug and towboat data compiled for this inventory to more accurately assign emissions to all coastal counties.

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REFERENCES

[1] Billings, R., H. Perez, and R. Chang, "Diesel Inventory of Marine Vessels Phase II"; Prepared for Texas Commission on Environmental Quality by Eastern Research Group, Inc., Morrisville, NC 2008.

[2] U.S. Coast Guard Navigation Center, U.S. Department of Homeland Security. *Automatic ID System*. http://www.navcen.uscg.gov/enav/ais/what_AIS_broadcasts.htm, 2009.

[3] International Maritime Organization. International Convention for the Safety of Life at Sea (SOLAS), 1974.

[4] AIRSIS, Inc. *Corporate Overview*. http://www.portvision.com/Public/company/, 2009.

[5] Fairplay, Ltd, *Lloyd's Register of Ships,* 8410 N.W. 53rd Terrace, Suite 207, Miami, FL, 2004.

[6] American Bureau of Shipping – 2004 Data Query, http://www.eagle.org/.

[7] Bureau Veritas – *2004 Data Query,* Paris, France, 2004.

[8] U.S. EPA*, Best Practices in Preparing Port Emission Inventories,* http://www.epa.gov/otaq/stateresources/rellinks/docs/bp-portemissions.pds, Office of Policy, Washington, DC, 2005.

[9] Swedish Environmental Protection Agency, Swedish Methodology for Environmental Data – Methodology for Calculating Emission From Ships, Stockholm, 2004.

[10] Eastern Research Group, Inc., "Houston/Galveston Routine Vessel Identification and Traffic Study"; Prepared for Texas Commission on Environmental Quality by Eastern Research Group, Inc., Morrisville, NC 2007.

[11] Department of Transportation, Bureau of Transportation Statistics. *National Transportation Atlas Database,* 2007.

Appendix 1. Points of Interest (POI) within Texas state waters study area.

POI Name	POI Type	Longitude	Latitude	Number Of Events
709	Landmark	-93.92	29.88	27,473
Alcoa R-10 North	Terminal	-96.56	28.65	443
Alcoa R-10 South	Terminal	-96.56	28.65	485
Amfels Dock	Terminal	-97.36	25.97	5
Bean's Fleet West	Terminal	-93.87	29.96	17,567
Beaumont Grain	Terminal	-94.08	30.07	1,115
Beaumont Reserve Fleet	Terminal	-94.01	30.03	14,483
Beaumont Ro-Ro/Barge Dock	Terminal	-94.09	30.07	1,105
Brownsville Jetties	Landmark	-97.15	26.07	4
Brownsville, TX	Landmark	-97.55	26.03	0
Carrol Street Extension	Terminal	-94.08	30.07	2,472
Carrol Street Wharf	Terminal	-94.08	30.07	1,106
CCND Barge Terminal	Terminal	-96.55	28.64	401
CCND Gen Cargo Dock	Terminal	-96.55	28.65	264
CCND Liquid Cargo Pier N	Terminal	-96.55	28.64	884
CCND Liquid Cargo Pier S	Terminal	-96.55	28.64	489
CCND Multi Purpose Dock	Terminal	-96.55	28.64	487
CG Sabine Pass	Terminal	-93.87	29.73	18
Chevron	Terminal	-93.97	30.01	2,636
Chevron #5, Sabine	Terminal	-93.97	30.01	4,153
Chevron Crude Dock #2	Terminal	-93.97	30.01	1,603
Chevron- Phillips BG Dock	Terminal	-93.96	29.83	1,817
CITGO 1 - Corpus	Terminal	-97.42	27.81	7,325
CITGO 2 - Corpus	Terminal	-97.42	27.81	2,261
CITGO 3 - Corpus	Terminal	-97.49	27.82	3,949
CITGO 6 - Corpus	Terminal	-97.49	27.82	1,581
CITGO 7 - Corpus	Terminal	-97.43	27.82	5,258
CITGO 8 - Corpus	Terminal	-97.41	27.81	6,178
Corpus Christi ADM/GROW	Terminal	-97.42	27.82	4,480
Corpus Christi Bay Inc.	Terminal	-97.49	27.82	5,416
Corpus Christi Bulk 1	Terminal	-97.46	27.82	1,621
Corpus Christi Bulk 2	Terminal	-97.47	27.82	1,548
Corpus Christi CD 09	Terminal	-97.40	27.82	3,060
Corpus Christi CD 12	Terminal	-97.41	27.82	544
Corpus Christi CD 8,14,15	Terminal	-97.40	27.81	6,279
Corpus Christi OD 1	Terminal	-97.40	27.82	4,150
Corpus Christi OD 11	Terminal	-97.44	27.82	2,063
Corpus Christi OD 12	Terminal	-97.41	27.81	158
Corpus Christi OD 3	Terminal	-97.43	27.82	661
Corpus Christi OD 4	Terminal	-97.43	27.82	9,639
Corpus Christi OD 7	Terminal	-97.44	27.82	2,117
Corpus Christi OD 8	Terminal	-97.52	27.84	3,082
Corpus Christi TDR	Terminal	-97.50	27.83	3,473
Corpus Harbor Bridge	Landmark	-97.40	27.81	2,758
Degusa	Terminal	-93.71	30.15	206

