

Final Report

Project 24-003

Improving Emission Rates Estimates of Commercial Marine Vessels

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EXECUTIVE SUMMARY

This project investigated emissions from commercial marine vessels in Galveston Bay by directly sampling exhaust plumes downwind of active shipping lanes. Using data from the University of Houston (UH) research boat, each plume was matched with a specific vessel and its operational characteristics.

Commercial marine vessels (CMV) primarily use diesel engines powered by heavy fuel oil, which contains 1–4.5% sulfur. Large vessels like tankers and container ships generate 5–100 megawatts of power and emit significant amounts of nitrogen oxides (NO_x), sulfur dioxide, carbon monoxide (CO), carbon dioxide (CO₂), and volatile organic compounds (VOC). These emissions remain largely unregulated and impact air quality on local to global scales. In the Houston-Galveston-Brazoria (HGB) nonattainment area, CMVs accounted for approximately 18% of NO_x emissions in 2019, which may significantly compromise regional air quality improvement initiatives. The TCEQ relies on emission inventories to develop the State Implementation Plan (SIP), which is crucial for managing air pollutants such as NO_x and ozone. Recognizing the significance of reliable data, the University of Houston and Ramboll teams performed this research project (24-003) to address the research priority identified by the AQRP to improve emission inventories for commercial marine vessels.

The UH research boat has been modified to carry instruments inside a climate-controlled cabin. Measurement sample inlets and meteorological sensors were positioned forward of the bow to reduce the impact of exhaust or obstructions from the research boat. The boat was anchored a safe distance downwind of the Houston Ship Channel (HSC) in order to sample plumes from passing vessels and document identifying information about the vessel in order to later determine the type and engine characteristics. Measurements were ratioed against CO₂ to calculate emission rates following the same approach used in prior on-road and marine plume studies.

The results showed that the nitrogen oxide emissions relative to carbon dioxide had good agreement with most vessels, however, the newer vessels observed tended to emit more than expected. This may be due to the low speeds at certain points in the channel, which resulted in reduced efficiency for exhaust aftertreatment systems, which are not well represented in emission inventories. Conversely, older vessels tended to be cleaner than expected, possibly due to undocumented engine rebuilds or replacements. While the observed ocean going vessels had sulfur dioxide emissions which were relatively consistent with expectations, the harbor craft fleet tended to emit significantly more sulfur than anticipated based on fuel requirements.

Suggestions for future work include identifying sources of verified engine and vessel information to reduce potential misclassification and sampling under different meteorological conditions, allowing for sampling under higher engine loads. The general sampling approaches could also be applied with even larger instrument suites to address other emission categories, such as locomotives.

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List of Abbreviations and Acronyms

AIS	Automatic Identification System
AROMA	Autonomous Rugged Optical Multigas Analyzer
AQRP	Air Quality Research Program
AUC	Area-under-the-curve
CMV	Commercial Marine Vessels
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CRF	Code of Federal Regulations
C1	Category 1
C2	Category 2
C3	Category 3
DOAS	Differential Optical Absorption Spectroscopy
DRI	Desert Research Institute
ECA	Emission Control Area
EPA	Environmental Protection Agency
ER _s	Emission rate of sulfur
FTIR	Fourier Transform Infrared
g	grams
GC-MS	Gas Chromatography–Mass Spectrometry
GPS	Global Positioning System
HCHO	Formaldehyde
HGB	Houston-Galveston-Brazoria
HFO	Heavy Fuel Oil
Hz	hertz
H ₂ O	Water
kW / kWh	Kilowatt/kilowatt-hour
L	liters
m	meter
mi	miles
mph	Miles per hour
MMSI	Maritime Mobile Service Identity
MW	megawatts
NO	Nitric Oxide
NO _x	Nitrogen Oxides
NO ₂	Nitrogen Dioxide
N ₂ O	Nitrous Oxide
O ₃	Ozone
OGV	Ocean-going vessels (large ships)
PC	Ruggedized industrial computer
PM	Particulate Matter
PM _{2.5}	Particulate matter 2.5
ppm	parts per million
ppbv	parts per billion by volume
s	second
SCR	Selective Catalytic Reduction
SIP	State Implementation Plan
SO ₂	Sulfur dioxide

TCEQ	Texas Commission on Environmental Quality
THC	Total hydrocarbons
TVOC	Total Volatile Organic Compound
UH	University of Houston
VOC	Volatile Organic Compound

1. INTRODUCTION

Commercial marine vessels, ranging from 20-meter (m) fishing boats to over 300 m cargo ships, primarily use diesel engines powered by heavy fuel oil (HFO), which contains 1–4.5% sulfur (Williams et al., 2009). Large vessels like tankers and container ships generate 5–100 megawatts (MW) of power and emit significant amounts of nitrogen oxides, sulfur dioxide, particulate matter (PM), carbon monoxide, carbon dioxide, and volatile organic compounds such as formaldehyde (HCHO) (Williams et al., 2009). While efficient in fuel combustion, these emissions remain largely unregulated and impact air quality on local to global scales. Emissions from commercial marine boats may significantly compromise regional air quality improvement initiatives. Commercial ships have a significant influence on air pollution, contributing up to 30% of anthropogenic NO_x and 8% of SO₂ emissions globally (Corbett et al., 2007; Eyring et al., 2005). As a result, national and international regulations have been created to reduce emissions from the marine industry.

The TCEQ relies on emission inventories to develop the State Implementation Plan SIP, crucial for managing air pollutants such as NO_x and ozone (O₃). Recognizing the significance of reliable data, the University of Houston and Ramboll teams proposed this research project to address the research priority identified by the AQRP to improve emission inventories for commercial marine vessels.

CMV emissions constitute a substantial portion of coastal NO_x emissions. In the Houston-Galveston-Brazoria nonattainment area, CMVs accounted for approximately 18% of NO_x emissions in 2019, with a continued significant contribution expected for years to come. Among different vessel categories, smaller commercial vessels, notably towboats, were responsible for about 42% of CMV NO_x emissions in Texas in 2019 (TCEQ, 2023). Towboat and tugboat emissions have greater uncertainty than other CMV categories due to the lack of information on engines and the uncertainties of engine loads and operating parameters. This project aims to improve our understanding of commercial marine exhaust emissions, with a focus on NO_x, VOCs, particulate matter 2.5 (PM_{2.5}), and hydrocarbon speciation.

2. OBJECTIVES

This study investigated emissions from commercial marine vessels in Galveston Bay by directly sampling exhaust plumes downwind of active shipping lanes. Using real-time Automatic Identification System (AIS) data from onboard the UH Osprey, each plume was matched with a specific vessel and its operational characteristics. Emissions were evaluated through the analysis of NO_x, SO₂, and CO to CO₂ concentration ratios in exhaust plumes that followed the same approach used in prior on-road and marine plume studies (for example, Bishop et al., 2022, and Williams et al., 2009). For each plume measurement, the concentration ratio of emissions to CO₂ was converted to emissions per fuel consumed ratios using a carbon balance method. The specific objectives of this study include:

- Sampled uniquely identified CMV plumes directly downwind of Galveston Bay shipping lanes.
- Used AIS data to confirm vessel identity, speed, heading, and engine load.
- Assessed emission rate characteristics by calculating observed pollutants (e.g., NO_x, CO, SO₂) to fuel consumption ratios.

3. METHODOLOGY

3.1 Sampling Platform

The UH research boat, an Osprey 30 (**Figure 1**) has been modified to carry a tandem shock-mounted equipment rack inside a climate-controlled cabin. The research boat is a 30-foot offshore fishing boat that has been specially modified to house research equipment and the associated supporting infrastructure. Propulsion is provided by a pair of Suzuki 300-horsepower outboard engines fed by two 115-gallon fuel tanks. The estimated useful range of the research boat is 180 miles (mi) and cruises in calm conditions at speeds of 30 miles per hour (mph) or more. Electrical power is provided by a 9-kilowatt (kW) diesel generator installed below the aft deck and fed by a dedicated 27-gallon diesel fuel tank. Online measurement sample inlets and meteorological sensors were positioned forward of the bow, approximately 1 meter, to reduce the impact of exhaust or obstructions from the research boat. Some of the instrumentation, such as the PM_{2.5} and boundary layer instruments, were mounted to the roof of the boat.



Figure 1. A picture of the UH Osprey sampling in Galveston Bay near the Houston Shipping Channel.

The instrumentation package included instrumentation for Nitric Oxide (NO), Nitrogen Dioxide (NO₂), Carbon Monoxide, Carbon Dioxide, Sulfur Dioxide, as well as Global Positioning System (GPS) receiver, an all-in-one weather station, and a ruggedized industrial computer (PC) with a cellular data connection. A ceilometer was also installed on the research boat to measure the boundary layer height over the water, which is often parameterized in photochemical models and can have a significant impact on model results. This data was collected to provide context for this project, as well as improve the usability of the data for future analysis projects. An Aroma-VOC

instrument (<https://entanglementtech.com/products/aroma-voc/>) was rented and operated for bulk VOC measurements to help indicate when to begin a VOC canister sample for offline analysis of certain plumes. Mobile extractive Fourier Transform Infrared (FTIR) and Differential Optical Absorption Spectroscopy (DOAS) was installed and collected measurements of 1) FTIR - total alkanes, methane, CO, CO₂, Nitrous Oxide (N₂O), HCHO, and acetaldehyde, and 2) DOAS - benzene, toluene, ethylbenzene, p-xylene, m-xylene, naphthalene, furfural, phenol, SO₂. The FluxSense instruments sampled from a 9-meter heated sample line with a PM_{2.5} cyclone at the inlet to remove most aerosols and minimize sample losses. PM_{2.5} was measured using a Teledyne T640 installed in an air-conditioned enclosure on the roof of the boat to minimize the sample inlet lengths and bends. Automated and crew operated cameras and the AIS information from the boat's systems was used to document passing vessel information and identity-

3.2 Sampling Activities

The UH boat was launched on February 14, 2025, from the Seabrook Marina and docked overnight at the Bayland Marina near the confluence of the Houston shipping channel and the north side of Galveston Bay for the duration of the field campaign. Sampling activities began on February 17, 2025 (**Figure 2**) after all instrumentation and boat systems were prepared and stabilized. Sampling activities concluded on April 11, 2025, followed by a final calibration of all instruments on board on April 15, 2025, marking the end of the field campaign. A total of sixteen sampling days were completed between February and April, with approximately 400 unique marine vessel plumes identified during the sampling period. In addition to the measurements, further information was logged about each ship, such as vessel speed, heading, engine load, and name, which can be used to derive other vessel characteristics. Extra information regarding whether the boat was pushing barges, the types of barges, and its contents was also recorded by the crew.

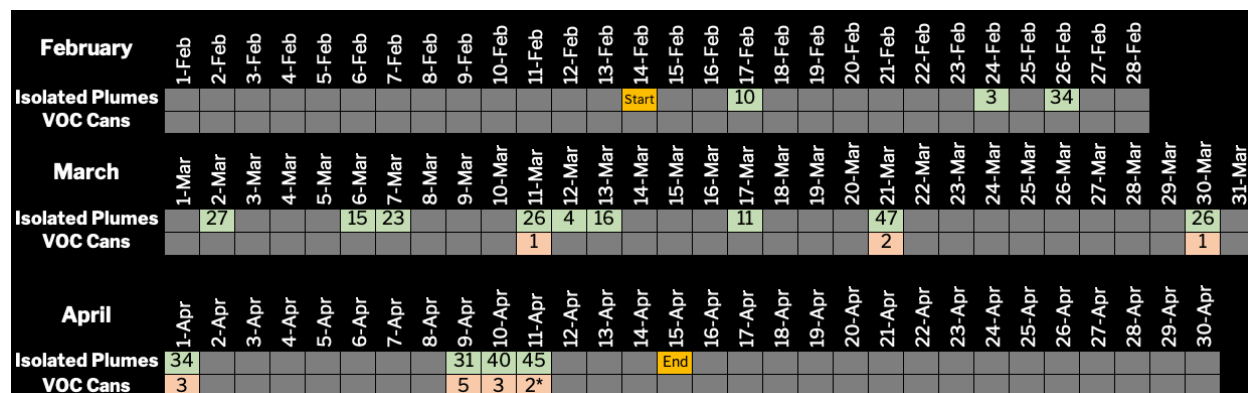


Figure 2. A chart showing the operational days for the UH Osprey during the field campaign. The yellow cells indicate the start and end of the measurement window, the green cells indicate days the Osprey sampled next to the shipping lanes with the number of isolated pushboat emissions identified during each sampling day, and the light orange cells indicate days and numbers of VOC canisters collected. The asterisk indicates a VOC canister sample that failed a leak check.

Due to the prevailing north-south winds during February–April, the more open water sections of the shipping lanes within Galveston Bay provided poor sampling geometries, as the channel in this area is also oriented north-south. As a result, the Osprey tended to sample north of the Highway 146 bridge, where the channel was oriented more east-west and allowed the Osprey to anchor downwind and close enough to the channel so the instruments would get strong signals in each plume. This also resulted in sampling in an area with other industrial emissions, so the enhancement calculations were done relative to measurements before and after the plumes. While the sampling location was relatively distant from roadways, it is possible that some on-road emissions were sampled, however the approach of making enhancement calculations relative to before and after the plumes should minimize the impact of other sources.

3.3 Audits of Data Quality

3.3.1 Discussion of QA/QC Activities and Results

3.3.1.1 University of Houston

Trace Gases

The University of Houston trace gas instrument package went through regular quality assurance measures throughout the campaign. These measures included inlet particulate filter changes before each sampling outing, nominal weekly multi-point calibration checks using blended gas standards (CO, NO, NO₂, SO₂) and reference standards (CO₂), as well as pre/post-departure span and zero air checks of all instruments. UH operators were able to view all live data collection through onboard display systems. Additionally, data was downloaded through daily data backups of the instrument package and plotted as a first-order measure of data quality assurance throughout the campaign.

The complete trace gas measurement dataset was baseline corrected using measured zero points from overflowing the inlet using generated zero air provided by a Teledyne T701. Additionally, some measurements (CO, NO) performed a routine baseline assessment and correction.

Individual trace gas species were also corrected using twenty-two calibration assessments against known blended gas standards that were performed throughout the campaign. Within these calibrations, an expanded multi-point calibration was conducted on trace gas instruments at the beginning (February 28, 2025), middle (March 14, 2025), and end (April 15, 2025) of the campaign.

Trace Gas Peak Alignment

To compute an accurate emission ratio, it is imperative to account for differences in instrument sample cycles and response times. Data alignment was conducted by aligning peaks in trace gases to those in the CO₂ data, since it was the fastest responding instrument. Most instruments were aligned with a single time value, however, the Teledyne NO₂ uses an adaptive filtering calculation which was locked into the firmware and could not be disabled. As a result, the

effective response time of the instrument varied based on the strength and gradient of NO₂ concentrations. After completing the alignment, a manual evaluation of the approximately 400 unique emission plumes was completed to ensure an optimized alignment.

Meteorology, Ceilometer, and PM_{2.5}

Meteorological data (wind speed/direction, temperature, relative humidity, and atmospheric pressure) was collected using an Airmar 220wx sensor. No corrections were made to the meteorological data, but any wind data collected during mobile periods (<1 knot) was invalidated due to uncertain instrument corrections for movement.

Boundary layer and cloud height information was collected using a Vaisala CL51 ceilometer. The ceilometer was included in the instrument package to aid in potential modeling/analysis efforts in the future. The ceilometer is a form of LiDAR that can identify aerosol gradients using backscatter returns. This can be used to identify up to three layers within the troposphere. From these measurements you can infer planetary boundary layer heights such as the convective boundary layer, nocturnal boundary layer and residual layer - when present. The raw aerosol backscatter is also provided.

PM_{2.5} data was collected using a Teledyne T640 instrument that was mounted to the roof of the vessel within a climate-controlled enclosure. This instrument was sampling on its own inlet system, which was not tied into the trace gas system to minimize bends in the intake. Data was recorded into the same PC-based acquisition system, which ensured that the data were aligned with all other measurements.

VOC Canisters

Volatile organic compounds were collected in 1-liter stainless steel SUMMA® canisters from the bow of the vessel and analyzed at the Desert Research Institute (DRI) using gas chromatography–mass spectrometry (GC-MS).

Completeness

In **Table 1** the data completeness percentage is shown for the UH trace gas data. Due to the need for the highest resolution data to make emissions estimates, the data was delivered in 1-second (s) time resolution. However, some instrument communication protocols occasionally resulted in a skipped point when the acquisition system was set to 1 s samples. Because the skipped points were sporadic, it is reasonable to interpolate across small sections, up to three seconds. Therefore, a raw data completeness percentage is shown for the data points collected, divided by the total number of seconds. Additionally, the value of interpolated completeness is also reported, which applies to a linear interpolation for up to three missing 1-second data points.

Table 1. A table of data completeness for the UH trace gases and PM measurements.

Trace Gas	Data Completeness % Raw/Interpolated
CO	79.1 / 95.7
CO ₂	97.7 / 99.9
NO	89.2 / 93.2
NO ₂	79.4 / 95.3
SO ₂	84.9 / 99.0
PM _{2.5}	81.7 / 99.8

Data Auditing

Data deliverables were 100% visually inspected for anomalies and quality issues as an additional quality assurance check. Any invalid data periods were flagged or removed before analysis.

3.3.1.2 FluxSense

Instrument QA on the Osprey

The FTIR and DOAS instruments were installed on the Osprey by a FluxSense operator and adjusted for optimal performance. The multi-pass cells were aligned for 100.8 m path length which was verified with a calibration gas before they were shipped to Houston. Checks were made after installation to ensure that the alignment was maintained, and only minor adjustments were made to maximize light intensities. The operator conducted extensive tests of instrument performance during the days before the sampling started and was present on the Osprey during the first sampling day (February 17, 2025) and made additional minor adjustments. On subsequent sampling days the instruments were monitored remotely by FluxSense operators at regular intervals by logging in to the measurement computer via mobile data link. The real-time results from the instruments were also monitored by the UH operators on board the Osprey.

