

# *Improving Emission Rates Estimates of Commercial Marine Vessels*



## *AQRP 24-003*



*This research presentation was supported by funding from the Texas Commission on Environmental Quality (TCEQ). The findings, opinions, or conclusions expressed do not necessarily represent those of the TCEQ.*

# Project Objectives

- Marine emissions can impact air quality
- Emissions estimates; particularly for smaller commercial vessels have significant uncertainty

## Objectives:

1. Field-measure marine emissions under varying load conditions.
2. Calculate emissions rates of harbor craft (HC) and ocean-going vessels (OGV) using field data.
3. Compare calculated rates against emissions estimates.

# Sampling Platform

- UH Osprey: 30' closed cabin boat powered by twin Suzuki 300 hp outboard engines.
- Power Generation: Perkins marine (diesel) 9 kW generator.
- Equipped with aircraft-style seat mounting track and hardware to secure science payloads.



# UH Instrumentation

- Trace Gases

- Carbon Dioxide (CO<sub>2</sub>) – LiCor 7000
- Carbon Monoxide (CO) – Teledyne T300U
- Nitric Oxide (NO) – Thermo 42C-TL
- Nitrogen Dioxide (NO<sub>2</sub>) – Teledyne T500U
- Sulfur Dioxide (SO<sub>2</sub>) – Thermo 43C

- Additional Measurements

- Particulate Matter (PM<sub>2.5</sub>) – Teledyne T640
- Bulk VOC's – AROMA
- Meteorology – AirMar 220WX
- Boundary Layer – Vaisala CL51
- 4-way Cameras



UH Osprey Instrument Package 2025

# Quality Assurance

- The trace gas instrument package was challenged with span gases (CO, NO, NO<sub>2</sub>, SO<sub>2</sub>) before and after every sampling mission.
- Expanded calibrations were performed at the beginning, middle and end of the campaign.
- A time alignment was necessary, primarily due to the differences in instrument design and plumbing.
- **All** plume data was audited for QA/QC.

Calibration Date
02/17/2025
02/25/2025
02/26/2025
*02/28/2025
03/2/2025
03/3/2025
*03/14/2025
03/17/2025
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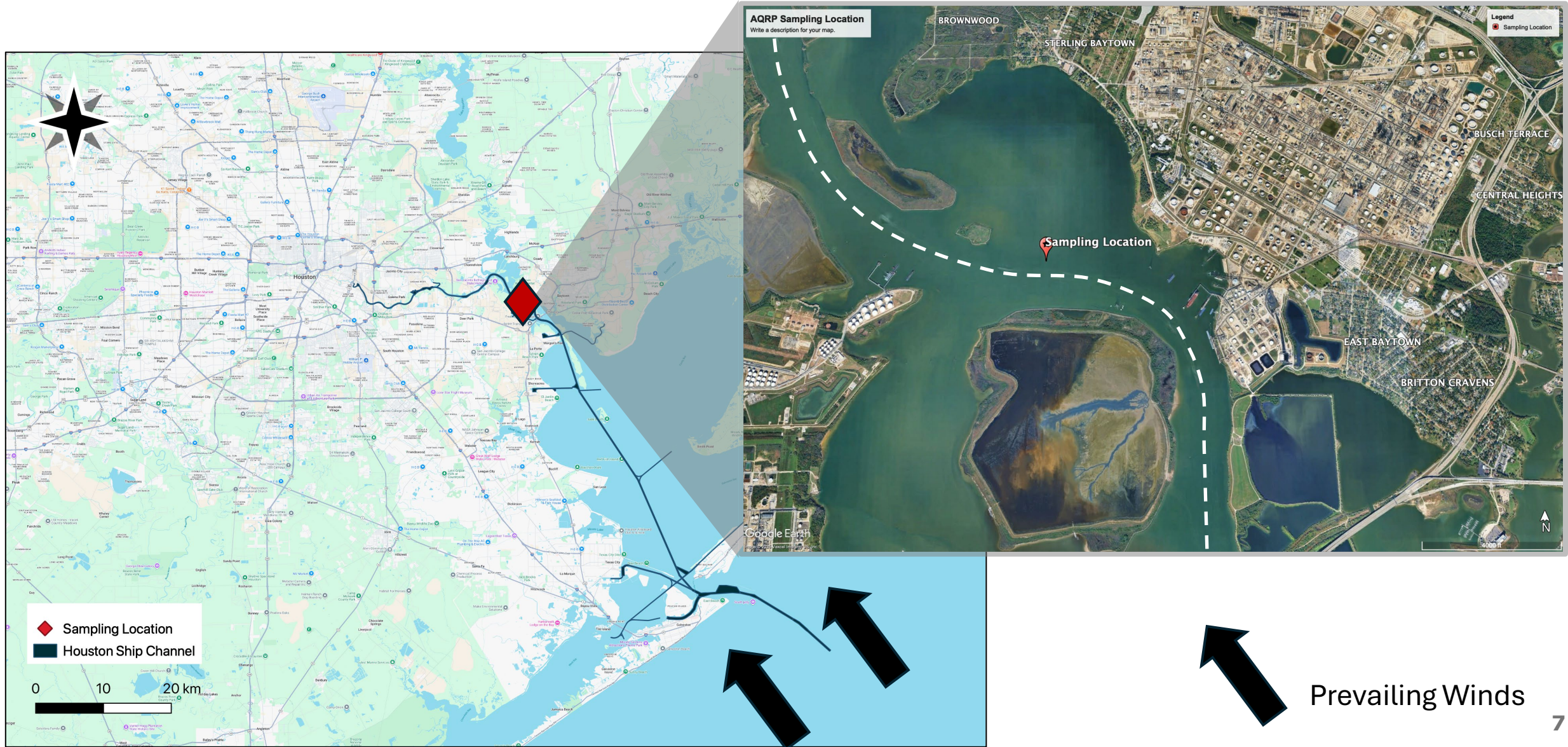
\*Expanded Multipoint

# Sampling Challenges

- Not all areas of Galveston Bay were practical for the crew and instruments to operate in.
- Prevailing southeasterly winds limited sampling locations to areas of the Houston ship channel which were oriented east/west.
- Needed to be close enough for positive ID and strong enough signal for all instruments but still maintain safety as the priority.