DuPont Chemical	Terminal	-94.03	30.02	2,236
ExxonMobil #2	Terminal	-94.07	30.08	3,175
ExxonMobil #4	Terminal	-94.07	30.08	2,377
ExxonMobil #5	Terminal	-94.06	30.07	1,431
ExxonMobil Chemical Dock	Terminal	-94.06	30.07	6,769
ExxonMobil Coke Dock	Terminal	-94.06	30.07	420
Flint Hills 1&2	Terminal	-97.42	27.81	5,329
Global/Pabtex	Terminal	-93.88	29.93	6,441
Golden Pass LNG Terminal	Terminal	-93.93	29.76	36
Government Mooring	Terminal	-93.97	29.82	27,643
Great Lakes Carbon	Terminal	-93.96	29.83	4,162
Great Lakes Carbon	Terminal	-93.96	29.83	376
Gulf Copper	Terminal	-93.97	29.84	20
Gulf Copper	Terminal	-93.97	29.85	1,307
Harbor Island A	Terminal	-94.09	30.08	149
Harbor Island A	Terminal	-94.09	30.08	753
Harbor Island B	Terminal	-94.09	30.08	787
Harbor Island C	Terminal	-94.09	30.08	342
Harbor Island C	Terminal	-94.09	30.08	15
Huntsman	Terminal	-93.93	29.99	1,447
Ingleside Kiewit	Terminal	-97.23	27.85	4,368
Ingleside Koch	Terminal	-97.20	27.82	1,817
Ingleside OCC	Terminal	-97.24	27.87	2,273
Ingleside SHAL	Terminal	-97.26	27.88	1,580
Interstate Elevator	Terminal	-97.47	27.81	1,116
JB Packing	Terminal	-93.97	29.84	211
JB Packing PA	Terminal	-93.93	29.87	154
KEIWITT OFFSHORE	Terminal	-97.19	27.83	4,083
Kinder Morgan	Terminal	-93.96	29.84	1,057
Kirby Staging Area	Terminal	-94.05	30.07	11,605
Lone Star Marine	Terminal	-93.87	29.94	6,433
Lower Fina Anchorage	Terminal	-93.90	29.99	3,183
Marine Fueling Service	Terminal	-93.87	29.96	10
Marine Fueling Service	Terminal	-93.86	29.97	3,910
Martin CCBT	Terminal	-97.40	27.81	3,571
Martin Mid Harbor Island	Terminal	-97.06	27.85	4,650
Martin Mid Port O'Connor	Terminal	-96.45	28.43	3,516
Martin Mid Sabine Pass	Terminal	-93.87	29.72	4,268
Martin Midstream / Stan	Terminal	-94.05	30.03	2,207
Martin Neches	Terminal	-94.04	30.06	5,076
Matagorda Harbor Marina	Terminal	-95.96	28.69	1,734
Matagorda Jetties	Landmark	-96.31	28.42	652
MLK Bridge, Port Arthur	Landmark	-93.94	29.85	255
Motiva PA #1	Terminal	-93.96	29.83	5,717
Motiva PA #6	Terminal	-93.96	29.83	5,311
Motiva PA #7	Terminal	-93.96	29.84	4,732
Motiva PN #1	Terminal	-93.94	29.99	1,802
Motiva PN #2	Terminal	-93.94	29.99	1,245
Motiva PN #3	Terminal	-93.93	29.99	2,174