The instrument cabinet initially lacked sufficient ventilation. As outside temperatures started to increase during the campaign, the interior of the cabinet saw significant diurnal variations in temperature. This affected especially the DOAS instruments which showed large variations in light intensity throughput along with the temperature variations. This led to a drift in evaluated concentrations and a decreased detection limit. These problems were partially mitigated by intensity optimizations performed at regular intervals. At the end of the campaign, this was further mitigated with the installation of a more powerful ventilation solution. During the period from March 6 to March 13, 2025, the normal detection limits for the DOAS species cannot be expected to hold due to these issues, but instead detection limits twice as large have been assigned for DOAS species for these days, as shown in **Table 6**. In reality, performance varied significantly during these days, so there may be periods when the detection limits were better, but a single value has been assigned to this whole period for simplicity.

Post-processing of spectral data

The real-time evaluations of the instrument spectra only included a few key species in order to ensure it could keep up with the measurements. Post-processing used a more advanced spectral retrieval algorithm that could compensate for some interfering artifacts and evaluate a larger suite of species. For the FTIR instrument, this included Methane, Ethane, C3+ Alkanes, Formaldehyde, Acetaldehyde, CO₂, CO, N₂O, and water (H₂O). For the DOAS instrument, this included Benzene, Toluene, p-Xylene, m-Xylene, Ethylbenzene, SO₂, O₃, Naphthalene, Furfural, and Phenol. All concentrations were converted to volume mixing ratios in ppb, except for CO₂ which was converted to ppm, using instantaneous cell temperature and pressure measurements. Since the C3+ Alkanes evaluation is sensitive to alkanes of different sizes and more proportional to mass than to number of molecules, the conversion to volume mixing ratios was made using the molar mass of Butane, meaning it should be thought of as Butane equivalents.

Plume interference

On some days, a notable interference coinciding with the plume sampling was seen in the DOAS data, mainly affecting the concentrations of m-Xylene, Ethylbenzene, and Toluene. This typically manifested itself as these three (3) species deviating from the baseline, with one or two of them going negative, and the other going positive. The exact cause of this is unknown. It might have been interference from the strong negative O₃ signal in the plumes due to NO titration, but this would not explain why it was only seen during a few days. All measurement days were examined for this type of interference episodes, but they were only found on February 17, February 26, and March 2. Caution should be taken when analyzing plumes of these species on these days.

3.3.1.3 Ramboll

The vessel plume dataset was reviewed to ensure accuracy, consistency, and completeness prior to analysis. A total of 402 plumes with valid peak times were provided, with second-by-second measurements of gaseous pollutants and particulate matter. Units were standardized across species, and basic checks identified some missing seconds of data.

Time alignment was carefully reviewed to confirm that plume peaks were consistently captured. While NO peaks generally aligned with CO₂, NO₂ peaks lagged by several seconds and were corrected to improve consistency. This is discussed in detail in section 3.3.1.1. Short gaps (up to three seconds) in pollutant data were filled using linear interpolation, while longer gaps were left unmodified to avoid introducing bias. Metadata were also verified, with missing vessel identifiers flagged and replaced with “unknown” where necessary.

Following these steps, the dataset was subset to include standardized plume windows (50 seconds before and 50 seconds after the plume center), and a derived NO_x variable was added. The dataset was then further processed, as discussed in **Section 4**.

3.3.2 Detection limits and uncertainties

3.3.2.1 University of Houston

Table 2 shows the combined uncertainty and lower limit of detection for trace gas measurements used to develop the emission ratios for the project. The combined uncertainty was calculated using the quadrature method (square root of the sum of the squares of identified sources of uncertainty) which included gas standard and dilution system mass flow controller tolerances as well as the stability of repeated spans and calibrations. The lower limit of detection was determined analytically by analyzing instrument responses to clean zero air over an extended period and averaged to the final reporting time intervals and taking the standard deviation of the results. This defines the precision of the measurement. For this program, the lower limit of detection is defined as three times the precision. Lower detection limits for measurements met or were lower than factory specifications, and calculated uncertainties were within an acceptable range of <10%.

Table 2. A table showing the calculated uncertainty and lower limit of detection values.

Measurement	Uncertainty (%)	Lower Limit of Detection
NO	7.6	0.6 ppbv*
NO ₂	8.6	0.2 ppbv
CO ₂	3.8	1 ppmv**
CO	5.6	50 ppbv
SO ₂	7.2	1.5 ppbv

*ppbv = parts per billion by volume

**ppmv = parts per million by volume

3.3.2.2 FluxSense.

Table 3 shows the lower limit of detection values for the species measured with the FTIR instrument, while **Table 4** shows the corresponding values for the species measured with the DOAS instrument. **Table 4** also includes the lower limit of detection values for the days with reduced sensitivity, March 6–13, 2025.

Table 3. A table showing the lower limit of detection values for the species measured with the FTIR instrument.

Species	Lower Limit of Detection (ppb)
Methane	20
Ethane	8
C3+ Alkanes	10
Formaldehyde	7
Acetaldehyde	18
CO ₂	2200
CO	6
N ₂ O	3

Table 4. A table showing the lower limit of detection values for the species measured with the DOAS instrument during normal operation, as well as the corresponding values during March 6–13, 2025.

Species	Lower Limit of Detection (ppb)	Lower Limit of Detection (ppb) March 6-13, 2025
Benzene	1	2
Toluene	2	4
p-Xylene	0.5	1
m-Xylene	3	6
Ethylbenzene	3	6
SO ₂	3	6
O ₃	1	2
Naphthalene	0.1	0.2
Furfural	0.03	0.06
Phenol	0.15	0.3

4. DISCUSSION

4.1 Plume Analysis

Emissions were calculated by comparing elevated pollutant levels to elevated CO₂ concentrations. This method was also used in previous studies, such as Comer et al. (2023), to estimate emission factors from measured pollutant and CO₂ concentrations along with accepted average fuel characteristics. This calculation follows the Code of Federal Regulations¹. In this approach, CO₂ serves as a proxy for the total fuel carbon content. While other carbon-containing species—such as carbon monoxide and total hydrocarbons (THC)—could be included to improve accuracy, diesel engines emit relatively low levels of CO and THC. Their exclusion introduces a negligible bias (typically less than 0.5%) while simplifying the calculation. Emissions of NO_x, CO, and SO₂ were estimated using this method. **Equation (1)** illustrates the calculation for NO_x, but it can be applied to other pollutants using appropriate gas concentrations and molecular weights.

$$ER_{NO_x} = \frac{NO_x \text{ plume} - NO_x \text{ background}}{CO_2 \text{ plume} - CO_2 \text{ background}} \times FCC \times \frac{46 \text{ g } NO_x}{12 \text{ g } C} \quad \text{Equation (1)}$$

ER _{NO_x}	= the NO _x emission rate (g-NO _x /g-fuel)
NO _x plume	= the concentration of NO _x (NO + NO ₂) in the plume
NO _x background	= the background concentration of NO _x
CO ₂ plume	= the concentration of CO ₂ in the plume
CO ₂ background	= the background CO ₂ concentration in parts per million (ppm) outside of the plume
46	= molecular weight of NO _x estimated as NO ₂ ²
12	= molecular weight of carbon
FCC	= fuel carbon content (0.87 g-C/g-fuel for diesel fuel)

The difference between the measured concentrations, as shown in **Equation (1)** can introduce higher uncertainty by including both the plume and background concentration variations. To reduce that uncertainty, NO_x (NO + NO₂) was linearly regressed against the CO₂ concentration, and the regressed slope was used to represent increased NO_x divided by the increased CO₂ in the plume, as shown in **Equation (1)**. By using the slope regression, uncertainty was reduced by including more data without the need to compensate for unstable background measurements during the sampling. More discussion on the analysis background, methods, and results uncertainty is provided in Appendix B.

4.2 NO_x Emissions Results

Figure 3 compares measured NO_x emission rates against the expected rates based on regulatory standards estimated for each vessel. Appendix C describes how the expected emissions rates were discovered using largely unverified public reports of the vessel build year, engine make, and model year. The OGV characteristics were found in the S&P Global dataset. This dataset was

1 CFR Title 40, Chapter I, Subchapter U, Part 1065, Subpart G

2 <https://www.epa.gov/air-emissions-inventories/how-are-oxides-nitrogen-nox-defined-nei>

used for the Ramboll TCEQ CMV EI projects and does not have harbor craft/tug data even for those tugs with IMO numbers.

The solid line represents the one-to-one correlation, while the dashed line shows the regression of the measured and expected values. As expected, the overall trend shows a decrease in NO_x emissions with more stringent Tier standards. However, notable deviations exist: some vessels measured higher emissions than expected, while others emitted less.

The discrepancies likely reflect a combination of operational factors and classification uncertainties.

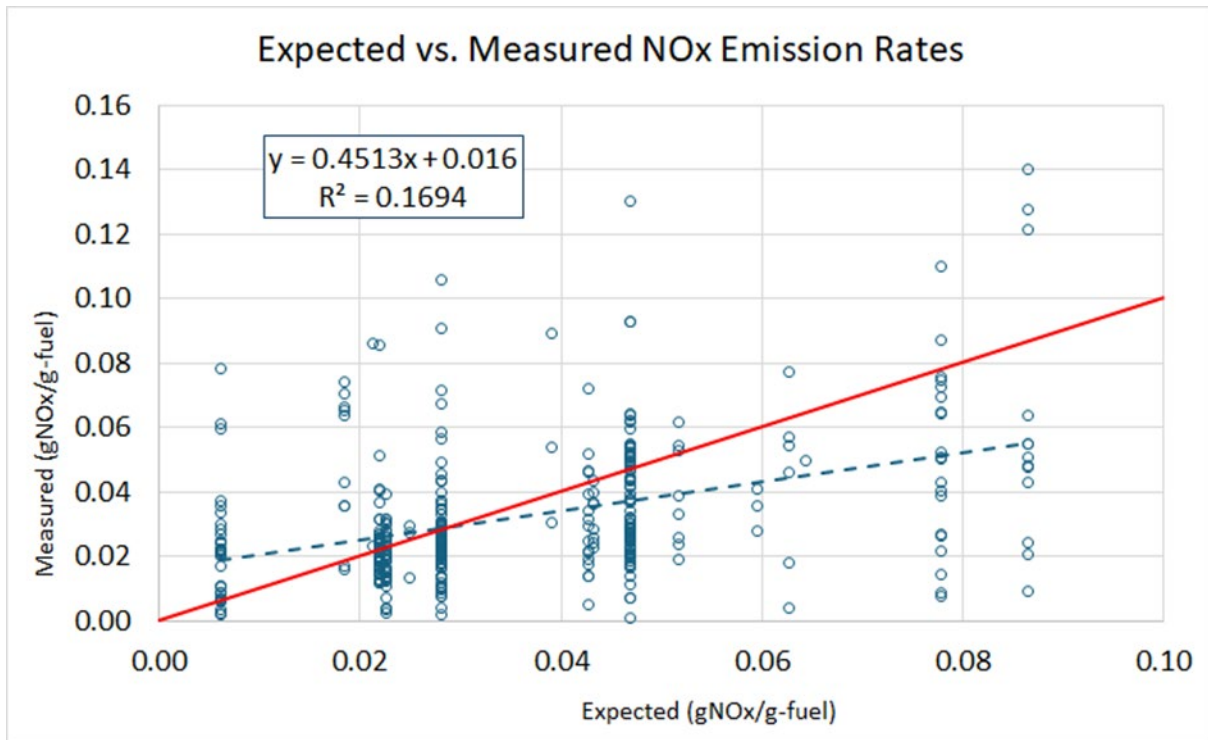


Figure 3. Measured Against Expected NO_x Emission Rates. (Solid Line – One-to-One Correlation; Dashed Line – Regression of Measured and Expected Values).

Table 5 summarizes the average NO_x emissions rates by Tier level grouping. Within a given Tier, regulatory limits vary by engine power and cylinder displacement, so expected emissions rates are grouped within a range. This reflects the inherent variability among vessels even when categorized under the same Tier.

Older vessels' engines may have been replaced or upgraded during a rebuild, which could result in lower emissions than expected, and engine replacement is usually not provided by the public websites. Therefore, some older vessels may have been incorrectly assigned to higher-emitting groups in **Table 5** than they should have been assigned.

Table 5. Expected and Average Measured Emissions Rates by Tier Level.

Range of Expected (gNO _x /g-fuel)	Test Points	Average Measured (gNO _x /g-fuel)	Median Expected (gNO _x /g-fuel)	Tier Level Description
<0.007	34	0.022	0.006	Tier 4 C1/C2
0.018 to <0.026	98	0.026	0.023	Tier 3 C1/C2 and Tier III OGV
0.026 to <0.030	89	0.027	0.028	Tier 2 C1/C2
0.038 to <0.053	113	0.037	0.047	Tier 1 C1/C2 and Oldest C1
0.059 to <0.065	10	0.041	0.063	Oldest C2 or OGV MSD
>0.07	33	0.055	0.080	Tier II or Older OGV

A unique challenge arises with low-load operation of Tier 4 Category 1 and 2 (C1/C2) vessels equipped with selective catalytic reduction (SCR) aftertreatment systems for NO_x emissions control. SCR technology is known to perform poorly at low exhaust temperatures, which are experienced during low engine loads (Damma et al., 2019). While the Environmental Protection Agency’s (EPA) expected average NO_x emission rate for Tier 4 engines is 0.006 g/g-fuel, actual emissions can be significantly higher under low-load conditions.³

This issue was observed in two assist tugs—vessels designed to help ocean going vessels (OGV) during maneuvering—that were reportedly built to Tier 4 standards. These tugs operate at high engine loads during maneuvers or transits but also spend time operating at low loads while moving slowly without assisting another vessel. Because, when all other variables are equal, engine load is roughly proportional to the cube of speed, a vessel traveling at 10 knots may operate at nearly twice the load compared to one traveling at 8 knots, with even greater disparities at greater speed differentials. Consistent with this relationship, the measured emissions from these assist tugs (highlighted in **Table 6**) were higher when operating at lower speeds—suggesting that low-load conditions led to poor SCR performance and to higher NO_x emissions rates above the Tier 4 average. These elevated measurements likely do not reflect the vessels’ average emissions over time.

For other vessels classified as Tier 4, elevated emissions may be due to factors unrelated to engine load. One such factor is the potential misidentification of the engine model year. In this analysis, it was assumed that the engine model year matched or closely followed the vessel build year. However, if an engine was manufactured more than one year before the vessel was built, it might only meet Tier 3 standards. In such cases, the observed emissions—while higher than expected for Tier 4—would be consistent with Tier 3 performance and reflective of the actual engine installed on board.

³ Marine engine manufacturers usually use a duty cycle that does not include modes below 25% engine load for emissions testing. (CFR Appendix II to Part 1042)

Table 6. Operating Conditions Effect on Tier 4 Category 1/2 Marine Engines.

Vessel	Vessel Speed (knots)	NO _x Emission Rate Measured (g/g-fuel)	NO _x Emission Rate Expected (g/g-fuel)
1	4	0.030	0.006
1	10	0.006	0.006
1	12	0.006	0.006
1	8	0.036	0.006
2	9	0.078	0.006
2	13	0.002	0.006

Because the vessel plume sampling was performed over several weeks and vessels often make regular voyages across the sampling position, many vessels were sampled more than once under different engine loads and atmospheric conditions. Multiple samples on the same vessels afford a better understanding of the test-to-test variability inherent in emission testing. Test-to-test uncertainty under different conditions is highlighted in **Table 7**, which shows the results when the vessel was sampled three more times. Since the engine operations and field conditions were changed for each test, the overall uncertainty was higher between the tests than in the regression analysis of each individual test. The confidence in the average results for each vessel can be improved by increasing the number of tests performed, as shown by the vessel with eight tests. More twice-repeated test results are provided in Appendix B. The test-to-test uncertainty should be considered when evaluating individual test results and comparing them to the expected emission rates, as shown in **Figure 3**.

Table 7. NO_x Results from Multiple Tests.

Vessel	Expected NO _x Rate (g/g-fuel)	Tests	Average Measured NO _x Rate (g/g-fuel)	90% Confidence Interval (g/g-fuel)	Relative Confidence	(Max.–Min.)/2 (g/g-fuel)
Pushboat	0.022	8	0.023	0.003	14%	0.007
Pushboat	0.043	4	0.039	0.017	43%	0.016
Assist Tug*	0.006	4	0.020	0.018	94%	0.015
Pushboat	0.023	4	0.025	0.013	53%	0.014
Pushboat	0.047	3	0.024	0.017	72%	0.010
Pushboat	0.047	3	0.041	0.019	48%	0.011
Pushboat	0.052	3	0.051	0.020	39%	0.012
Pushboat	0.047	3	0.042	0.023	56%	0.012
Pushboat	0.028	3	0.023	0.019	85%	0.010
Pushboat	0.047	3	0.035	0.044	126%	0.026
Pushboat	0.028	3	0.018	0.007	37%	0.004
Pushboat	0.028	3	0.082	0.035	43%	0.019
Pushboat	0.028	3	0.036	0.016	44%	0.009

Vessel	Expected NO _x Rate (g/g-fuel)	Tests	Average Measured NO _x Rate (g/g-fuel)	90% Confidence Interval (g/g-fuel)	Relative Confidence	(Max.–Min.)/2 (g/g-fuel)
Pushboat	0.022	3	0.019	0.009	50%	0.005
Pushboat	0.047	3	0.016	0.023	143%	0.013
Pushboat	0.023	3	0.025	0.015	59%	0.008
Pushboat	0.023	3	0.020	0.024	119%	0.013
Pushboat	0.022	3	0.015	0.007	45%	0.003
Pushboat	0.006	3	0.024	0.007	27%	0.004
Pushboat	0.022	3	0.026	0.023	88%	0.012
Pushboat	0.006	3	0.013	0.011	90%	0.007
Pushboat	unknown	3	0.029	0.008	27%	0.004
Assist Tug*	0.006	2	0.040			0.038

* Vessels 1 and 2 in Table 2.