# Sampling Location



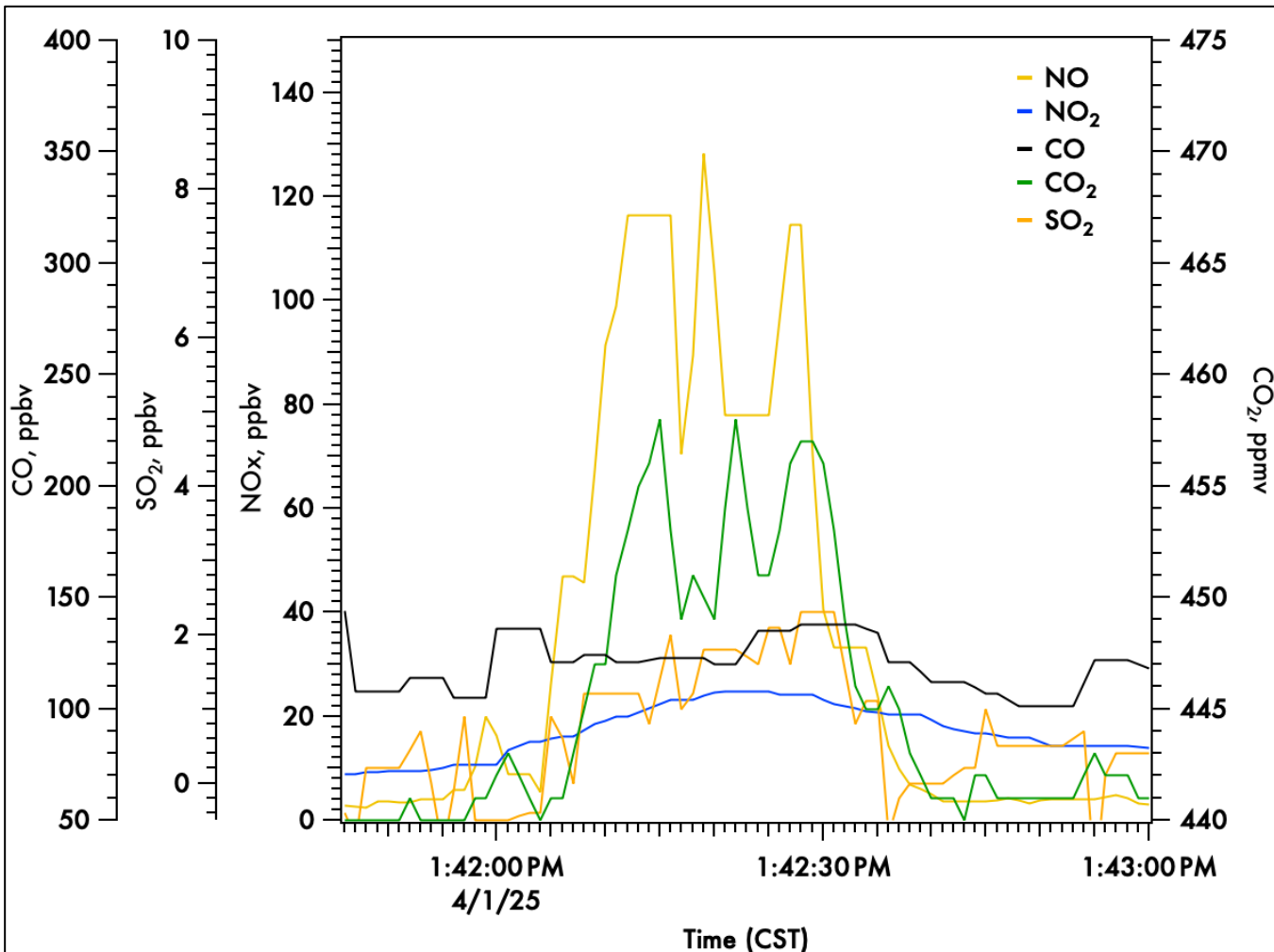
# Sampling Data

February		1-Feb	2-Feb	3-Feb	4-Feb	5-Feb	6-Feb	7-Feb	8-Feb	9-Feb	10-Feb	11-Feb	12-Feb	13-Feb	14-Feb	15-Feb	16-Feb	17-Feb	18-Feb	19-Feb	20-Feb	21-Feb	22-Feb	23-Feb	24-Feb	25-Feb	26-Feb	27-Feb	28-Feb			
Isolated Plumes															Start			10							3		34					
VOC Cans																																
March		1-Mar	2-Mar	3-Mar	4-Mar	5-Mar	6-Mar	7-Mar	8-Mar	9-Mar	10-Mar	11-Mar	12-Mar	13-Mar	14-Mar	15-Mar	16-Mar	17-Mar	18-Mar	19-Mar	20-Mar	21-Mar	22-Mar	23-Mar	24-Mar	25-Mar	26-Mar	27-Mar	28-Mar	29-Mar	30-Mar	31-Mar
Isolated Plumes			27				15	23				26	4	16				11				47									26	
VOC Cans												1										2									1	
April		1-Apr	2-Apr	3-Apr	4-Apr	5-Apr	6-Apr	7-Apr	8-Apr	9-Apr	10-Apr	11-Apr	12-Apr	13-Apr	14-Apr	15-Apr	16-Apr	17-Apr	18-Apr	19-Apr	20-Apr	21-Apr	22-Apr	23-Apr	24-Apr	25-Apr	26-Apr	27-Apr	28-Apr	29-Apr	30-Apr	
Isolated Plumes	34									31	40	45			End																	
VOC Cans	3									5	3	2*																				

**Total  
Unique  
Plumes:  
401**

- **16** days of sampling
- Harbor Craft: **341**
- Ocean-Going Vessels: **48**
- Other/Recreational: **12**
- VOC Cans: **17**

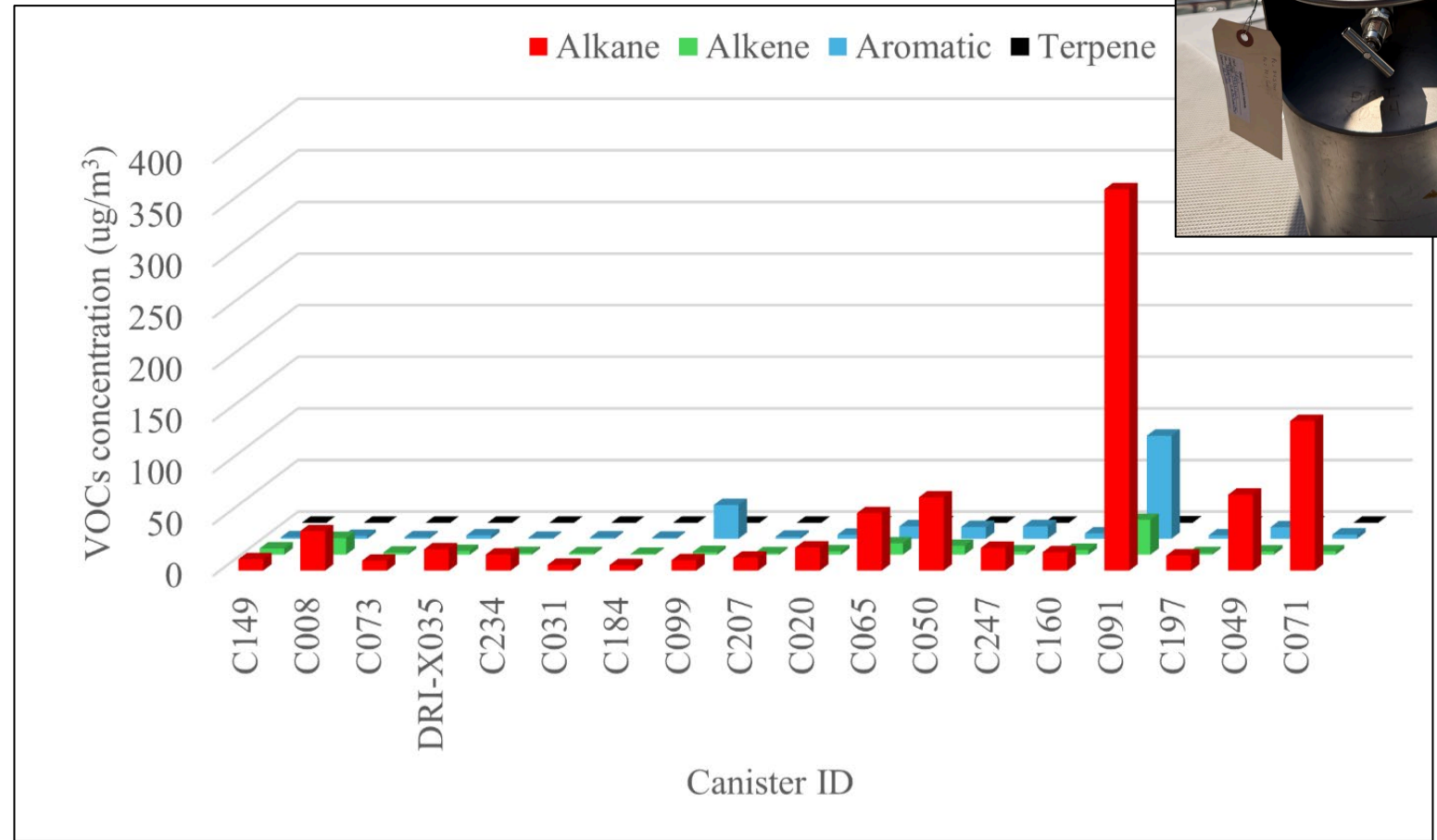
# Example Plume



- A typical plume would be sampled for ~30-90 seconds.
- Once a plume was observed, the vessel information was logged using real-time AIS data.
- A picture of the vessel and signage was also captured if possible.