MSQTPt.	Landmark	-93.90	29.76	9,185
MSRC Corpus Christi	Terminal	-97.22	27.85	34
Neches Gulf	Terminal	-93.89	29.74	626
NRI	Landmark	-93.85	29.97	71,804
Oiltanking A Dock	Terminal	-94.04	30.02	1,658
Oiltanking Beaumont North	Terminal	-94.04	30.03	2,840
Oiltanking Beaumont South	Terminal	-94.04	30.03	1,911
Pabfacs/Coastwise	Terminal	-93.96	29.84	2,831
PAYC Marina	Terminal	-93.93	29.87	95
Port Aransas Jetties	Landmark	-97.04	27.83	8,242
Port of Beaumont 2,3	Terminal	-94.09	30.08	367
Port of Beaumont 4	Terminal	-94.09	30.08	388
Port of Beaumont 5,6	Terminal	-94.09	30.08	256
Port of Beaumont 7	Terminal	-94.09	30.08	241
Port of Beaumont Dock 1	Terminal	-94.09	30.08	37
Port of Orange	Terminal	-93.72	30.07	449
Port of Port Arthur	Terminal	-93.94	29.86	4,780
PSN Dock	Terminal	-97.08	27.85	641
R&R Marine	Terminal	-93.89	29.92	2,201
Rowan Dock	Terminal	-93.86	29.72	6,101
Sabine Pass Pilot Station	Terminal	-93.87	29.72	8,156
Signal Dry Dock	Terminal	-93.95	29.82	1,568
Stanolind Anchorage	Terminal	-94.04	30.05	5,102
Sunoco #1	Terminal	-93.98	30.01	1,061
Sunoco #2	Terminal	-93.99	30.01	672
Sunoco #3	Terminal	-93.99	30.01	689
Sunoco #4	Terminal	-94.00	30.01	1,191
Sunoco #5	Terminal	-94.01	30.01	14,015
Sunoco A & B Barge	Terminal	-93.98	30.01	753
Sunoco Lower Anchorage	Terminal	-93.99	30.01	2,080
Sunoco Upper Anchorage	Terminal	-94.00	30.02	1,562
Texas Island Intersection	Landmark	-93.96	29.82	43,912
Texas Island Intersection	Terminal	-93.96	29.82	7
Texas Lehigh Cement	Terminal	-97.42	27.82	671
Total #1	Terminal	-93.88	29.98	3,642
Total #2	Terminal	-93.88	29.98	2,386
Total #3	Terminal	-93.88	29.98	24,617
Transit Mix	Terminal	-93.97	29.84	2,950
Upper Fina Anchorage	Terminal	-93.93	29.99	867
Valero Corpus Christi 2	Terminal	-97.48	27.82	2,123
Valero Corpus Christi 3	Terminal	-97.48	27.82	1,895
Valero Port Arthur	Terminal	-93.97	29.85	9,051

Key Words: Automatic Identification Systems, Texas, state waters, marine vessels, emission estimates, AIS