4.3 Sulfur Emissions Results

The diesel fuel sulfur used in vessels within the United States waters is regulated⁴ to be less than 15 ppm by weight (g/g-fuel) with exemptions for the unique situations outlined here:

- 1) Alternative sulfur standards apply for 500 ppm locomotive and marine diesel fuel and Emission Control Area (ECA) marine fuel as specified in the Code of Federal Regulations (CFR) §§1090.320. (A 500 ppm per gallon maximum for locomotive and marine fuel from a transmix processor or pipeline operator.⁵) and CFR 1090.325 (Per-gallon maximum sulfur content of 1,000 ppm standards for marine fuel used in vessels powered by Category 3 (C3)⁶ engines when operating in ECA), respectively.
- 2) Exemption provisions apply as specified in subpart G of the CFR reference for marine diesel fuel. (Refers to allowing sales of higher global marine sulfur limits for use in steamships or C3 marine vessels when operating outside of ECA boundaries.)

Therefore, it was expected that tugs and other harbor craft primarily using smaller Category 1/2 propulsion engines to use 15 ppm sulfur diesel, a level that was essentially undetectable in this study. There could be infrequent situations where up to 500 ppm sulfur might be allowed in the smaller displacement Category 1/2 engines for fuel produced during the transmixing of product

⁴ <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1090/subpart-D>

⁵ <https://www.federalregister.gov/documents/2012/12/26/2012-30960/regulation-of-fuels-and-fuel-additives-modifications-to-the-transmix-provisions-under-the-diesel> The diesel transmix amendments will reinstate an allowance for transmix processors and pipeline operators to produce 500 ppm sulfur diesel fuel for use in older technology locomotive and marine diesel outside of the Northeast Mid-Atlantic (NEMA) Area and Alaska after 2014.

⁶ <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1090/subpart-D> : Category 3 means relating to a reciprocating marine engine with a specific engine displacement at or above 30.0 liters per cylinder.

in a pipeline. Vessels using larger displacement Category 3 engines were subject to 1,000 ppm fuel sulfur limits and were identified in this study as ‘ocean-going vessels’ (OGV).

The analysis for sulfur was conducted using the same technique of regressing the sulfur dioxide against the CO₂ concentrations to estimate the relative sulfur to fuel consumed amounts. The analysis **Equation (2)** for the emission rate of sulfur (ER_s) is the same as the one used for NO_x emissions, with a change in the molar weight of sulfur (32) substituted for the molar weight of NO₂ (46).

$$ER_s(g/g - fuel) = \frac{SO_2 \text{ plume} - SO_2 \text{ background}}{CO_2 \text{ plume} - CO_2 \text{ background}} \times 0.87 \times \frac{32 \text{ g S}}{12 \text{ g C}} \quad \text{Equation (2)}$$

Figure 2 shows that fuel sulfur levels for OGVs were generally consistent with expectations, averaging 769 ppm. In contrast, diesel harbor craft exhibited higher-than-expected sulfur levels, with an average of 308 ppm, as shown in **Figure 4**. However, the full range of calculated values was wide, and in some cases, negative values were observed, highlighting a high degree of uncertainty. In general, the lower values (even the larger magnitude negative values) showed poor correlations of SO₂ with CO₂. This indicates more uncertainty about results with low sulfur, compared to higher sulfur results with better correlation in **Figures 3 and 5**.

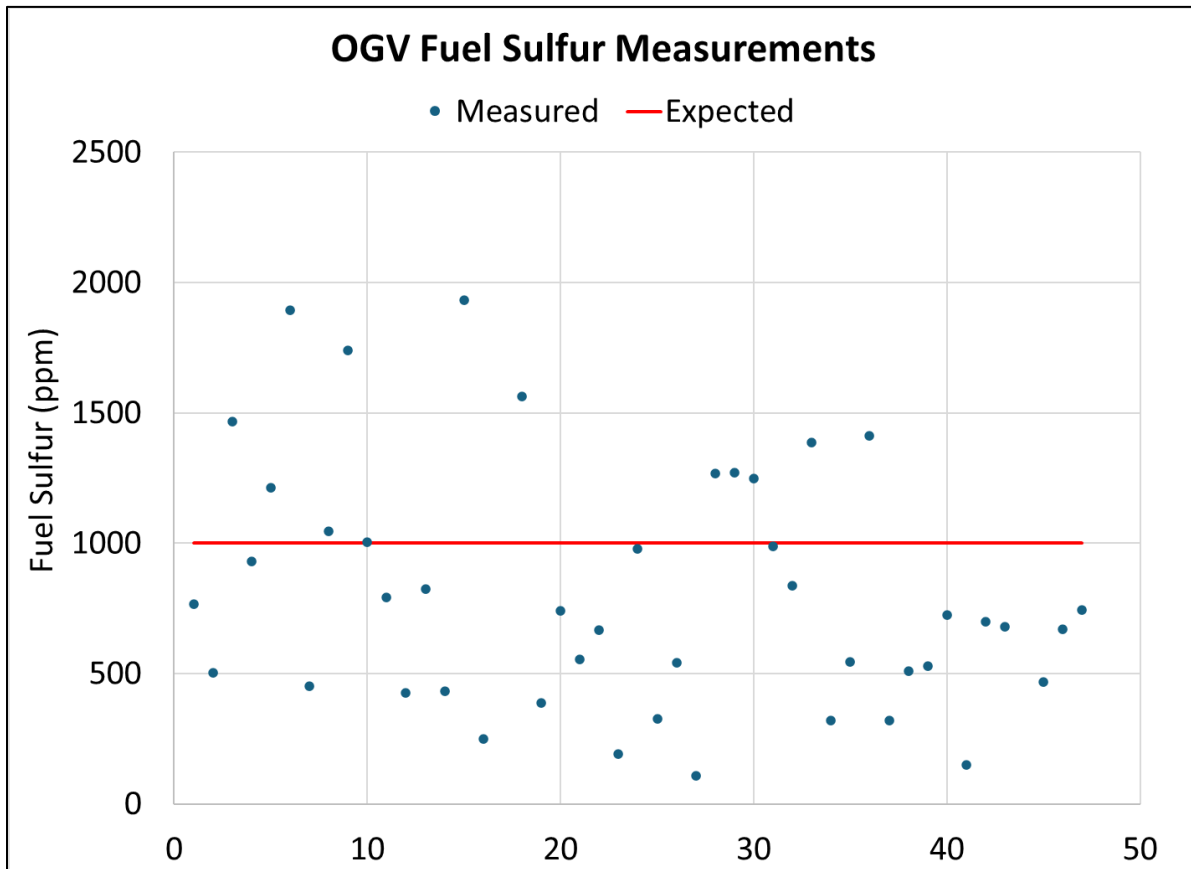


Figure 4. Ocean-Going Vessel Fuel Sulfur Measurements (unordered).

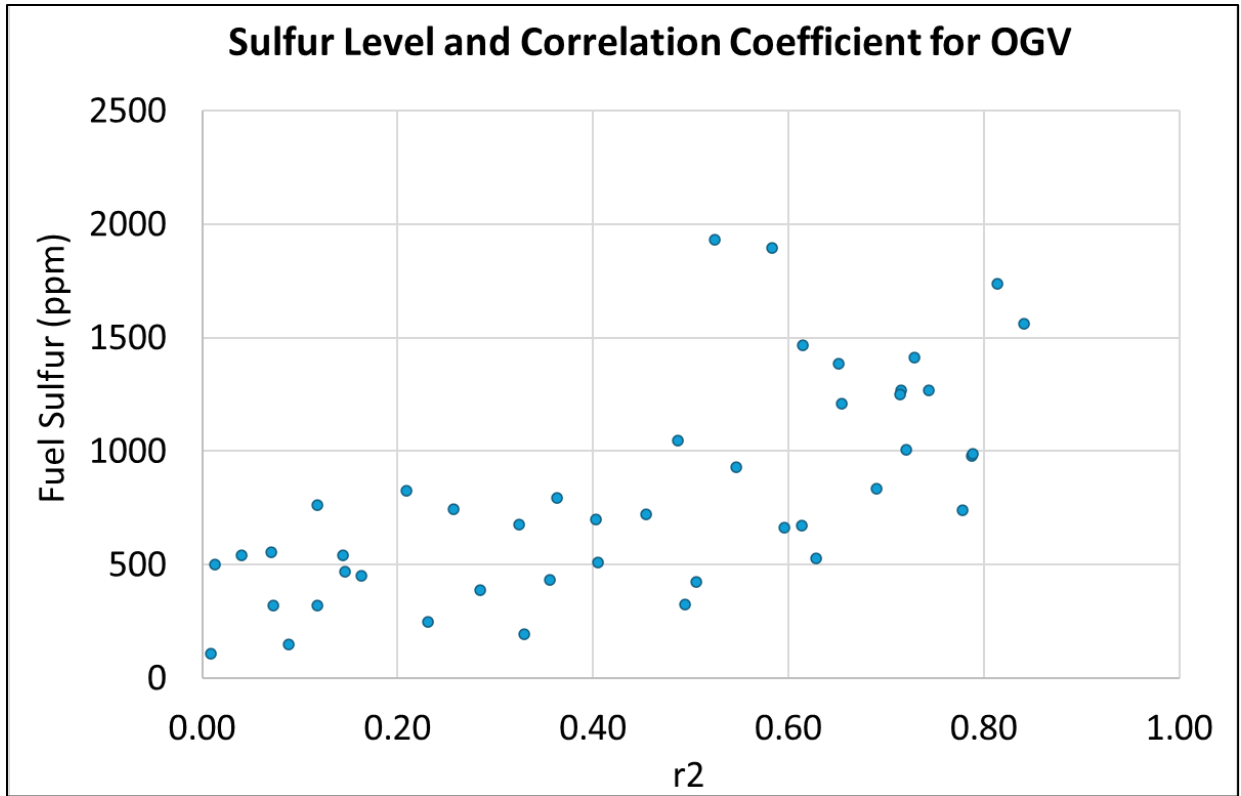


Figure 5. Ocean-Going Vessel Fuel Sulfur Measurements Measurement Correlation.

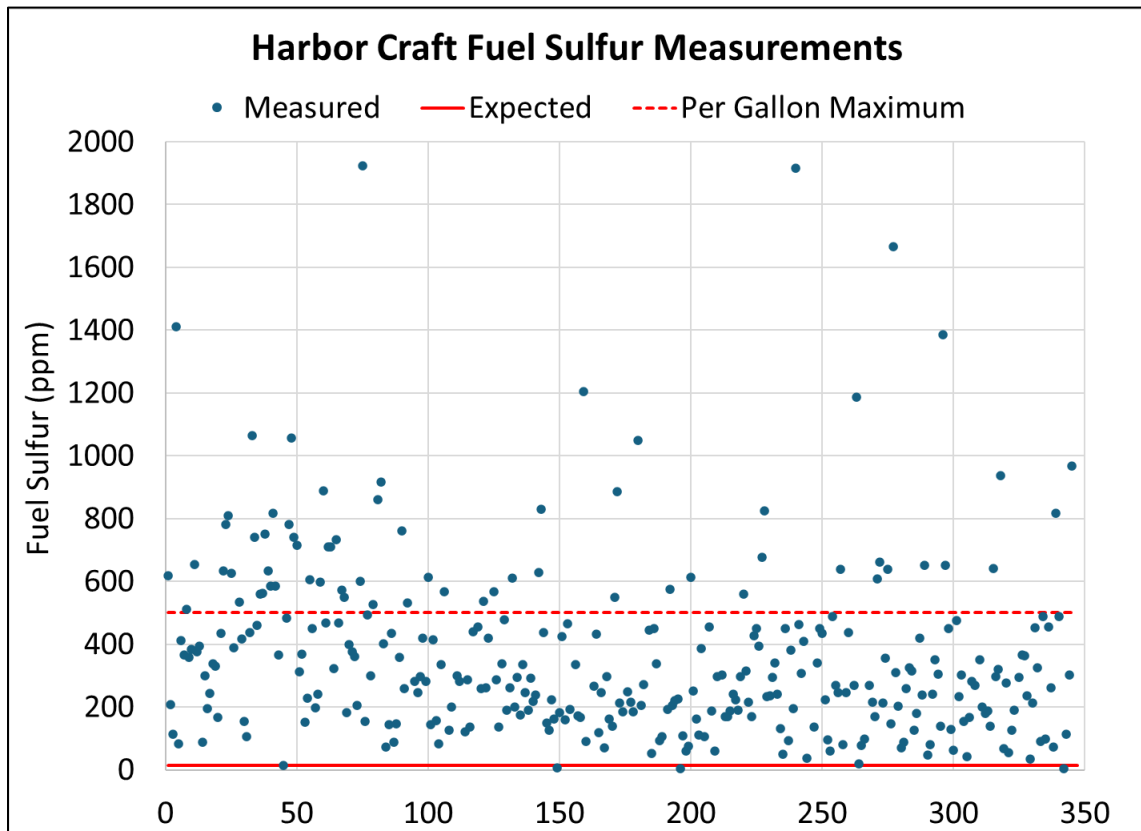


Figure 6. Harbor Craft Vessel Fuel Sulfur Measurements (unordered).

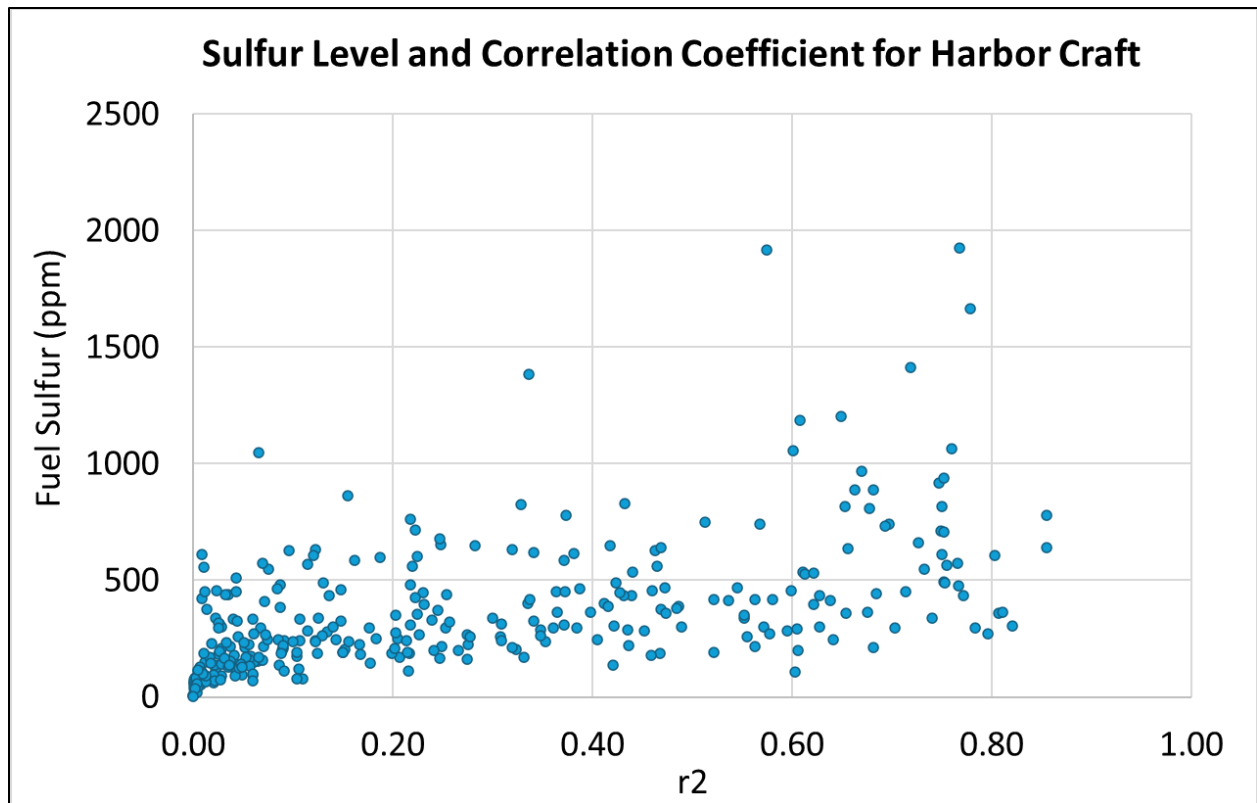


Figure 7. Harbor Craft Vessel Fuel Sulfur Measurements Correlations.

For harbor craft measurements, multiple samples on the same vessel in **Table 8** show similar results to all tests in **Figure 4**, but multiple tests highlight the test-to-test uncertainty. Using high confidence levels of 95% or 99%, a few results could be considered statistically significantly higher than the 15 ppm fuel sulfur expected. More testing will likely better demonstrate if harbor craft vessels are using fuel with higher-than-expected sulfur levels, such as the vessel that was sampled eight separate times.

Table 8. Average Fuel Sulfur and Confidence Interval Significance for Harbor Craft.

Test Plumes	Sulfur Average (ppm)	95% Confidence Interval (ppm)	Significantly >15 ppm 95% Confidence	Significantly >15 ppm 99% Confidence
8	194	109	Yes	Yes
4	712	153	Yes	No
4	308	376	No	No
4	338	347	No	No
4	222	281	No	No
3	411	214	Yes	No
3	472	394	Yes	No
3	589	561	Yes	No
3	439	305	Yes	No
3	198	355	No	No

Test Plumes	Sulfur Average (ppm)	95% Confidence Interval (ppm)	Significantly >15 ppm 95% Confidence	Significantly >15 ppm 99% Confidence
3	517	624	No	No
3	-92	910	No	No
3	321	219	Yes	No
3	632	487	Yes	No
3	266	393	No	No
3	149	395	No	No
3	313	680	No	No
3	-213	2206	No	No
3	199	92	Yes	No
3	121	180	No	No
3	300	91	Yes	Yes
3	279	311	No	No
3	133	308	No	No

4.4 Carbon Monoxide Emissions Results

Carbon monoxide emissions were expected to be low due to the lean burn combustion of diesel engines employed by OGV and harbor craft. **Table 9** shows that CO emissions were generally consistent with the expected levels estimated by the EPA for engine make and model years, especially considering the standard confidence interval estimated. Because of the low values for CO emissions, many CO measurements showed poor correlation with elevated CO₂ levels. CO emissions from diesel engines are not strictly regulated, with the EPA harbor craft levels set to be no more than 3.5 (g/kWh), which translates to 0.016 gCO/g-fuel, which is two or three times higher than the average result found during testing. More detailed data handling steps are described in Appendix B.