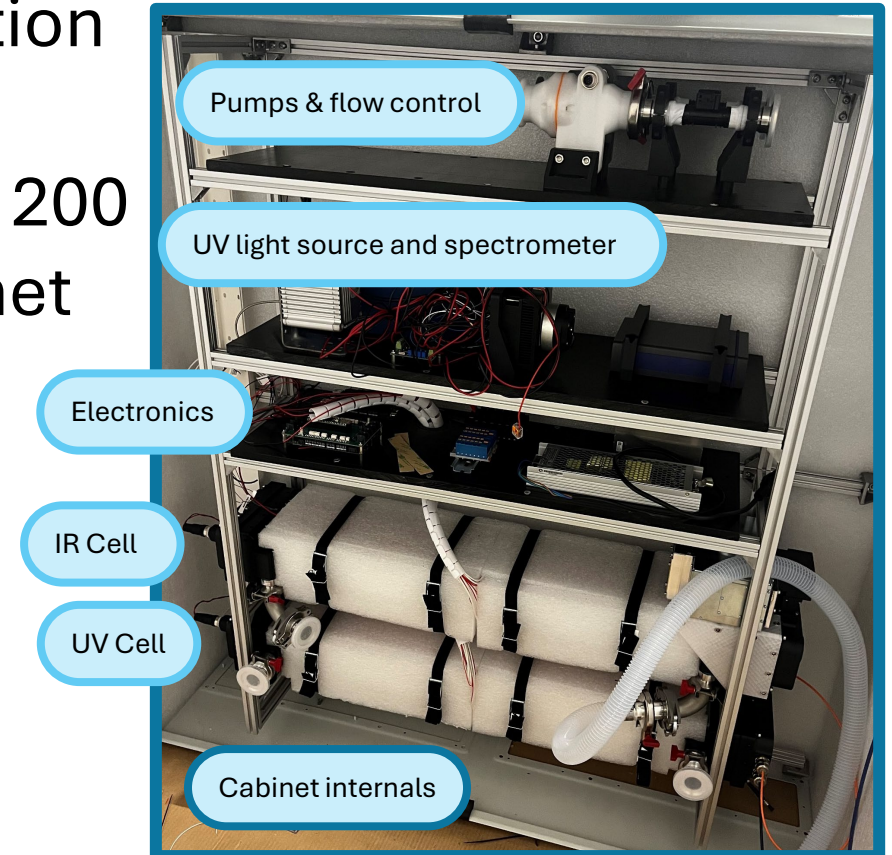
# VOC Canisters

- A total of 17 1-liter canisters were sampled (1 blank) during verified emission plumes.
- Most of the plumes exhibited a profile typical of diesel exhaust
- A couple canisters did show high xylene/benzene ratio



# Twin (FTIR + UV) multi-pass cells

- UV and IR multi-reflection absorption cells with nearly identical format and configuration
- Temperature-regulated cells and air flows
- Installed externally on Osprey in a 1200 x 1200 x 300 mm (48 x 48 x 12") sheet metal cabinet

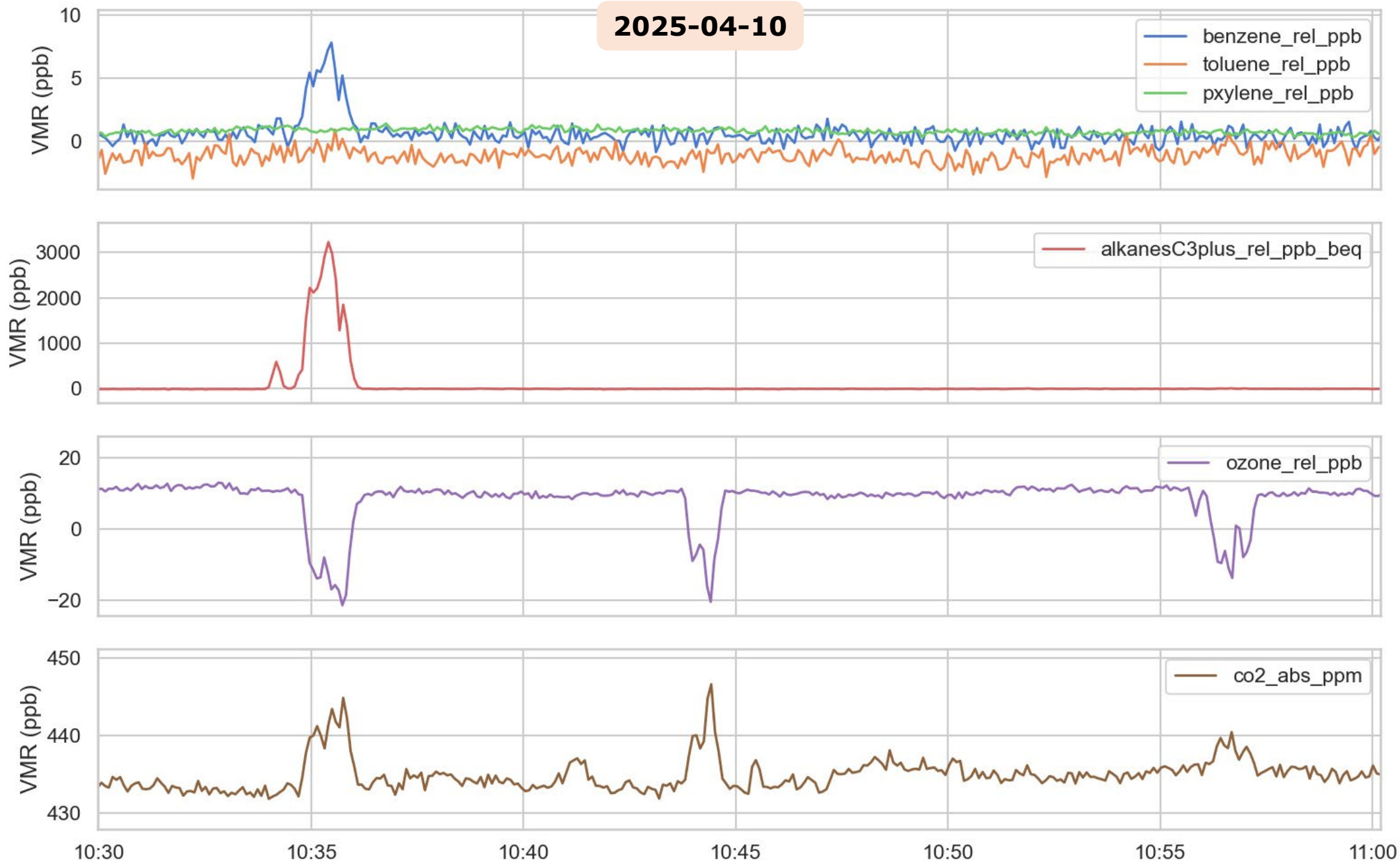


# Instrument Specs

Cell Parameters	
Path length	100.8 m
Volume	5 liters
Flow	50 LPM
Time constant	~6 seconds
Outer dimensions	~ 950 x 200 x 150 mm (~ 38 x 8 x 6 ")
FTIR band / resolution	2-6 $\mu\text{m}$ / 1 $\text{cm}^{-1}$
UV band / resolution	250-280 nm / 0.2 nm
FTIR species (delivered)	Methane, Ethane, C3+ Alkanes, Formaldehyde, Acetaldehyde, $\text{CO}_2$ , CO, $\text{N}_2\text{O}$ , $\text{H}_2\text{O}$
UV species (delivered)	Benzene, Toluene, p-Xylene, m-Xylene, Ethylbenzene, $\text{SO}_2$ , $\text{O}_3$ , Naphthalene, Furfural, Phenol

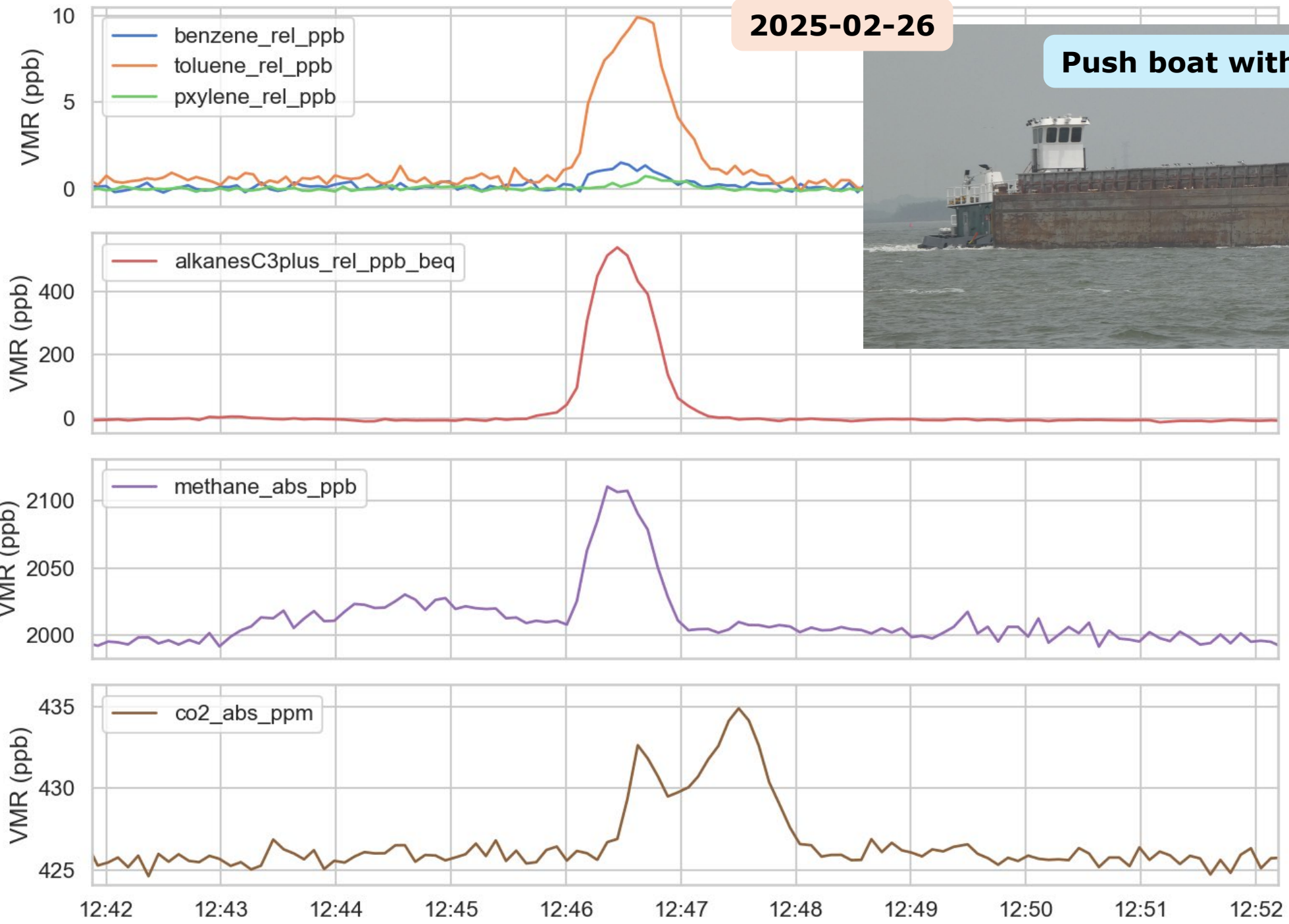
Species	LOD (ppb)
Methane	20
Ethane	8
C3+ Alkanes	10
$\text{CO}_2$	2200
CO	6
$\text{N}_2\text{O}$	3
Benzene	1
Toluene	2
p-Xylene	0.5
m-Xylene	3
Ethylbenzene	3