Table 9. Average Emissions Rates of CO.

Vessel	Count	Expected (gCO/g-fuel)	Measured Average (gCO/g-fuel)	90% Confidence Interval (gCO/g-fuel)
OGV	46	0.008	0.012	0.012
Harbor Craft	342	0.005-0.012	0.005	0.002

4.5 Particulate Emissions Results

Particulate matter emissions did not show elevated levels within the plume. PM measurements, response rates, and records were lower than the 1 hertz (Hz) rate of the CO₂ records, which would have made it difficult to perform an analysis even if we could have identified PM plumes.

4.6 VOC

4.6.1 Canister Results

Emissions from ocean-going ships are major contributors to global air pollution, affecting air quality, climate, and human health (Eyring et al., 2010; Corbett et al., 1999; Vutukuru and Dabdub, 2008). Studies have linked ship exhaust to tens of thousands of premature deaths globally (Corbett et al., 2007; Tian et al., 2013). VOC composition plays a key role in evaluating the health and climate impacts of ship emissions.

Analysis revealed that alkanes and aromatics- particularly n-butane, toluene, m,p-xylene, and light alkanes such as n-pentane and i-pentane- were the dominant contributors to total VOCs (TVOCs) (**Figure 8**). The i-pentane/n-pentane ratio >2 in canisters C008, C073, C031, and C247, suggesting evaporative fuel emissions (Velasco et al., 2007). Toluene accounted for ~35% of total aromatics and ~6% of TVOCs. While the toluene/benzene ratio remained below 3 in most canisters, indicative of evaporative sources, canisters C031 (3.8) and C091 (10.0) exhibited higher ratios, which are consistent with fresh diesel exhaust (Huang et al., 2015). Canister C031 and C091 collected plume from a tugboat and pushboat. The m,p-xylene to ethylbenzene (m,p-X/E) ratios across the canister samples range from 1.2 to 16.5, with most values falling between 2 and 4, indicating fresh aromatic hydrocarbon emissions. However, for canisters C031 and C184, the ratio exceeded 10. High m,p-xylene to ethylbenzene ratios above 10 typically reflect very fresh emissions from onboard fuel operations, solvent use, or nearby industrial port sources, rather than aged or background urban air. Canister C031, which sampled a plume from a tugboat, exhibited a mixed emission profile. The i-pentane/n-pentane ratio >2 suggests evaporative gasoline-related emissions, while the toluene/benzene ratio of 3.8 points to fresh diesel exhaust. Notably, the m,p-xylene/ethylbenzene ratio exceeded 10, reinforcing the presence of fresh emissions, as high xylene/ethylbenzene ratios are indicative of minimal atmospheric aging. This combination implies that C031 likely captured a complex plume influenced by both fresh diesel exhaust from the tug and concurrent evaporative emissions, possibly from nearby port infrastructure or fuel storage handling activities.

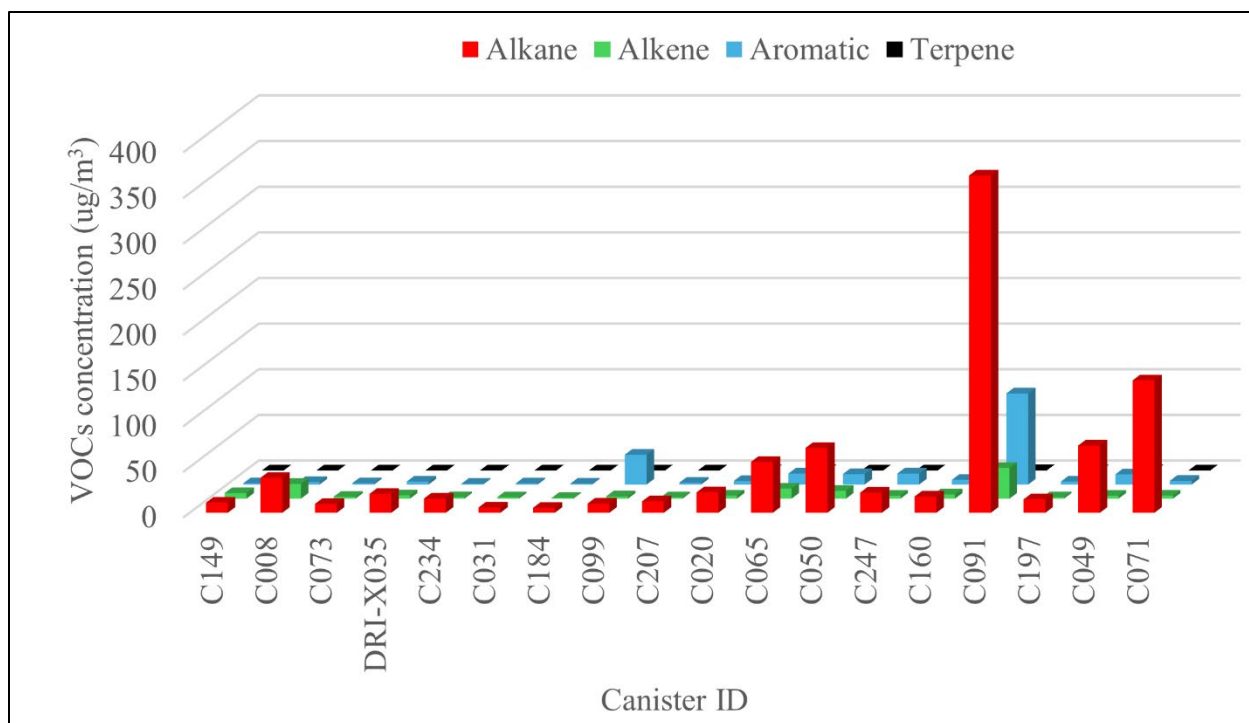


Figure 8. The bar plot shows VOC classes across different canisters.

4.6.1 DOAS and FTIR results

The DOAS and FTIR measurements showed large variations in VOC content between the different ship plumes intercepted. A majority of the plumes did not show any VOCs above detection limits. This is exemplified by the three consecutive plumes from April 10, 2025, shown in **Figure 9**, only one of which featured a detectable VOC plume. In some cases, there was a time separation between the VOC plume and the CO₂ plume (accompanied by a negative Ozone signal due to titration by NO). This could be interpreted as gas slip from a barge while the CO₂ plume comes from engine exhaust from the push boat. An example of such a separation between the VOC and CO₂ plume from February 26, 2025, is shown in **Figure 10**. Sometimes the same ship was measured more than once with seemingly quite different plume VOC content.

Figure 11 shows the same oil product tanker entering the Ship Channel on April 9, 2025, and then going out again the next day. Even though a stronger CO₂ plume was intercepted on the way in, there were almost no VOCs measured on the way in, but a strong alkane plume accompanied by a distinct Methane, Benzene, and Toluene content was observed going out. Whether the tanker was loaded or unloaded in Houston is unclear at this time.

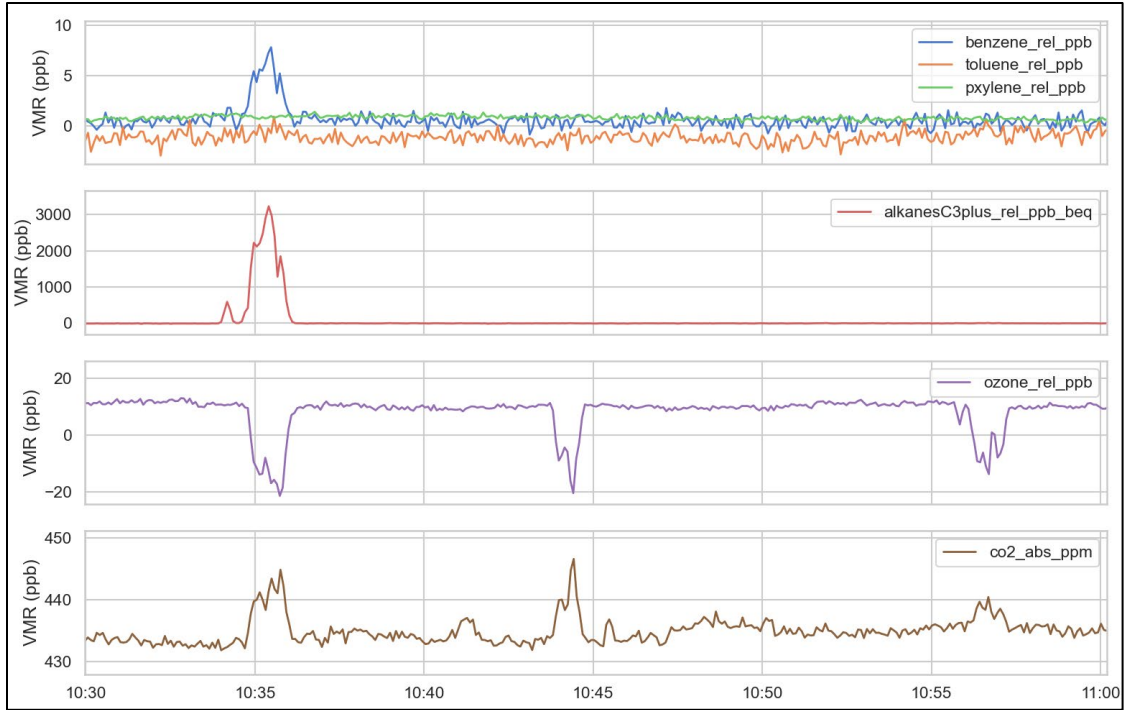


Figure 9. Three different plumes, clearly visible in CO₂ and in decreased Ozone concentrations. Only one of these shows any VOC above detection levels. Typically, the majority of the plumes measured showed no significant VOC.

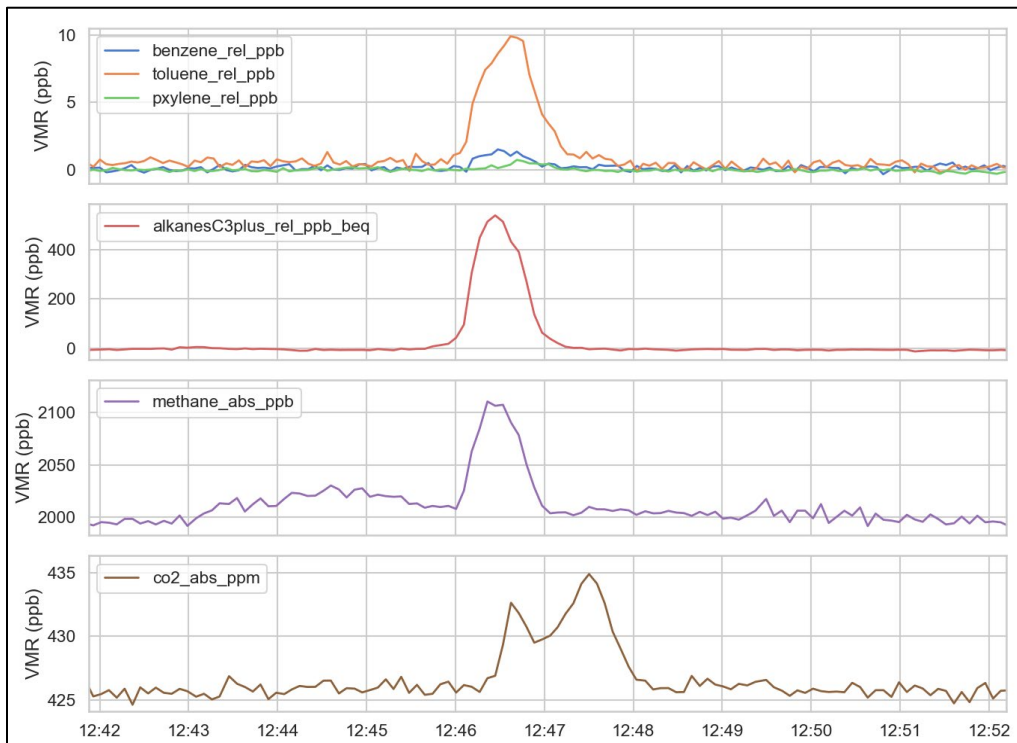


Figure 10. Temporary displacement of the VOC plume and the CO₂ plume from the same ship, a push boat with barges. This can be interpreted as gas slip from the barge load, while the CO₂ is from the push boat engine aft of the barges.

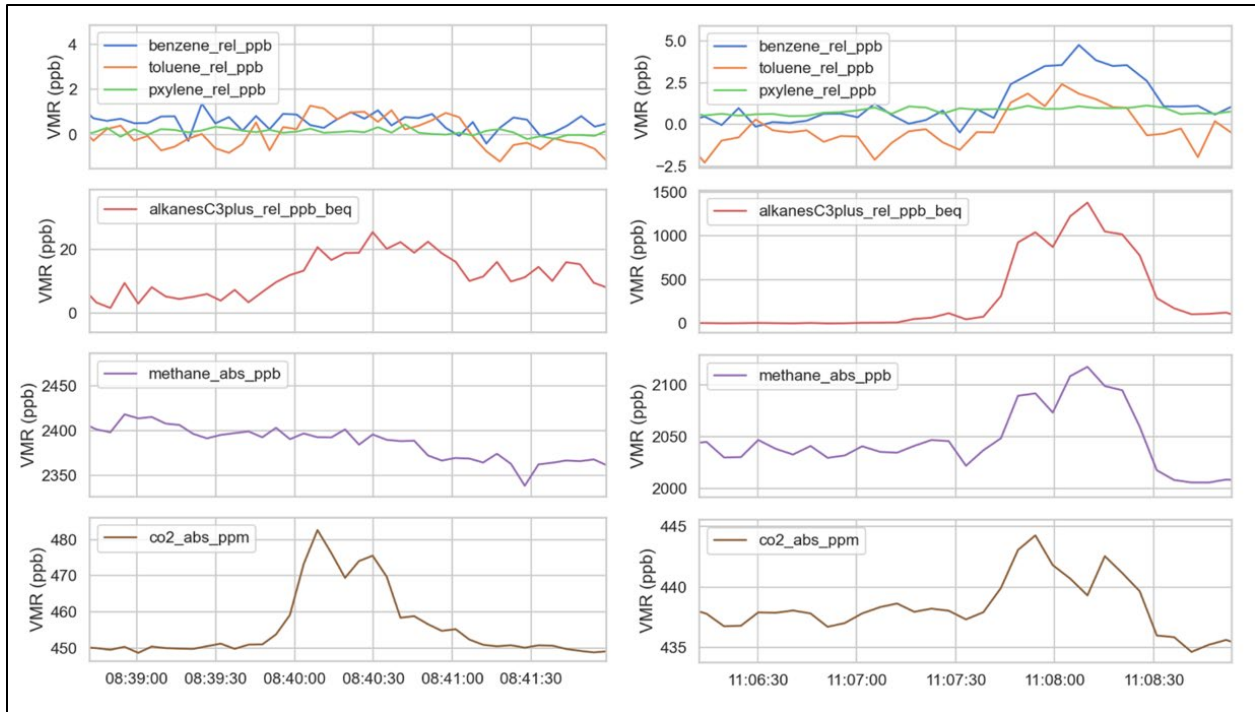


Figure 11. The plume measured from an oil tanker at two consecutive days. The first shows no significant detection of VOC despite a quite strong CO₂ plume, indicating a good sampling, while the weaker plume in the second panel shows significant VOC. This is interpreted as a possible change in the ship's cargo status. Note, the scales are different between the left and right figures.

5. CONCLUSION

The successful completion of the measurement campaign by the UH Osprey demonstrated the effectiveness of coupling high-resolution air quality instruments onto a capable water-borne platform. Over the course of the field deployment, the UH Osprey system reliably collected quality-controlled data under dynamic environmental conditions, validating both the platform's design and its operational capabilities with a new use case of data collection.

The measurements resulted in numerical estimates of NO_x, CO, and sulfur emissions rates relative to fuel consumption that were largely consistent with expected values. The results confirm that the measurement equipment and method can be used to measure emissions rates in the field. The measurement method demonstrated that multiple observations of the same target could be effectively accomplished to reduce the uncertainty and increase confidence in the results. Multiple measurements of the same target vessel highlighted operational considerations that affect emissions rates and were essential to elucidate test-to-test variability.

Observed sulfur emissions of the ocean-going vessel class were generally within the expected range (<1000 ppm). However, abnormally high sulfur emissions within the harbor craft observations warrant further examination, as the average (308 ppm) was more than an order of magnitude higher than expected. Particulate matter measurements were not of a high enough time resolution or concentration within the plume to be analyzed with the other vessel emissions in this project. Offline VOC canister collection was successful at characterizing marine vessel exhaust, with the majority of canisters following a typical signature of diesel/gasoline exhaust. One canister did show a high (>10) xylene/ethylbenzene ratio, which may have also captured a local evaporative emissions source, highlighting the variety of sources within the industrialized marine environment.

Future sampling strategies can be refined by incorporating lessons learned from this campaign, particularly the influence of wind direction on sampling locations. Different seasonal prevailing wind directions would allow for sampling within the open water of Galveston Bay for improved characterization of vessels under differing load conditions. Building on the success of field evaluations of emissions sources, a similar sampling approach could be extended to other mobile sources, such as locomotives, using a platform like the University of Houston's Mobile Air Quality Lab 3 truck, which is capable of deploying a broad suite of high-resolution and advanced instruments. The observations collected during this project, which included ozone precursors, VOCs, boundary layer, and meteorological measurements, are also expected to be useful for evaluating the impacts of emissions changes through coupled atmospheric modeling (e.g., WRF-CAMx) to improve predictive capabilities.

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APPENDIX A – MEASUREMENT FIELD NOTES

The following sections summarize field activities and contemporaneous notes recorded during each sampling day. These notes reflect the observer’s real-time impressions and may differ from interpretations that emerge through more detailed data analysis. While the notes have been reviewed and lightly edited for clarity, they were often written quickly during active vessel operations, so occasional typographical errors may remain. The format and level of detail vary by observer. These notes are presented with minimal edits to accompany the data files and may serve as a valuable reference for future analyses. Please contact James Flynn (jhflynn@uh.edu) for any clarification if needed.

February 17, 2025

Numerous plumes were observed and documented while navigating through Galveston Bay and surrounding channels under clear skies and steady onshore winds (~090° at 10 knots). Sampling began after instrument calibration, and the team departed the dock at 10:09 a.m., immediately encountering a variety of vessels, including ocean-going ships, pushboats, dredgers, and tugboats. Emission plumes were consistently identified from vessels. Many of these vessels were confirmed using Automatic Identification System (AIS) data to assess speed, heading, and engine load. A distinct plume from a vessel was recorded at 1:42 p.m., followed by multiple back-to-back plumes from pushboats and tankers. Around 2:18 p.m., a particularly notable plume containing ~5 ppb NO and ~2 ppm CO₂ was recorded. Later in the afternoon, benzene and aromatic-rich plumes were detected near 3:11 p.m. and 3:16 p.m., likely linked to nearby barge traffic. The sampling route included anchoring near Red Fish Island Cove for vessel identification and concluded with a return toward Baytown Marina.

February 24, 2025

Mobile air sampling was carried out in the Houston Ship Channel under foggy skies and light surface winds (~6 kts from 301°). After calibration and ambient sampling, the vessel departed Baytown Marina and encountered a mix of commercial marine traffic, including pushboats, dredgers, and ocean-going vessels. At 1:19 p.m., a pushboat (flagged for benzene cargo) was encountered inbound, with a small NO plume observed shortly after. Around 2:33 p.m., the PGC Marina, an inbound tanker, emitted a visible black plume, followed by a second plume at 2:44 p.m. Another significant event occurred at 3:28 p.m., when a pushboat, carrying a barge labeled for benzene, passed and a plume was observed. Additional plumes were noted from smaller pushboats at 3:36 p.m., which was pulling long piping. The sampling vessel returned to Baytown Marina by 4:14 p.m., where post-sampling calibrations were performed.

February 26, 2025

On this foggy-to-clear day with light surface winds (~100° at 2 knots), the sampling team departed Baytown Marina and entered the Houston Ship Channel, encountering steady commercial traffic. Numerous emission plumes were observed and linked to specific vessels. A distinct SO₂-containing plume was detected from an outbound tanker around 10:16 a.m. Shortly

afterward, strong plumes were measured from pushboats, both of which were towing barges labeled for benzene or LPG. Between 11:30 a.m. and noon, substantial plumes were detected from pushboats hauling benzene and acrylonitrile, and an ocean-going tanker. The sampling vessel returned to Baytown Marina by 2:48 p.m., where post-sampling calibrations were performed.

March 02, 2025

On an overcast morning with winds from 090° at 10 mph around 7 a.m., the team began instrument calibration at 5:22 a.m. before departing Baytown Marina at 8:51 a.m. Throughout the day, the sampling team navigated the Houston Ship Channel, anchoring to conduct air quality sampling and detecting multiple plumes from pushboats and ocean-going vessels. Key plume detections included diesel exhaust plumes from pushboats between 10:19 a.m. and 10:21 a.m., and container cargo vessel plumes around 9:33 a.m. and 12:38 p.m. After extensive plume monitoring and instrument checks, the team returned to Baytown Marina by 4:36 p.m., concluding the day's field operations.

March 06, 2025

On a clear day, the team began instrument calibration at 6:53 a.m. before departing Baytown Marina at 9:15 a.m. Throughout the transit and sampling along the Houston Ship Channel, the team encountered and sampled plumes from numerous pushboats with barges, as well as several ocean-going vessels. Plume detections were noted from approximately 9:47 a.m. through the afternoon, with notable emissions including elevated SO₂, NO, NO₂, and benzene levels. After continuous plume monitoring and maneuvering through the channel, the team returned to Baytown Marina dock by 3:18 p.m. and began post-calibration procedures.

March 07, 2025

On an overcast day with winds from 119° at 5 mph, the team began pre-calibration at 6:41 a.m. and departed Baytown Marina at 8:38 a.m. Significant plume encounters included diesel exhaust from a gas-powered vessel at 8:58 a.m., a pushboat at 9:52 a.m., and an ocean-going vessel at 10:00 a.m. At 10:14 a.m. and 10:21 a.m., plumes from pushboats were sampled. Elevated SO₂ (~8 ppb) was observed at 11:17 a.m. Later in the day, notable at 1:14 p.m. (SO₂ ~15 ppb), a tanker at 2:12 p.m. (SO₂ ~15 ppb), and pushboat at 3:24 p.m. (SO₂ ~10 ppb). Additional pushboats with benzene signage were also sampled. The team returned to Baytown Marina at 4:48 p.m. and completed post-calibration activities by early evening.

March 11, 2025

Under clear skies with light winds (100° at 5 mph), calibration began at 5:33 a.m. and the vessel departed Baytown Marina at 7:54 a.m. Multiple plume encounters were recorded throughout the transect. A strong plume was first detected at 8:08 a.m. on an ocean-going vessel. Additional notable plumes at 8:27 a.m., 8:37 a.m., 8:52 a.m., 8:56 a.m., and 9:24 a.m. Between 10:03 and 10:47 a.m., plumes were encountered from 10:03 a.m., 10:06 a.m., 10:10 a.m., 10:24 a.m., noted for benzene and toluene signals at 10:27 a.m. and 10:36 a.m. A p-xylene plume was detected by

the DOAS at 1:07 p.m. and again at 1:31 p.m. under calm, variable winds. The team began reeling anchor at 1:33 p.m. and returned to Baytown Marina by 2:25 p.m. and began post-calibration procedures.

March 12, 2025

Under clear skies and light winds from (~170° at 7 mph), instrument pre-calibration started at 5:55 a.m. and initiated CO₂ calibration by 7:21 a.m. RapidScan sampling on an Autonomous Rugged Optical Multigas Analyzer (AROMA) started at 7:41 a.m. The vessel departed Baytown Marina at 9:15 a.m. and entered the Houston Ship Channel shortly after. Notable plume encounters included pushboats at 9:42 a.m., 9:51 a.m., and between 10:15–10:20 a.m. A strong, visible exhaust plume was observed from a pushboat starting at 10:31 a.m. and continuing through 10:35 a.m. Additional plumes were encountered from a tugboat (10:37 a.m.) and pushboat at 11:09 a.m., with the team trailing it until 11:21 a.m. The AROMA instrument registered significant responses to dienes, aromatics, and ethylene oxide near a facility on the south side of the channel around 11:44 a.m. The vessel returned to Baytown Marina by 12:06 p.m. post-calibration began at 12:10 p.m., followed by CO₂ calibration at 12:45 p.m.

March 13, 2025

Under overcast skies with southerly winds, the vessel moved to the fuel dock at 8:02 a.m. and departed for sampling at 9:14 a.m. Plume encounters began early with a gas-powered boat at 9:40 a.m., followed by recreational and pushboat sources at 9:47 a.m., 9:52 a.m., and 9:54 a.m. Significant emissions were recorded from pushboat at 9:59 a.m. and from a tanker at 10:04 a.m. Notable repeated plume intercepts occurred at 10:23 a.m.–10:24 a.m. and 10:27–10:32 a.m. Final intercepts occurred before returning to Baytown Marina at 1:25 pm. Post-calibration began at 1:37 p.m.

March 17, 2025

Under clear skies with light winds from 095° at 4 mph, operations began with a power recovery and inlet filter replacement. Pre-calibration was initiated at 6:20 a.m., followed by RapidScan startup and system readiness. The vessel departed Baytown Marina at 8:33 a.m. and entered the Houston Ship Channel shortly after. Plumes encountered by a tanker (9:58 a.m.) and pushboat (10:03–10:06 a.m.). A strong aromatic signal was detected from a pushboat (10:19 a.m.) and another pushboat (11:03 a.m.), which had benzene signage. The vessel remained active in plume sampling through the late morning, with ambient benzene, toluene, xylene (BTX) calibrations run between 1:27 p.m. and 2:00 p.m. using the AROMA instrument, before resuming ambient air sampling.

March 30, 2025

Under clear skies, pre-calibration and AROMA RapidScan laser calibration began at 6:09 a.m., followed by CO₂ calibration at 7:33 a.m. and ambient air sampling at 7:36 a.m. The vessel departed Baytown Marina at 8:08 a.m., entering the Houston Ship Channel by 8:20 a.m. The team repositioned near marker 85 around 10:10 a.m. for extended sampling. The DOAS software

crashed at 11:22 a.m. but resumed shortly after. VOC canister #C073 was collected at 2:09 p.m. in a pushboat plume. The Osprey returned to Baytown Marina at 2:50 p.m. Post-outing calibrations began at 3:55 p.m., CO₂ calibration followed at 4:17 p.m., and ambient air sampling resumed by 4:43 p.m. after adjusting the adaptive filter settings.

April 01, 2025

Under dense morning fog and winds from 137° at 12 mph, pre-calibration began at 5:54 a.m., followed by RapidScan laser calibration around 6:00 a.m. The vessel departed Baytown Marina at 7:23 a.m. and reached the anchoring area near marker 112B by 7:51 a.m. Approximately at 8:54 a.m., duplicate VOC samples (C184 and C031) were taken in a pushboat plume. Additional plumes from an ocean-going tanker at 8:36 a.m., pushboat at 9:10 a.m. (NO autozeroed), and at 9:18 a.m. when VOC sample C020 was collected. At 10:21 a.m., a significant plume was recorded from a pushboat (NO autozeroed). AROMA sampling was paused for RapidScan recalibration at 10:26 a.m. and resumed by 10:39 a.m. Later, a large plume from a pushboat carrying benzene-marked barges was detected at 1:32 p.m. The vessel returned to Baytown Marina around 3:10 p.m. A ~1.5-hour communication loss with the FTIR was noted prior to arrival. At 4:00 p.m., the FTIR power cable broke during handling. Post-outing calibrations began with NO₂ at 4:28 p.m., followed by CO₂ at 5:02 p.m.

April 09, 2025

Under clear sky and winds from 150° at 6 mph, pre-outing calibrations began at 6:00 a.m., including a full RapidScan restart after the instrument froze. RapidScan measurements started at 6:52 a.m., followed by zero air and BTX calibration gas introduction. Power was recycled again at 8:00 a.m. due to compressor issues. The vessel departed the marina at 8:09 a.m. and entered the Ship Channel by 8:15 a.m. A visible plume from a tanker was encountered at 8:21 a.m., followed by several pushboats and recreational boat plumes. VOC canister samples were taken at 9:21 (C005), at 9:41 (C247), at 10:14 (C160), and at 11:33 (C091) a.m. within pushboat plumes. Post-outing calibrations began at 2:44 p.m., with CO₂ calibration starting at 4:10 p.m.

April 10, 2025

Clear skies with wind from 165° at 9 mph; pre-outing calibration began 5:56 a.m., CO calibration at 7:19 a.m., zeroing at 7:23 a.m. Vessel left marina at 9:24 a.m., entered Baytown Channel at 9:27 a.m., and Houston Ship Channel at 9:36 a.m. Major plume encounters occurred between 9:49–10:20 a.m. and again from 11:00 a.m. to 12:50 p.m. with multiple pushboats and vessels; additional plume events took place intermittently in the afternoon until returning to the marina by 4:37 pm, followed by post-outing calibration at 4:40 pm.

April 11, 2025

Clear skies with winds from 339° at 12 mph. Pre-outing calibration began at 5:47 a.m., CO₂ calibration at 7:12 a.m., and AROMA calibration around 7:35 a.m. Vessel left dock at 7:49 a.m., passing under the Fred Hartman Bridge at 8:05 a.m. Multiple plume encounters occurred mainly between 8:08 a.m. and 11:30 a.m. from police boats, pushboats, and ocean-going vessels.

Additional plumes were noted intermittently throughout the afternoon, with several VOC samples taken. Returned to the marina at 5:09 p.m.; post-outing calibration started at 5:10 p.m., followed by CO₂ calibration at 6:33 p.m.

APPENDIX B – PLUME DATA ANALYSIS AND STATISTICAL RESULTS

Analysis Technique for Emission Estimations

Emissions were calculated by comparing elevated pollutant concentrations to CO₂, using the carbon balance method. This method, also used in studies such as Comer et al. (2023t), estimates emission factors from measured pollutant and CO₂ concentrations along with accepted average fuel characteristics. This calculation follows the Code of Federal Regulations (CFR Title 40, Chapter I, Subchapter U, Part 1065, Subpart G). In this approach, CO₂ serves as a proxy for total fuel carbon content. While other carbon-containing species—such as CO and total hydrocarbons—could be included to improve accuracy, diesel engines emit relatively low levels of CO and THC. Their exclusion introduces a negligible bias (less than 0.5%) while simplifying the calculation. Emissions of NO_x, SO₂, and CO were estimated using this method. **Equation (3)** illustrates the calculation for NO_x, but it can be applied to other pollutants using appropriate concentrations and molecular weights.

$$ER_{NO_x} = \frac{NO_x \text{ plume} - NO_x \text{ background}}{CO_2 \text{ plume} - CO_2 \text{ background}} \times FCC \times \frac{46 \text{ g } NO_x}{12 \text{ g } C} \quad \text{Equation (3)}$$

ER _{NO_x}	= the NO _x emission rate (g-NO _x /g-fuel)
NO _x plume	= the concentration of NO _x (NO + NO ₂) in the plume
NO _x background	= the background concentration of NO _x
CO ₂ plume	= the concentration of CO ₂ in the plume
CO ₂ background	= the background CO ₂ concentration in ppm outside of the plume
46	= molecular weight of NO _x estimated as NO ₂ ⁷
12	= molecular weight of carbon
FCC	= fuel carbon content (usually about 0.87 for diesel fuel)

There are two main approaches for estimating emissions from plume measurements:

- Area-under-the-curve (AUC) method: This approach compares the excess pollutant and CO₂ concentrations—i.e., the difference between plume and baseline values—over the entire duration of the plume. It integrates the total excess above background for each gas, then uses its ratio to calculate emissions.
- Linear regression method⁸: This method regresses second-by-second pollutant concentrations against CO₂, using the slope of the regression line to represent the pollutant-to-CO₂ enhancement ratio.

While both methods are theoretically valid, the AUC approach is more sensitive to uncertainties in background concentrations. In many cases, baseline drift or noise makes it difficult to

⁷ <https://www.epa.gov/air-emissions-inventories/how-are-oxides-nitrogen-nox-defined-nei>

⁸ Aaron G. Meyer University of Utah, “Characterizing Basin Scale GHG Emissions in Northern Utah Using Sun Tracking Spectrometers,” <https://byu.app.box.com/v/s4s-2025-slides/file/1813633693614>

determine the actual difference between plume and background accurately. For example, in **Figure 12**, the CO₂ plume rises no more than 5 ppm above baseline, while the CO₂ measurement uncertainty is around ±0.5 ppm—when applied to the difference between the measured and baseline estimates represented more than 20% of the signal. When factoring in additional uncertainty from pollutant measurements and possible influence from nearby land-based sources on all measurements, the AUC method becomes increasingly unreliable.

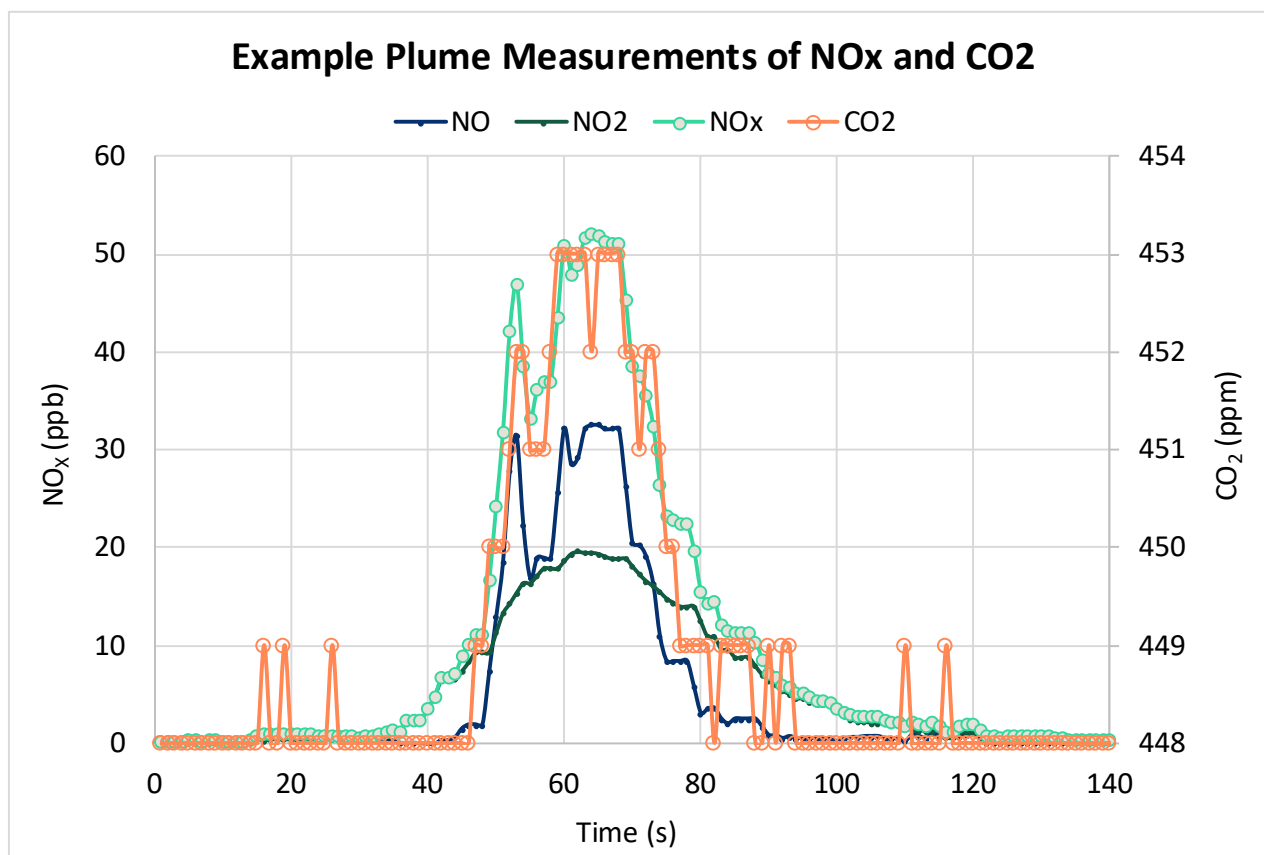


Figure 12. Example plume measurements with raw data.