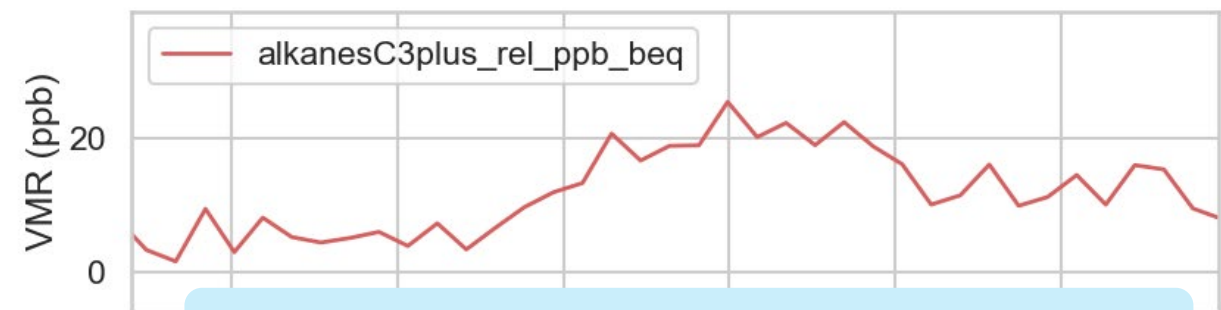
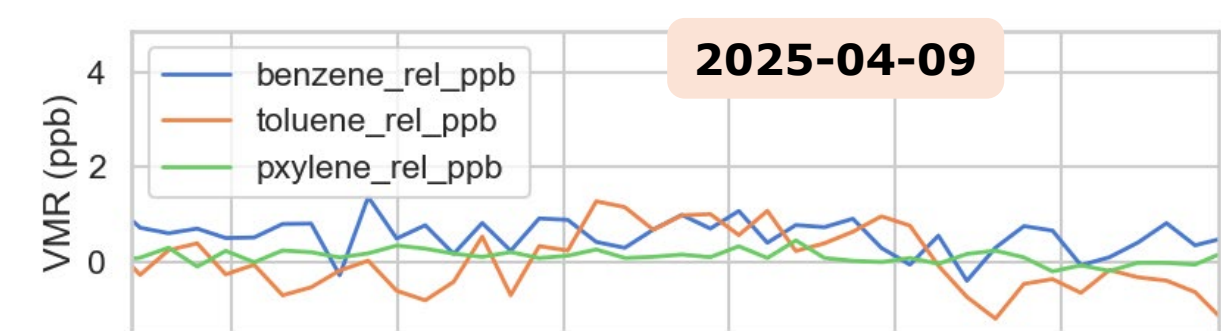
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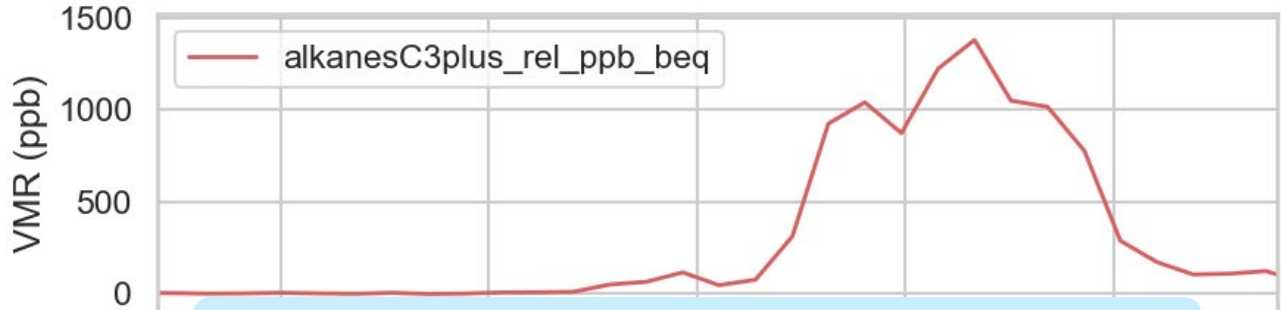
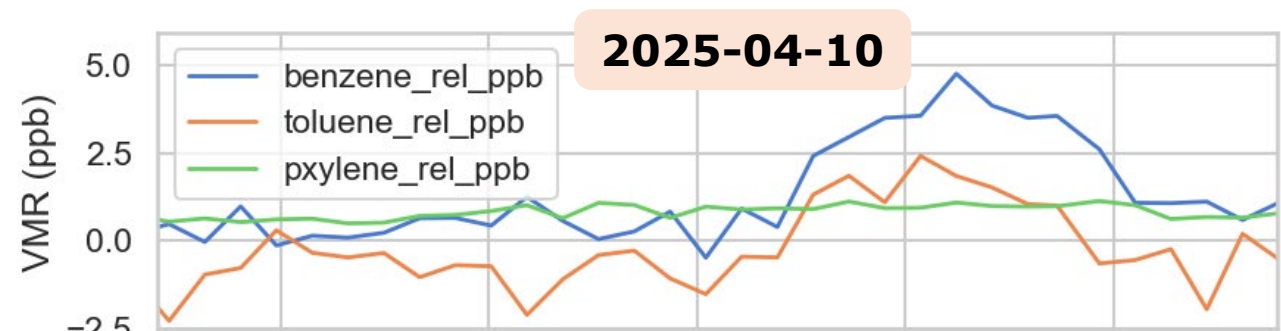
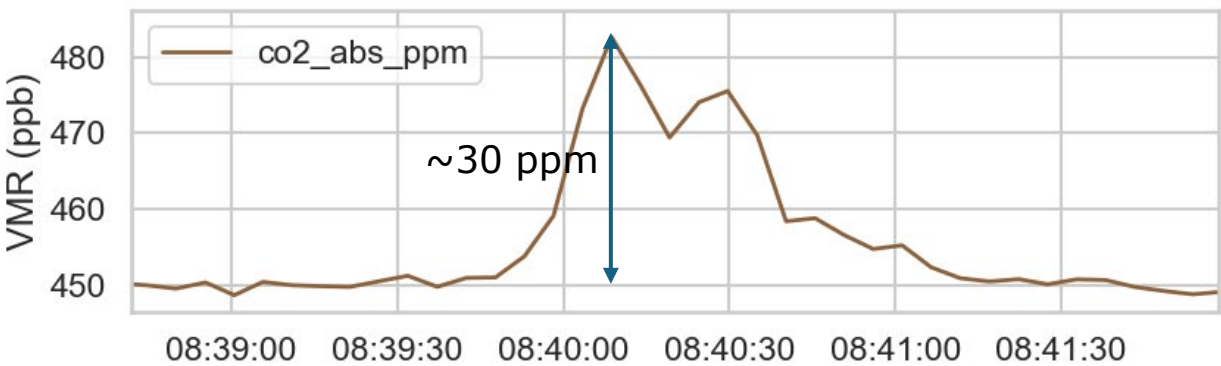
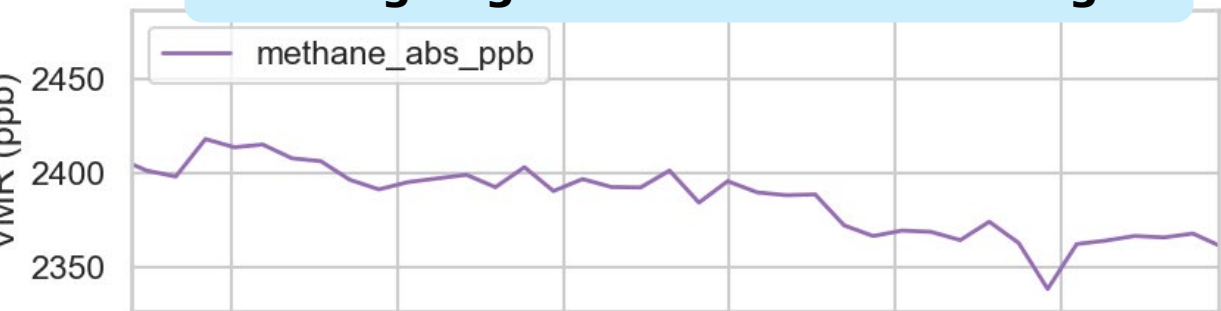
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Push boat with barge slip

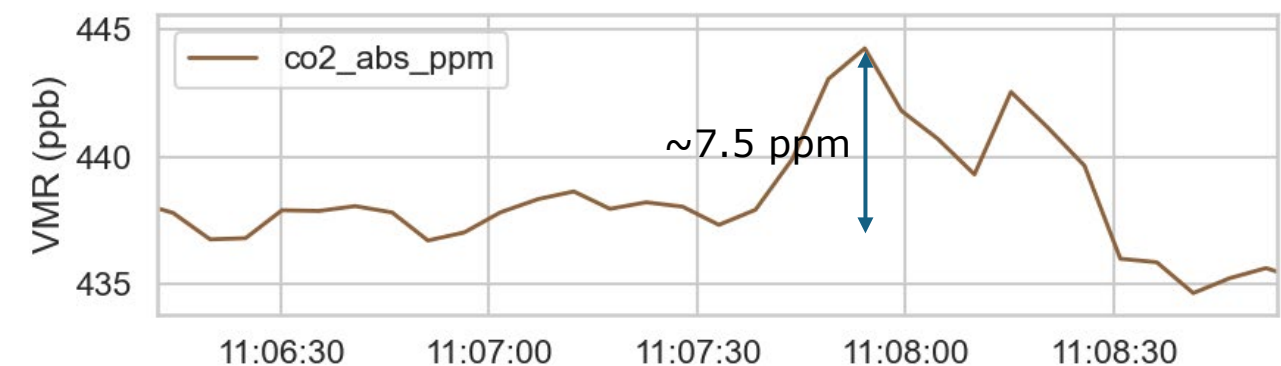
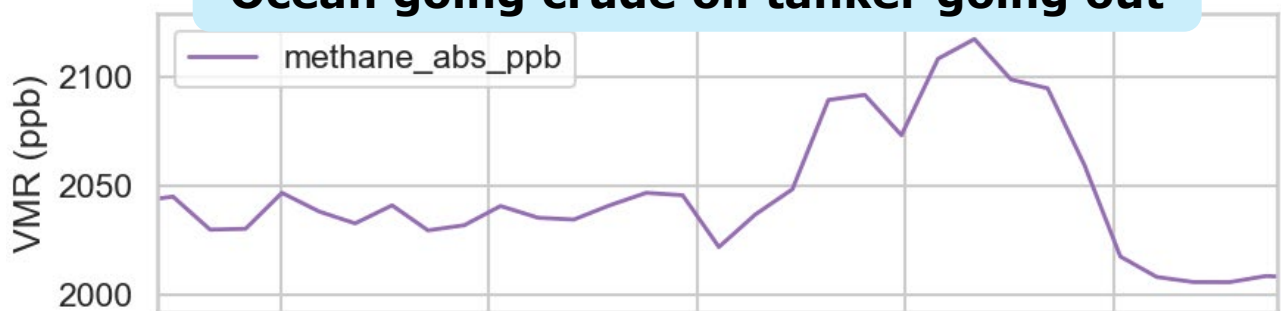




**Ocean going crude oil tanker coming in**

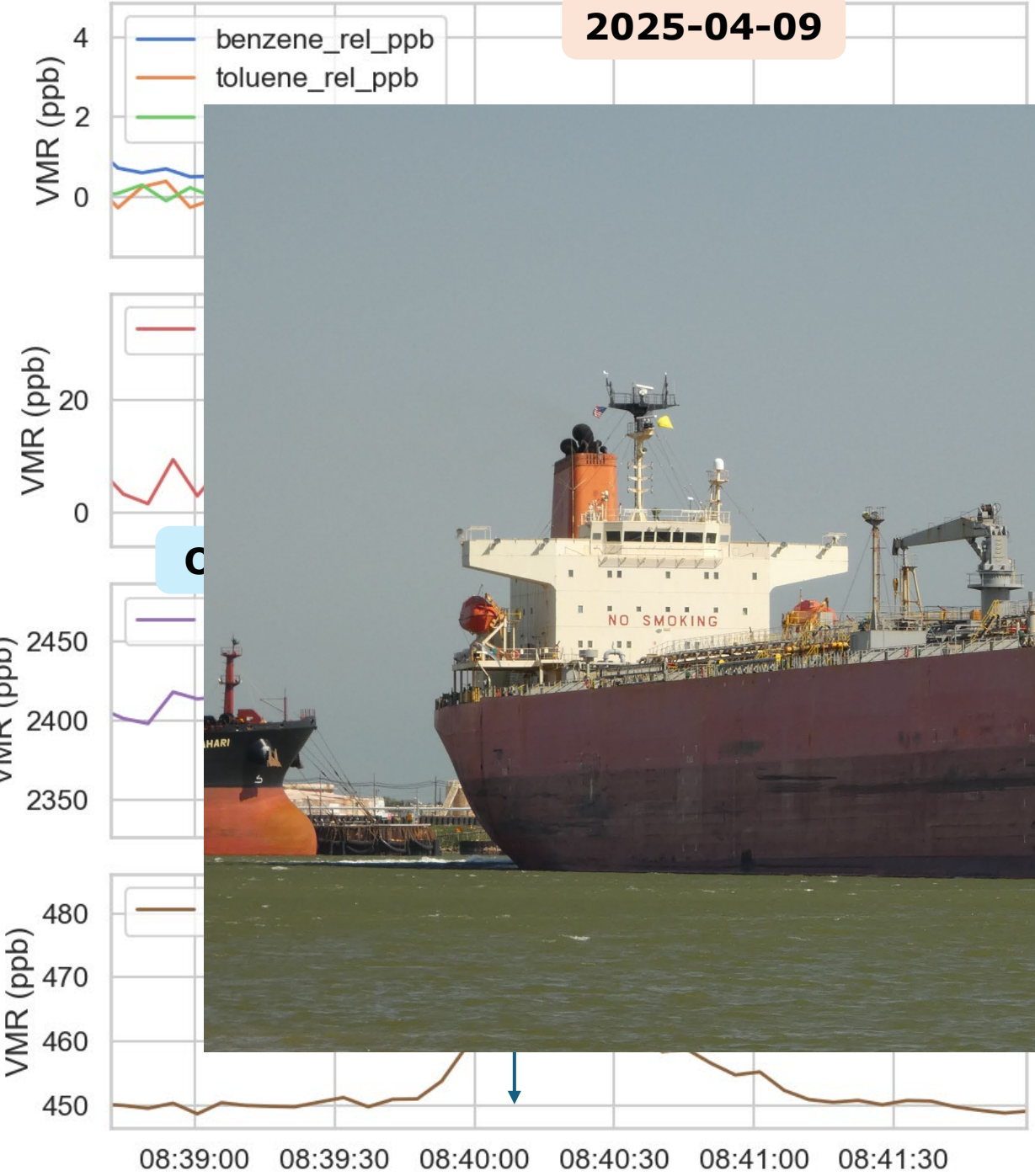


**Ocean going crude oil tanker going out**



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2025-04-10



C

out



# Vessel Types

## Ocean-Going Vessels (OGV)

- Transport cargo and/or people between different ports
- Typically have Category 3 (C3) propulsion engines; some OGV have smaller Category 1 (C1) or Category 2 (C2) auxiliary engines; and boilers

## Harbor Craft

- Smaller ships that tend to operate closer to shore, and along inland and intercoastal waterways
- Typically have C1/C2 engines

# Vessel Types

## Ocean-Going Vessels (OGV)

- Tanker (oil/chemical/LNG), containership, cruise ship, large ferries, refrigerated reefer, roll-on/roll-off (RORO), bulk carrier, oil platform support, etc.