In contrast, the linear regression method provides a more robust estimate by incorporating more data points and minimizing the influence of individual fluctuations. For this reason, the regression approach was adopted for this study.

Data Preparation and Analysis Methods

The raw data was reviewed in detail by the team and determined methods to prepare and refine it for analysis.

1. Data Sources

The team provided time-resolved vessel plume measurement data and vessel metadata, including the ship identifier. A total of 402 plumes were identified with valid peak times, covering the

period from February 17 to April 11, 2025. Data was provided second-by-second (1 Hz); however, some missing seconds were discovered. Data units for NO, NO₂, SO₂, and CO gas concentration were in ppb units, while CO₂ was in ppm units.

2. Plume Time Selection

Each plume was extracted based on its peak time. An initial window of ± 50 seconds around the peak was considered sufficient to capture the core of the plume. However, to allow flexibility for alignment testing, the window was expanded to ± 55 seconds. In a few examples reviewed, the NO_x peak appeared 1–2 seconds earlier than the CO₂ peak.

3. Time Alignment Review and Correction

Upon examining time series plots, it was found that NO peaks generally aligned well with CO₂ peaks, but NO₂ peaks often lagged NO and CO₂ peaks by 7–15 seconds or more. This issue was resolved by manually realigning NO₂ data for all 402 plumes. The data for SO₂ and CO did not exhibit lags in peak concentrations.

4. Interpolation of Short Gaps

To improve data continuity, we linearly interpolated missing values for each pollutant (NO, NO₂, SO₂, CO, CO₂, PM_{2.5}, and PM₁₀) but limited this to gaps of up to 3 consecutive missing values. Larger gaps were left unfilled to avoid introducing artificial trends. Interpolated values were stored in new columns with a `_filled` suffix. Any missing Maritime Mobile Service Identity (MMSI) values were replaced with "unknown". There were four vessels with missing MMSI, and their information is listed below:

Table 10. *Vessels with missing MMSI values.*

Date	MMSI	Name of Boat	Boat Type	Peak Time (CST)
3/21/2025	unknown	unknown	recreational	3/21/2025 8:23
3/30/2025	unknown	coast guard crewboat	recreational	3/30/2025 12:34
4/9/2025	unknown	Small Fishing Boat	recreational	4/9/2025 8:45
4/9/2025	unknown	fishing boat	recreational	4/9/2025 9:09

5. Plume Subsetting

From the interpolated data, the dataset was filtered to include only records within ± 50 seconds of each plume's peak time. Pollutant values (filled), CO₂, and relevant metadata (e.g., `Plume_ID`, `Boat_Type`, `Sample_Number`, `Seconds_From_Peak`, etc.) were retained. A new NO_x column was computed as the sum of NO and NO₂, but only when both values were available.

The processed data was saved in an Excel workbook with separate sheets for each pollutant, including NO_x. Additional summary tables were included: one summarizing the number of valid records per plume for each pollutant, and another showing record counts within the ± 20 -second core plume window.

The following plumes did not have NO_x data available and were excluded from further analysis of NO_x emission rates, resulting in 396 plumes to analyze.

Table 11. Plumes did not have NO_x data that were excluded from the analysis.

Plume_ID
010_minnie_t_367768480
035_san_brendan_367404910
057_dimmit_368044440
274_sebastian_d_367663890
300_the_riverside_368399980
395_miss_braylee_368260040

6. Emission Ratio Estimation

Using linear regression, we estimated per-plume emission ratios between pollutants (e.g., NO_x) and CO₂ using `scipy.stats.linregress` in a Python program. This function calculates a linear least-squares regression for two sets of measurements. For each plume, the slope, intercept, r², p-value, standard error, and number of data points were calculated.

To express NO_x-to-CO₂ ratios in mass terms, slope values (NO_x ppb/CO₂ ppm) were converted to g NO_x per g fuel using the formula:

$$gNO_x/gfuel = Slope \times 10^{-3} \times \frac{46.0055 \text{ g}}{\text{mol NO}_x} \times \frac{0.87 \text{ fuel carbon content}}{12.011 \text{ g/molC}} \quad \text{Equation (4)}$$

For other pollutants, using the same formula with the appropriate molar weight.

For NO_x, the following plumes have either insufficient data or negative slopes and thus were excluded from further analysis, resulting in 391 plumes. The same processing steps were repeated for other pollutants.

Table 12. Plumes with insufficient data or negative slopes.

Plume ID	Sample Number	n Points	Slope	Emission Rate (g/g-fuel)
052_capt_rodney_adams_367656160	1	21		
141_danielle_guidry_366993270	1	22	-0.08542	-0.00028
282_mr_bennett_367479930	2	3		
361_acer_arrow_565440000	1	88	-0.1788	-0.0006
362_joe_lochrico_367772180	1	21	-0.29537	-0.00098

Estimates of NO_x Plumes

The linear regression technique used to determine the NO_x-to-CO₂ ratio (also applied to other pollutants) requires that the NO_x and CO₂ time series be properly aligned. Although both gases are sampled simultaneously, the instruments used can exhibit different response lags. As shown in **Figure 12**, the total NO_x signal (NO + NO₂) generally aligns with CO₂, though the NO₂ peak appears broader than the NO or CO₂ peaks. This time, misalignment must be addressed to avoid bias in the estimated emission ratios.

Aligning the NO₂ signal posed a particular challenge. The instrument used for direct optical NO₂ measurement, the Teledyne T500U, applies adaptive filtering: when it detects strong concentration gradients, the internal smoothing filter shrinks to capture peak details, then reverts to a longer smoothing window during stable periods. While effective for resolving sharp transitions, this adaptive processing caused some peaks—especially smaller ones—to be misaligned by as much as 15–20 seconds. Spot checks confirmed that while major peaks aligned well with CO₂ (the fastest responding gas), smaller peaks often lagged.

Although the University of Houston worked with Teledyne to reduce the smoothing window to a minimum for all periods, instrument performance appeared unaffected by user settings—suggesting that filtering parameters may be hardcoded into the firmware and not linked to instrument controls. As a result, visual inspection and manual alignment were performed for all identified plumes to ensure consistency in time alignment between NO_x and CO₂.

Figure 13 shows the resulting regression of the time-aligned data from **Figure 12**. Using **Equation 1** and the EPA's estimated specific fuel consumption of 213 g-fuel/kWh for this tugboat, the regression slope yields a NO_x emission rate of 6.8 g/kWh. This is slightly above the expected value of 6.0 g/kWh, based on the reported engine model and year. The standard error of the slope is ±3%, indicating strong statistical confidence.

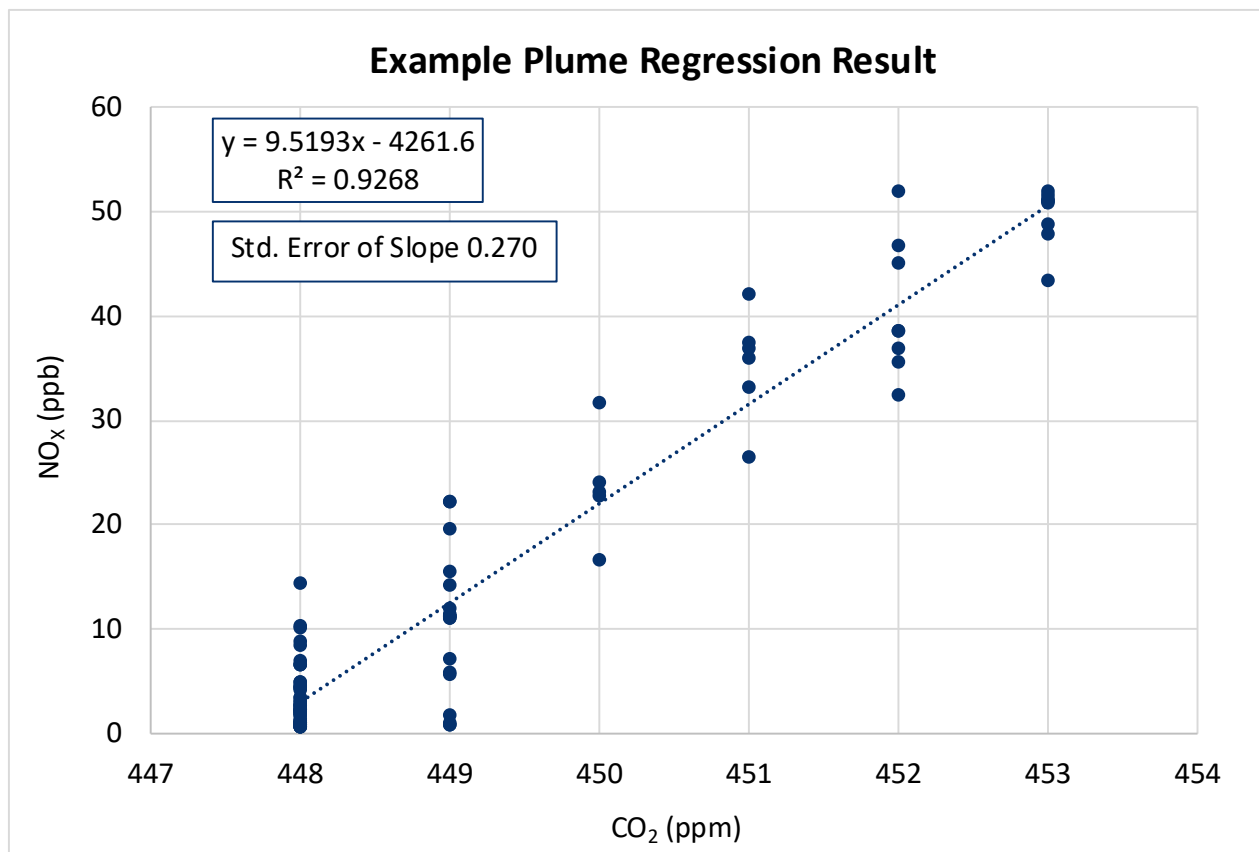


Figure 13. Plume regression result for the time-aligned Figure 9 plume.

Another important source of uncertainty arises from the specific conditions under which vessels were operating during sampling. These include operational factors (e.g., engine load), atmospheric conditions (e.g., wind direction and mixing), and other variables that influence either the vessel emissions or the behavior of the exhaust plume. Because measurements were conducted in open-air environments, upwind (background) air concentrations directly affected the observed plume concentrations.

Engine load during sampling, in particular, is a key uncertainty that could not be directly measured. It was instead inferred qualitatively, for example, by observing the number and draft of barges being pushed, which provides only an approximate indication of propulsion effort.

Because the vessel plume sampling was performed over several weeks and vessels often make regular voyages across the sampling position, many vessels were sampled more than once under different engine loads and atmospheric conditions. Multiple samples on the same vessels afford a better understanding of the test-to-test variability inherent in emission testing. To assess how varying operating conditions influence emission estimates, repeated measurements taken from the same vessels were examined. For vessels with only two measurements ($n = 2$), the average emission rate, and the range between the two results was reported. For vessels with three or more measurements ($n \geq 3$), 90% confidence intervals using a t-test was calculated, as summarized in **Table 13**.

In general, the relative confidence interval (i.e., the interval divided by the average) from repeated tests was larger than the standard error of the regression slope derived from any single test—indicating that test-to-test variability due to changing real-world conditions dominated the overall uncertainty.

This variability can be substantial. In some cases, the confidence interval was greater than the mean value itself. To illustrate this spread, the range (maximum minus minimum) divided by two was also reported as a simple metric of uncertainty. Vessels with only a few measurements typically showed wider uncertainty bounds, while one vessel with eight repeat measurements had a much narrower 90% confidence interval—just 14% of the mean—demonstrating how additional sampling can greatly improve the reliability of average emission estimates.

Table 13. *NO_x results from multiple tests by vessel.*

Vessel	NO _x Expected(g/g-fuel)	No. of Tests	Measured NO _x Average (g/g-fuel)	90% Confidence Interval (g/g-fuel)	Relative Confidence	(Max–Min)/2 (g/g-fuel)
Pushboat	0.022	8	0.023	0.003	14%	0.007
Pushboat	0.043	4	0.039	0.017	43%	0.016
Assist Tug*	0.006	4	0.020	0.018	94%	0.015
Pushboat	0.023	4	0.025	0.013	53%	0.014
Pushboat	0.047	3	0.024	0.017	72%	0.010
Pushboat	0.047	3	0.041	0.019	48%	0.011
Pushboat	0.052	3	0.051	0.020	39%	0.012
Pushboat	0.047	3	0.042	0.023	56%	0.012
Pushboat	0.028	3	0.023	0.019	85%	0.010
Pushboat	0.047	3	0.035	0.044	126%	0.026
Pushboat	0.028	3	0.018	0.007	37%	0.004
Pushboat	0.028	3	0.082	0.035	43%	0.019
Pushboat	0.028	3	0.036	0.016	44%	0.009
Pushboat	0.022	3	0.019	0.009	50%	0.005
Pushboat	0.047	3	0.016	0.023	143%	0.013
Pushboat	0.023	3	0.025	0.015	59%	0.008
Pushboat	0.023	3	0.020	0.024	119%	0.013
Pushboat	0.022	3	0.015	0.007	45%	0.003
Pushboat	0.006	3	0.024	0.007	27%	0.004
Pushboat	0.022	3	0.026	0.023	88%	0.012
Pushboat	0.006	3	0.013	0.011	90%	0.007
Pushboat	unknown	3	0.029	0.008	27%	0.004
OGV	0.086	2	0.029			0.019
OGV	0.086	2	0.036			0.012
Recreational	0.025	2	0.021			0.008

Vessel	NO _x Expected(g/g-fuel)	No. of Tests	Measured NO _x Average (g/g-fuel)	90% Confidence Interval (g/g-fuel)	Relative Confidence	(Max-Min)/2 (g/g-fuel)
Pushboat	0.047	2	0.028			0.001
Pushboat	0.047	2	0.031			0.001
Pushboat	0.043	2	0.023			0.002
Pushboat	0.023	2	0.018			0.001
Pushboat	0.047	2	0.057			0.005
Pushboat	0.063	2	0.067			0.010
Pushboat	0.047	2	0.053			0.001
Pushboat	0.047	2	0.054			0.011
Pushboat	0.039	2	0.072			0.017
Pushboat	0.043	2	0.026			0.002
Pushboat	0.043	2	0.030			0.007
Pushboat	0.028	2	0.021			0.003
Pushboat	0.028	2	0.067			0.024
Pushboat	0.047	2	0.093			0.000
Pushboat	0.028	2	0.029			0.009
Pushboat	0.028	2	0.017			0.004
Pushboat	0.047	2	0.029			0.018
Pushboat	0.052	2	0.021			0.002
Pushboat	0.028	2	0.025			0.005
Pushboat	0.028	2	0.032			0.009
Pushboat	0.028	2	0.020			0.003
Pushboat	0.028	2	0.023			0.014
Pushboat	0.028	2	0.024			0.007
Pushboat	0.028	2	0.035			0.008
Pushboat	0.028	2	0.027			0.001
Pushboat	0.028	2	0.013			0.001
Pushboat	0.028	2	0.016			0.006
Pushboat	0.022	2	0.026			0.001
Pushboat	0.047	2	0.033			0.016
Pushboat	0.022	2	0.017			0.005
Pushboat	0.028	2	0.032			0.001
Pushboat	0.028	2	0.014			0.003
Pushboat	0.047	2	0.036			0.013
Pushboat	0.023	2	0.016			0.005
Pushboat	0.047	2	0.022			0.002
Pushboat	0.047	2	0.020			0.001
Pushboat	0.022	2	0.021			0.002
Pushboat	0.006	2	0.023			0.002

Vessel	NO _x Expected(g/g-fuel)	No. of Tests	Measured NO _x Average (g/g-fuel)	90% Confidence Interval (g/g-fuel)	Relative Confidence	(Max–Min)/2 (g/g-fuel)
Pushboat	0.047	2	0.058			0.004
Assist Tug*	0.006	2	0.040			0.038
Pushboat	0.006	2	0.005			0.002
Pushboat	0.022	2	0.020			0.005
Pushboat	0.063	2	0.050			0.004
Pushboat	0.028	2	0.058			0.001
Pushboat	0.028	2	0.021			0.003
Pushboat	0.006	2	0.041			0.020
Pushboat	0.052	2	0.040			0.014
Pushboat	0.006	2	0.004			0.002
Pushboat	unknown	2	0.021			0.012
OGV	0.078	2	0.035			0.008
OGV	0.078	2	0.070			0.005
OGV	0.078	2	0.018			0.004

* - Operating conditions effects.

A unique challenge arises with low-load operation of Tier 4 Category 1 and 2 (C1/C2) vessels equipped with selective catalytic reduction (SCR) aftertreatment systems for NO_x emissions control. SCR technology is known to perform poorly at low exhaust temperatures, which are typical during low engine loads (Damma et al., 2019). While the EPA’s expected average NO_x emission rate for Tier 4 engines is 0.006 g/g-fuel, actual emissions rates can be significantly higher under low-load conditions⁹.