## Harbor Craft

- Barge, dredging, excursion, towboat/pushboat, pilot, tugboat, etc.

# Category 3 Engine

- Emission factors for each emission source depend on the following engine characteristics:
  - Group (propulsion, auxiliary, or boiler)
  - Fuel Type
  - Keel-laid Year
  - Engine Type (SSD, MSD, GT, ST, LNG, or boiler)

- Data source
  - S&P Global Sea-Web Ships database (purchased January 2024)

# Category 1 and 2 Engine

- Emission factors for each emission source depend on the following engine characteristics:
  - Engine category (C1 or C2)
  - Group (propulsion or auxiliary)
  - Cylinder Displacement Range (L/cyl)
  - Rated Engine Power (kW)
  - Engine Model Year
- No national registration database for small U.S. vessels with engine details
- Online search
  - U.S. Army Corps of Engineers' vessel data (2023)
  - AIS websites
  - Company websites
  - Fan websites
  - Trade journals

# Vessel Data Search Results

Data Source	Search Input	Vessel ID	Vessel Build Year	Power	Engine Model	Owner or 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	Name	Name (may have other)	Yes	Mostly	Mostly	Yes
Company Website	Name	Name	Mostly	Mostly	Often	Yes

## Notes on uncertainty:

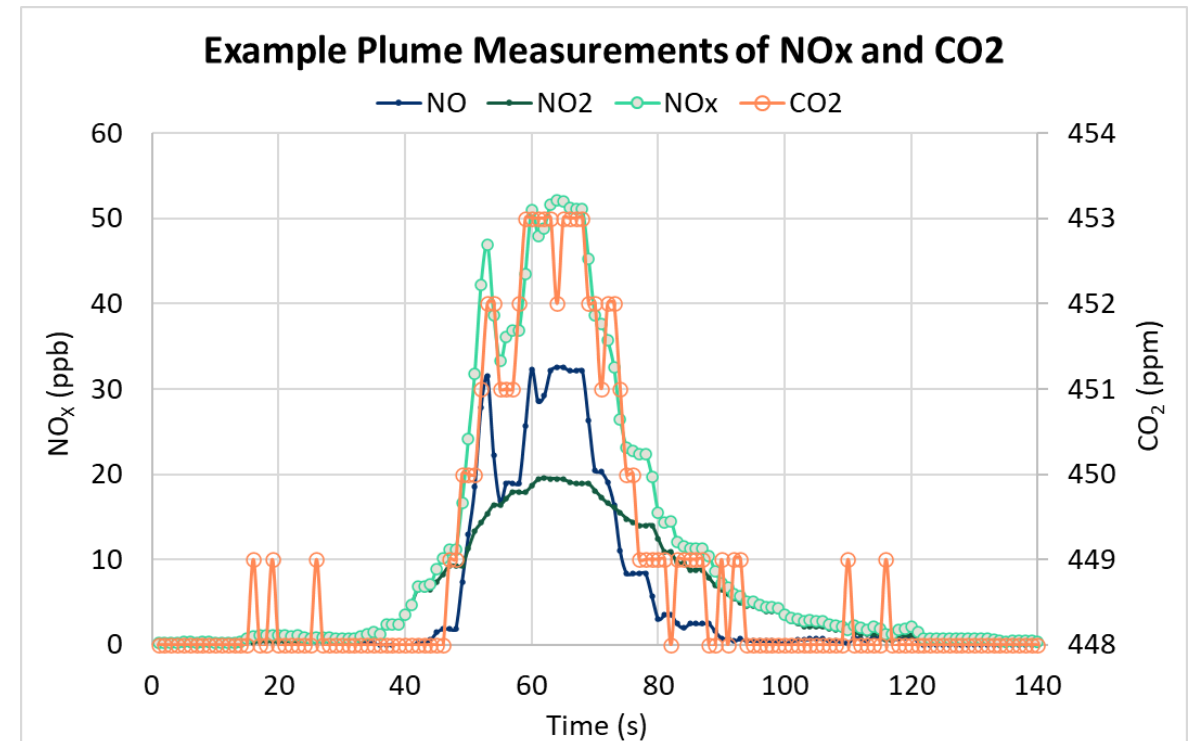
1. Government datasets (Army Corps, Coast Guard) largely unverified
2. Possible undocumented engine replacements or upgrades
3. Limited reporting on engine specs means reliance on assumptions
4. Web-sourced data varies in accuracy
5. Assumed engine model year is one year earlier than build year

# Estimation Methods

## Area-under-the-curve (AUC) method:

- Compares the excess pollutant and CO<sub>2</sub> concentrations—i.e., the difference between plume and baseline values—over the entire duration of the plume.
- Integrates the total excess above background for each gas, then uses their ratio to calculate emissions.
- Example equation for NO<sub>x</sub>:

$$ER_{NO_x} = \frac{NO_x \text{ plume} - NO_x \text{ background}}{CO_2 \text{ plume} - CO_2 \text{ background}} \times FCC \times \frac{46 \text{ g } NO_x}{12 \text{ g } C}$$

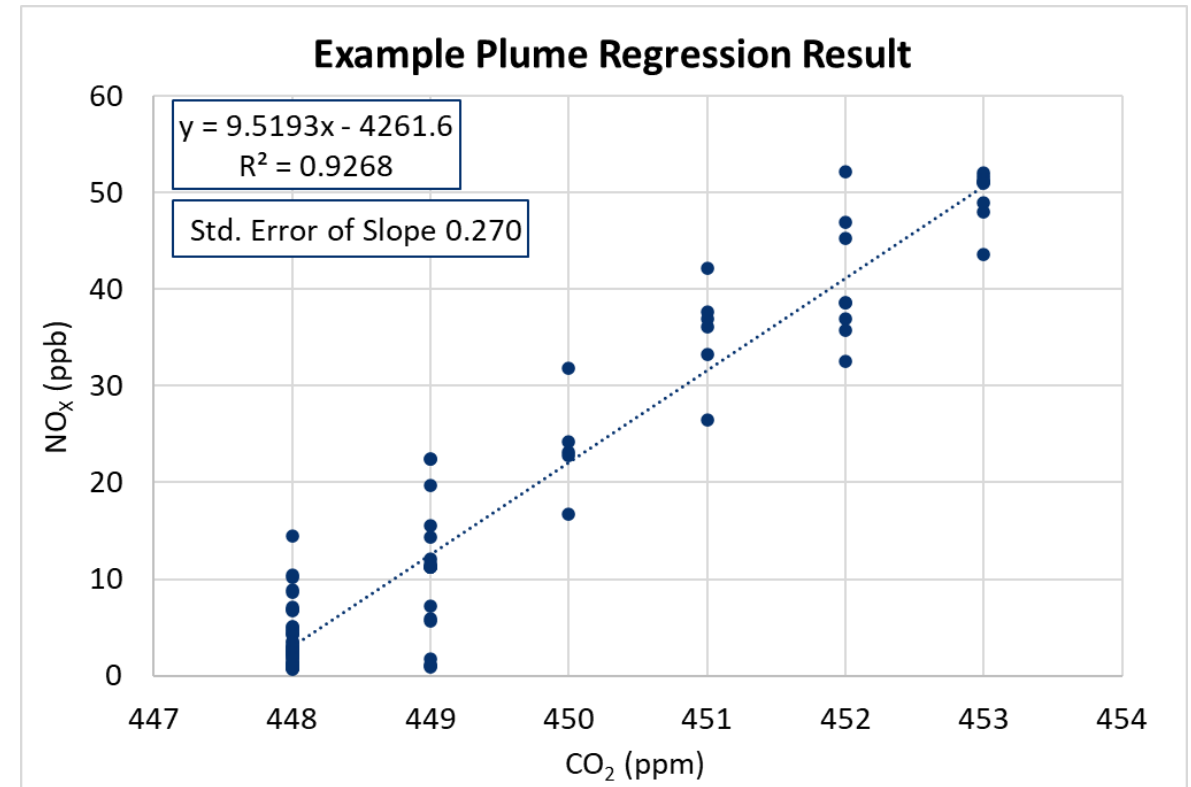


# Estimation Methods

## Linear regression method:

- Regresses second-by-second pollutant concentrations against CO<sub>2</sub>
- Use the **slope** of the regression line to represent the pollutant-to-CO<sub>2</sub> enhancement ratio
- More robust estimate by incorporating more data points and minimizing the influence of individual fluctuations
- Example equation for NO<sub>x</sub>:

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



# Emission Rate

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

- SFC = specific fuel consumption
- Harbor Craft:
  - 213 g-fuel/kWh for C1/C2 engines
- OGVs:
  - 185 g-fuel/kWh for direct drive slow speed C3 engines
  - 205 g-fuel/kWh for geared drive medium speed C3 engines

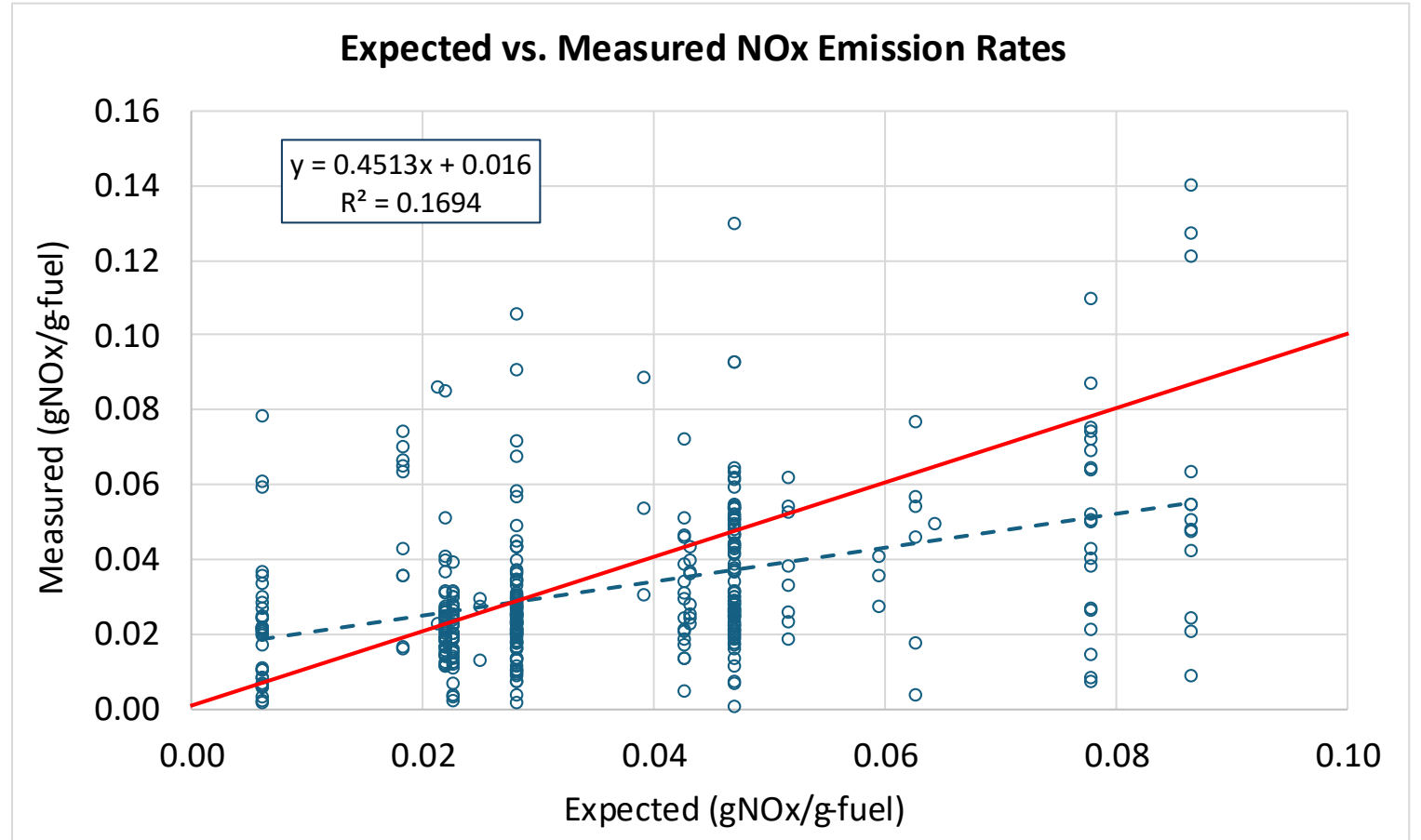
## EPA Emission Factors as Benchmark

- EPA's *Port Emissions Inventory Guidance* (April 2022) provides the latest Emission Factors (EFs).
- Available at <https://www.epa.gov/state-and-local-transportation/port-emissions-inventory-guidance>

# Results of Plume Analysis

# NO<sub>x</sub>: Measured vs. Expected

- 388 plumes
- 280 vessels



# NOx: Emission Rates by Tier

Tier Level Description	Data Points	Range of Expected Emission Rate (gNOx/g-fuel)	Average Measured Emission Rate (gNOx/g-fuel)
<b>Tier 4 C1/C2</b>	34	<0.007	<b>0.022</b>
<b>Tier 3 C1/C2 and Tier III OGV</b>	98	0.018 to <0.026	0.026
<b>Tier 2 C1/C2</b>	89	0.026 to <0.030	0.027
<b>Tier 1 C1/C2 and Older C1</b>	113	0.038 to <0.053	0.037
<b>Oldest C2 or OGV MSD</b>	10	0.059 to <0.065	<b>0.041</b>
<b>Tier II or Older OGV</b>	33	>0.07	<b>0.055</b>



- Some older vessels may have had engine upgrades during rebuilds, but missing records led to misclassification with higher expected emissions.

# Tier 4 Challenges

## SCR Performance at Low Load

- Selective Catalytic Reduction (SCR) requires high exhaust temperatures
- At low engine loads, SCR is less effective, leading to elevated NOx emissions
- Observed in assist tugs operating slowly or idling

Assist Tug	Vessel Speed (knots)	NOx Emission Rate Measured (g/g-fuel)	NOx Emission Rate Expected (g/g-fuel)
1	4	0.030	0.006
1	8	0.036	0.006
1	10	0.006	0.006
1	12	0.006	0.006
2	9	0.078	0.006
2	13	0.002	0.006

## Engine Model Year Misidentification

- Assumed engine model year is one year earlier than vessel build year
- If engine manufactured earlier, vessel may actually meet Tier 3 standards
- Misclassification can explain unexpectedly high emissions in some Tier 4 vessels

# NOx: Repeated Measurements

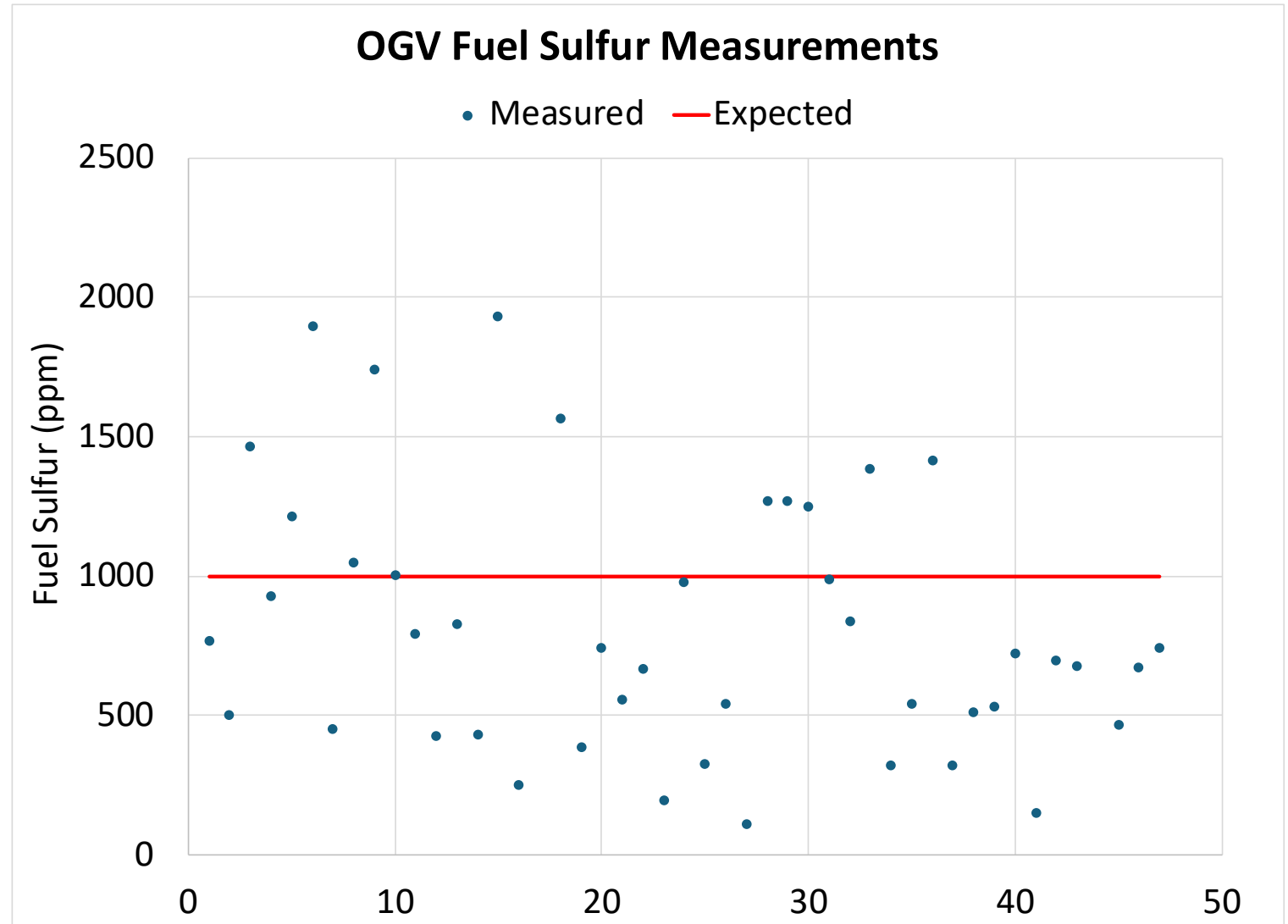
- Many vessels were sampled multiple times across different conditions
- Repeat sampling reveals variability due to changing engine load and atmosphere
- Confidence intervals (CI) often exceeded regression error, showing real-world variability dominates.
- More tests improve confidence in average results (e.g., vessel with 8 samples)