This issue was observed in two assist tugs—vessels designed to help OGVs during maneuvering—that were reportedly built to Tier 4 standards. These tugs operate at high engine loads during maneuvers or transits but also spend time operating at low loads while moving slowly without assisting another vessel. Because, when all other variables are equal, the engine load is roughly proportional to the cube of speed, a vessel traveling at 10 knots may operate at nearly twice the load compared to traveling at 8 knots, with even greater disparities at lower speeds. Consistent with this relationship, the measured emissions from these assist tugs (highlighted in **Table 13**, with plume-level data in **Table 14**) were higher when operating at lower speeds—suggesting that low-load conditions led to poor SCR performance and therefore led higher NO_x emissions rates above the Tier 4 average. These elevated measurements likely do not reflect the vessels’ average emissions over their full duty cycle.

For other vessels classified as Tier 4, elevated emissions may be due to factors unrelated to engine load. One such factor is the potential misidentification of the engine model year. In this

⁹ Marine engine manufacturers usually use a duty cycle that does not include modes below 25% engine load for emissions testing. (CFR Appendix II to Part 1042)

analysis, it was assumed (based on the EPA guidance) that the engine model year was one year older than the vessel build year. However, if an engine was manufactured more than one year before the vessel's build year, it might meet only the Tier 3 standard instead. In such cases, the observed emissions—while higher than expected for Tier 4—would be consistent with Tier 3 performance and reflective of the actual engine installed in that vessel.

Table 14. Operating Conditions Effect on Tier 4 Category 1/2 Marine engines.

Vessel	Vessel Speed (knots)	NO _x Emission Rate Measured (g/g-fuel)	NO _x Emission Rate Expected (g/g-fuel)
1	4	0.030	0.006
1	10	0.006	0.006
1	12	0.006	0.006
1	8	0.036	0.006
2	9	0.078	0.006
2	13	0.002	0.006

Humidity Adjustments for NO_x Emissions Estimates

Absolute humidity (expressed as mole/mole of dry air) influences NO_x emissions from diesel engines. The EPA emissions testing is conducted under controlled laboratory conditions—including fixed temperature and humidity—and field measurements must be adjusted to align with these standards. According to the EPA regulations (40 CFR §1065.670), a humidity correction is applied using **Equation (5)** to account for the fact that higher humidity suppresses NO_x formation, while drier conditions can increase NO_x emissions. The correction is applied by multiplying the unadjusted field-measured NO_x emission rate by the calculated humidity factor, resulting in values more consistent with the EPA laboratory conditions.

$$E_{NOx\ Corrected} = E_{NOx\ Uncorrected} \times (9.953 \times Humidity + 0.832) \quad \text{Equation (5)}$$

**Where Humidity is Moles H₂O / Moles Dry Air*

In this study, absolute humidity was estimated based on air temperature and relative humidity¹⁰. The resulting correction factors ranged from 0.90 (a 10% reduction of the field-measured NO_x) to 1.07 (a 7% increase). Higher correction values occurred during warm and humid conditions, while lower values were associated with cooler, drier air, which holds less moisture. Since the testing occurred in spring, these corrections were relatively modest compared to other sources of uncertainty.

¹⁰ <https://www.ready.noaa.gov/READYmoistcal.php>

Results for NO_x Emissions Estimates

Figure 3 compares measured NO_x emission rates against expected rates based on regulatory standards. The solid line represents the one-to-one correlation, while the dashed line shows the regression of the measured and expected values. As expected, the overall trend shows decreasing NO_x emissions with more stringent Tier standards. However, notable deviations exist: some vessels measured higher emissions than expected, while others emitted at rates lower than expected.

These discrepancies may reflect a combination of operational factors and classification uncertainties. For instance, some older vessels likely had engine upgrades or replacements—such as during rebuilds—that resulted in lower emissions than originally assumed. Because public records rarely include engine replacement information, these vessels may have been misclassified with higher expected emissions.

Conversely, some newer vessels may have been miscategorized as Tier 4. If construction began before the Tier 4 standard took effect—even if the vessel was launched afterward—they may have been equipped with Tier 3 engines. This issue, along with operational conditions such as low engine loads (especially relevant for some tugs), can lead to higher-than-expected NO_x emissions due to reduced aftertreatment effectiveness at low exhaust temperatures.

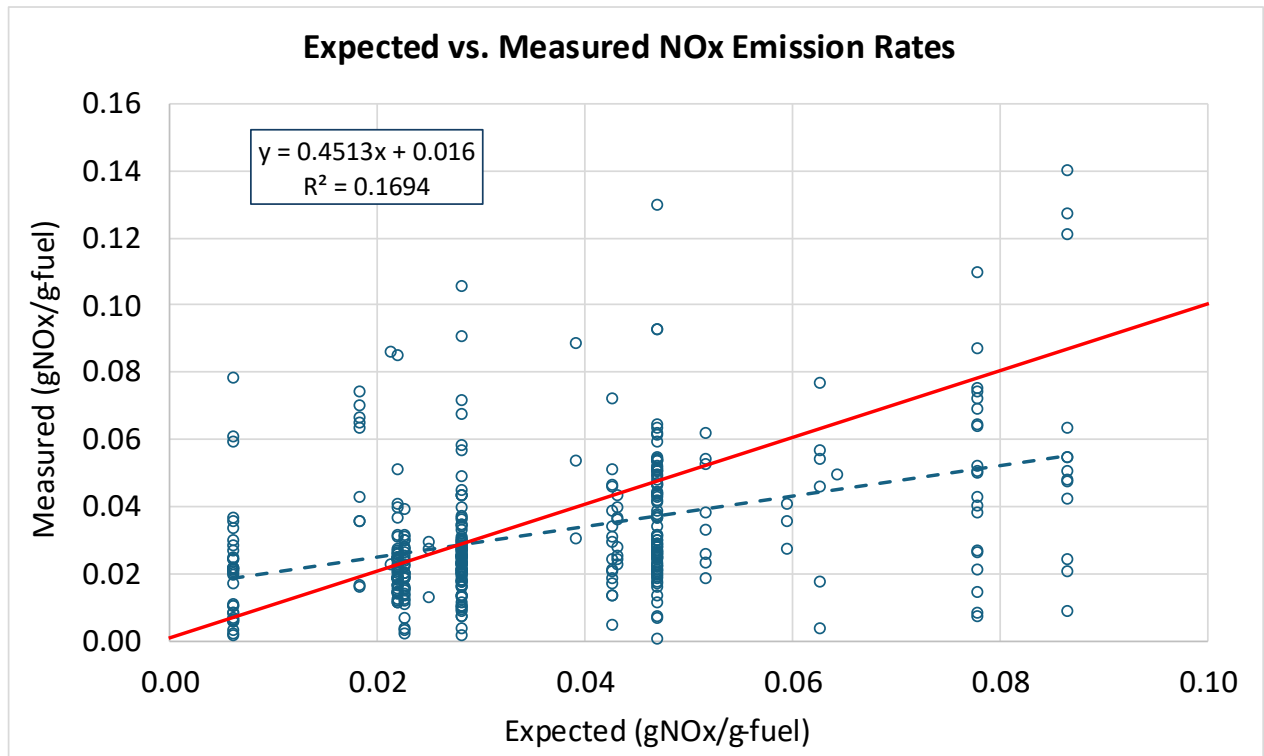


Figure 14. Measured Against Expected NO_x Emission Rates.
(Solid Line – One-to-One Correlation; Dashed Line – Regression of Measured and Expected Values).

Table 15 summarizes average measured emissions by Tier group. Note that within a given Tier, the EPA estimated emissions factors vary by engine power and cylinder displacement, so expected emissions rates are expressed as a range. This reflects the inherent variability among vessels even when categorized under the same Tier.

Table 15. Expected and Average Measured Emission Rates by Tier Level.

Range of Expected (gNO _x /g-fuel)	Test Points	Average Measured (gNO _x /g-fuel)	Median Expected (gNO _x /g-fuel)	Tier Level Description
<0.007	34	0.022	0.006	Tier 4 C1/C2
0.018 to <0.026	98	0.026	0.023	Tier 3 C1/C2 and Tier III OGV
0.026 to <0.030	89	0.027	0.028	Tier 2 C1/C2
0.038 to <0.053	113	0.037	0.047	Tier 1 C1/C2 and Older C1
0.059 to <0.065	10	0.041	0.063	Oldest C2 or OGV MSD
>0.07	33	0.055	0.080	Tier II or Older OGV

To provide an example of emissions factors per kW-hour and kg fuel, **Table 16** compares emission factors for NO_x and PM in different units for two common engine types (C1 and C2) used for towboat propulsion power, and larger (C3) OGV ship propulsion engines. Generally, newer engines are expected to have lower emission factors.

Table 16. Examples of Marine Diesel Engine Emission Rates (EPA, 2022).

Model Year Standard	Tier	NO _x		PM		Fuel Consumption Rate (g/kW-hr)
		g/kW-hr	g/kg-fuel	g/kW-hr	g/kg-fuel	
Example Engine: Cat 3500 Category 1 (<5 l/cylinder) - smaller commercial vessel						
Precontrolled	0	11.0	52	0.21	0.99	213
2004	1	9.2	43	0.15	0.70	213
2007	2	6.0	28	0.20	0.94	213
2013	3	4.8	23	0.11	0.52	213
2015	4	1.3	6	0.04	0.19	213
Example Engine: EMD 710 Category 2 (11.5 l/cylinder) - smaller commercial vessel						
Precontrolled	0	13.36	63	0.21	0.99	213
2004	1	10.55	50	0.21	0.99	213
2007	2	8.33	39	0.31	1.45	213
2013	3	5.97	28	0.11	0.52	213
2015	4	1.3	6	0.03	0.14	213
Example Engine: Slow speed Category 3 - OGV						
Precontrolled	0	17	92	0.15	0.84	185
2000	I	16	86	0.15	0.84	185
2011	II	14.4	78	0.15	0.84	185
2016	III	3.4	18	0.15	0.84	185

Estimates of Fuel Sulfur

The diesel fuel sulfur used in vessels within the US waters is regulated¹¹ to be less than 15 ppm by weight (g/g-fuel) with exemptions for the unique situations outlined here:

- Alternative sulfur standards apply for 500 ppm locomotive and marine diesel fuel and ECA marine fuel as specified in CFR §§1090.320. (A 500 ppm per gallon maximum for locomotive and marine fuel from a transmix processor or pipeline operator.¹²) and CFR 1090.325 (Per-gallon maximum sulfur content of 1,000 ppm standards for marine fuel used in vessels powered by Category 3¹³ engines when operating in Emission Control Area, respectively).
- Exemption provisions apply as specified in subpart G of the CFR reference for marine diesel fuel. (Refers to allowing sales of higher global marine sulfur limits for use in steamships or Category 3 marine vessels when operating outside of ECA boundaries.)

Therefore, it was expected that tugs and other harbor craft primarily using smaller Category 1/2 propulsion engines to use 15 ppm sulfur diesel, a level that was essentially undetectable in this study. There could be infrequent situations where up to 500 ppm sulfur might be allowed in the smaller displacement Category 1/2 engines for fuel produced when transmixing products in a pipeline. Vessels using larger displacement Category 3 engines were subject to 1,000 ppm fuel sulfur limits and were identified in this study as ‘ocean-going’.

The analysis for sulfur was conducted using the same technique of regressing the SO₂ against the CO₂ concentrations to estimate the relative sulfur to fuel consumed amounts. The analysis **Equation (6)** for the Emission Rate of sulfur (ER_S) is the same as the one used for NO_X emissions with a change in the molar weight of sulfur (32) substituted for the molar weight of NO₂ (46).

$$ER_S(g/g - fuel) = \frac{SO_2 \text{ plume} - SO_2 \text{ background}}{CO_2 \text{ plume} - CO_2 \text{ background}} \times 0.87 \times \frac{32 \text{ g S}}{12 \text{ g C}} \quad \text{Equation (6)}$$

Figure 15 shows that fuel sulfur levels for OGVs were generally consistent with expectations, averaging 769 ppm. In contrast, diesel harbor craft exhibited higher-than-expected sulfur levels, with an average of 308 ppm, as shown in **Figure 17**. However, the full range of calculated values was wide, and in some cases, negative values were observed, highlighting a high degree of uncertainty. In general, the lower values (even the larger magnitude negative values) showed

¹¹ <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1090/subpart-D>

¹² <https://www.federalregister.gov/documents/2012/12/26/2012-30960/regulation-of-fuels-and-fuel-additives-modifications-to-the-transmix-provisions-under-the-diesel> The diesel transmix amendments will reinstate an allowance for transmix processors and pipeline operators to produce 500 ppm sulfur diesel fuel for use in older technology locomotive and marine diesel outside of the Northeast Mid-Atlantic (NEMA) Area and Alaska after 2014.

¹³ <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1090/subpart-D> : Category 3 means relating to a reciprocating marine engine with a specific engine displacement at or above 30.0 liters per cylinder.

poor correlations of SO₂ with CO₂, indicating more uncertain estimates for those results, indicating low sulfur compared with better correlation for higher sulfur results in **Figure 16** and **Figure 18**.

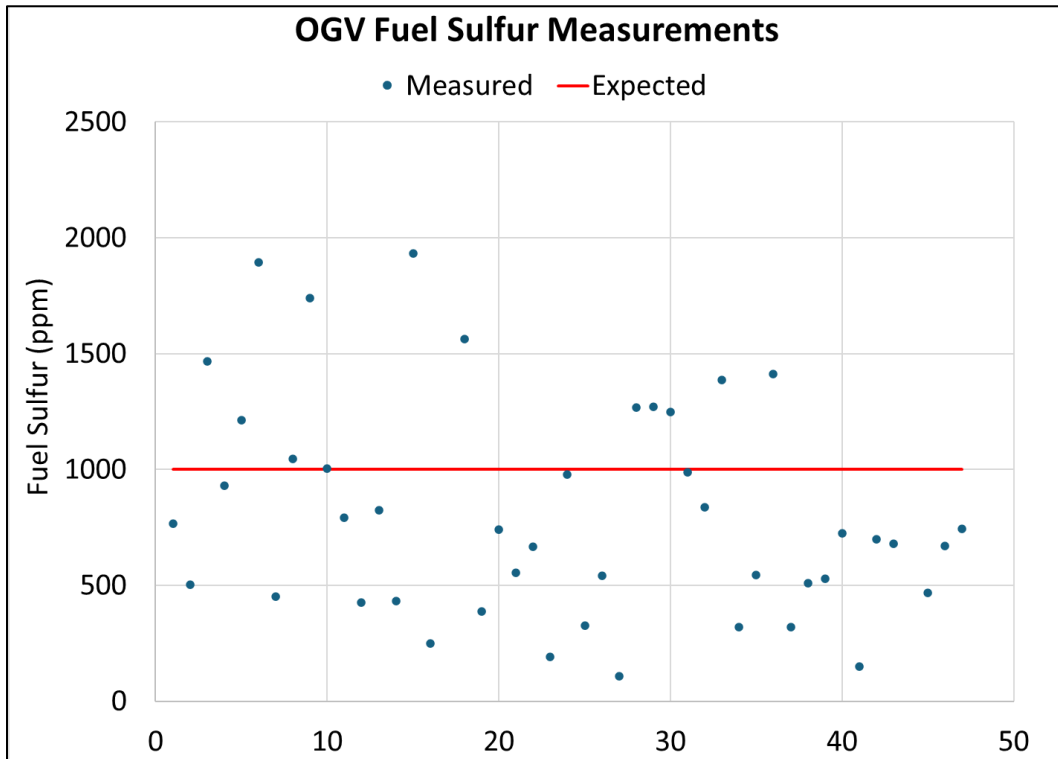


Figure 15. Ocean-Going Vessel Fuel Sulfur Measurements (unordered).

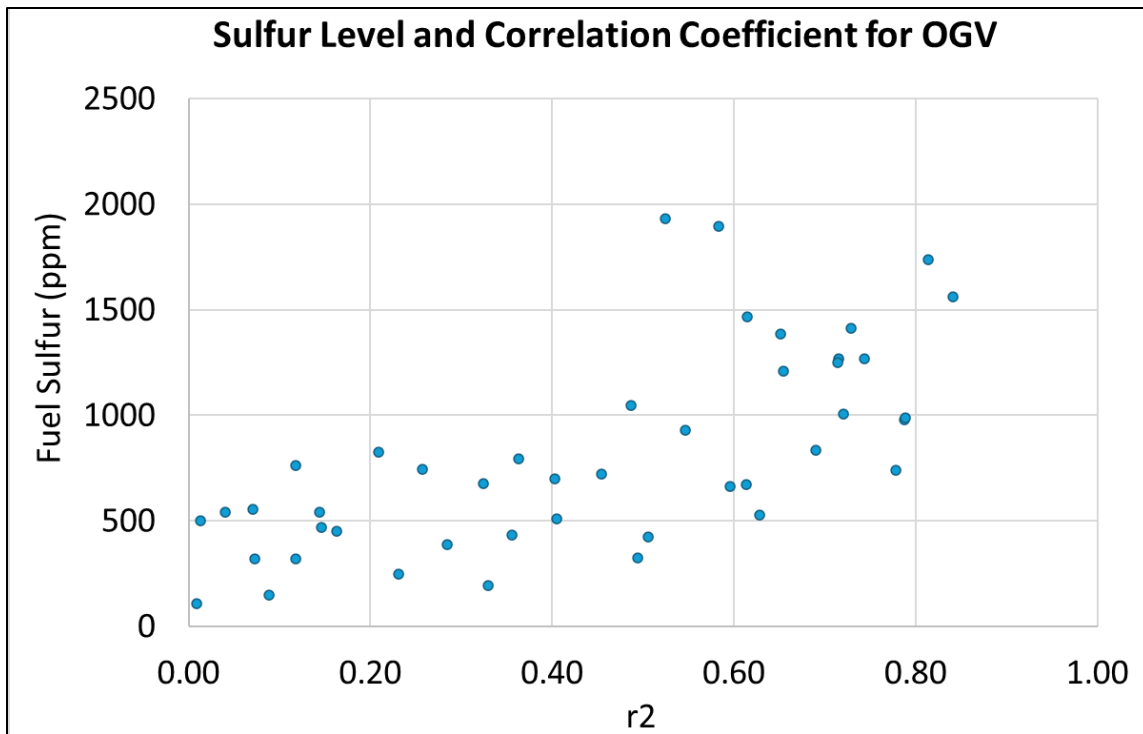


Figure 16. Ocean-Going Vessel Fuel Sulfur Measurements Measurement Correlation.