Confidence interval (CI) is a range of values so defined that there is a specified probability that the value of a parameter lies within it  
 Relative confidence interval expresses the width of a confidence interval in relation to the estimated value (as a percentage).

Vessel	Expected NOx Rate (g/g-fuel)	No. of Tests	Average Measured NOx Rate (g/g-fuel)	90% CI (g/g-fuel)	Relative CI
Pushboat	0.022	8	0.023	0.003	14%
Pushboat	0.043	4	0.039	0.017	43%
Assist Tug	0.006	4	0.020	0.018	94%
Pushboat	0.023	4	0.025	0.013	53%
Pushboat	0.047	3	0.035	0.044	126%
Pushboat	0.022	3	0.019	0.009	50%
Pushboat	0.006	3	0.013	0.011	90%

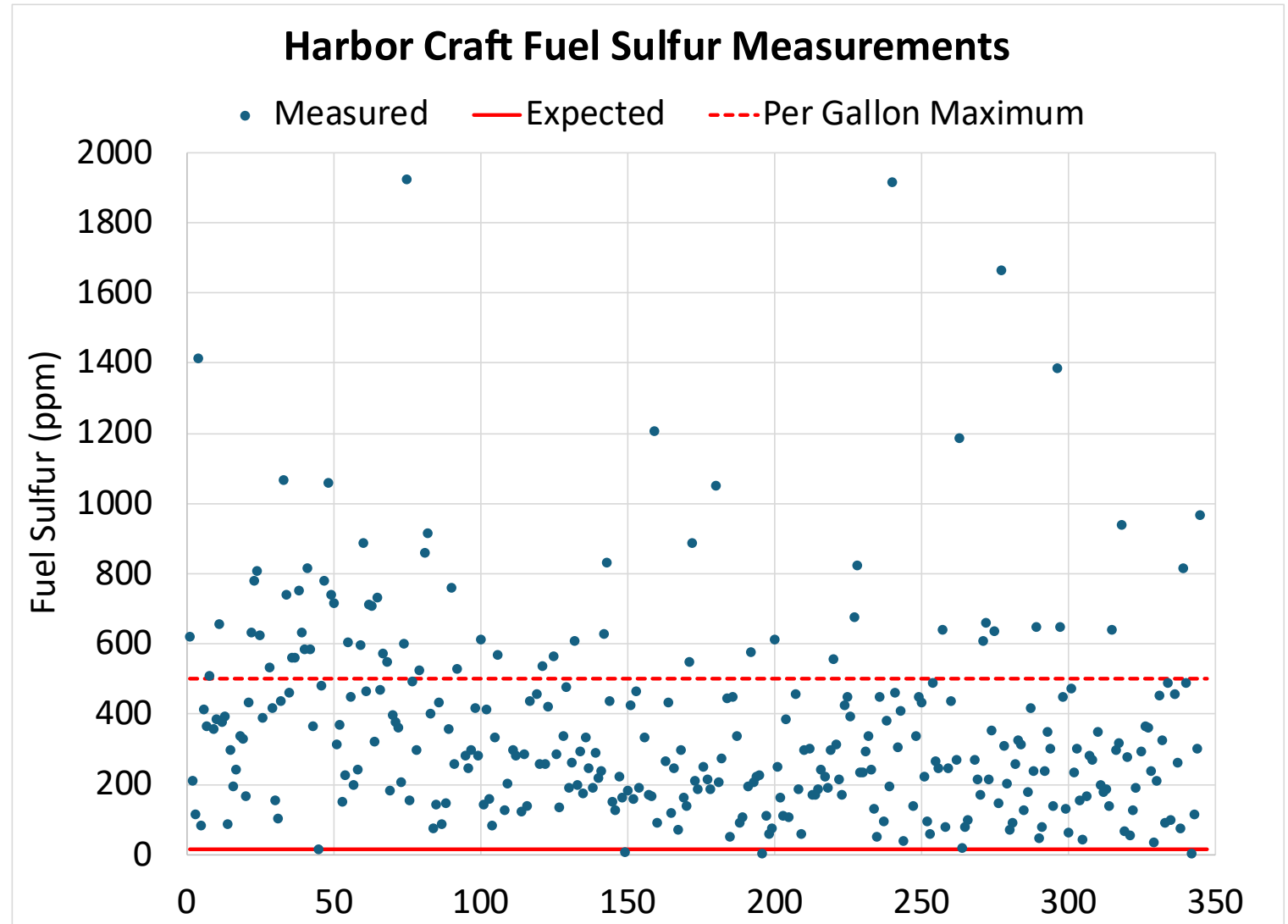
# Fuel Sulfur Regulatory Context

- Category 3 OGVs are allowed up to **1,000 ppm** sulfur in Emission Control Areas (ECA).



# Fuel Sulfur Regulatory Context

- Harbor craft with Category 1 and 2 engines are expected to use less than 15 ppm sulfur diesel.
- Would be essentially undetectable in this study
- Exemptions allow up to 500 ppm in limited cases such as pipeline transmix.



# Fuel Sulfur: Repeated Measurements

- Repeated tests on the same vessels showed variability, and only a few harbor craft results were statistically above the 15 ppm standard.
- More repeat testing is needed to confirm if certain harbor craft are regularly using higher-sulfur fuel.

No. of Test	Sulfur Average (ppm)	95% CI (ppm)	>15 ppm 95% Confidence	>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	266	393	No	No
3	149	395	No	No
3	313	680	No	No

# Carbon Monoxide (CO) and Particulate Matter (PM)

## Carbon Monoxide (CO)

- CO emissions were expected to be low due to lean burn combustion in diesel engines.
- Measured averages: 0.005 g CO/g-fuel for harbor craft and 0.012 g CO/g-fuel for OGVs; generally consistent with EPA expectations by engine make and model year.
- Many CO measurements showed weak correlation with CO<sub>2</sub> because of the low values observed.

## Particulate Matter (PM)

- PM emissions did not show elevated levels in the sampled plumes.
- Instrument response rates for PM were slower and had lower resolution than CO<sub>2</sub> measurements.
- PM could not be reliably assessed in this study.

# Summary

- Demonstrated that field-based plume sampling is feasible for quantifying vessel emission rates.
- Measurements of NO<sub>x</sub> and CO were broadly consistent with EPA expectations, validating both the method and equipment.
- Sulfur emissions from most ocean-going vessels were within expected limits (<1000 ppm),
- Sulfur from harbor craft showed unexpectedly high averages (~308 ppm), warranting further investigation.
- The study provided real-world data that revealed operational effects (e.g., low-load SCR performance) not visible in inventories alone.

# Future Work and Improvements

- **Vessel Data** - Vessel engine information is often incomplete or unverified; better reporting would reduce misclassification.
- **Sampling Strategy** – Increased observations under varying conditions per vessel would reduce uncertainty and strengthen confidence in the results.
- **Using Experimental Design to Address Emission Uncertainties** – Mobile laboratories provide an effective approach for quantifying emission sources with high uncertainty, such as those from locomotives.

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