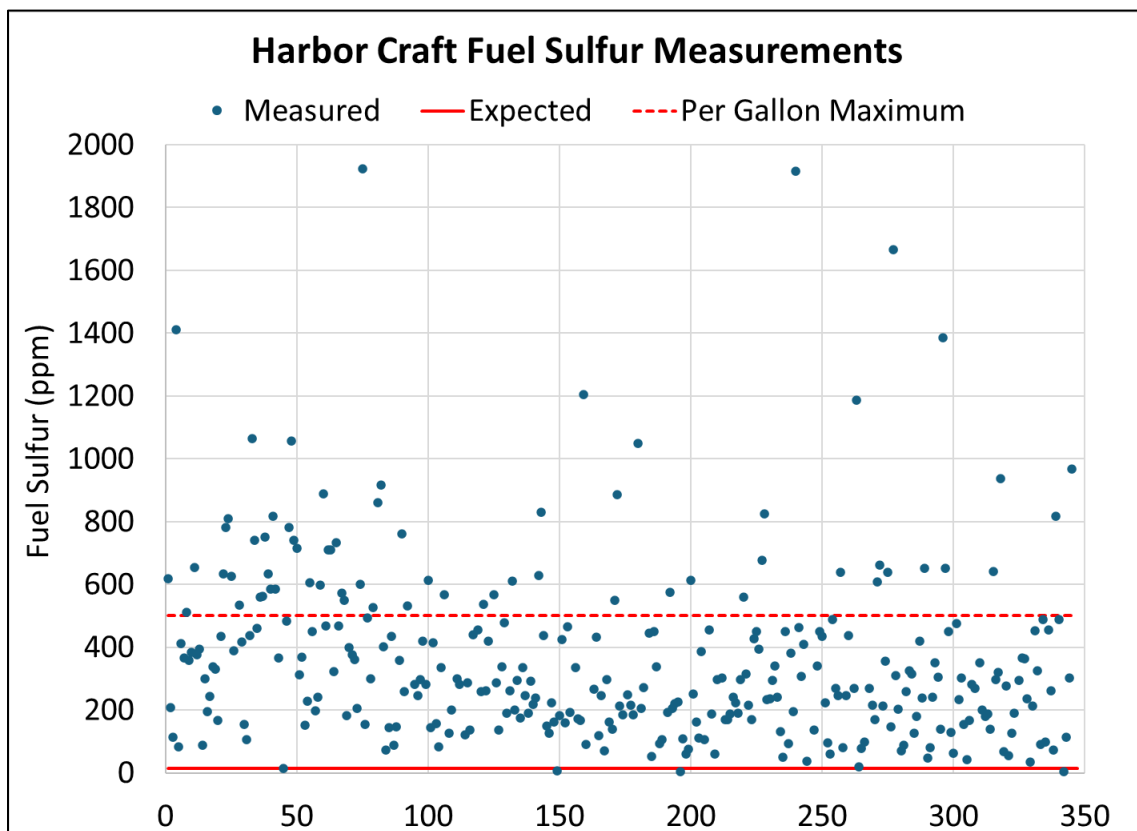


Figure 17. Harbor Craft Vessel Fuel Sulfur Measurements (unordered).

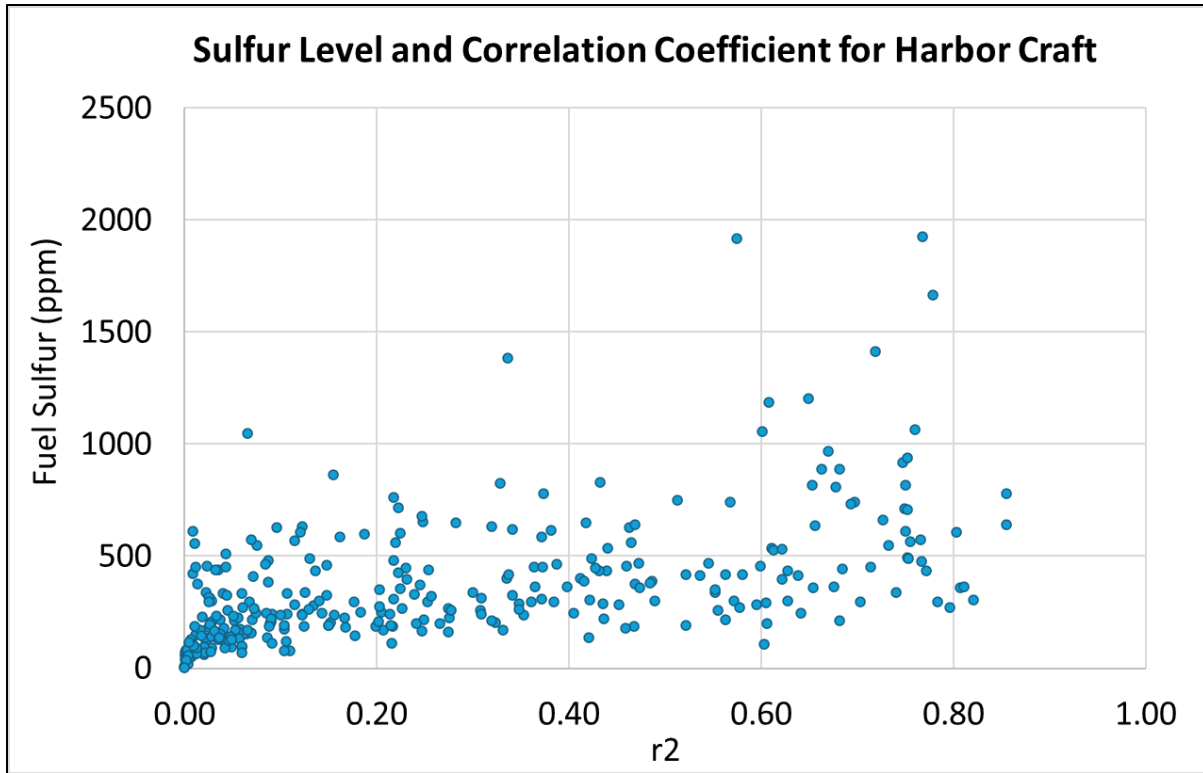


Figure 18. Harbor Craft Vessel Fuel Sulfur Measurements Correlations.

For harbor craft measurements, multiple samplings on the same vessel in **Table 17** shows similar results to all tests in **Figure 17** but multiple tests highlight the test-to-test uncertainty. Using high confidence levels of 95% or 99%, few tests could be considered statistically significantly higher than the 15 ppm fuel sulfur expected. More testing will likely better demonstrate if harbor craft vessels are using fuel with higher-than-expected sulfur levels, such as the vessel that was sampled eight separate times.

Table 17. Average Fuel Sulfur and Confidence Interval Significance for Harbor Craft.

Test Plumes	Sulfur Average (ppm)	95% Confidence Interval (ppm)	Significantly >15 ppm 95% Confidence	Significantly >15 ppm 99% Confidence
8	194	109	Yes	Yes
4	712	153	Yes	No
4	308	376	No	No
4	338	347	No	No
4	222	281	No	No
3	411	214	Yes	No
3	472	394	Yes	No
3	589	561	Yes	No
3	439	305	Yes	No
3	198	355	No	No
3	517	624	No	No

Test Plumes	Sulfur Average (ppm)	95% Confidence Interval (ppm)	Significantly >15 ppm 95% Confidence	Significantly >15 ppm 99% Confidence
3	-92	910	No	No
3	321	219	Yes	No
3	632	487	Yes	No
3	266	393	No	No
3	149	395	No	No
3	313	680	No	No
3	-213	2206	No	No
3	199	92	Yes	No
3	121	180	No	No
3	300	91	Yes	Yes
3	279	311	No	No
3	133	308	No	No

Estimates of Carbon Monoxide Plumes

Carbon monoxide emissions were expected to be low due to the lean burn combustion of diesel engines employed by OGV and harbor craft. **Table 18** shows that CO emissions were generally consistent with expected levels estimated by the EPA, especially considering a standard confidence interval. Because of the low values for CO emissions, many CO measurements showed poor correlation with elevated CO₂ levels. CO emissions from diesel engines are not strictly regulated, with the EPA harbor craft levels set to be no more than 3.5 (g/kWh), which translates to 0.016 g-CO/g-fuel and is two to three times higher than the average result found during testing.

Table 18. Average Emissions Rates of CO.

Vessel	Count	Expected (gCO/g-fuel)	Average (gCO/g-fuel)	90% Confidence Interval (gCO/g-fuel)
OGV	46	0.007	0.012	0.012
Harbor Craft	342	0.005	0.005	0.002

Estimates of Particulate Matter Plumes

Particulate matter emissions did not show elevated levels within the plume. **Figure 19** shows a representative example that PM was uncorrelated with the plume identified by higher carbon dioxide levels. PM measurements, response rates, and records were at a lower rate than the 1 Hz rate of the CO₂ records, which would have made it difficult to perform an analysis even if we could have identified PM plumes.

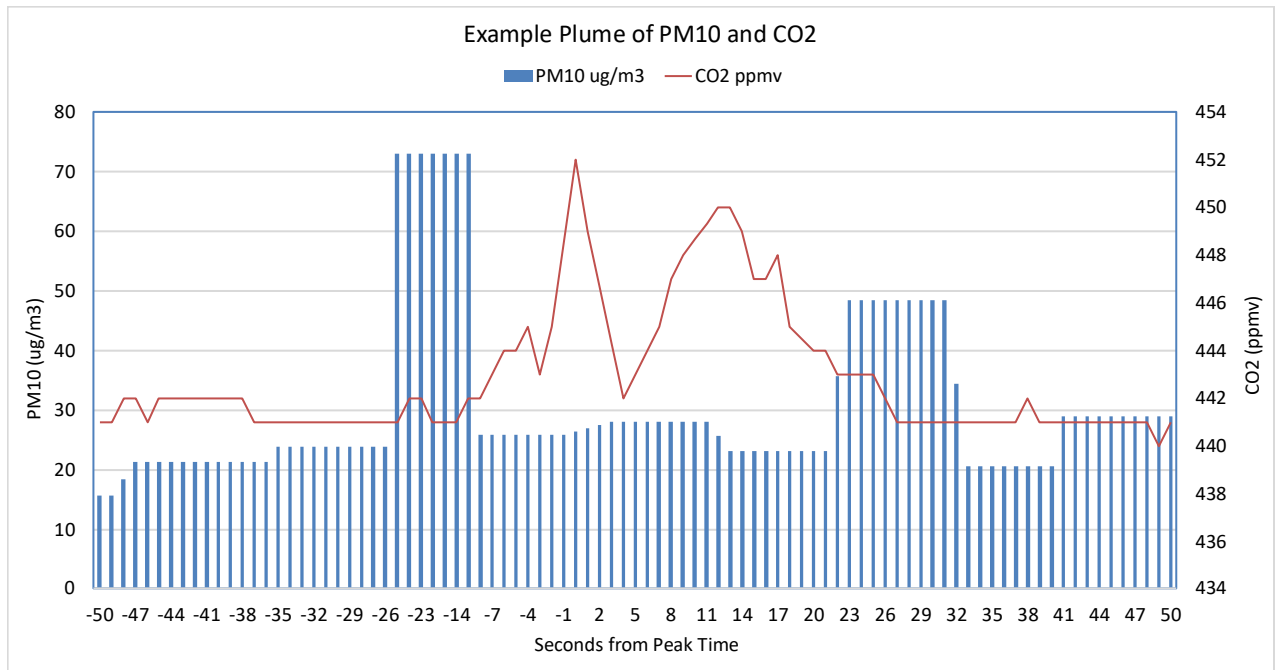


Figure 19. Sample Particulate Matter Plume Measurements.

APPENDIX C – VESSEL ENGINE CHARACTERISTICS FOR HARBOR CRAFT

The EPA expected emission rates provide a comparison with the measured emission rates. The EPA¹⁴ published emission factors in units of grams per kilowatt-hour (g/kWh) defined by ‘engine’ model year, cylinder displacement, and power range for Category 1 and 2 engines used in harbor craft. For Category 3 ocean going vessels, the engine build date provided by the S&P Global Sea-Web database was used and compared with the emission factor for that engine build year.

There is no registration database of smaller US vessels that provides the engine characteristics. However, the Army Corps of Engineers¹⁵ publishes U.S. vessel data - most recently for calendar year 2023, presumably collected from Coast Guard registration- that includes the vessel name, ‘vessel’ build year, often installed power (usually the total propulsion power of all engines), operator or owner) home port, and Coast Guard numbers. The vessel data may include a rebuild date, but a rebuild does not necessarily mean replacement with new engines or existing engines upgrades. The vessel build year likely refers to when the vessel is completed and put in service and therefore will always follow the engine purchase date.

According to the EPA commercial marine engine emissions regulations¹⁶, the engine model year corresponds to when the vessel’s keel is laid or when construction begins. As a result, the engine model year may be one or more years earlier than the vessels’ build date, especially when several similar vessels are constructed concurrently using similar designs. To account for this lag, it was assumed that the engine build year was one year earlier than the vessel build date, consistent with typical construction timelines described in the EPA guidance. For newer vessels¹⁷, the lag between the engine and vessel build date may have been longer than one year. Other engine information, such as the make and model to discover the cylinder displacement, is not provided by the Army Corps vessel list.

To supplement this missing information, a web search was conducted of each vessel measured using the MMSI and vessel name to find information about the propulsion engines installed on the vessel. Although auxiliary engines may also have been operating during emissions measurements, they usually have less than 10% of the rated power of the propulsion engines and thus have a minimal impact on total emissions.

¹⁴ <https://www.epa.gov/state-and-local-transportation/port-emissions-inventory-guidance> , Appendix H

¹⁵ <https://www.iwr.usace.army.mil/About/Technical-Centers/WCSC-Waterborne-Commerce-Statistics-Center/WCSC-Vessel-Characteristics/>

¹⁶ <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1042>

¹⁷ Tier 4 emissions controls on harbor craft engines often require aftertreatment, so many vessels could have been started more than one year prior to final build year to avoid an early transition to aftertreatment. Rebuilds on older vessels may not have reported whether or not if the engine was replaced or rebuilt to lower emissions standards.

Because vessel names can be duplicated between two or more vessels or changed over time, vessel identity was verified using their MMSI numbers and AIS websites, such as Marine Traffic and Vessel Finder websites. These platforms provide vessel photos that often show the vessels’ owner/operator logos along with their current positions. The Army Corps vessel list and company websites were also used to verify that the vessel name, MMSI, and owner/operator data were consistent.

Fan websites and videos sometimes provided supplemental information, including engine characteristics and installed power, which were cross validated with the Army Corps data. Public data sources listing vessel owners or operators were also useful, particularly when operators published technical details of their fleets. In addition, commercial or trade news sources, e.g., christening announcements, sometimes publish vessel and engine characteristics for prominent vessels. Despite these efforts, engine power and build year could not be identified for nine vessels due to reasons such as name changes, recent construction, exclusion from vessel lists, noncommercial vessels using outboard gasoline motors, or insufficient public data.

Once an engine model was identified, engine manufacturer websites were used to determine cylinder displacement. However, it is possible that some engines have been replaced without public documentation, in which case, the listed data may not reflect the current engine in use. Additionally, even government-maintained datasets, such as those from the Army Corps or Coast Guard, are largely unverified and often lack mandatory reporting on engine specifications.

Table 19. *Data Source Results for Vessel and Engine Information Type and Availability.*

Data Source	Search Input	Vessel ID	Vessel Build Year	Power	Engine Model	Owner\ Operator
Army Corps	Name	Name, CG#, if IMO exists	Vessel only	Often	No	Yes
AIS Signal Public Sites	MMSI	Name	No	No	No	Only from Vessel Markings
Public Fan Websites and Videos with Comments	Name, MMSI	Name (may have other)	Mostly	Yes	Mostly	Mostly
Trade Journals (when available)	Name	Name (may have other)	Yes	Mostly	Mostly	Yes
Company Website	Name	Name	Mostly	Mostly	Often	Yes

For most vessels, reported propulsion power includes the total from all engines. In large ocean-going vessels (OGVs), propulsion is typically provided by a single engine, with detailed engine data available from the S&P Global database for vessels with IMO numbers. In contrast, smaller vessels—such as tugs, pushboats, and harbor craft—commonly use two propulsion engines. Unless specific information indicated otherwise, dual-engine configurations were assumed, and the reported total propulsion power was divided by two to estimate single-engine power for the EPA emission factor (EF) lookup.

The EPA EF is defined by the engine model year, power level, and cylinder displacement. The EF divided by the EPA estimated specific fuel consumption (SFC) rate provides the expected emission rate per unit of fuel consumed. The EPA estimated the SFC as follows:

- 213 g-fuel/kWh for Category 1 and 2 (C1/C2) marine engines in tugs, pushboats, and other harbor craft,
- 185 g-fuel/kWh for direct drive slow speed Category 3 (C3) OGVs,
- 205 g-fuel/kWh for geared drive medium speed C3 engines in OGVs.

These g-emission/g-fuel emission estimates were used to compare against the plume-derived estimates, which are discussed in Appendix B.

$$Emission\ Rate\ (g/g - fuel) = \frac{EF\ (g/kWh)}{SFC\ (g/kWh)} \quad \text{Equation (7)}$$

A spreadsheet table of the vessel engine characteristics and data source sites is provided with this report.